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UNIVERSITY OF THE WITWATERSRAND

DOCTORAL THESIS

SEARCH FOR HIGH-MASS RESONANCES IN THE $Z\gamma$ CHANNEL AND
QUALITY ASSURANCE OF SCINTILLATION DETECTOR MODULES
OF TILE CALORIMETER PHASE-I UPGRADE OF THE ATLAS
DETECTOR

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Declaration

I hereby declare that this doctoral thesis represents my original work and scholarly contribution. This thesis is being submitted to fulfill the requirements for the award of a Doctor of Philosophy degree at the University of the Witwatersrand. It has not been previously submitted for consideration for any other academic degree or examination at any other institution.



Date: 11/09/2024

Gaogalalwe Mokgatitswane

To my parents, sisters and brothers

My father, Mr Kelaotswe Mokgatitswane,

In awe of your unwavering love for education and your remarkable journey of self-improvement, this doctoral thesis is dedicated to you. Your relentless pursuit of knowledge, even in your later years, has been an inspiration to me.

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Abstract

This thesis presents a search for narrow, high-mass resonances decaying to a Z boson and a photon ($Z\gamma$) in the final state. The analysis utilizes the full Run 2 dataset collected by the ATLAS experiment at the CERN Large Hadron Collider (LHC), corresponding to an integrated luminosity of 140 fb^{-1} of proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 13\text{ TeV}$. The search focuses on a mass range of 220 GeV and 3400 GeV, aiming to identify deviations from the expected background arising from Standard Model processes. A small excess is observed at 250 GeV within the area of interest, with a combined significance of 2.1 standard deviations, indicating the need for further investigation with more data. Upper limits are set on the production cross-section times branching ratio for resonances decaying to $Z\gamma$ across the investigated mass range. When considering spin-0 resonances produced through gluon-gluon fusion, the observed limits at a 95% confidence level range from 65.5 fb to 0.6 fb. For spin-2 resonances produced via gluon-gluon fusion (with quark-antiquark initial states), the limits vary between 77.4 (76.1) fb and 0.6 (0.5) fb. The thesis also highlights the successful Phase-I upgrade of the Tile Calorimeter in the ATLAS detector, ensuring its continued performance. This involved the replacement of degraded Gap-Crack scintillators and Minimum Bias Trigger Scintillators (MBTS) with non-irradiated ones, along-

side optimising their geometry, all in preparation for data taking during LHC Run 3. These upgrade endeavors encompassed the design of new Gap-Crack and MBTS counters, including extensions to higher rapidity, the assembly of these counters, their rigorous qualification, and characterization using radioactive sources (^{90}Sr and ^{137}Cs), along with their seamless integration onto the ATLAS detector.

Keywords: high-mass, $Z\gamma$ resonance, full Run 2 dataset, leptonic decay, HIGGS, Phase-I upgrade, scintillators.

Contents

Declaration	i
Acknowledgements	iii
Research Output	v
Abstract	vii
List of Figures	xiv
List of Figures	xx
List of Tables	xxi
List of Tables	xxii
Nomenclature	xxiii
1 Introduction and Theoretical Background	2
1.1 Introduction	2
1.2 Dissertation Outline	5
1.3 The Standard Model of particle physics	6

1.3.1	Interaction Dynamics	8
1.3.2	The Higgs boson mass measurements	13
1.4	The SM Higgs boson at the LHC	15
1.4.1	Higgs boson production mechanisms	15
1.4.2	Higgs boson decay mechanisms	17
1.5	The multi-lepton anomalies at the LHC	19
1.5.1	The 2HDM+ S model	27
2	The Large Hadron Collider and ATLAS Detector	31
2.1	The Large Hadron Collider	31
2.2	The ATLAS Experiment at the LHC	36
2.2.1	Magnetic system	38
2.2.2	Inner Detector	39
2.2.3	Calorimeter system	41
2.2.4	Muon Spectrometer	45
2.2.5	Trigger and data acquisition system	46
3	The Tile Calorimeter	49
3.1	Segmentation of cells	50
3.1.1	Intermediate Tile Calorimeter	51
3.2	Scintillating tiles and WLS fibers	53
3.3	Light readout system	55
3.4	Radiation environment	57
4	Phase-I Upgrade of the Tile Calorimeter	60
4.1	Introduction	60
4.2	Geometry optimisation and materials	61
4.2.1	Crack counters	61
4.2.2	Minimum Bias Trigger Scintillators (MBTS)	66
4.3	Assembly of detector modules	69

4.3.1	Crack counters	69
4.3.2	Minimum Bias Trigger Scintillators	72
4.4	Quality assurance	73
4.4.1	Scanning of Crack counters with ^{90}Sr source	73
4.4.2	Scanning of MBTS with ^{137}Cs	79
4.5	Installation of detector modules in the ATLAS detector	86
4.5.1	Crack counters	86
4.5.2	MBTS counters	87
4.6	The development of ^{90}Sr Tile scanning table	88
4.6.1	Overview of ^{90}Sr scanning table	89
4.6.2	One-coordinate scanning mechanism	89
4.6.3	Scanner control and data acquisition	92
5	Physics Objects Reconstruction, Identification and Selection at ATLAS	95
5.1	Tracks	96
5.2	Vertices	97
5.3	Topological Clusters	98
5.4	Photons	100
5.5	Electrons	101
5.6	Muons	104
5.7	Jets	106
5.8	Missing transverse momentum	108
6	Search of heavy resonances in the $X \rightarrow Z\gamma$ decay channel	110
6.1	Analysis strategy	110
6.2	Data and Monte Carlo simulation samples	111
6.2.1	Data samples	111
6.2.2	Monte Carlo modeling	114
6.3	Analysis Framework	116

6.4	Object and event selections	116
6.4.1	Object selection	117
6.4.2	Overlap removal	120
6.4.3	Reconstruction and selection of $Z \rightarrow \ell\ell$ decays	122
6.4.4	$X \rightarrow Z\gamma$ reconstruction and selection	124
6.5	Total selection efficiencies	128
6.6	Modeling signal and background processes	130
6.6.1	Signal modeling	131
6.6.2	Background composition	134
6.6.3	Background modeling	140
6.7	Experimental systematic uncertainty	146
6.8	Statistical analysis	151
6.8.1	Likelihood definition	151
6.8.2	The p -value calculation	153
6.8.3	Limit setting	154
6.9	Results	155
6.9.1	Expected only limits	156
6.9.2	Observed limits	159
7	Conclusions	165
Appendix A	TileCal Phase-I upgrade	168
A.1	Response of Crack counters to ^{90}Sr source	169
A.1.1	Regular scans (EBC counters)	169
A.2	Photographs during Installation of detector modules	177
Appendix B	Signal modeling	181
B.1	Double Sided Crystal Ball fits (DSCB)	185
Appendix C	Systematic Uncertainties	195

C.1	Systematic uncertainty on the signal $m_{\ell\ell\gamma}$ distribution	195
C.2	Systematic uncertainty on the signal efficiency	198
C.2.1	Systematic uncertainty on background modeling	206
Appendix D Kinematic distributions		208
Appendix E A list of MC samples		211
Appendix F Searching for heavy scalar resonances in the LHC Run		
2 dataset in the $Z\gamma$ final states using machine learning techniques		214
F.1	Introduction	214
F.2	Methodology	216
F.2.1	Full supervised learning	216
F.2.2	Weakly supervised learning	216
F.2.3	Toolkit for Multivariate Data Analysis (TMVA)	217
F.2.4	Signal and Background samples	217
F.3	Invariant mass spectrum of $Z + \text{photon resonance}$ ($M_{Z\gamma}$)	218
F.3.1	Preselection	219
F.4	Input variables used for S/B classification	220
F.5	Results	222
F.5.1	Overtraining check for DNN classifier	222
F.5.2	Performance evaluation of the DNN classifier	222
F.6	Conclusion	223
F.7	1D distributions of input variables	224

List of Figures

1.1	Table of elementary particles.	7
1.2	Higgs potential $V(\Phi)$	12
1.3	Spectrum of the invariant mass ($m_{\gamma\gamma}$) in the decay process $H \rightarrow \gamma\gamma$. 15	
1.4	Leading Higgs boson production mechanisms in the SM at the LHC. 16	
1.5	Production cross-sections of Higgs boson at $\sqrt{s} = 13$ TeV. 17	
1.6	Higgs boson decay branching ratios, along with their corresponding error bands, are plotted against the Higgs mass. 18	
1.7	Feynman diagrams of the BSM hypothesis. 22	
1.8	The p_T distributions obtained from Run 1 of ATLAS and CMS experiments. 23	
1.9	Plot showing the variation of minimized χ^2 values with respect to the mass of H 25	
1.10	The SM+BSM fit to di-lepton invariant mass spectrum (ATLAS Run 1, $e\mu + b\text{-jet}$). 26	
1.11	The profile likelihood ratios, corresponding to negative 2 times the logarithm, for each individual fit result. 28	
2.1	The LHC ring and its major experiments. 32	

2.2	The integrated luminosity delivered to the ATLAS detector during stable beams for pp collisions.	35
2.3	The mean number of collisions, denoted by $\langle \mu \rangle$, calculated over the integrated luminosity for the years 2015-2018.	35
2.4	A cutaway view of the ATLAS detector.	36
2.5	A right-handed Cartesian and cylindrical co-ordinate used by the ATLAS detector.	37
2.6	The ATLAS inner detector	40
2.7	The Calorimeter System in ATLAS detector	42
2.8	Illustration of an ECAL barrel module at $\eta = 0$	43
2.9	Structure of the ATLAS Muon Spectrometer	45
2.10	The ATLAS TDAQ system for Run 2	47
3.1	Diagram showing TileCal module's mechanical assembly and optical readout.	50
3.2	Segmentation of modules within the Tile Calorimeter.	51
3.3	Gap region scintillators	52
3.4	Sketch of dimensions of the Minimum Bias Trigger Scintillators.	53
3.5	A photograph of fiber routing in one of the extended barrels.	57
3.6	Simulation of the total ionising dose in the TileCal region for Run 1.	58
3.7	A photograph of one of the MBTS counters after operation from 2015 to 2018 (Run 2).	59
4.1	Geometry optimization of Crack scintillator detector module.	62
4.2	Picture of the inner radius of the Crack scintillators with a corresponding diagram showing the locations of the outer heating elements.	63
4.3	Peak position of E/E_{true} and resolution as a function of pseudorapidity for electrons, comparing the MVA calibration with E4 tiles for the Crack region to the initial MVA calibration used for MC15.	64

4.4	Energy resolution ($\sigma_{E_{calib}}/E_{gen}$) estimated from the interquartile range of E_{calib}/E_{gen} as a function of $ \eta $ for electrons in different E_T ranges.	65
4.5	High-performance PVT EJ-208 scintillating tiles and the emission spectrum.	65
4.6	Y-11 green WLS optical fibres, absorption and emission spectra.	66
4.7	Geometry optimization of MBTS scintillator detector module.	67
4.8	Inner and outer MBTS plates right after production, without fibre grooves.	68
4.9	Absorption and emission spectra of dyes.	69
4.10	Standard Tyvek for E3 and E4.	70
4.11	Wrapping scintillator tiles with a Tyvek.	70
4.12	A wrapped E3 tile with a black tape placed along the edge.	70
4.13	Aluminum cans for housing scintillator tiles.	71
4.14	WLS fibre placement.	71
4.15	A complete assembled Crack counter.	72
4.16	Assembly of MBTS detector modules.	73
4.17	Radiation source and scintillation light transmission.	74
4.18	Experimental setup of the ^{90}Sr scan.	75
4.19	Fine and regular scans	76
4.20	PMT voltage response Vs. the position of the source for EBC Crack counters.	77
4.21	Special E4 segment of EBC4 connected to orange fibres.	78
4.22	Relative voltage Vs. source position (Crack counters).	78
4.23	Slopes for EBC and EBA Crack counters.	80
4.24	The highest signal output for EBC and EBA Crack counters	81
4.25	^{137}Cs γ -source scan system.	82
4.26	Pedestal values of PMT2 and PMT14 measured without the source.	83
4.27	MBTS ADC counts response before and after subtracting the pedestal.	83

4.28	Zoomed regions of maximum signal output for PMT14 and PMT2 of run 11316.	84
4.29	Relative ADC counts of maximum amplitude and average for C-side inner counters and outer MBTS counters.	85
4.30	Maximum ADC counts comparison for C-side and A-side of inner counters and outer counters.	86
4.31	Relative maximum amplitude and average ADC counts for A-side inner counters and outer.	86
4.32	Certified crack counters transported to Point-1 for installation. . .	87
4.33	The ^{90}Sr scan box.	90
4.34	Radiation source positioning mechanism.	91
4.35	Daisy chain configuration.	91
4.36	Arduino microcontroller connected to X-NUCLEO-IHM02A1 expansion board.	92
4.37	Schematic representation of the ^{90}Sr scanbox setup.	93
4.38	A photograph of ^{90}Sr scanning-box facility.	94
4.39	Validation plots of the scan box.	94
5.1	Vertex topologies important for physics analyses in ATLAS. . . .	98
6.1	$Z \rightarrow ee$ and $Z \rightarrow ee(\gamma)$ selection efficiency for Z bosons produced in $X \rightarrow Z(ee)+\gamma$ and $X \rightarrow Z(ee(\gamma))+\gamma$ events versus m_X applying acceptance cuts only on the reconstructed objects.	123
6.2	Data m_{ll} distributions in the ee channel for events containing ee , $ee(\gamma)$ and $ee + ee(\gamma)$ pairs.	125
6.3	Distributions of kinematic properties for photons associated with reconstructed Z boson candidates ($m_{\ell\ell} > 200 \text{ GeV}$) in both MC and real data.	127

6.4	3-body mass distribution $m_{\ell\ell\gamma}$ for background $Z\gamma$ simulated events for either $p_T^\gamma > 15$ GeV, $p_T^\gamma/m_{\ell\ell\gamma} > 0.2$ and $p_T^\gamma/m_{\ell\ell\gamma} > 0.3$ requirements.	128
6.5	The efficiency of reconstructing and selecting the $X \rightarrow Z\gamma$ final state, including kinematic acceptance, is plotted against the mass point m_X	130
6.6	The definition of DSCB function.	132
6.7	Results of simultaneous fits to high-mass ggF spin-0 simulations for ee channel with ee and $e + e(\gamma)$ events.	133
6.8	Results of simultaneous fits to high-mass ggF spin-0 simulation for the $\mu\mu$ channel.	134
6.9	Feynman diagrams for $Z + \gamma$ production from Initial State Radiation.	135
6.10	Results of the template fit to the calorimeter isolation distribution of photon candidates in the ee channel.	138
6.11	Results of the template fit to the calorimeter isolation distribution of photon candidates in the $\mu\mu$ channel.	139
6.12	$Z + \gamma$ purities versus the resonance mass extracted using the template fit for the ee and $\mu\mu$ channels.	139
6.13	$Z\gamma$ mass distributions comparing data to MC expected background.	140
6.14	The $m_{\ell\ell\gamma}$ distributions of $Z\gamma$, Z +jets and purity-reweighted Z +jets events.	143
6.15	The $m_{\ell\ell\gamma}$ distributions of $Z\gamma$, Z + jets and reweighted- $Z\gamma$ events.	145
6.16	The ratio of the expected signal yield (S) to its uncertainty due to the background model (δS) as a function of the resonance mass (m_X).	146
6.17	The invariant $Z\gamma$ mass distributions of events satisfying the high-mass selection in data for the $ee\gamma$ and $\mu\mu\gamma$ channels. The lower mass region is zoomed in and displayed in the inset plot where an excess of 2.1σ at 250 GeV can be seen.	157

6.18	The invariant $Z\gamma$ mass distributions of events satisfying the high-mass selection in data for the $ee\gamma$ and $\mu\mu\gamma$ channels. The lower mass region is zoomed in and displayed in the inset plot where an excess of 2.3σ at 420 GeV can be seen.	158
6.19	Observed local p -value versus the distribution of the invariant mass $m_{Z\gamma}$	159
6.20	Expected upper limits at 95% CL in the mass range between 200 GeV and 3500 GeV for ggF spin-0 resonance.	160
6.21	Comparison between the expected upper limits at a 95% CL of high mass resonance production cross sections as a function of $m_{ll\gamma}$ for $ee + \mu\mu$ channels and $ee + \mu\mu$, including the $e + e(\gamma)$ events. . . .	161
6.22	A graphical representation of the expected upper limits at a 95% CL on the product of the production cross section times branching ratio (BR) for a spin-2 resonance, X , decaying to $Z\gamma$ ($q\bar{q}$ and ggF production processes).	162
6.23	A graphical representation of the 95% CL upper limits on the product of the production cross section times branching ratio (BR) of a narrow-width spin-0 resonance, X , decaying to $Z\gamma$ (ggF).	163
6.24	A graphical representation of the 95% CL upper limits on the production cross section times branching ratio (BR) of a narrow-width spin-2 resonance, X , decaying to $Z\gamma$ ($q\bar{q}$ and ggF).	164
A.2	PMT voltage response Vs. the position of the source for EBC crack counters.	173
A.3	PMT voltage response Vs. the position of the source for EBA crack counters.	173
A.4	PMT voltage response Vs. the position of the source for EBC crack counters.	174

A.5	PMT voltage response Vs. the position of the source for EBA crack counters.	174
A.6	E3E4 plots with low signal output due to physically damaged connecting fibre cable.	175
A.7	E3E4 strange plots.	176
A.8	Special E3E4 counters connected to orange fibres.	177
A.9	Installation of crack counters on the ATLAS detector.	178
A.10	A photograph of clear optical cable connecting MBTS counters to the calorimeter.	178
A.11	Installation of MBTS counters on the ATLAS detector.	179
A.12	Finalization of the installation with the aluminium foil.	180
F.1	A schematic Feynman diagrams of the production and decay of scalars in the RSH and AZH models.	217
F.2	Invariant mass distribution of the $Z\gamma$ in association with E_T^{miss} . . .	219
F.3	Preselection for the pure signal and pure background in the mass-window, and pure background in the sideband.	220
F.4	Evaluation of classifier training output for weakly supervised and full supervised.	222
F.5	Background rejection versus signal efficiency plot.	223

List of Tables

1.1	A summary of the four fundamental forces and their relative strengths. The gravity interaction is not included in the SM.	8
1.2	Field Theory Boson Properties.	14
1.3	Compilation of ATLAS and CMS results on potential anomalous observations	19
1.4	Overview of multi-lepton excesses in LHC measurements.	25
1.5	Summary of the SM+BSM fit results	27
4.1	ADC counts from Cs runs for MBTS C-side counters at maximum and average with pedestal subtracted.	84
4.2	ADC counts from Cs runs for MBTS A-side counters at maximum and average with pedestal subtracted.	85
6.1	Trigger strategy for 2015-2018 data and MC.	112
6.2	Summary of object selections.	120
6.3	Selection requirements for high-mass $Z(\rightarrow \ell\ell)\gamma$ analysis.	128
6.4	Parameterization of the DSCB parameters with respect to m_X in the simultaneous fit.	133
6.5	Extracted $Z + \gamma$ purity using template fit for ee and $\mu\mu$ channels.	138

6.6	Description of Functions	141
6.7	Description of Dijet Models	141
6.8	The background models satisfying the criteria of spurious signal study.	146
C.1	Sources of systematic uncertainty influencing the measurement of $\sigma(pp \rightarrow X \rightarrow Z\gamma)$ and their corresponding effects on the measurement uncertainty.	196
C.2	Impacts of grouped dominant systematic uncertainties.	197
C.3	Absolute value of spurious signal for both $ee\gamma$ and $\mu\mu\gamma$ channels within the mass range of 220–3400 GeV.	207
E.1	The fast simulation MC $Z + \gamma$ background samples in three-body invariant mass slices.	211
E.2	The full simulation MC $Z + \gamma$ background samples in slices of the transverse momentum of the photon.	212
E.3	ggF spin-0 signal samples from 200 GeV to 5000 GeV.	212
E.4	ggF spin-2 signal samples from 200 GeV to 5000 GeV.	212
E.5	$q\bar{q}$ spin-2 signal samples from 200 GeV to 5000 GeV.	213

Nomenclature

Acronyms

ATLAS	A Toroidal LHC Apparatus
BSM	Beyond the Standard Model
CERN	Conseil Européen pour la Recherche Nucléaire
CMS	Compact Muon Solenoid
DSCB	Double-sided crystal ball
EB	Extended Barrel
EM	Electromagnetic
EW	Electroweak
EWSB	Electroweak symmetry breaking
ggF	gluon–gluon fusion
HEP	High Energy Physics
ID	Inner Detector
IP	Interaction point

ITC	Intermediate Tile Calorimeter
LABS	Laboratory for Accelerator Based Sciences
LAr	Liquid Argon Calorimeter
LB	Long Barrel
LHC	The Large Hadron Collider
LINAC	LINEar ACcelerator
LO	Leading order
MBTS	Minimum Bias Trigger Scintillators
MC	Monte Carlo
MeV	Mega Electronvolt
NLO	Next-to-leading Order
NNLO	Next-Next-to-leading Order
PMT	PhotoMultiplier Tube
PMT	Photomultiplier Tube
POPOP	Di-phenyloxazolyl
PS	Polystyrene
PSB	Proton Synchrotron Booster
PTP	p-Terphenyl
PVT	Polyvinyl toluene
QCD	Quantum Chromodynamics
Run-I	The LHC data taking period in the year 2009 to 2012
Run-II	The LHC data taking period in the year 2015 2018

SCT	Semiconductor Tracker
SM	Standard Model
SPS	Super Proton Synchrotron
TileCal	Tile Hadronic Calorimeter
TRT	Transition Radiation Tracker
UPS 923A	Ukrainian Polystyrene-based Scintillator
VBF	Vector boson fusion
vev	Vacuum expectation value

Symbols

β_g	The strength of the Yukawa coupling of H to top quarks
η	Pseudorapidity
γ	Photon
$\mathcal{L}$	Lagrangian density
$\mathcal{L}$	Likelihood function
μ	Muon
ν_τ	Tau neutrino
Φ	General field
ϕ	Scalar complex field
$\sqrt{s}$	Center-of-mass energy
τ	Tau lepton
$\mathbf{c}$	Charm quark
b	Bottom quark

c	Speed of light in vacuum
d	Down quark
e	Electron
g	Gluon
H	Heavy boson, heavier than h
h	Standard Model Higgs boson
L	Lagrangian
N_i	Heavy neutrinos unlike the SM neutrino ν
p_T	The transverse momentum of a particle
pp	Proton-proton
S	Higgs-like scalar boson
s	Strange quark
t	Top quark
u	Up quark
$W^\pm$	W -boson
Z^0	Z -boson
E_T^{miss}	Transverse missing energy

Introduction and Theoretical Background

1.1 Introduction

Particle physics delves into the fundamental constituents of matter and the forces governing their interactions. Over the past century, theoretical advancements and groundbreaking experiments have revolutionized our understanding of the subatomic realm. Cutting-edge technologies, diverse experimental approaches, and the construction of large-scale facilities have been instrumental in this progress. These efforts culminated in the development of the Standard Model (SM) of particle physics, a concise and elegant theoretical framework that successfully explains and predicts a vast array of experimental observations. The discovery of the Higgs boson at the Large Hadron Collider (LHC) marked the experimental confirmation of all fundamental particles within the SM.

Despite its remarkable success, the SM remains incomplete. Several key questions in particle physics lie outside its explanatory scope. These include the observed asymmetry between matter and antimatter, the origin of neutrino masses, and the nature of dark matter and dark energy. Recent experimental findings have also challenged the SM. Anomalies in the muon's magnetic dipole moment measured by the Muon $g - 2$ experiment and discrepancies in the W boson mass observed

by the Collider Detector at Fermilab experiment point towards potential limitations of the SM. In response to these inconsistencies, physicists have proposed numerous theoretical models extending beyond the Standard Model (BSM). These BSM theories postulate new particles and forces to address the shortcomings of the SM, and dedicated experiments are underway to search for evidence of these phenomena.

Recent analyses by the ATLAS and CMS collaborations at the LHC have revealed discrepancies between observed and predicted rates of multi-lepton production in proton-proton collisions [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]. These anomalies encompass various final states, including pairs of opposite-sign or same-sign leptons, and configurations with three leptons, both accompanied by b -quarks or not. Notably, these discrepancies are observed in specific phase-space regions dominated by different SM processes.

To explain these anomalies, several theoretical models have been developed as extensions to the SM, introducing additional scalar fields denoted as H and S . The mass of the H field is approximately 270 GeV, while the S field resembles the SM Higgs boson with a mass around 150 GeV. This motivates the search for Higgs-like resonances with masses in the electroweak scale range, where SM backgrounds are prevalent. To explore and gain a deeper understanding of these phenomena, the wealth of data produced by the LHC and the complexities of theoretical models in high-energy physics require sophisticated techniques for anomaly detection and analysis.

This thesis comprises two parts. The first part focuses on the exploration of heavy resonances in the $Z(\rightarrow ee \text{ or } \mu\mu)\gamma$ final states using the ATLAS detector. This analysis utilizes a large dataset collected by ATLAS to investigate new phenomena in physics. While the discovery of a novel boson consistent with the SM Higgs boson has opened up new avenues of research, many questions remain unanswered. Searches for BSM physics and investigations of theoretical models

related to production processes of Higgs boson are areas of active research that may provide answers using the vast datasets from the LHC. The ATLAS and CMS experiments have been at the forefront of these endeavors.

The second part of this thesis focuses on the quality control of scintillation detector modules of the ATLAS Tile Calorimeter (TileCal). Accurate measurements of various parameters in physics data analysis heavily rely on the exceptional performance of all sub-detector systems in the ATLAS detector. In this regard, enhancements to the ATLAS experiment are discussed, with a specific focus on the ATLAS TileCal sub-detector system. The Crack and Minimum Bias Trigger scintillator counters within the TileCal are vital for adjusting the electromagnetic (EM) energy response and providing inputs to the trigger, respectively. However, these scintillator counters are susceptible to radiation damage in the harsh environment within the ATLAS detector. Over time, their optical properties degrade, potentially compromising the effectiveness of the detector. Hence, there is a critical need to investigate the long-term durability of detector modules used in high-energy physics applications.

During the Run 2 data collection period (2015-2018) at the LHC with an energy of $\sqrt{s} = 13$ TeV, the Gap scintillators, located on the front of the Liquid Argon EM End-cap calorimeters and in close proximity to the beam axis, experienced radiation-induced degradation. As a result, they had to be replaced with non-irradiated, radiation-tolerant scintillators with optimized geometry during the Phase-I upgrade. Extensive experiments were conducted to understand the optical properties affected by radiation-induced degradation of plastic scintillators. These investigations aided in the selection of suitable replacement plastic scintillators for the counters' production. The upgrade activities included the design, assembly, qualification, and characterization of the new Crack and Minimum Bias Trigger scintillator counters using radioactive sources (^{90}Sr and ^{137}Cs) to ensure optimal performance in terms of linearity and signal homogeneity. Subsequently,

these counters were installed on the ATLAS detector.

1.2 Dissertation Outline

Chapter 1 provides a concise overview of the Standard Model, including a discussion on Higgs phenomenology, Higgs production modes, and decay channels. Furthermore, it briefly reviews a Beyond Standard Model theory, setting the theoretical foundation for the subsequent chapters in the thesis. Chapter 2 delves into the details of the Large Hadron Collider and the ATLAS detector, which are crucial for conducting the experiment and collecting the data needed for analysis. The information in this chapter is drawn from the Technical Design Reports, providing a comprehensive understanding of the experimental setup. Chapter 3 introduces TileCal, covering various aspects such as cell segmentation, scintillating tiles, wavelength-shifting (WLS) fibers, and the radiation environment. In Chapter 4, an in-depth overview of TileCal Phase-I Upgrade activities is provided. Chapter 5 focuses on the reconstruction algorithms necessary for accurately defining the physics objects under study, such as electrons, photons, muons, and jets. This includes reconstruction from initial detector information, calibration techniques, and final particle identification. Chapter 6 presents study on the search for heavy resonances decaying into a Z boson and a photon, with the Z boson further decaying into an electron or muon pair. This chapter outlines the methodology and analysis techniques employed in the search for this specific decay mode, which is a key focus of the thesis. Additionally, this study is complemented by the machine learning analysis approach in Appendix F, which also focuses on the search for heavy resonances in the $Z\gamma$ final states using machine learning techniques. Overall, these chapters provide a comprehensive framework for the analysis conducted in the thesis, laying the groundwork for the subsequent findings and conclusions presented in Chapter 7.

1.3 The Standard Model of particle physics

Centuries of scientific inquiry have culminated in the development of the SM of particle physics, a highly successful theoretical framework that describes the fundamental building blocks of matter and the forces governing their interactions [11, 12]. As illustrated in Figure 1.1, the SM categorizes all fundamental particles into two classes based on their spin: fermions, with half-integer spin that obey Fermi-Dirac statistics, and bosons, with integer spin that adhere to Bose-Einstein statistics [13].

The SM posits four fundamental interactions: the EM, weak, and strong interactions, each mediated by its own set of force-carrying bosons. While gravity is recognized as a fundamental interaction, it remains outside the scope of the current SM framework based on quantum field theory (QFT). The immense weakness of gravity relative to the other forces at the subatomic level renders it negligible in most SM research.

Fermions, a fundamental particle class, encompass six leptons, six quarks, and their corresponding antiparticles. These particles are further organized into three generations based on significant mass differences.

- **Leptons:** Three charged lepton types exist: the electron (e^-), muon (μ^-), and tau (τ^-). Each comes with a corresponding neutral counterpart, the neutrinos: electron neutrino (ν_e), muon neutrino (ν_μ), and tau neutrino (ν_τ). Charged leptons interact via the weak force and electromagnetism. Notably, each lepton has an antilepton partner with identical mass but opposite charge (or no charge for neutral leptons).
- **Quarks:** Unlike leptons with whole-number charges, quarks exhibit fractional electric charges of either $+\frac{2}{3}e$ or $-\frac{1}{3}e$. The six quark “flavors” include up, down, charm, strange, top, and bottom. Up, charm, and top quarks

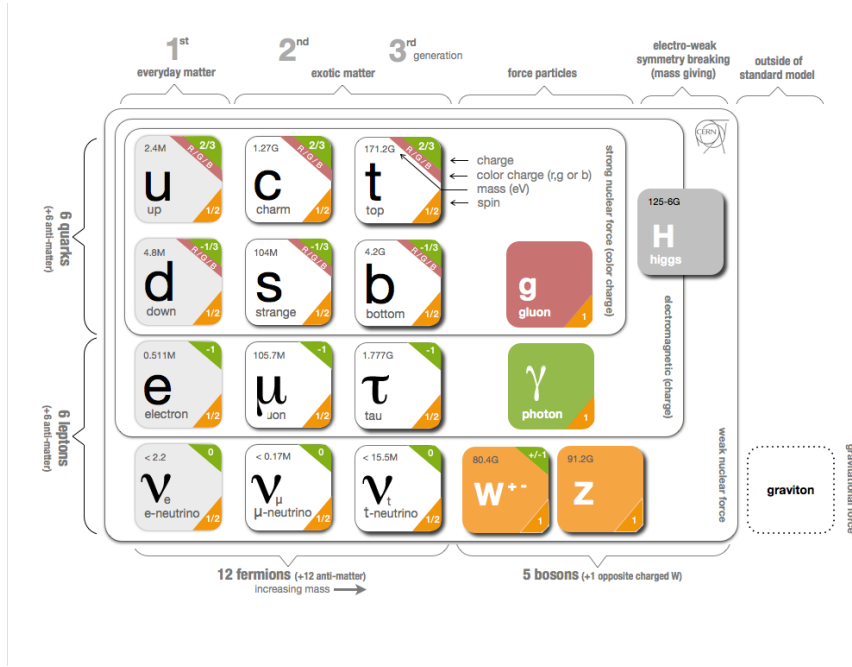


Figure 1.1: Table of elementary particles [14].

possess a charge of $+\frac{2}{3}e$, while down, strange, and bottom quarks carry a charge of $-\frac{1}{3}e$. A distinguishing feature of quarks is their “color charge”, a property responsible for their strong interactions. Importantly, quarks are never observed as free particles, but rather exist in bound states called hadrons, such as mesons and baryons.

In the context of QFT, various dynamics are used to describe the interactions. Table 1.1 displays the field theory and attributes of the SM bosons, with the exception of the Higgs boson.

The SM also contains another class of elementary particles known as bosons. Bosons mediate forces between all elementary particles and are classified into gauge and scalar bosons based on their spin quantum numbers, which are 1 and 0, respectively. The gauge bosons include massless photons (γ), 8 different kinds of massless gluons (g), charged weak bosons ($W^\pm$), and the neutral weak boson (Z). On the other hand, the scalar bosons include only one particle called Higgs boson.

Table 1.1: A summary of the four fundamental forces and their relative strengths. The gravity interaction is not included in the SM [15].

Interaction	Theory	Mediator	Spin	Mass [GeV]
Strong	Quantum	Gluon (g)	1	0
	Chromodynamics (QCD)			
Electromagnetic	Quantum	Photon (γ)	1	0
	Electrodynamics (QED)			
Weak	Electroweak Theory	$W^\pm$	1	80.4
		Z^0	1	91.2
Gravity	General Relativity	Graviton (G)	2	0

1.3.1 Interaction Dynamics

The SM utilizes QFT as its mathematical framework. QFT describes particles as excitations of quantum fields and their interactions using Lagrangians. The SM is constructed based on the gauge symmetry group $SU(3)_C \times SU(2)_L \times U(1)_Y$, which gives rise to the three fundamental interactions. The theories corresponding to each interaction are explained in the rest of this section.

1.3.1.1 Quantum Chromodynamics

Quantum Chromodynamics (QCD) is a Quantum Field Theory (QFT) that elucidates the strong force responsible for binding atomic nuclei and other particles known as hadrons [16]. It is a non-Abelian gauge theory characterized by the $SU(3)_C$ local symmetry, with the color charge denoted by the subscript C .

The QCD Lagrangian density is given by:

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4}G_{\mu\nu}^a G_a^{\mu\nu} + \sum_{f=1}^{N_f} \bar{\psi}_f (i\gamma^\mu D_\mu - m_f) \psi_f, \quad (1.3.1)$$

where $G_{\mu\nu}^a$ is the field strength tensor for the gluon field A_μ^a , m_f is the mass of the f th quark, ψ_f is the quark field, and D_μ is the covariant derivative. The gluon field has eight degrees of freedom, corresponding to the eight generators of $SU(3)$.

The covariant derivative is given by:

$$D_\mu = \partial_\mu - ig_s T^a A_\mu^a, \quad (1.3.2)$$

where g_s is the strong coupling constant, T^a are the generators of the $SU(3)$ group, and A_μ^a is the gluon field.

The strong force interacts via color charge, which can be red, green, or blue [17]. Hadrons are bound states that are created when particles with color charge combine. If a quark is ejected from a hadron, the strong force's increasing strength with distance causes stored energy to be released. This energy spontaneously creates new particles with color charge from the vacuum, which bind with the free quark in a process known as hadronization. The hadronization process leads to the creation of showers of hadrons, which can be detected and reconstructed as jets in a particle detector. It is essential to understand the behavior of the strong force and the hadronization process to study high-energy particle collisions and to make precise predictions in particle physics.

1.3.1.2 Quantum Electrodynamics

Quantum Electrodynamics (QED) is a quantum field theory that describes the interaction of EM radiation with electrically charged matter. It is based on the principle of gauge invariance and is formulated using a local $U(1)$ gauge symmetry.

The QED Lagrangian density is given by:

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - m)\psi \quad (1.3.3)$$

where $F_{\mu\nu}$ is the EM field tensor, ψ is the fermion field, m is the fermion mass, D_μ is the covariant derivative, and γ^μ are the Dirac matrices.

The covariant derivative is defined as:

$$D_\mu = \partial_\mu - ieA_\mu, \quad (1.3.4)$$

where e is the electric charge, and A_μ is the EM gauge field. The gauge field is required to maintain local $U(1)$ gauge invariance, which means that the physical predictions of the theory cannot depend on the choice of gauge.

The QED Lagrangian density makes predictions regarding the existence and properties of photons, which act as the mediators of the EM force. Specifically, photons are predicted to be massless particles with spin 1. In addition to this, QED also predicts the phenomenon of electron-positron pair production and annihilation. Pair production occurs when a high-energy photon interacts with matter and creates an electron-positron pair, while annihilation is the process by which an electron and a positron annihilate, resulting in the production of a photon. QED has demonstrated exceptional success in describing a broad array of physical phenomena and has undergone rigorous experimental verification. Additionally, the theory's predictive power has enabled the computation of physical quantities with remarkable accuracy, positioning it as one of the most precise theories in physics.

1.3.1.3 ElectroWeak Theory and Higgs mechanism

The electroweak theory unifies the electromagnetic (EM) and weak forces into a single description [12, 18]. This theory utilizes a non-Abelian gauge theory with the gauge group $SU(2)_L \times U(1)_Y$. The $SU(2)_L$ group is associated with the weak interaction, while the $U(1)_Y$ group is linked to the EM interaction.

The foundation of the electroweak theory lies in the Lagrangian density, represented by Equation 1.3.3. The covariant derivative, which takes into account the gauge symmetry of the theory, is defined as:

$$D_\mu = \partial_\mu - ig_2 \frac{\tau^i}{2} W_\mu^i - ig_1 \frac{Y}{2} B_\mu, \quad (1.3.5)$$

where g_1 and g_2 are the coupling constants for the $U(1)_Y$ and $SU(2)_L$ groups, respectively. τ^i represent the Pauli matrices, W_μ^i are the gauge fields associated with the $SU(2)_L$ group, and B_μ is the gauge field for the $U(1)_Y$ group. The concept of hypercharge, denoted by Y , is defined as $Y = 2(Q - T_3)$, where Q represents the electric charge of a particle and T_3 signifies the third component of its weak isospin.

The Higgs field is also introduced in the electroweak theory to give mass to the weak gauge bosons. The Higgs field is a complex scalar field that transforms as a doublet under $SU(2)_L$:

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \quad (1.3.6)$$

where ϕ^+ and ϕ^0 are complex scalar fields. The Lagrangian density for the Higgs field is given by:

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi), \quad (1.3.7)$$

where $V(\Phi)$ is the Higgs potential defined as:

$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2, \quad (1.3.8)$$

where Φ is the Higgs field, λ represents the self-coupling parameter, and μ signifies the mass parameter. In order for the potential to possess a finite minimum, corresponding to the vacuum state, λ must be positive, but μ^2 need not be. If $\mu^2 > 0$, the potential will possess a minimum at $\Phi = 0$, which is unremarkable;

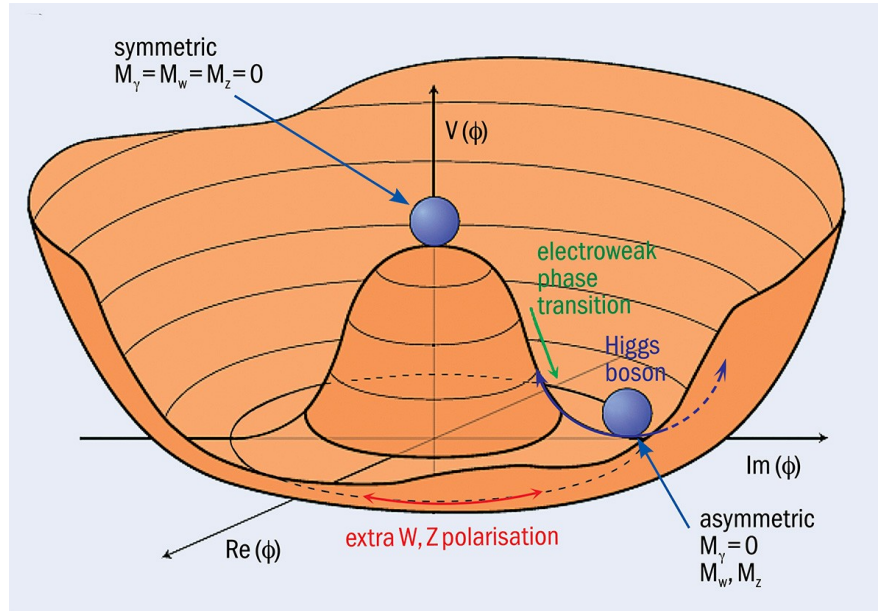


Figure 1.2: Illustration of the Higgs potential, denoted as $V(\Phi)$, as a function of the Higgs field (Φ). The potential is described by Equation 1.3.8 and exhibits a characteristic shape resembling a Mexican hat due to the term with $\mu^2 < 0$. This specific case, where μ^2 is negative, is crucial for the Higgs mechanism to endow elementary particles with mass [19].

however, if $\mu^2 < 0$, the potential will have an infinite set of degenerate minima. This results in a non-zero vacuum expectation value (VEV) ν , such that:

$$\Phi^\dagger \Phi = \frac{\nu^2}{2} = -\frac{\mu^2}{2\lambda}, \quad (1.3.9)$$

where the potential is represented graphically as a “Mexican hat” shape as illustrated in Figure 1.2. Despite the symmetry of the potential, the vacuum state only corresponds to a specific point, which breaks the symmetry. This phenomenon is referred to as spontaneous symmetry breaking¹ [20, 21, 22, 23]. The vacuum state is conventionally chosen as:

¹The BEH mechanism and the Higgs boson, utilized by Higgs, Brout, and Englert in 1964, explains the masses of $W^\pm$ and Z^0 bosons.

$$\Phi^0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu \end{pmatrix}, \quad (1.3.10)$$

and expanding the field around its minimum and expressing it in the unitary gauge,

$$\Phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu + h(x) \end{pmatrix}, \quad (1.3.11)$$

the Equation 1.3.7 can be written as:

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - \frac{1}{2}(-2\mu^2)h^2 - \lambda\nu h^3 - \frac{1}{4}\lambda h^4, \quad (1.3.12)$$

where the second term in Equation 1.3.12 allows for the extraction of the mass of the Higgs field as:

$$m_H = \sqrt{-2\mu^2} = \nu\sqrt{2\lambda}. \quad (1.3.13)$$

Fermions acquire mass through their interaction with the Higgs field via the Yukawa coupling. The strength of this interaction, denoted by the coupling constant λ_f , is directly proportional to the mass m_f of the specific fermion involved. This relationship can be mathematically expressed as:

$$m_f = \frac{\lambda_f \nu}{\sqrt{2}} \quad (1.3.14)$$

1.3.2 The Higgs boson mass measurements

The discovery of the Higgs boson in 2012 at the LHC at CERN stands as a landmark achievement in particle physics. This long-sought particle, postulated

Table 1.2: Field Theory Boson Properties [15].

Field	Spin	EM Charge	Color	Mass (GeV)	Y_W	T_3
Higgs Boson	0	0	no color	125.25 ± 0.17	$\pm \frac{1}{2}$	± 1

in the 1960s as a cornerstone of the SM, plays a crucial role in explaining how other fundamental particles acquire mass. The successful detection of the Higgs boson culminated from decades of theoretical and experimental endeavors, involving collaborations by thousands of scientists and engineers worldwide [24, 25].

Following its discovery, extensive research has focused on precisely measuring the properties of the Higgs boson, including its mass, spin, and interaction strengths with other particles, as summarized in Table 1.2. These detailed measurements offer invaluable insights into the nature of the universe and contribute significantly to refining our understanding of the fundamental particles and forces governing it.

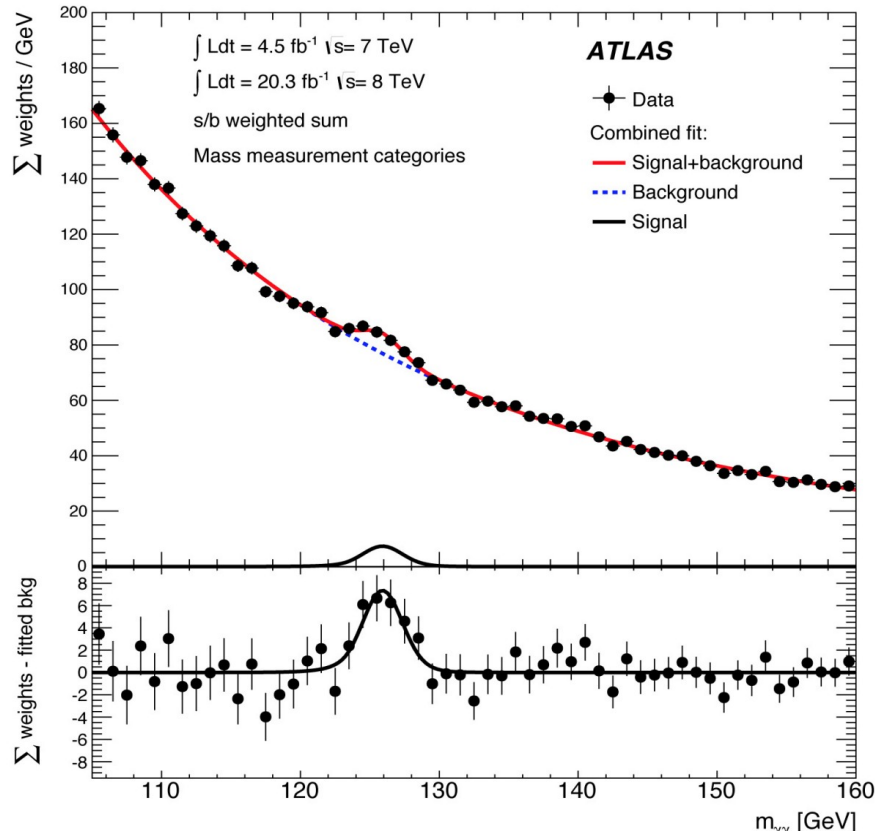


Figure 1.3: Spectrum of the invariant mass ($m_{\gamma\gamma}$) in the decay process $H \rightarrow \gamma\gamma$, using the combined data from $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV, within the mass range of 105-160 GeV [26].

1.4 The SM Higgs boson at the LHC

1.4.1 Higgs boson production mechanisms

Within the SM, the Higgs boson exhibits the strongest interactions with massive particles, such as top and bottom quarks, as well as the W and Z bosons [15, 27]. Consequently, its production at the LHC is dominated by four key mechanisms, each characterized by distinct Feynman diagrams illustrated in Figure 1.4.

- **Gluon-gluon Fusion (ggF):** This is the most prevalent Higgs boson production mode at the LHC, primarily occurring through a fermion loop. In this process, two gluons from the colliding protons interact to produce the

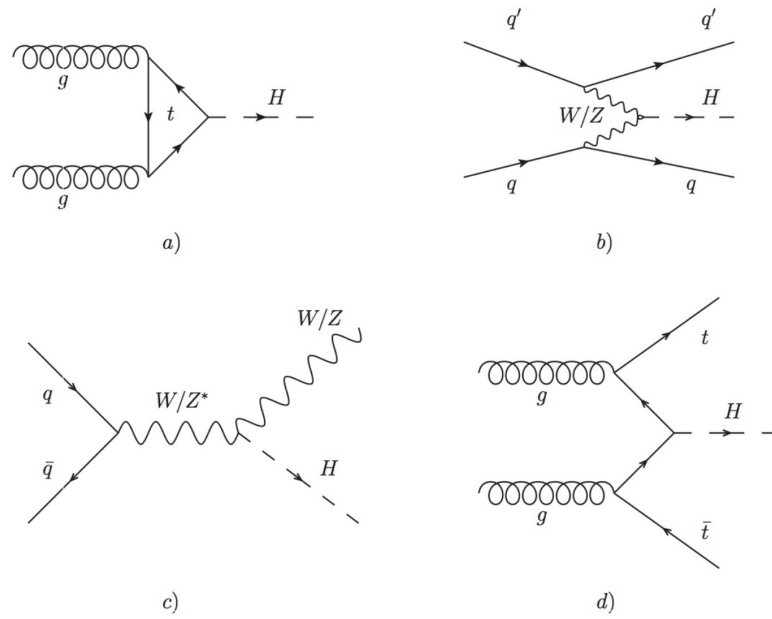


Figure 1.4: Leading Higgs boson production mechanisms in the SM at the LHC: (a) $gg \rightarrow H$, (b) VBF, (c) VH ($V = W, Z$), and (d) $t\bar{t}H$ [28].

Higgs boson.

- **Vector Boson Fusion (VBF):** This process involves the radiation of a vector boson (W or Z) by each of the initial state quarks. These radiated bosons subsequently annihilate to produce the Higgs boson. The two quarks hadronize into jets, typically emitted in the forward regions of the detector, offering a distinctive final state signature for VBF production. While the VBF cross-section is significantly lower than ggF, its distinct topology allows for cleaner identification of the Higgs boson signal.
- **Higgs Strahlung (WH or ZH):** This process involves the production of a W or Z boson along with a Higgs boson in the collision of a quark and an antiquark. However, the W or Z boson must possess sufficient energy to radiate the Higgs boson, making this a less frequent production mode.
- **Top-associated Production ($t\bar{t}H$):** This is the least common production

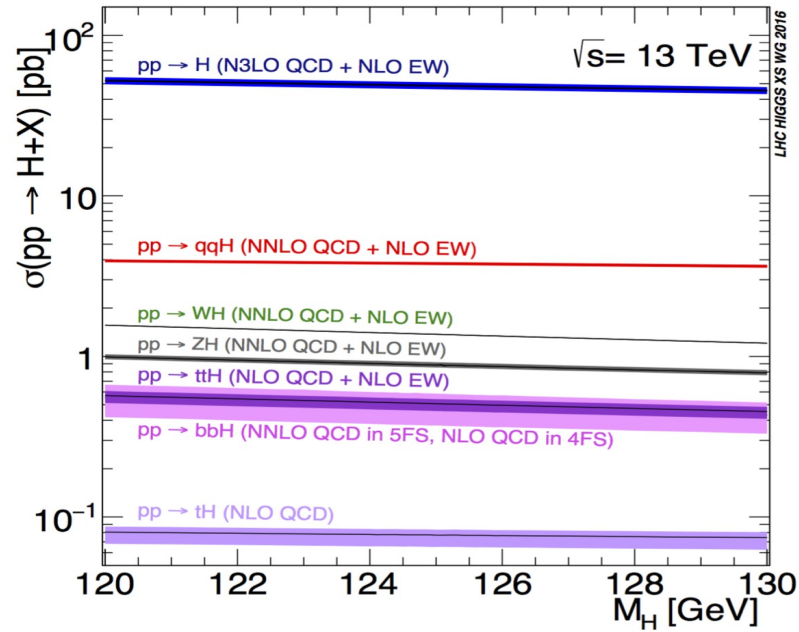


Figure 1.5: Production cross-sections of Higgs boson at $\sqrt{s} = 13$ TeV [29].

mechanism, where the Higgs boson is produced in association with a top quark-antiquark pair. As top quarks are the most massive fundamental particles, this process has the lowest production cross-section amongst the four mechanisms.

Figure 1.5 presents the relative cross-sections for these production processes as a function of the Higgs boson mass.

1.4.2 Higgs boson decay mechanisms

The SM predicts various decay channels for the Higgs boson, each with a specific probability quantified by its branching ratio. Figure 1.6 illustrates these branching ratios as a function of the Higgs boson mass [29].

- The most frequent decay channel involves the Higgs boson transforming into a bottom quark-antibottom quark pair ($b\bar{b}$), occurring in roughly 57% of cases. However, this channel is challenging to study at the LHC due

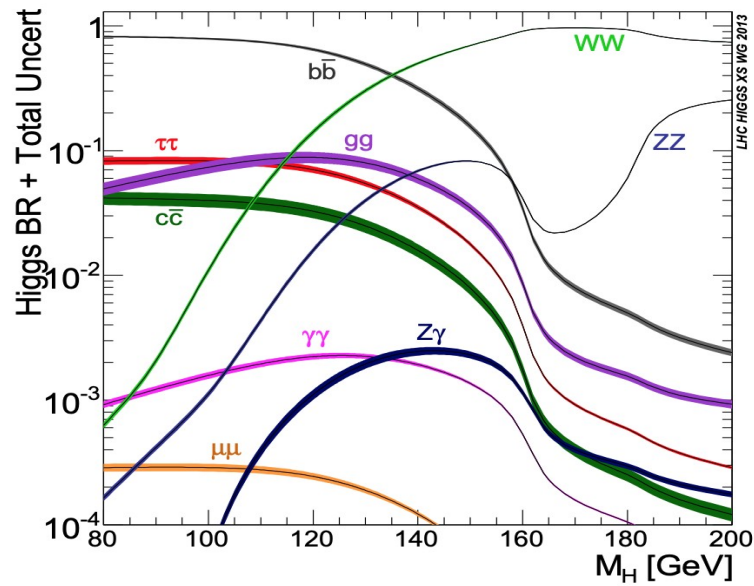


Figure 1.6: Higgs boson decay branching ratios, along with their corresponding error bands, are plotted against the Higgs mass [29].

to the difficulty of distinguishing bottom quark jets from other background processes.

- Higgs bosons can also decay into pairs of gauge bosons: W bosons (WW) and Z bosons (ZZ). These decays happen in 22% and 2.7% of cases, respectively. The ZZ channel offers excellent resolution due to its distinctive signature of four electrons or muons in a single event.
- Another significant decay mode (around 6%) involves the Higgs boson transforming into a tau lepton pair ($\tau\tau$). While offering insights into the Higgs-lepton interaction, this channel suffers from high background contamination arising from similar Z boson decays.
- Decaying into a pair of photons ($\gamma\gamma$) or a Z boson and a photon ($Z\gamma$) occurs rarely (around 0.1% each). These channels benefit from high-resolution reconstruction and efficient background suppression, making them valuable for specific studies, with $Z\gamma$ decays requiring further exploration.

Table 1.3: Compilation of ATLAS and CMS results on potential anomalous observations [1].

Result	Publication	
Differential Higgs boson p_T spectra	ATLAS	Fiducial cross section measurements on $h \rightarrow \gamma\gamma$ [32] and $h \rightarrow ZZ^* \rightarrow 4l$ [33]
	CMS	Fiducial cross section measurements on $h \rightarrow \gamma\gamma$ [34] and $h \rightarrow ZZ^* \rightarrow 4l$ [35]
Di-Higgs boson resonance searches	ATLAS	Limits on $H \rightarrow hh \rightarrow b\bar{b}\tau\tau, \gamma\gamma WW^*, \gamma\gamma b\bar{b}$ and $b\bar{b}b\bar{b}$ [36]
	CMS	Limits on $H \rightarrow hh \rightarrow \gamma\gamma b\bar{b}$ [37], $b\bar{b}\tau\tau$ [38] and multi-lepton [39]
Top associated Higgs boson production	ATLAS	Limits on $h \rightarrow \gamma\gamma$ [40], Measurements on multi-lepton decay channels [41] and $h \rightarrow b\bar{b}$ [42]
	CMS	Limits on $h \rightarrow \gamma\gamma$ and $b \rightarrow b\bar{b}$ [43]
$H \rightarrow VV$ decays	ATLAS	Limits on $H \rightarrow WW$ [44] and $H \rightarrow ZZ$ [45]
	CMS	Limits on $H \rightarrow WW$ and $H \rightarrow ZZ$ [46]

1.5 The multi-lepton anomalies at the LHC

The ATLAS and CMS experiments [24, 30] at the LHC discovered a novel boson consistent with the SM Higgs Boson h [31, 21, 22]. This discovery has broadened the scope of research, allowing for an in-depth exploration of the nature of the Higgs boson and facilitating investigations into various physical phenomena. This includes endeavors such as searching for BSM physics through extensive datasets and examining theoretical models related to Higgs boson production processes.

During LHC Run 1, both the ATLAS and CMS experiments detected several distinctive irregularities in the datasets, which are detailed in Table 1.3 that summarizes the corresponding publications. These anomalies included deviations in the transverse momentum spectrum of the Higgs boson, denoted as p_T^h , as well as elevated levels of associated jet activity and increased occurrences of leptons in conjunction with b -tagged jets. These observations collectively signify significant excesses and serve as indirect indications of potential new physics emerging at the

electroweak scale [1, 2, 3, 4, 5, 6, 7, 8]. In an effort to elucidate this phenomenon, an extra heavy scalar H BSM was introduced, which extended the Lagrangian of the SM. The complete effective Lagrangian can be described by the following equation:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{BSM}}, \quad (1.5.1)$$

where the $\mathcal{L}_{\text{BSM}}$ Lagrangian encompasses all novel interactions and states and is explicitly defined as:

$$\mathcal{L}_{\text{BSM}} = \mathcal{L}_H + \mathcal{L}_Y + \mathcal{L}_T + \mathcal{L}_Q, \quad (1.5.2)$$

where the terms $\mathcal{L}_H$, $\mathcal{L}_Y$, $\mathcal{L}_T$, and $\mathcal{L}_Q$ in this formulation correspond to the production of the heavy scalar H , Yukawa interactions, trilinear interactions, and quartic interactions, respectively. Each term of this Lagrangian is defined as follows:

$$\mathcal{L}_H = -\frac{1}{4}\beta_g\kappa_{hgg}^{\text{SM}}G_{\mu\nu}G^{\mu\nu}H + \beta_V\kappa_{hVV}^{\text{SM}}V_\mu V^\mu H, \quad (1.5.3)$$

- H : is a heavy scalar particle.
- κ_{hgg}^{SM} : the effective coupling strength of gluons to the heavy scalar H , defined as $\alpha_s/(3\pi\nu)$.
- β_g : controls the rate of production of H via gluon-gluon fusion (ggF).
- $\beta_g\kappa_{hgg}^{\text{SM}}$: this product represents the effective coupling strength of gluons to H .
- κ_{hVV}^{SM} : denotes the coupling of the H to weak vector bosons and has a value of m_V^2/ν .
- β_V : controls the branching ratio of H decaying into weak vector bosons (i.e.,

$H \rightarrow VV$).

$$\mathcal{L}_Y = -\frac{1}{\sqrt{2}} [y_{ttH}\bar{t}tH + y_{bbH}\bar{b}bH], \quad (1.5.4)$$

Equation 1.5.4 describes the Yukawa couplings between H and the heaviest quarks, which are considered as Standard Model-like Yukawa couplings.

$$\mathcal{L}_T = -\frac{1}{2}v [\lambda_{Hhh}Hhh + \lambda_{h\chi\chi}h\chi\chi + \lambda_{H\chi\chi}H\chi\chi], \quad (1.5.5)$$

- χ : is a candidate for dark matter (DM).
- ν : represents the VEV, with a value of 246 GeV.

$$\begin{aligned} \mathcal{L}_Q = & -\frac{1}{2}\lambda_{Hh\chi\chi}Hh\chi\chi - \frac{1}{4}\lambda_{HHhh}HHhh \\ & -\frac{1}{4}\lambda_{hh\chi\chi}hh\chi\chi - \frac{1}{4}\lambda_{HH\chi\chi}HH\chi\chi, \end{aligned} \quad (1.5.6)$$

Equations 1.5.5 and 1.5.6 describe the potential trilinear and quartic couplings between the heavy scalar H , the Higgs boson h , and the dark matter candidate χ (assumed to be scalar). The trilinear coupling in Equation 1.5.5 allows for $H \rightarrow hh$ decays, which can explain the excesses observed in resonant di-Higgs production results and elucidates the distortion in the Higgs p_T spectrum. The quartic couplings in Equation 1.5.6 enable Higgs boson decays in association with missing transverse energy.

The proposed model was subjected to constraints from the four categories of constraints presented in Table 1.3, and both ATLAS and CMS experimental results were used to ensure impartiality. A simultaneous fit was performed by minimizing a combined χ^2 value while varying the effective gluon coupling, β_g , for different mass hypotheses of the heavy scalar H , denoted by m_H . Lower values of m_H were found to fit the experimental data better than higher ones. Among all the tested mass points, $m_H = 270$ GeV yielded the smallest value of χ^2 . Examples of fits

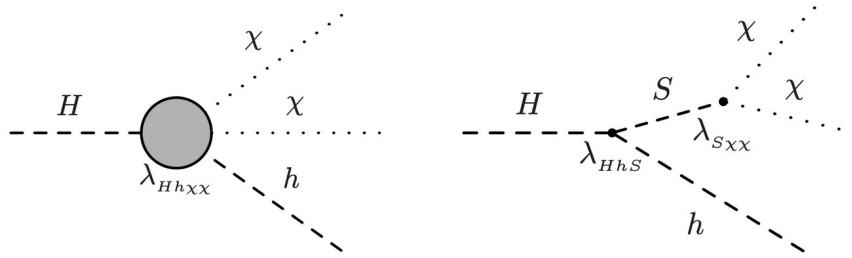


Figure 1.7: Feynman diagrams of the BSM hypothesis are shown. The left diagram represents the decay of a heavy scalar, H , through the effective quartic $\lambda_{Hh\chi\chi}$ vertex, while the right diagram represents the decay due to the additional scalar S under a λ_{HhS} , $\lambda_{S\chi\chi}$ replacement [47].

to ATLAS and CMS Run 1 fiducial differential distributions of the Higgs boson p_T at the minimized χ^2 are shown in Figure 1.8. The application of interpolation techniques among the mass points led to the attainment of the most optimal combined minimized value of χ^2 at $m_H = 272$ GeV. This is evident from the best fit shown in Figure 1.9, which also indicates the upper and lower errors as 12 GeV and 9 GeV, respectively.

To obtain a more profound comprehension of the effective decay, further exploration of search prospects for new scalars beyond the Standard Model was conducted. The decay of $H \rightarrow h\chi\chi$ is suggested to occur through an effective quartic interaction in Equation 1.5.6, which is assumed to be mediated by S (refer to Figure 1.7). This, in turn, suggests that the interaction results in a 100% branching ratio of S decaying to DM candidates. However, according to Ref. [49], the DM candidates may actually originate from an inert scalar S with a mass of $m_h \leq m_S \leq m_H - m_h$, which can introduce new processes associated with the decays of H . Therefore, the mediator S is incorporated in the 2HDM model, and the focus is altered to heavy CP-even scalar, H , decaying mostly into SS, Sh , where h denotes the SM Higgs boson and $S \rightarrow \chi\chi$. This decay provides an opportunity to investigate a broad spectrum of phenomenological aspects predicted by the model, leading to the embedding of the proposed hypothesis into a Two-Higgs-Doublet

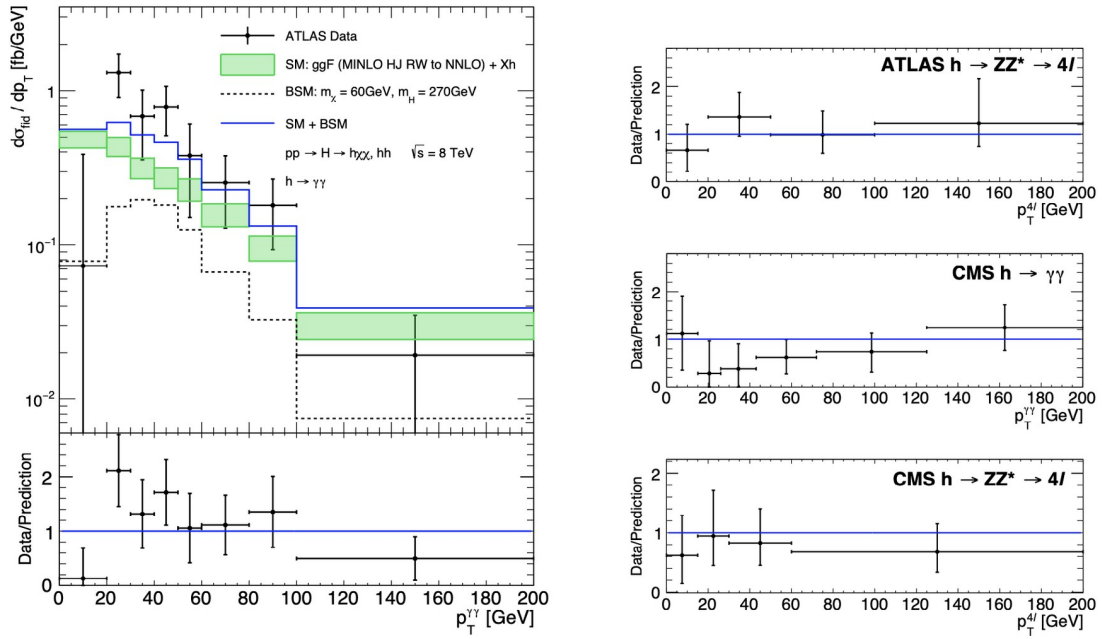


Figure 1.8: The p_T distributions obtained from Run 1 of ATLAS and CMS have been subjected to fitting. The left plot illustrates the fitting of the ATLAS $H \rightarrow \gamma\gamma$ result [32], with the SM and SM+BSM predictions. Conversely, the plot on the right shows the ratio plots of the data and SM+BSM predictions for both the ATLAS $H \rightarrow ZZ$ result [33] and CMS result [34, 48].

model plus scalar singlet (2HDM+ S) to better explain the multi-lepton anomalies. In accordance with the effective theory approach and after electroweak symmetry breaking (EWSB), the Lagrangian for a singlet real scalar S can be formulated as:

$$\mathcal{L}_S = \mathcal{L}_K + \mathcal{L}_{SVV'} + \mathcal{L}_{Sf\bar{f}} + \mathcal{L}_{hHS} + \mathcal{L}_{S\chi}, \quad (1.5.7)$$

where the terms in the Lagrangian given in Equation 1.5.7 can be defined as follows:

$$\mathcal{L}_K = -\frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}m_S^2 SS, \quad (1.5.8)$$

$$\begin{aligned}
\mathcal{L}_{SVV} = & \frac{1}{4}\kappa_{Sgg}\frac{\alpha_S}{12\pi v}SG^{a\mu\nu}G_{\mu\nu}^a + \frac{1}{4}\kappa_{S\gamma\gamma}\frac{\alpha}{\pi v}SF^{\mu\nu}F_{\mu\nu} \\
& + \frac{1}{4}\kappa_{SZZ}\frac{\alpha}{\pi v}SZ^{\mu\nu}Z_{\mu\nu} + \frac{1}{4}\kappa_{SZ_\gamma}\frac{\alpha}{\pi v}SZ^{\mu\nu}F_{\mu\nu} \\
& + \frac{1}{4}\kappa_{SWW}\frac{2\alpha}{\pi S_w^2 v}SW^{+\mu\nu}W_{\mu\nu}^-,
\end{aligned} \tag{1.5.9}$$

$$\mathcal{L}_{Sf\bar{f}} = -\sum_f K_{Sf}\frac{m_f}{v}S\bar{f}f, \tag{1.5.10}$$

$$\mathcal{L}_{HhS} = -\frac{1}{2}v[\lambda_{hhS}hhS + \lambda_{hSS}hSS + \lambda_{HHS}HHS + \lambda_{HSS}HSS + \lambda_{HhS}HhS], \tag{1.5.11}$$

$$\mathcal{L}_{S\chi} = -\frac{1}{2}v\lambda_{S\chi\chi}S\chi\chi - \frac{1}{2}\lambda_{SS\chi\chi}SS\chi\chi, \tag{1.5.12}$$

In this context, we define V and V' as $V, V' \equiv g, \gamma, Z$ or $W^\pm$. The tensor $W_{\mu\nu}^\pm$ is given by $W_{\mu\nu}^\pm = D_\mu W_\nu^\pm - D_\nu W_\mu^\pm$, where $D_\mu W_\nu^\pm = [\partial_\mu \pm ieA_\mu]W_\nu^\pm$. We neglect other possible self-interaction terms for S as they are not of any phenomenological interest for our studies. Therefore, the total effective Lagrangian can be expressed as:

$$\mathcal{L}_{\text{tot}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_S. \tag{1.5.13}$$

In order to gain deeper insights into the observed excesses, an investigation concentrated on the decay of S into di-lepton final states was conducted. This study involved comparing the di-lepton signal from BSM with the data from ATLAS and CMS with Run 1 data, as detailed in Ref. [4]. Figure 1.10 shows the di-lepton invariant mass distribution, comparing ATLAS data, SM background, and BSM signal after requiring events with two opposite-sign leptons of different flavors and a minimum of one b -tagged jet [4]. Table 1.4 provides a summary of deviations

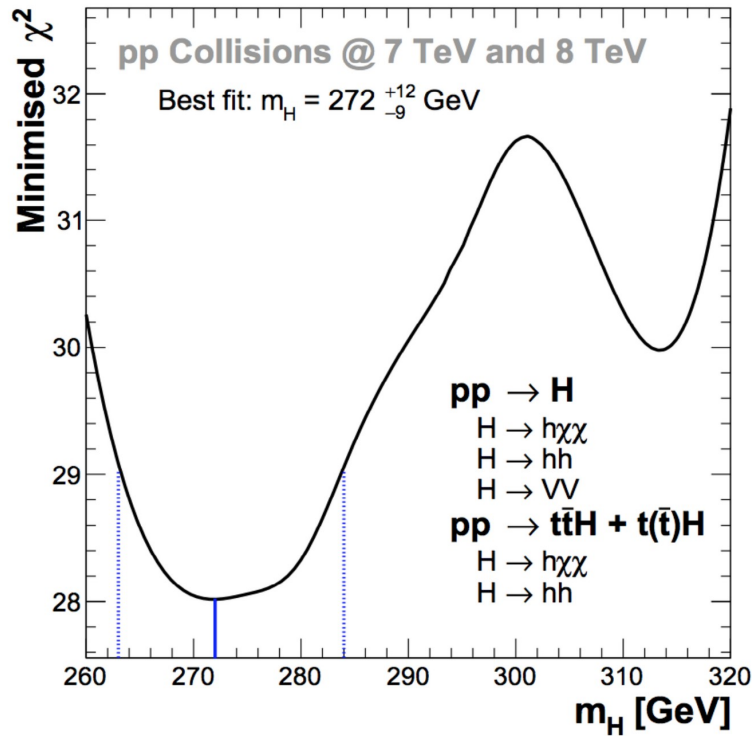


Figure 1.9: Plot showing the variation of minimized χ^2 values with respect to the mass of H [47].

Table 1.4: Overview of multi-lepton excesses in LHC measurements [50].

Final State	Characteristics	SM Backgrounds	Significance
$\ell^+\ell^- + (b\text{-jets})$ [51, 52, 53]	$m_{\ell\ell} < 100 \text{ GeV}, (1b, 2b)$	$t\bar{t}, Wt$	$> 5\sigma$
$\ell^+\ell^- + (\text{no jet})$ [51, 54]	$m_{\ell\ell} < 100 \text{ GeV}$	W^+W^-	$\approx 3\sigma$
$\ell^\pm\ell^\pm, 3\ell + (b\text{-jets})$ [8, 55, 56]	Moderate H_T	$t\bar{t}W^\pm, t\bar{t}t\bar{t}$	$> 3\sigma$
$\ell^\pm\ell^\pm, 3\ell, (\text{no } b\text{-jet})$ [7, 57, 58]	In association with h	$W^\pm h(125), WWWW$	$\gtrsim 4\sigma$
$Z(\rightarrow \ell\ell)\ell, (\text{no } b\text{-jet})$ [51, 59]	$p_T^Z < 100 \text{ GeV}$	$ZW^\pm$	$> 3\sigma$

within this category of excesses.

The fit yields a best-fit value of β_g^2 , that is the rate of production via gluon gluon fusion as 4.09 ± 1.37 , which corresponds to a significance of 2.99σ . The distribution of invariant mass within the range of 0 to 100 GeV, as shown in Figure 1.10, exhibits a noticeable discrepancy that can be more effectively elucidated by considering the $H \rightarrow Sh$ signal. The masses of H and S being set as $m_H = 270 \text{ GeV}$ and $m_S = 150 \text{ GeV}$ respectively, with only β_g^2 being the sole parameter of the

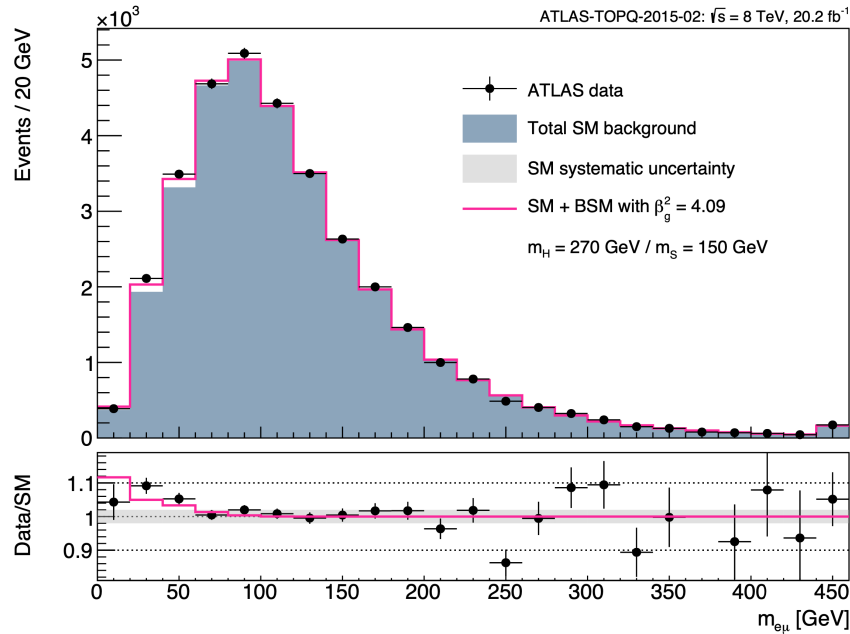


Figure 1.10: The SM+BSM fit to di-lepton invariant mass spectrum (ATLAS Run 1, $e\mu + b\text{--jet}$) [60].

BSM model that requires constraint. In Figure 1.11, the profile likelihood ratio is presented for each of the individual outcomes and their combination, achieved through simultaneous fits incorporating all the measurements listed in Table 1.5. The best fit value is $\beta_g^2 = 2.92 \pm 0.35$, with a corresponding significance of 8.04σ . The results of this study confirm the deviations observed between the SM predictions and the data, providing an explanation for the multi-lepton anomalies at the LHC [51].

The 2HDM+ S model predicts the emergence of multi-lepton anomalies, as substantiated by the findings in Refs. [4, 60, 8, 7, 61, 62, 63, 64]. In particular, Ref. [4] predicts a mass of 150 GeV for S . Significant excesses at 151.5 GeV have been reported in Refs. [10, 63]. Subsequently, a combined analysis of CMS and ATLAS data in the WW channel, aiming at the SM Higgs boson search, has been conducted. This analysis allows for the possibility of a scalar candidate at 151 GeV decaying into W bosons (see Ref. [62] for detailed information). In parallel, investigations into the side-bands of the SM Higgs analyses, coupled with a dedicated

Table 1.5: Summary of the SM+BSM fit results [51].

Selection	Best-Fit β_g^2	Significance (σ)
ATLAS Run 1 SS $ll + b$ -jets	6.51 ± 2.99	2.37
ATLAS Run 1 OS $e\mu + b$ -jets	4.06 ± 1.37	2.99
ATLAS Run 2 SS $ll + b$ -jets	2.22 ± 1.19	2.01
CMS Run 2 SS $ll + b$ -jet	1.41 ± 0.80	1.75
CMS Run 2 OS $e\mu$	2.79 ± 0.52	5.45
ATLAS Run 2 OS $e\mu + b$ -jets	5.42 ± 1.28	4.06
CMS Run 2 $lll + E_T^{miss}$	9.70 ± 3.88	2.36
ATLAS Run 2 $lll + E_T^{miss}$	9.05 ± 3.35	2.52
Combination	2.92 ± 0.35	8.04

analysis in the context of BSM, were employed to explore growing excesses. Notably, Ref. [63] reports significant hints for new scalars at approximately 95 GeV (S') and 152 GeV (S). Moreover, additional analyses focused on uncovering new Higgses have been carried out, specifically examining multi-lepton anomalies in the $t\bar{t}$ channel [64]. Confirming the initial prediction of 150 GeV stemming from the non-resonant WW channel, Ref. [64] affirms the consistency of anomalies in $t\bar{t}$ with the anticipated mass of 150 GeV.

If the 2HDM+ S model is supplemented by a DM candidate, it can further elucidate on a multiple anomalies in astrophysics [65]. It can be easily extended [6] to account for the muon $g - 2$ anomaly (see Refs. [9, 50] for a review of anomalies).

1.5.1 The 2HDM+ S model

A concise overview of the 2HDM extended with a real singlet field Φ_S (2HDM+ S) is presented. This model is employed to elucidate the observed multi-lepton

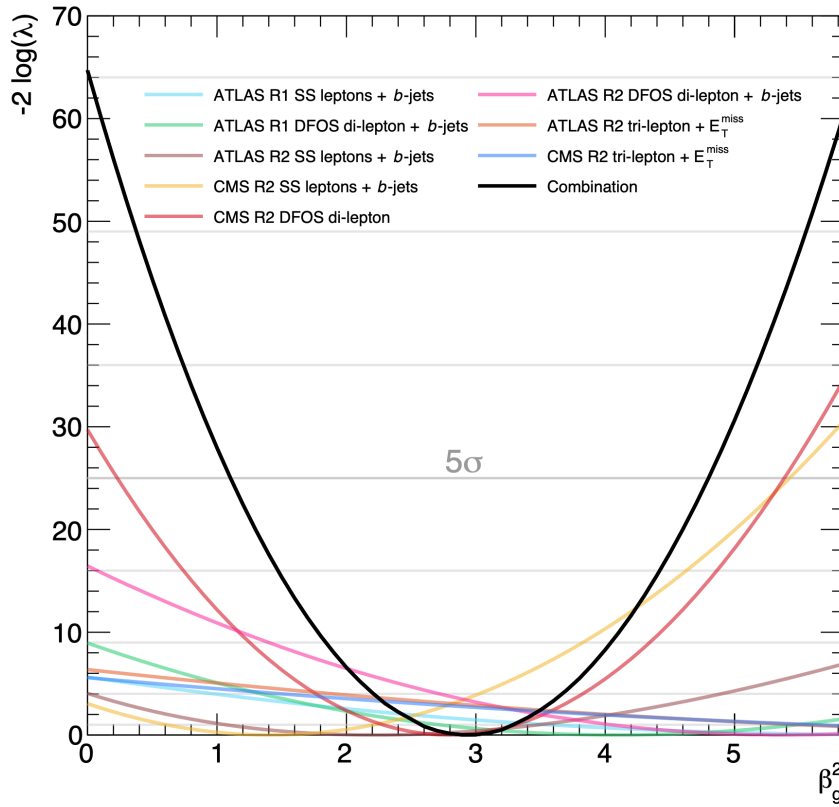


Figure 1.11: The profile likelihood ratios, corresponding to negative 2 times the logarithm, for each individual fit result discussed are displayed. The combined profile likelihood ratio is also overlaid for comparison. The significance of a result is determined by finding the point at which it intersects the y-axis (representing the SM-only hypothesis with $\beta_g = 0$) and taking the square root of that value [60].

anomalies in LHC data, and the potential of the model is given by:

$$\begin{aligned}
 V(\Phi_1, \Phi_2, \Phi_S) = & m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + h.c.) \\
 & + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) \\
 & + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) + \frac{\lambda_5}{2} [(\Phi_1^\dagger \Phi_2)^2 + h.c.] \\
 & + \frac{1}{2} m_S^2 \Phi_S^2 + \frac{\lambda_6}{8} \Phi_S^4 + \frac{\lambda_7}{2} (\Phi_1^\dagger \Phi_1) \Phi_S^2 + \frac{\lambda_8}{2} (\Phi_2^\dagger \Phi_2) \Phi_S^2,
 \end{aligned} \tag{1.5.14}$$

where the fields Φ_1 and Φ_2 in the potential represent the $SU(2)_L$ Higgs doublets, and Φ_S denotes the singlet field. The first three lines detail the potential for the

2HDM, while the last line outlines the contribution from the singlet field [47]. To prevent tree-level neutral currents from inducing flavor-changing effects (FCNC), a Z_2 symmetry is imposed on the 2HDM+ S potential (Equation 1.5.14), which can be softly broken by the term $m_{12}^2 \neq 0$. This symmetry requires all quarks of a given charge to couple to a single Higgs doublet. Furthermore, tree-level FCNC can also be avoided by extending the Z_2 symmetry to the Yukawa sector, where the real singlet field Φ_S acquires a VEV, maintaining Z_2 symmetry. In other words, the singlet scalar becomes a robust dark matter candidate if the Z_2 symmetry remains unbroken.

In order to minimize the potential and Electro-Weak symmetry breaking with three Higgs fields, an assumption is made regarding the VEVs of the fields: $\Phi_1 \rightarrow v_1/\sqrt{2}$, $\Phi_2 \rightarrow v_2/\sqrt{2}$, and $\Phi_s \rightarrow v_s$. The fulfillment of the following requirements becomes necessary in this scenario:

$$\frac{\partial V}{\partial[v_1, v_2, v_s]} = 0. \quad (1.5.15)$$

The fields conditions are described as:

$$m_{11}^2 = -\frac{1}{2}(v_1^2\lambda_1 + v_2^2\lambda_{345} + v_s^2\lambda_7)\frac{v_2}{v_1}m_{12}^2, \quad (1.5.16)$$

$$m_{22}^2 = -\frac{1}{2}(v_2^2\lambda_2 + v_1^2\lambda_{345} + v_s^2\lambda_8)\frac{v_2}{v_1}m_{12}^2, \quad (1.5.17)$$

$$m_S^2 = -\frac{1}{2}(v_1^2\lambda_7 + v_2^2\lambda_8 + v_s^2\lambda_6), \quad (1.5.18)$$

where $\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$. Upon minimization, the scalar sector is populated by three CP even scalars h , H , and S , one CP odd scalar A , and the charged scalar $H^\pm$ [47, 66, 60, 7, 65, 6]. In this study, Lagrangian interactions of S with

three types of dark matter candidates χ_r , χ_d , and χ_v with spins 0, 1/2, and 1, respectively, are considered:

$$\mathcal{L}_{int} = \frac{1}{2}M_{\chi_r}g_{\chi_r}^S\chi_r\chi_r S + \bar{\chi}_d(g_{\chi_d}^S + ig_{\chi_d}^P\gamma_5)\chi_d S + g_{\chi_v}^S\chi_v^\mu\chi_{v\mu}S, \quad (1.5.19)$$

where M_{χ_i} and g_{χ_i} represent the coupling strengths of dark matter masses and dark matter particles with the singlet real scalar S .

1.5.1.1 Exploring high-mass resonances in the $Z\gamma$ final states within the 2HDM+ S model

Extensions of the SM have made exciting predictions about the emergence of novel high-mass states that undergo decay into two photons. This particular decay channel, resulting in a di-photon final state, offers a pristine experimental signature characterized by remarkable precision in measuring invariant masses and manageable background interference [67]. Within this realm of extensions, the BSM 2HDM+ S framework, which we have previously discussed in relation to multi-lepton anomalies, shines as a particularly promising avenue for the exploration and revelation of novel physics phenomena.

To this end, the primary objective of this thesis is to delve into the search for high-mass resonances within the $Z\gamma$ final states. The investigation focuses on a hypothetical high-mass resonance, denoted as H , which undergoes a distinctive decay process into $Z\gamma$ ($H \rightarrow Z\gamma$). It is noteworthy that H is an integral component of the 2HDM+ S model. This thesis focuses on the exploration of the Z boson decaying into either electron-antielectron (e^+e^-) or muon-antimuon ($\mu^+\mu^-$) pairs. The choice of the $Z\gamma$ channel is well-justified, as a Higgs-like boson resonance is more likely to decay into a $Z\gamma$ final state compared to a di-photon final state. Furthermore, the well-reconstructed vertices of $Z\gamma$ events provide a robust foundation for our pursuit of potential signal excesses.

The Large Hadron Collider and ATLAS Detector

This chapter provides a comprehensive introduction to both the Large Hadron Collider and the ATLAS experiment. Section 2.1 introduces the Large Hadron Collider, while Section 2.2 outlines the structure of the ATLAS detector, including its sub-systems.

2.1 The Large Hadron Collider

Situated at the Switzerland-France border, the Large Hadron Collider (LHC) complex stands as an extraordinary feat accomplished by the European Organisation for Nuclear Research (CERN). This colossal structure represents the pinnacle of particle acceleration and High Energy Physics experimentation worldwide. Comprising a two-ring superconducting hadron accelerator and collider, the LHC resides in an extensive circular tunnel spanning a remarkable distance of 27 kilometers. It is located at an average depth of 100 meters beneath the Earth's surface. This awe-inspiring facility incorporates numerous acceleration points strategically placed along the tunnel to enhance the energy of particles traversing its paths.

The LHC is a powerful particle accelerator that propels two high-energy particle

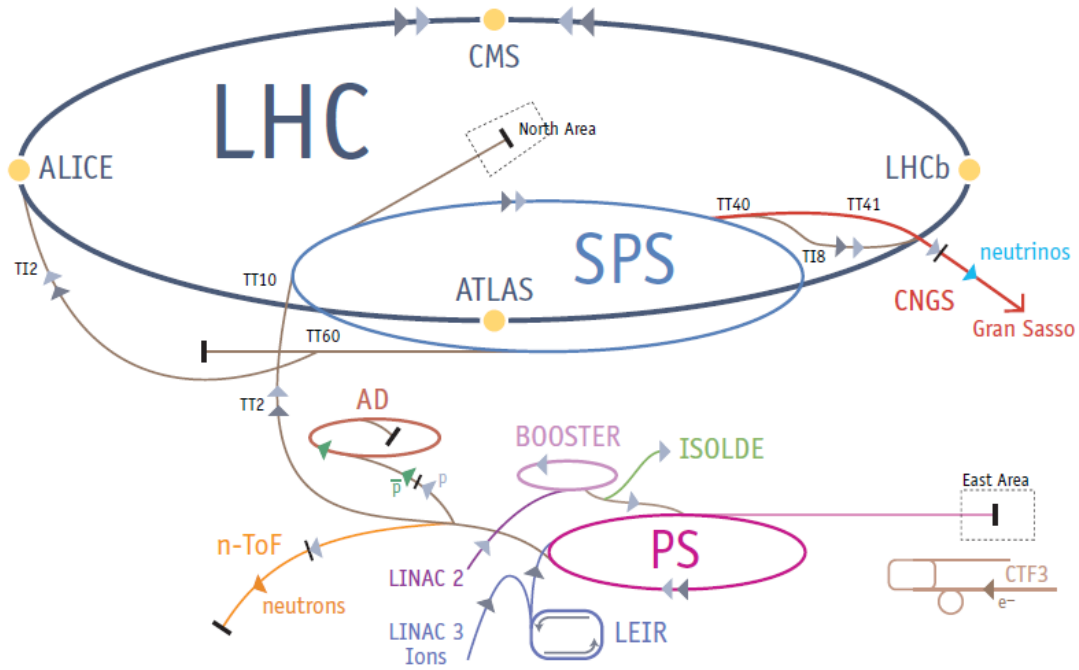


Figure 2.1: The LHC ring and its major experiments [73].

beams in opposite directions along separate beam pipes, which are maintained in an ultrahigh vacuum of about 10^{-7} Pa. These beams are accelerated to collide head-on at a center-of-mass energy of $\sqrt{s} = 13.6$ TeV, with a luminosity, as explained later, of $10^{34} \text{ cm}^{-2} \cdot \text{s}^{-1}$. At the main interaction points (IPs), where the collision occurs, this process repeats an astounding 40 million times per second. To facilitate these experiments, four large-scale detectors have been constructed: A Toroidal Large Hadron Collider Apparatus (ATLAS) [68], Compact Muon Solenoid (CMS) [69], A Large Ion Collider Experiment (ALICE) [70], and Large Hadron Collider-beauty (LHCb) [71]. Figure 2.1 provides an artistic representation of the LHC complex, indicating the positions of four primary detectors. ATLAS and CMS serve as versatile detectors designed for high-luminosity experiments conducted at the LHC. In contrast, LHCb specializes in the study of particles containing b -quarks, while ALICE is optimized for investigating heavy-ion collisions [72].

Within the LHC complex, the process of accelerating proton bunches involves multiple stages leading up to their collision at specific IPs. Initially, hydrogen gas is ionized to generate positively charged hydrogen ions (protons). These protons are then introduced into the Linear Accelerator (LINAC), where they undergo acceleration, reaching an energy level of 50 MeV [74]. Subsequently, the protons are transported to the Proton Synchrotron Booster (PSB), where they are further accelerated to an energy of 1.4 GeV, preparing them for injection into the Proton Synchrotron (PS) [75]. In the PS the protons experience additional acceleration, reaching an energy of 26 GeV, before being injected into the Super Proton Synchrotron (SPS) [76]. Within the SPS the protons continue their acceleration, achieving speeds approaching that of light and attaining an energy level of 450 GeV [77].

Following preparation, the proton beam is injected into the LHC's main ring where it separates into two counter-rotating beams. These beams are further accelerated to their final design energy, typically around 7 TeV per beam. Stable beams are then brought into collision at designated IPs. The rate of these collisions is quantified by a parameter known as luminosity (represented by the symbol $\mathcal{L}$).

Luminosity essentially describes the number of potential interactions occurring per unit time per unit area at the IP. Mathematically, it is expressed as:

$$\mathcal{L} = \frac{N_b^2 n_b f_{rev} \gamma_r}{4\pi \epsilon_n \beta^*} F(\theta), \quad (2.1.1)$$

where:

- N_b represents the number of protons per bunch.
- n_b is the number of bunches per beam.
- f_{rev} denotes the revolution frequency of the beams within the LHC ring.
- γ_r is the relativistic gamma factor for the protons.

- The term $4\pi\epsilon_n\beta^*$ characterizes the effective area of beam overlap at the IP, with ϵ_n being the normalized transverse beam emittance and β^* representing the beta function at the IP, a parameter related to the beam focus.
- $F(\theta)$ is a geometric reduction factor accounting for the crossing angle (θ) between the beams at the IP. This factor is defined as:

$$F(\theta) = \frac{1}{\sqrt{1 + \left(\frac{\theta\sigma_z}{2\sigma_{x,y}}\right)^2}}, \quad (2.1.2)$$

where σ_z and $\sigma_{x,y}$ represent the longitudinal and transverse Gaussian widths of the colliding beams, respectively.

The LHC's instantaneous luminosity ($\mathcal{L}$) is a crucial parameter that quantifies the rate of proton-proton collisions occurring at the ATLAS detector. Higher luminosity translates to a greater number of collisions per unit time, leading to a larger dataset for analysis. Figure 2.2 (left) depicts the integrated luminosity delivered to ATLAS during stable beams from 2011 to 2018. This value is proportional to the number of interactions and the number of particles created in the collision that occurred within the detector over this period.

The LHC's instantaneous luminosity has steadily increased over the years. It reached a peak of $2.6 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ in Run 1 (2009-2012) and further improved to $1.1 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$ during Run 2 (2015-2018). Run 3 (2022-2026) aims to achieve a peak luminosity of $2 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$. The accumulated luminosity delivered to ATLAS from 2015 to 2018 is shown in Figure 2.2 (right) [78].

A higher luminosity directly translates to a larger number of interactions per bunch crossing. This is referred to as pileup. Figure 2.3 displays the distribution of the average number of interactions per crossing for proton-proton collision data recorded by ATLAS during stable beams at 13 TeV center-of-mass energy from 2015 to 2018. The figure also includes the integrated luminosity and the mean

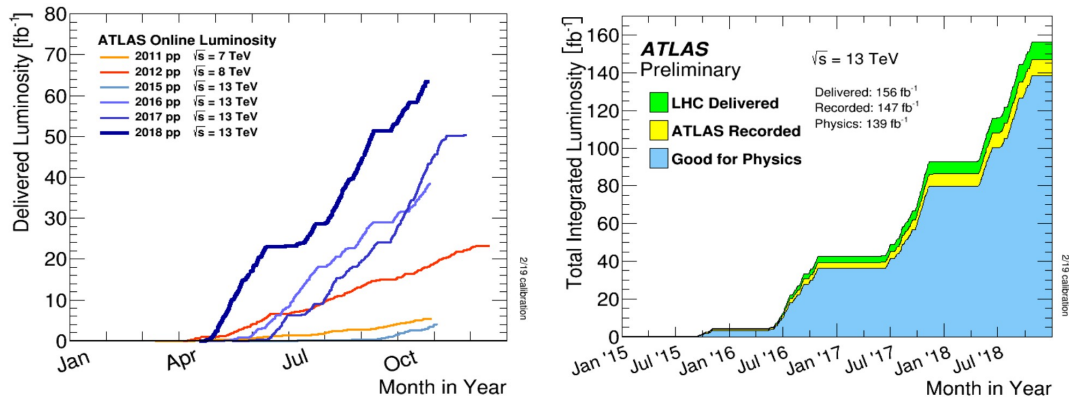


Figure 2.2: The integrated luminosity delivered to the ATLAS detector during stable beams for pp collisions. The left graph shows the trend over time from 2011 to 2018, highlighting the increasing collision rate at the LHC. The right graph focuses on the period of stable beams for pp collisions at a center-of-mass energy of 13 TeV, from 2015 to 2018. Here, the data points are color-coded to represent: Green: Integrated luminosity delivered to ATLAS (potential interactions), Yellow: Integrated luminosity recorded by ATLAS, and Blue: Integrated luminosity certified as good quality data [78].

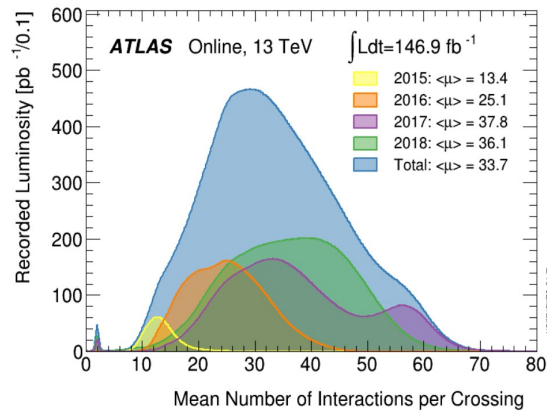


Figure 2.3: The mean number of collisions, denoted by $\langle \mu \rangle$, calculated over the integrated luminosity for the years 2015-2018 [78].

value denoted by μ . The average number of interactions per crossing can be calculated using the instantaneous luminosity per bunch, the inelastic proton-proton cross-section (typically around 80 mb for 13 TeV collisions), and the LHC revolution frequency [78].

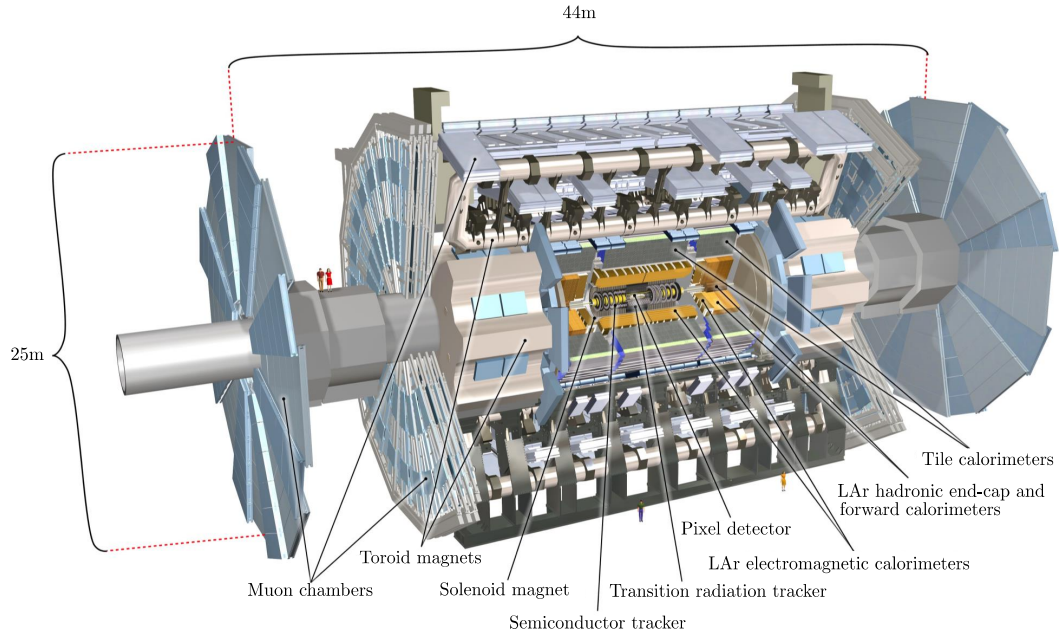


Figure 2.4: A cutaway view of the ATLAS detector [79].

2.2 The ATLAS Experiment at the LHC

The ATLAS experiment is a versatile detector, one of two designed for broad and comprehensive studies at the LHC at CERN. It is specifically designed for high-luminosity proton-proton and heavy-ion collision physics studies. ATLAS is situated at one of the four main IPs of the LHC (see Figure 2.1). The detector itself is a cylindrical structure with a length of approximately 46 meters and a diameter of 25 meters. Its weight is around 7,000 tonnes, making it one of the largest and heaviest particle detectors ever constructed.

The ATLAS experiment employs a right-handed coordinate system, with both Cartesian and cylindrical components, for describing particle positions and momenta. A depiction of this coordinate system is provided in Figure 2.5. The IP, where the proton beams collide, serves as the origin of the system.

The z -axis aligns with the beam axis and is perpendicular to the transverse plane

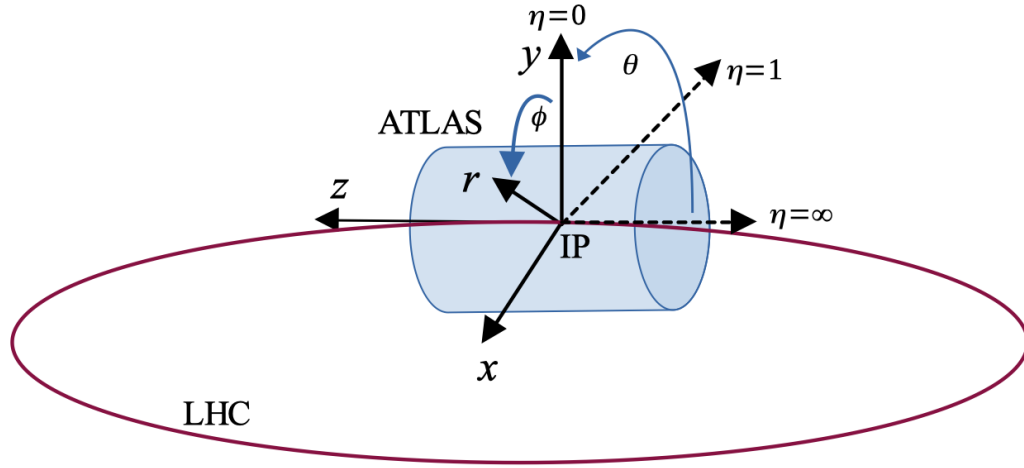


Figure 2.5: A right-handed Cartesian and cylindrical co-ordinate used by the ATLAS detector.

defined by the x and y axes. The transverse plane is essential for calculating particle transverse momenta (p_T). The x -axis points towards the center of the LHC ring, while the y -axis points upwards. The ATLAS detector itself is divided into positive and negative z regions, referred to as the “A-side” and “C-side”, respectively.

Within the cylindrical coordinate system, the radial distance from the beamline is denoted by r , and the azimuthal angle around the beamline (measured from the x -axis) is represented by ϕ . The polar angle, θ , is measured relative to the positive z -axis from the y -axis. In high-energy physics experiments like those conducted at the LHC, pseudorapidity (η) is frequently used instead of θ . Pseudorapidity is defined as $\eta = -\ln(\tan(\theta/2))$. The distance between two particles in η - ϕ space is expressed as $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$.

Proton-proton collisions at the IP generate a cascade of particles, including short-lived and heavy particles that decay further, producing additional particles. Each particle carries valuable information about the initial collision. The ATLAS detector is designed to capture and analyze these collision products, identifying particle

types and precisely measuring their energies and transverse momenta.

The ATLAS detector is comprised of four main sub-detectors, each playing a critical role in particle identification and momentum/energy measurements. These sub-detectors, as illustrated in Figure 2.4, work together to achieve the overall goals of the experiment. A more detailed description of each sub-detector system will be provided in subsequent sections.

2.2.1 Magnetic system

The ATLAS experiment employs a powerful magnet system to achieve precise momentum measurements of charged particles. This system is comprised of four superconducting magnets, each generating a distinct magnetic field for optimal track deflection within specific detector regions (see Figure 2.4):

- **Central Solenoid:** Located between the Inner Detector (ID) and the Electromagnetic Calorimeter (ECAL), it provides a uniform 2 T magnetic field for efficient track curvature measurement within the ID volume. This solenoid is constructed with approximately 9 km of superconducting wire and boasts a length of 5.3 m, a diameter of 2.4 m, and a thickness of 4.5 cm.
- **Barrel Toroid:** Surrounding the central solenoid, this long magnet generates a stronger 4 T field to effectively bend the trajectories of muons within the Muon Spectrometer. The barrel toroid has a length of 25.3 m and an outer diameter of 20.1 m.
- **End-Cap Toroids:** Two additional toroid magnets are positioned at each end of the barrel toroid to extend the strong magnetic field coverage for muon tracks. These end-cap toroids have a diameter of 10.7 m and an axial length of 5.0 m.

All three toroid magnets require a cryogenic environment of 4.5 K to maintain their superconducting state. Liquid helium is used as the primary coolant for

these magnets.

- **Central Solenoid Cooling:** In contrast to the toroids, the central solenoid utilizes an indirect cooling approach. By leveraging the surrounding cold mass of the LAr ECAL, the solenoid achieves the necessary cooling without introducing additional material in the tracking region.

This design prioritizes minimizing the central solenoid's thickness while ensuring efficient cooling for its superconducting components.

2.2.2 Inner Detector

The ATLAS Inner Detector (ID) is the innermost tracking sub-system of the experiment, situated closest to the IP [80]. Its primary function is the precise reconstruction of tracks and momentum measurements (p_T) for charged particles produced in proton-proton collisions (see Figure 2.4). The ID achieves high-resolution tracking within a pseudorapidity acceptance of $|\eta| < 2.5$ [80].

Figure 2.6 depicts a cutaway view of the ATLAS ID, showcasing its overall cylindrical structure. The lower image within the figure provides a breakdown of the three main sub-detectors: the Pixel Detector (PD) closest to the beam pipe, the Semi-Conductor Tracker (SCT) surrounding the PD, and the Transition Radiation Tracker (TRT) as the outermost layer.

- **Pixel Detector (PD):** Located closest to the beam pipe, the PD provides high-resolution, three-dimensional spatial measurements of charged particle tracks using silicon pixel sensors [82]. The PD design incorporates a central barrel module with four layers and two end-cap disks, achieving a total of 80.4 million readout channels for excellent track resolution over a radial range of 50 to 122.5 mm [82].
- **Semi-Conductor Tracker (SCT):** The SCT surrounds the PD and utilizes silicon microstrip sensors to deliver high-precision tracking information.

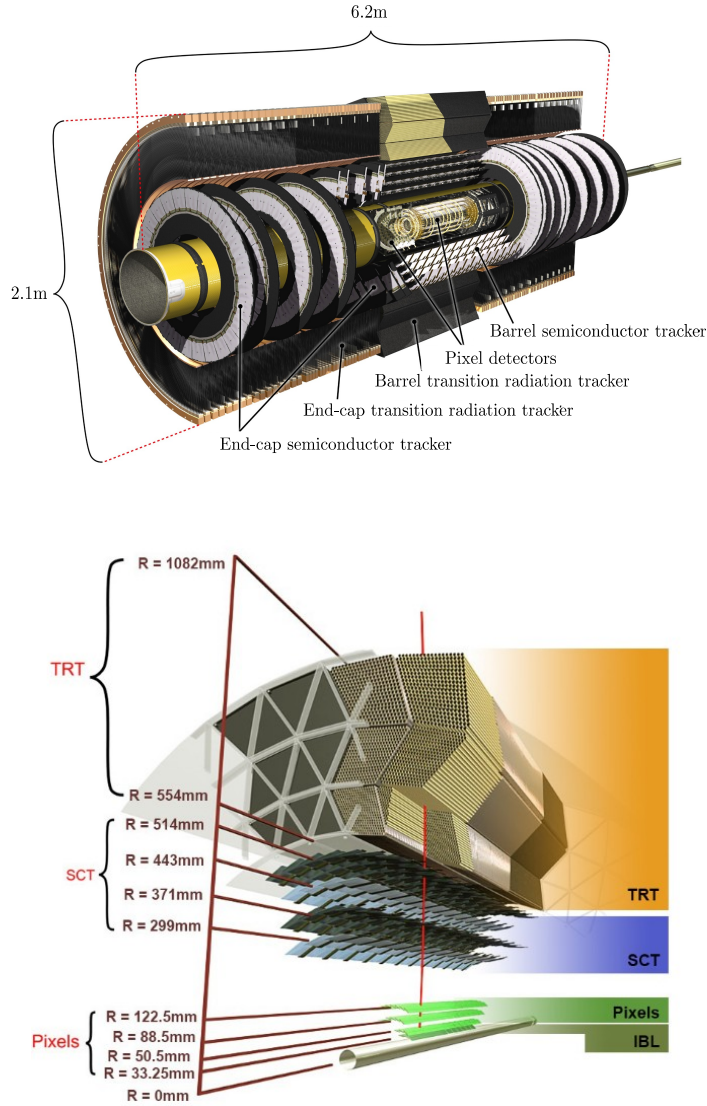


Figure 2.6: Top: Cutaway view of the ID, illustrating its cylindrical structure and key subdetectors. Bottom: Breakdown of the individual subdetectors comprising the ATLAS ID [81].

The SCT offers on average eight spatial measurements per track, enabling accurate determinations of momentum, impact parameter, and vertex position within a radial range of 299 mm to 514 mm. The SCT is comprised of 4088 modules arranged in four barrel layers and nine disks per end-cap, providing two-dimensional spatial measurements in both the $r - \phi$ and z

directions [83].

- **Transition Radiation Tracker (TRT):** The outermost layer of the ID, the TRT employs straw drift tubes filled with a gas mixture for track detection. Charged particles traversing the tubes ionize the gas, generating a current signal. The TRT offers an average of 36 hits per track and covers a radial range of 554 to 1082 mm. The TRT is crucial for distinguishing electrons from charged hadrons through the detection of transition radiation [84].

2.2.3 Calorimeter system

The ATLAS Calorimeter system, depicted in Figure 2.7, consists of several components, including the Liquid Argon (LAr) ECAL, the hadronic Tile calorimeter (TileCal), and the Endcap and Forward cap Calorimeters (FCAL). These elements collectively cover the central region of the ATLAS detector, encompassing a pseudorapidity range of up to $|\eta| < 4.9$. The primary goal of the Calorimeter system is to measure the energy of various particles, such as hadrons, electrons, and photons, while excluding undetectable particles like muons and neutrinos. It is designed to capture and measure the energy of EM and hadronic showers resulting from particle interactions. This capability is crucial for accurately determining the energy of interacting particles and is essential for the proper functioning of the ATLAS detector. The energy resolution of any calorimeter can be expressed by the following equation:

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c, \quad (2.2.1)$$

where E represents the energy of the incoming particle, σ_E is the energy resolution, a , b , and c are the stochastic, noise, and constant terms specific to the calorimeter design and operating conditions. The symbol $\oplus$ represents non-

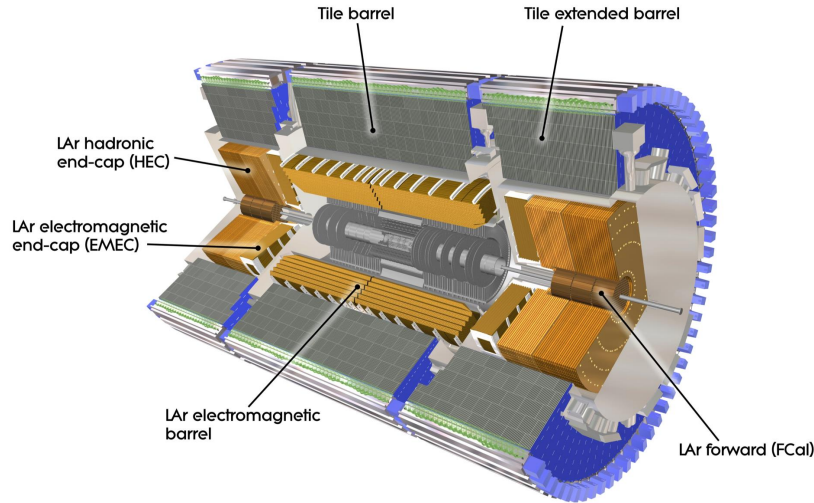


Figure 2.7: The Calorimeter System in ATLAS detector [85].

commutative addition, commonly used to indicate the sum in quadrature of two or more terms.

2.2.3.1 Electromagnetic Calorimeter

The ATLAS experiment employs a high-granularity ECAL to precisely measure the energy of electrons and photons interacting via electromagnetic forces. The ECAL covers a pseudorapidity range of $|\eta| < 3.2$, encompassing a barrel region for $|\eta| < 1.475$ and two end-cap wheels extending the coverage to $1.375 < |\eta| < 3.2$.

The ECAL utilizes a sampling calorimeter design, featuring alternating layers of passive material and active medium. Lead (Pb) serves as the passive absorber due to its short radiation length ($X_0 = 0.56$ cm), effectively converting the energy of incoming electrons and photons into electron-positron pairs. Liquid Argon (LAr) acts as the active medium, offering excellent stability against radiation damage and providing a signal proportional to the deposited energy. Copper electrodes positioned between the lead layers collect the ionization signal generated within the LAr.

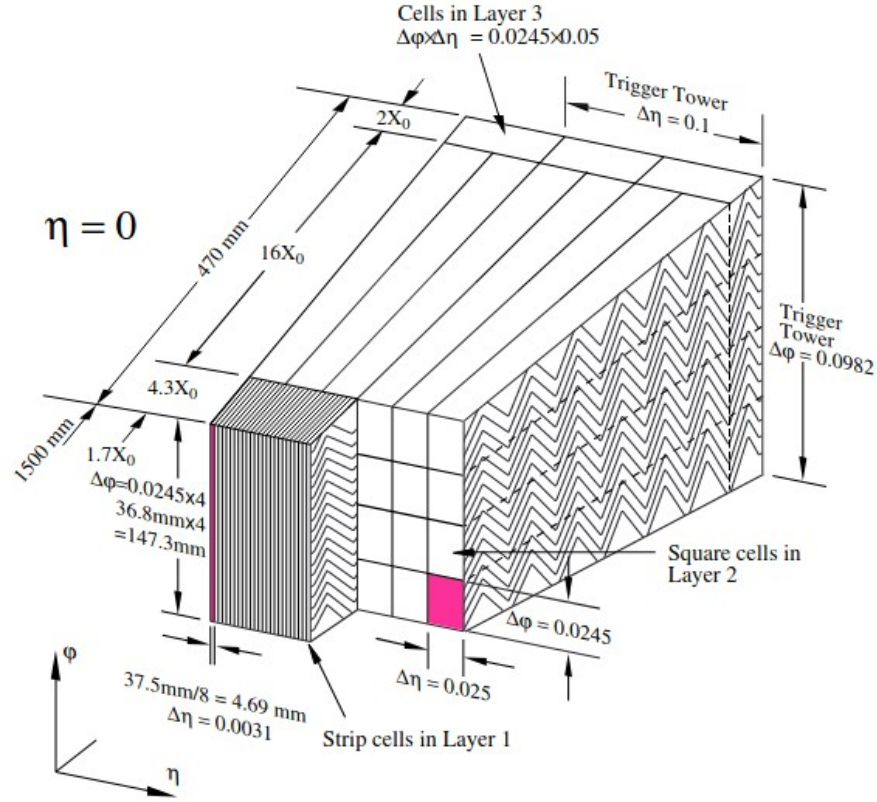


Figure 2.8: Illustration of an ECAL barrel module at $\eta = 0$. The illustration also shows the granularity of the cells in three distinct layers in terms of η and ϕ [79].

To ensure complete azimuthal coverage (ϕ), both the absorber and electrode layers in the barrel and end-cap sections employ an “accordion geometry”. This design eliminates potential gaps between modules, enabling seamless energy measurement across the entire detector. The central barrel module, located at $\eta = 0$ and illustrated in Figure 2.8, comprises three layers with a total radiation length of $22X_0$, offering high resolution for electron and photon energy measurements.

The first layer with a depth of $4.3X_0$ has high granularity for precise particle positioning. The second layer is the thickest, spanning $(0.025, 0.0245)$ in (η, ϕ) coordinates and featuring a significant depth of $16X_0$. It is primarily used to collect the majority of energy deposits, particularly from photons and electron-positron pair cascades. The third layer is designed to collect the EM shower tails.

The presampler, positioned in front of the inner surface of the barrel, consists of a thin layer of liquid-argon. Its function includes the recovery of energy lost within the cryostat and facilitating shower sampling. In the endcap regions, which encompass the range of $1.375 < |\eta| < 3.2$, the primary structural components consist of two inner and outer wheels, each with a thickness equivalent to $24X_0$. The region between these wheels typically contains low-density material. Notably, the space between the endcaps and barrel accommodates various detector services. Positioned within the center of the liquid argon gap, electrodes play a crucial role in collecting electrons and measuring the energy of particles passing through. The fractional resolution of the ECAL, after noise subtraction, is measured to be $\frac{\sigma_E}{E} = \frac{10.1\%}{\sqrt{E}} \oplus 0.2\%$ in the barrel region [86], and $\frac{\sigma_E}{E} = \frac{12.1\%}{\sqrt{E}} \oplus 0.4\%$ in the end-cap region [87].

2.2.3.2 Hadronic Calorimeters

The Hadronic Calorimeter surrounds the ECAL and measures the energy of particles that interact hadronically in the region up to $|\eta| < 4.9$. It comprises three distinct subsystems: the TileCal [88], the Hadronic End-cap Calorimeter (HEC) [89], and the FCal [90]. The TileCal employs scintillating tiles and steel absorber plates, providing coverage for the pseudorapidity range up to $|\eta| < 1.7$. The energy resolution of the TileCal is given by: $\frac{\sigma_E}{E} = \frac{50\%}{\sqrt{E}} \oplus 3\%$. Detailed insights into its design and specifications can be found in Chapter 3. Conversely, the HEC covers a region of $1.5 < |\eta| < 3.2$ and utilizes liquid argon as the active material, with copper serving as the absorber. The measured energy resolution of the HEC is given by: $\frac{\sigma_E}{E} = \frac{70.6\%}{\sqrt{E}} \oplus 5.8\%$. As for the FCal, it encompasses the region of $3.1 < |\eta| < 4.9$ and comprises three sub-components in each endcap: one ECAL and two hadronic calorimeters. The first component utilizes copper as an absorber and is optimized for EM measurements, while the remaining two components use tungsten to measure the hadronic energy deposition. The energy resolution of the FCal is measured as: $\frac{\sigma_E}{E} = \frac{94.2\%}{\sqrt{E}} \oplus 7.4\%$

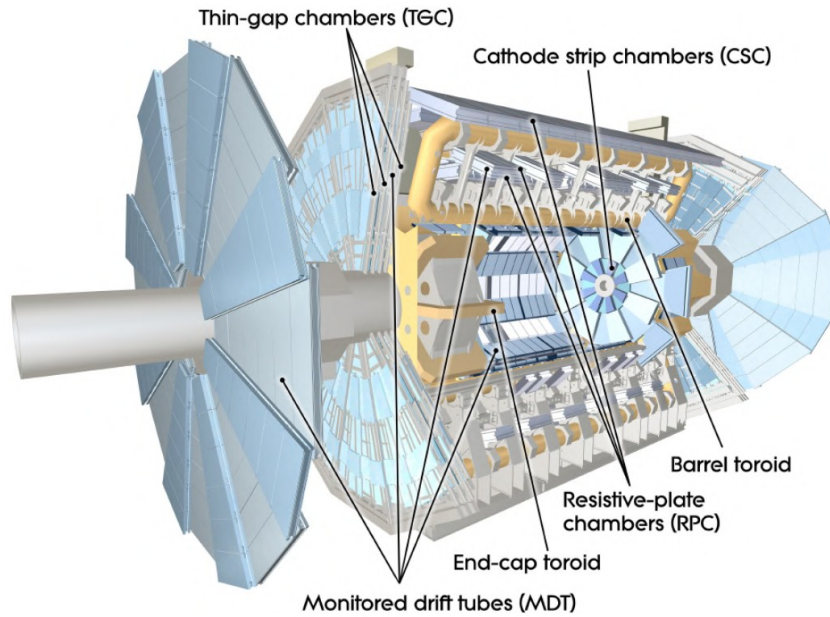


Figure 2.9: Structure of the ATLAS Muon Spectrometer [91].

2.2.4 Muon Spectrometer

The Muon Spectrometer (MS), situated as the outermost layer of the ATLAS detector (see Figure 2.4), is dedicated to the detection and precise characterization of muons. Muons, unlike most other particles produced in proton-proton collisions, have a high probability of escaping the ID and calorimeter systems undetected due to their minimal interaction with matter. The strategic placement of the MS allows for the identification and momentum measurement of these elusive particles.

To effectively measure muon properties, the MS leverages a magnetic field generated by a system of eight toroidal magnets [79]. These magnets curve the trajectories of muons as they pass through the MS, enabling a precise determination of their momenta based on the curvature. The MS incorporates four distinct detector technologies to achieve high-precision tracking: New Small Wheel (NSW), Resistive Plate Chambers (RPC), Thin Gap Chambers (TGC), and Monitored Drift

Tubes (MDT). Each technology plays a crucial role in the accurate reconstruction of muon tracks within the ATLAS detector.

The MS utilizes TGC and RPC technologies to trigger on events involving high transverse momentum (p_T) muons within the pseudorapidity range of $|\eta| < 2.4$. For more precise tracking, the CSC and MDT chambers are employed in the $|\eta| < 2.7$ region, offering a momentum resolution of 10% for muons with a p_T of 1 TeV. The magnetic field system comprises barrel toroids encompassing the MS in the central region (up to $|\eta| < 1.0$) and end-cap toroids for the forward and backward regions ($1.4 < |\eta| < 2.7$). The barrel section features three concentric layers of chambers (MDT and RPC), while the end-caps house four detector disks (wheels) on each side, equipped with TGC, MDT, and NSW components. This combination of technologies enables the MS to achieve high-precision measurements of muon momenta and trajectories.

2.2.5 Trigger and data acquisition system

The ATLAS experiment, designed to explore the properties of new particles and phenomena produced in high-energy pp and heavy-ion collisions, generates a massive amount of data with each collision [79]. The Trigger and Data Acquisition System (TDAQ) plays a crucial role in selecting events of scientific interest from this data deluge [79]. It filters the data and transmits relevant information to the data storage and processing facilities.

The ATLAS trigger system, depicted in Figure 2.10, employs a three-tiered architecture for progressively refined event selection. The first level, the Level-1 Trigger (L1), utilizes custom electronics for a rapid, preliminary selection based on data from the calorimeter and muon detectors. This initial filtering reduces the event rate significantly. The subsequent High-Level Trigger (HLT), encompassing both the Level-2 Trigger (L2) and the Event Filter, performs a more detailed analysis using information from all sub-detectors. The HLT further refines the event selec-

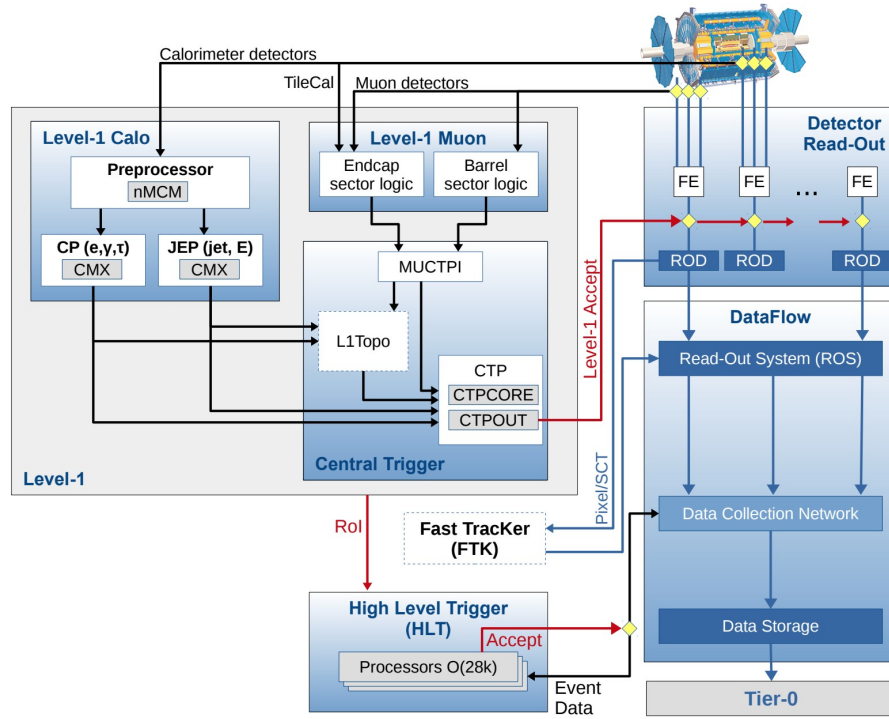


Figure 2.10: The ATLAS TDAQ system for Run 2 [92].

tion before transmitting the chosen events for storage and further processing [79, 93].

The L1 trigger consists of four sub-systems: L1 Calorimeter (L1 Calo), L1 Muon, L1 Topological (L1 Topo), and the Central Trigger Processor (CTP) [79, 93]. The L1 Calo identifies events containing objects other than muons using data from the calorimeters. The L1 Muon identifies muons based on information from the Muon Spectrometer (see Figure 2.9 for reference). The L1 Topo component then evaluates the spatial correlations between these initial selections. Finally, the L1 Calo, L1 Muon, and L1 Topo triggers transmit information to the CTP, which makes the final L1 decision and forwards accepted events for further processing [79].

The L1 outputs are fed into the HLT for a more comprehensive analysis. The HLT comprises two stages: the L2 trigger and the Event Filter. The L2 trigger utilizes a combination of custom electronics and commercial processors to perform

a more detailed spatial selection (Regions of Interest - RoI) based on data from the calorimeter, muon, and tracking detectors. The RoI concept identifies specific detector regions with potentially interesting events based on measurements like pseudorapidity (η), azimuthal angle (ϕ), and transverse momentum (p_T). Finally, the Event Filter, employing a farm of commercial processors, performs a very detailed event selection using information from all the ATLAS sub-detectors. This multi-stage filtering process significantly reduces the event rate from the initial 40 MHz to a manageable level of approximately 100 Hz, allowing for efficient data storage and analysis [79].

The TDAQ system also includes functionalities for data quality monitoring. A comprehensive assessment is conducted on the entire dataset to identify potential detector issues during data acquisition, such as abnormal voltages, temperatures, or malfunctioning detector cells. Events associated with such issues are flagged and excluded from further analysis through the generation of a “Good Run List” (GRL). The GRL ensures that only high-quality data, captured by functioning detector components, is used for physics analyses [79].

The Tile Calorimeter

The TileCal serves as the central hadronic calorimeter within the ATLAS detector [88]. It covers a region up to $|\eta| < 1.7$. The primary functionality of TileCal is to deliver accurate measurements of energy and position for various particles, including hadrons, taus, and jets (quarks and gluons). Additionally, it plays a vital role in reconstructing missing transverse energy resulting from high-energy pp collisions [94].

The TileCal consists of three longitudinal sections: a central long barrel (LB) covering the region of $|\eta| < 1.0$, spanning a length of 5.8 m, and two extended barrels (EBs) on either side, with coverage of $0.8 < |\eta| < 1.7$ and each extending 2.6 m in length. Each barrel (EBA, EBC, LBA, and LBC), where A and C are defined in Chapter 2.2, comprises 64 azimuthally stacked modules, as depicted in Figure 3.1. These modules consist of 3 mm thick trapezoidal tiles of plastic scintillators positioned between steel absorber plates.

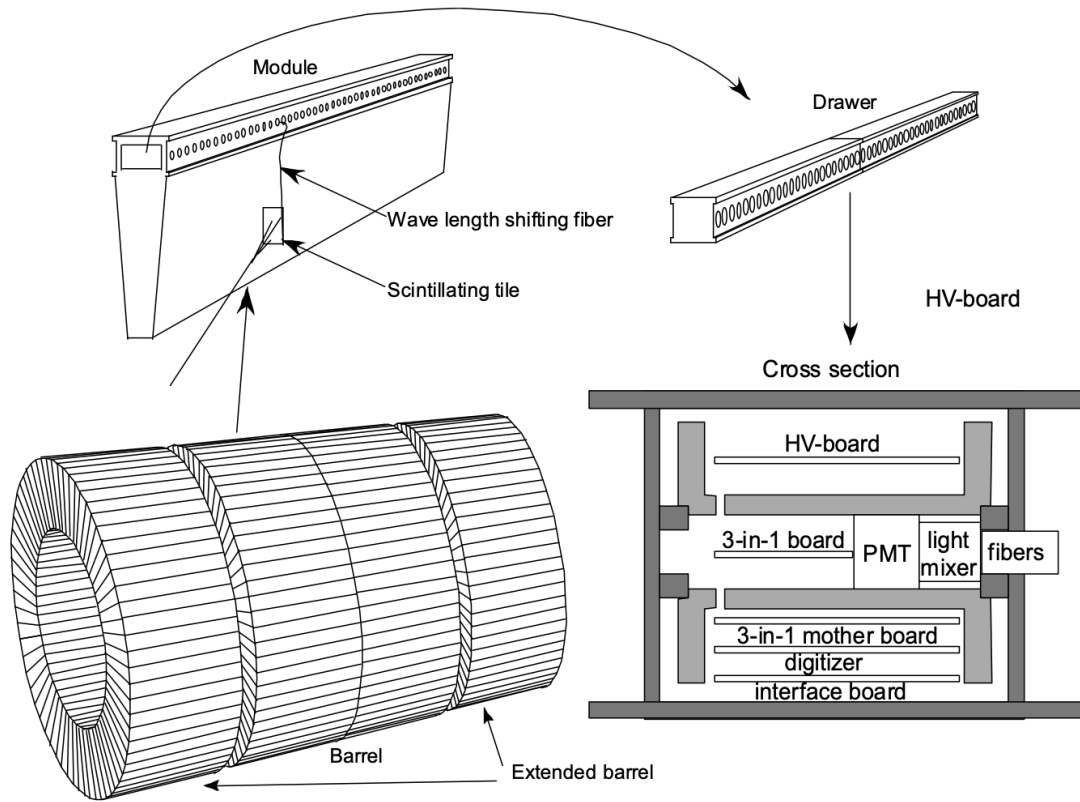


Figure 3.1: Diagram showing TileCal module's mechanical assembly and optical readout. [95].

3.1 Segmentation of cells

The TileCal modules are divided into three longitudinal layers referred to as A, BC, and D. In the barrel region, these layers have approximate thicknesses of 1.5, 4.1, and 1.8 nuclear interaction lengths, respectively. In the extended barrel region at $\eta = 0$, the corresponding thicknesses are 1.5, 2.6, and 3.3. Each type of cell is assigned a number based on the range of pseudorapidity it covers. Cells of type A and BC are numbered in pseudorapidity intervals of 0.1, while D-type cells are numbered in intervals of 0.2. Figure 3.2 depicts a schematic representation of the module segmentation for both LB and EB [88].

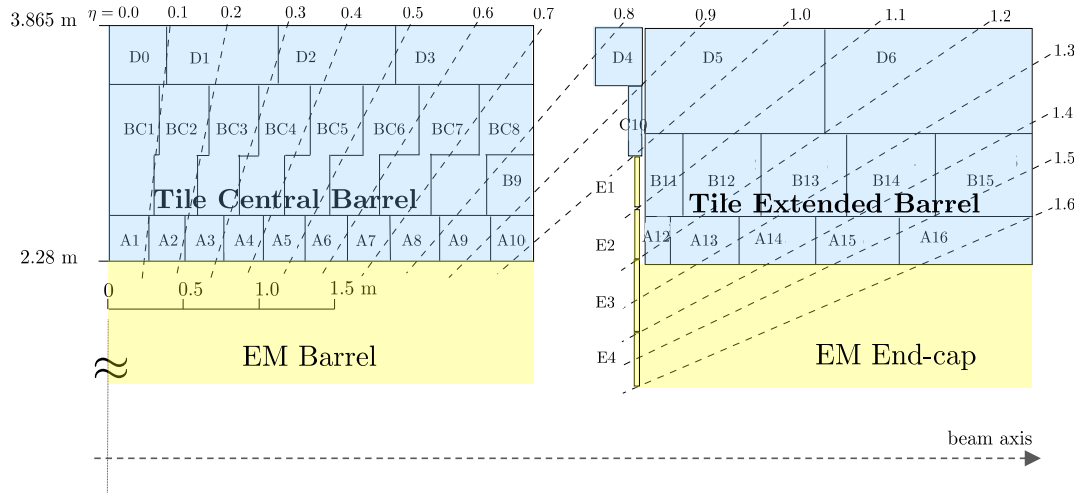


Figure 3.2: Segmentation of modules within the Tile Calorimeter [96].

3.1.1 Intermediate Tile Calorimeter

The Intermediate Tile Calorimeter (ITC) is a distinct section within the EB region, covering the $0.8 < \eta < 1.0$ region. In Figure 3.2, the cells identified as C10 and D4 reside within the gap region between the LB and EB. Additionally, the scintillators labeled E1 and E2, known as the gap scintillators, cover the range $1.0 < |\eta| < 1.2$.

The Crack scintillators, labeled E3 and E4, depicted in Figure 3.3, are positioned radially at the front of the Liquid Argon EM End-cap calorimeters. Their coverage spans the region $1.2 < |\eta| < 1.72$ (area between the two white circles). The purpose of these Crack scintillators is to correct the electromagnetic energy responses. They measure the energies of particle showers that interact with inactive materials, including ID cables and the cryostat walls of the electromagnetic calorimeters, within the gap region.

Additionally, alongside the standard cells and ITC, the Minimum Bias Trigger Scintillators (MBTS) are mounted on the LAr endcap cryostats, covering the

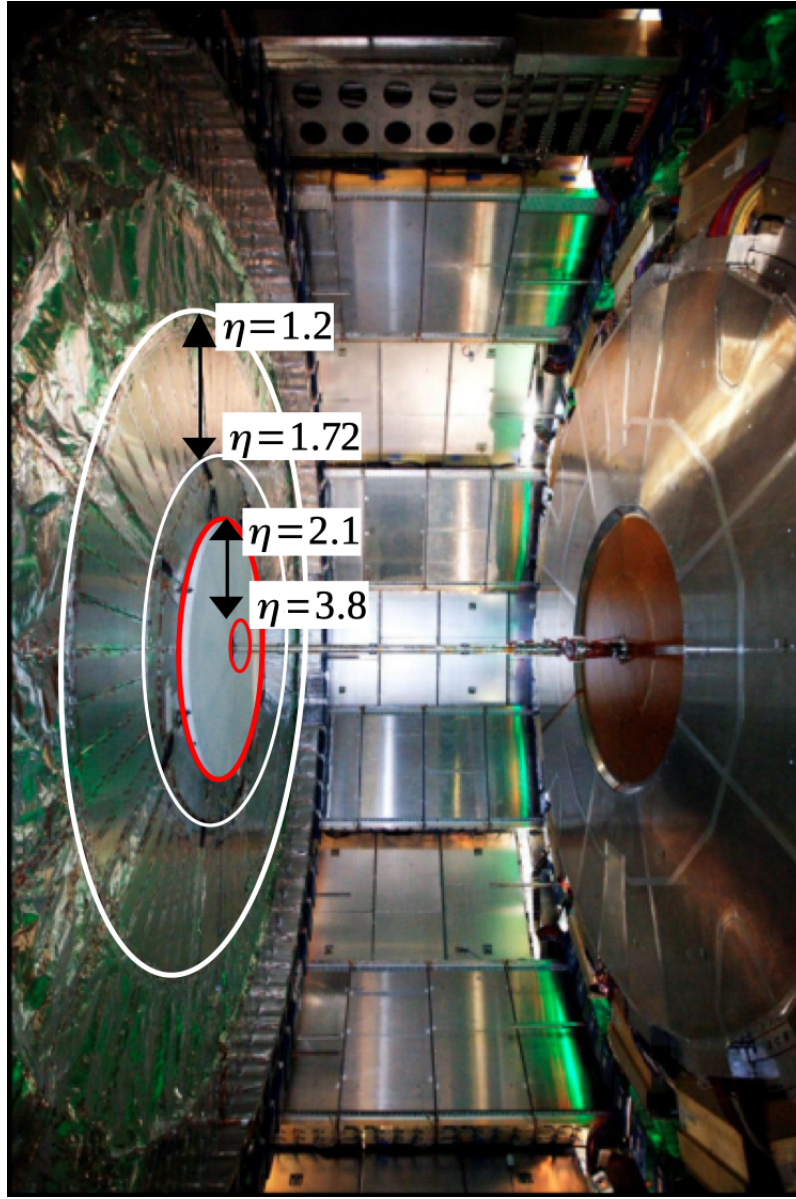


Figure 3.3: Crack scintillators ($1.2 < |\eta| < 1.72$) and MBTS ($2.1 < |\eta| < 3.8$) in the gap region [97].

region $2.1 < |\eta| < 3.8$ between the two red circles in Figure 3.3. The dimensions of MBTS are illustrated in Figure 3.4 [98]. The MBTS counters form an essential component of the level-1 hardware-based trigger system, designed specifically to trigger on proton-proton collisions during periods of low-intensity running, heavy ion running, and van der Meer scans [99, 100].

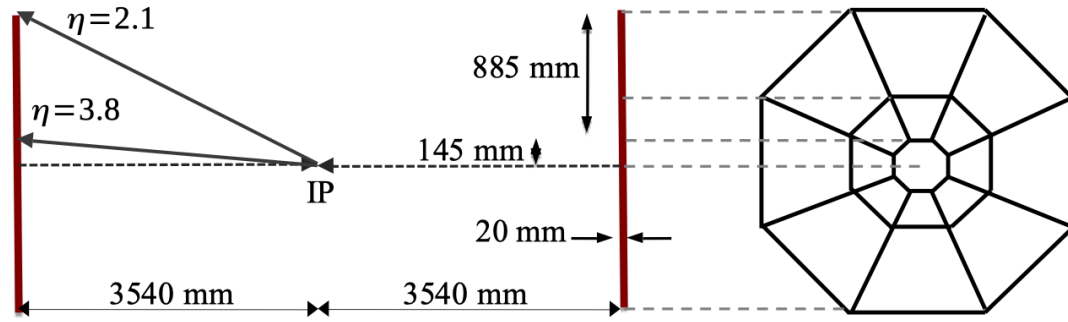


Figure 3.4: Sketch of dimensions of the Minimum Bias Trigger Scintillators [98].

3.2 Scintillating tiles and WLS fibers

Plastic scintillating tiles and wavelength shifting fibers have become extensively utilized in the construction of detectors for High Energy Physics experiments [101]. They serve as crucial components for tracking and calorimetric applications, finding widespread use in the field. Since the 1980s, they have been employed in calorimeters, serving as both the active medium and the light output guiding material. These scintillating fiber-based devices have been utilized as trackers and calorimeters in various experiments due to their excellent optical properties. WLS fibers have become commonly used in conjunction with scintillating tile calorimeters, which are now widely popular, as readout devices in hadronic calorimeters of experiments such as ATLAS and CMS.

Tile Calorimeters use scintillating tiles to absorb and detect particles, generating light signals in the form of photons. To guide these photons out of the calorimeter, WLS fibers are utilized. These fibers can be embedded within the tiles or placed on their surfaces. The WLS fibers are designed to capture the ultraviolet or blue light emitted by the scintillating tiles and then re-emit it at a longer wavelength, typically in the visible range. This property of wavelength shifting facilitates the efficient transmission of scintillation light from the tiles to the readout system, which comprises photodetectors that are sensitive to visible light.

The scintillator tiles utilized in the Tile Calorimeter were fabricated by melting and baking a mixture of transparent polystyrene granules, serving as the base polymer, and finely dispersed dopants for wavelength shifting. The dopants included 1.5% of p-Terphenyl and 0.04% of di-phenyloxazolyl-benzene (POPOP), which were blended in a heated screw cylinder.

Around 460,000 scintillator tiles were produced for TileCal, with thorough monitoring of critical properties such as light yield and transmission, ensuring exceptional quality. In contrast, the readout fibers used in TileCal were high-quality wavelength shifting fibers obtained from Kuraray [102], a well respected manufacturer in the field. These fibers, designated Y-11(200)¹, were capable of shifting 450 nm (blue) to 530 nm (green) wavelengths and were renowned for their superior properties, such as high luminescence and attenuation length. A total of 578,000 of these exceptional WLS fibers were manufactured for use in TileCal.

Quality control of the scintillators and WLS fibers is crucial after their production to ensure that they meet the required specifications and are of high quality as detailed in Refs. [103, 104]. The following are some of the quality control measures that are taken:

Visual inspection The scintillators and WLS fibers are visually inspected to check for any physical defects, such as cracks, scratches, or discoloration.

Dimensional measurement The dimensions of the scintillators and WLS fibers are measured to ensure that they meet the required specifications, such as length, width, and thickness.

Light output measurement The scintillators' light output is measured using a photomultiplier tube to ensure that it meets the required specifications. The light output of the WLS fibers is also measured to ensure that they are transmitting the scintillation light efficiently.

¹Kuraray reference: Y-11(200), Multi-cladding, 1MM D., S-type

Attenuation length measurement The attenuation length of the WLS fibers is measured to ensure that they are not losing too much light during transmission.

Radiation damage testing The scintillators and WLS fibers are exposed to particles to simulate the conditions that they will experience in the ATLAS detector. The light output and attenuation length are then measured again to ensure that they have not been significantly affected by the radiation.

Temperature cycling The scintillators and WLS fibers are subjected to temperature cycling within the range of -20°C to 50°C for 100 cycles to ensure that they can withstand the temperature changes that they will experience in the ATLAS detector without losing their physical or optical properties.

Longevity testing The scintillators and WLS fibers are subjected to extended use to ensure that they can maintain their physical and optical properties over time.

Overall, these quality control measures ensure that the scintillators and WLS fibers used in the Tile Calorimeter are of high quality and meet the required specifications, thus contributing to the overall performance of the ATLAS detector.

3.3 Light readout system

Upon traversing the detector, highly energetic hadrons resulting from proton-proton collisions interact with the atomic nuclei present in the steel plates. The incoming hadrons are absorbed, leading to the formation of a cascade of low-energy particles. Subsequently, these particles deposit their energy within the plastic scintillator tiles, causing them to emit light within the visible spectrum through fluorescence. To capture this emitted light, WLS fibers are coupled to the exposed edges of each scintillator tile. These fibers serve to collect and transmit the light.

For a visual representation of a typical TileCal module and its constituent elements refer to Figure 3.1.

Each module consists of an arrangement of plastic scintillator tiles organized into read-out cells. The wavelength shifting optical fibres which are routed from individual tiles and suitably bundled, transmit light to the photocathode of PhotoMultiplier Tubes (PMTs) (see Figure 3.5). The PMT signals undergo shaping and amplification in specialized 3-in-1 boards [105, 106], located adjacent to each photomultiplier. These boards generate two output signals, one with high gain and another with low gain, with a gain ratio of 64:1. Following amplification, the signals from both gains are sampled and digitized at a 40 MHz frequency using 10-bit analog-to-digital converters (ADC) [95], resulting in a pulse represented by seven samples. The high gain signal is used by default; however, if any of the seven samples saturate the ADC, the system switches to the low gain signal that has a factor 64 with respect to the high gain. Subsequently, the sampled data are temporarily stored in a pipeline memory, awaiting the L1 trigger decision as described in Section 2.2.5.

Each cell within TileCal contains 2 PMTs, resulting in over 10,000 readout channels in total. TileCal consists of 256 modules, and Figure 3.1 (left) shows a diagram of a layout of 64 modules placed side-by-side [79].

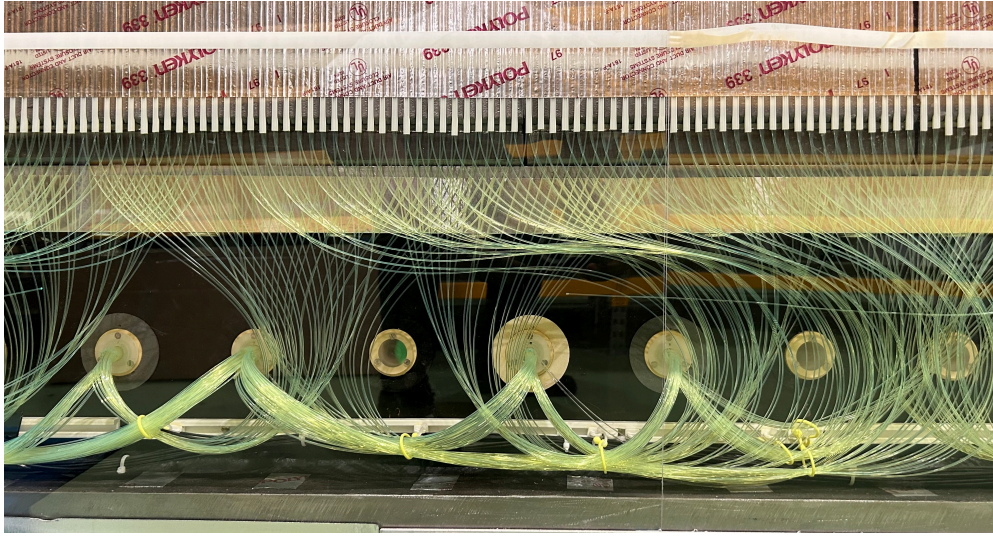


Figure 3.5: A photograph of fiber routing in one of the extended barrels.

3.4 Radiation environment

Background radiation in the LHC primarily originates from collisions of the proton beams at the interaction point. Prior to Run 1 of the LHC (operating at a center-of-mass energy of 7 TeV for proton-proton collisions), extensive simulations were conducted to assess the impact of this background radiation on the performance of the ATLAS detector [79].

To achieve accurate predictions of the background radiation within ATLAS, versatile MC particle transport software was employed. These software packages simulate the interactions and transport of particles through matter, allowing researchers to predict the types and rates of particles reaching the detector components. Two prominent examples of such software used in ATLAS are GEANT3-CALOR (GCALE) [107] and FLUKA [108].

Simulations predicted that sub-detector elements closest to the beam axis would experience the most significant radiation dose rates. This is due to the higher density of particles produced in these regions during beam collisions. Conversely, the radiation levels within the gaps between sub-detectors were expected to be

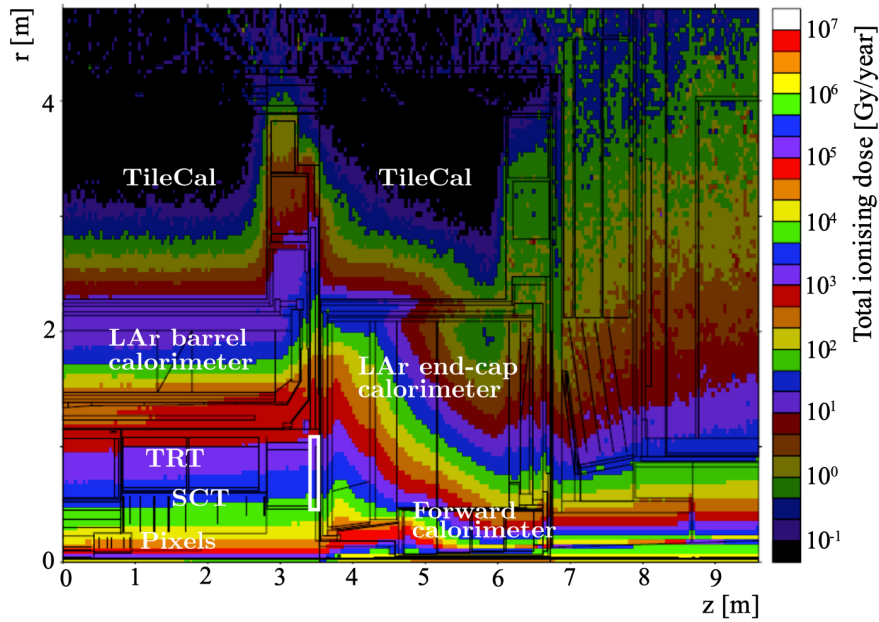


Figure 3.6: Radiation map depicting the total ionising dose accumulated over one year in the TileCal region during Run 1. The white box indicates the MBTS region [79].

even higher compared to the barrel regions [79].

Figure 3.6 depicts a GCALOR prediction of the total ionising dose per year (Gy/year) at $\sqrt{s} = 14$ TeV. The assumed scenario considers one year of LHC operation corresponding to 8×10^{15} inelastic proton-proton collisions. These collisions are based on a nominal luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$, an inelastic cross-section of 80 mb, and a data acquisition time of 10^7 seconds [79, 109, 110].

The MBTS counters were originally intended to operate only in the first few years of the LHC, where the vast majority of crossings would not result in a beam-beam interaction. The counters would serve to provide a trigger to discriminate beam-beam interactions from beam-gas interactions. Originally, there were no TileCal electronic channels available for the MBTS counter readout. To create the needed channels, one-eighth of the Crack counters were removed from the detector on each extended barrel (EBA and EBC). These counters were missing from the following modules: EBA 03, 12, 23, 30, 35, 44, 53, 60 and EBC 04, 13,

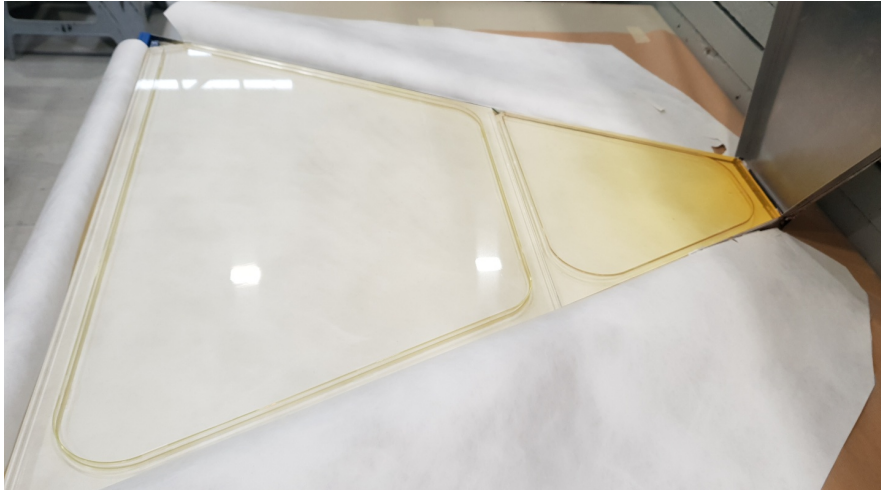


Figure 3.7: A photograph of one of the MBTS counters after operation from 2015 to 2018 (Run 2).

20, 28, 37, 45, 54, 61. The light signals from the MBTS counters were connected to the optical cables originally used for the missing Crack counters. Later, for Run 2, additional channels were made available by merging the light signals from adjacent E1 counters, and the missing Crack counters were reinstalled.

The MBTS counters have maintained their functionality throughout Run 2, even with the loss of up to 95% of the light at the inner radius. Figure 3.7 shows one sector of the MBTS counter, where intense radiation damage is indicated by the yellowing of the scintillator. The radiation dose at the inner radius was approximately 20 MRad, which is more than what was predicted. In 2015, the luminosity prediction for the full Run 2 was 100 fb^{-1} , but eventually, 140 fb^{-1} was delivered. The Crack counters are located at a lower rapidity, but in the case of E4, in a region corresponding to electromagnetic shower max. This position results in a higher radiation dose, but an accurate sampling of the energy deposited by electrons and photons in this region is crucial for improving the energy resolution degraded by the material present. The corrections provided by the Crack counters improve both the peak value of the energy measurement and the energy resolution.

The replacement of Crack and MBTS Scintillator Detector Modules for Phase-I Upgrade of the Tile Calorimeter

4.1 Introduction

The Phase-I upgrade of the Tile Calorimeter during the Long Shutdown 2 involved the complete replacement of the E3E4 (Crack scintillators) and Minimum Bias Trigger Scintillator (MBTS) counters. As explained in Chapter 3, these counters, located between the central and extended Tile Calorimeter barrels, play a crucial role in correcting electromagnetic energy responses and providing trigger inputs. During the LHC Run 2 data-taking period (2015-2018) at a collision energy of $\sqrt{s} = 13$ TeV, the original counters have deteriorated by radiation and had to be replaced for Run 3.

The upgrade activities consisted of the re-design of the Crack and MBTS counters, extending to higher rapidity, assembly of the counters, qualification and characterization using radioactive sources, such as ^{90}Sr and ^{137}Cs , and their subsequent installation in the ATLAS detector. The University of the Witwatersrand contributed to the radiation qualification and selection of scintillator material for

the production of these counters, as well as their installation [111, 112, 113, 114, 115]. The replacement process was designed to be easily implementable [116, 117, 118, 119]. Nonetheless, it's noteworthy that the MBTS counters underwent an upgrade solely for Run 3. In the subsequent High Luminosity LHC Phase-II upgrade during Run 4, they will be substituted with a new detector known as the High Granularity Timing Detector [120].

This chapter focuses on the upgrade and quality checks conducted on the Crack and MBTS counters, with the aim of enhancing the performance of the Tile Calorimeter. It highlights the improvements made to these counters and provides an overview of the rigorous quality checks performed to ensure their optimal and homogeneous performance within the Tile Calorimeter system.

4.2 Geometry optimisation and materials

4.2.1 Crack counters

The Crack counters were extended from a maximum pseudo-rapidity coverage from up to 1.6 to up to 1.72 (see Figure 4.1), motivated by the need to improve the e/γ energy resolution in this extended range. This is supported by multivariate analysis (MVA) calibration of the reconstructed electron energy in the extended range [121], which shows a significant improvement in the energy resolution (refer to Figures 4.3 and 4.4). After conducting simulation and rate studies, it was determined that the E3 section would cover the rapidity range of 1.2 to 1.6, freeing up the E4 channels to cover the region from 1.6 to 1.72. Since the rate in the old E3 counter (1.2–1.4) was considerably smaller than in the old E4 counter (1.4–1.6), the performance was not seriously affected by combining the two rapidity regions in the same readout [121]. Consequently, this arrangement provides reasonable rates for both the new E3 and E4 counters.

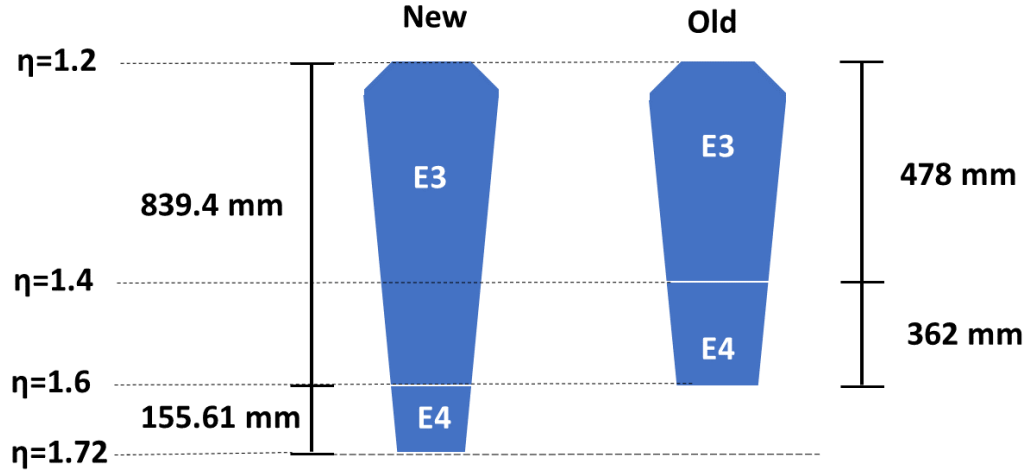


Figure 4.1: Sketch of the geometry of old Crack counter Vs. geometry of the new counter.

To achieve an ideal increase in maximum rapidity, the value should be around 1.75. However, it was crucial to exercise caution to prevent any interference with the heating plates of the forward cryostat, and as a result, the counters were limited to a rapidity of 1.72. The current location of the inner radius of the Crack counters and the location of the outer heating plates is shown in Figure 4.2. The Crack counters are mounted to the inner radius of the extended barrels and are designed to be easily installed/dismounted.

Additionally, it was imperative to prevent any electrical contact between the aluminum shells of the Crack counters and the cryostat wall, and this was achieved through the use of Mylar®¹ for insulation purposes.

The new Crack counter design aimed to improve the counter alignment system, which was previously carried out at the outer radius where the counters were attached to the TileCal extended barrel. However, this type of alignment was

¹Mylar, or BoPET (Biaxially-oriented polyethylene terephthalate), is a polyester film with high tensile strength, chemical stability, transparency, reflectivity, gas and aroma barriers, and electrical insulation properties, made by stretching polyethylene terephthalate (PET).

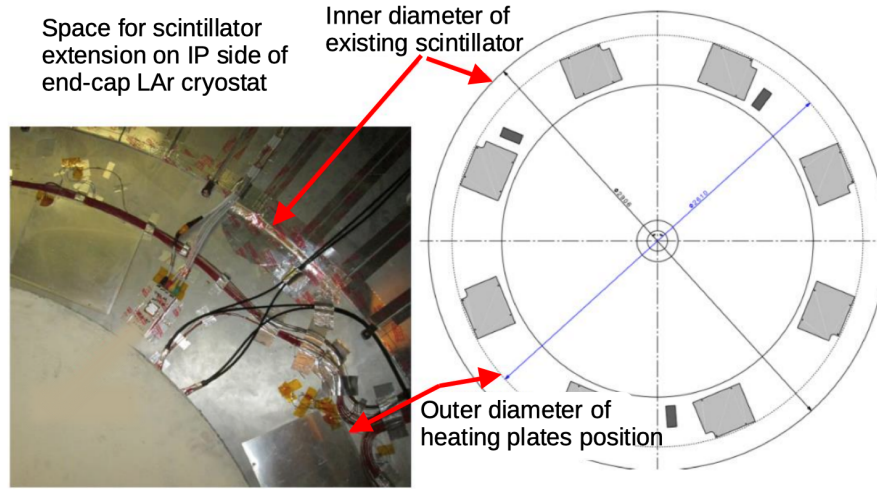


Figure 4.2: Picture of the inner radius of the Crack scintillators with a corresponding diagram showing the locations of the outer heating elements.

highly sensitive to the actual radius of the extended barrel and any non-circularity, resulting in gaps between counters at the inner radius ranging from 0 mm to over 1 cm. To address this issue, the counter shapes were re-designed based on detailed in situ measurements of the gaps and the actual radius of the extended barrels, with the aim of providing a more comprehensive fiducial coverage and inner radius alignment using specialized spacers to maintain a uniform 1 mm space between any two counters (see the installation of Crack counters in Figure A.9).

A module-zero consisting of eight counters was constructed at Michigan State University and temporarily installed on one of the extended barrels to test the new design and alignment scheme. The results demonstrated sufficient flexibility for the connection of the outer radius of the counters to the extended barrel to be adjusted to preserve the 1 mm spacing at the inner radius. With the installation of all 64 new counters, complete closure with the uniform 1 mm gap at the inner radius was obtained on both the A and C sides, effectively demonstrating the success of the new design and alignment approach.

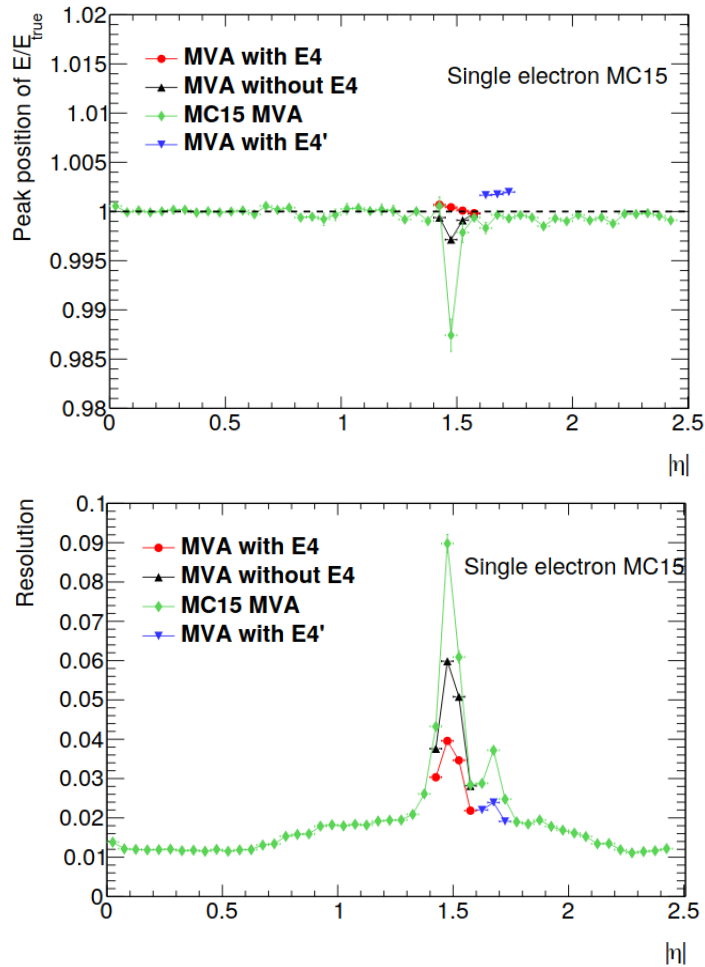


Figure 4.3: Peak position of E/E_{true} [left] and resolution [right] as a function of pseudorapidity for electrons, comparing the MVA calibration with E4 tiles for the Crack region to the initial MVA calibration used for Monte Carlo samples for 2015 data analysis (MC15) [121].

4.2.1.1 Summary of scintillating materials used in Crack counters production

A new Crack counter is composed of a radiation hard and high-performing PolyvinylToluene (PVT) based plastic scintillator (EJ-208) [123]. This scintillator has a long emission spectrum at 435 nm, providing additional resistance to radiation damage, as such damage typically results in increased optical attenuation at shorter wavelengths (see Figure 4.5).

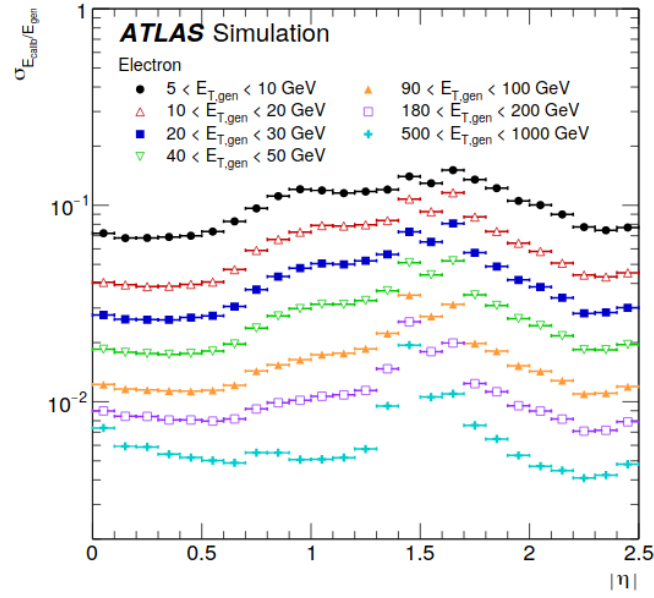


Figure 4.4: Energy resolution ($\sigma_{E_{calib}}/E_{gen}$) estimated from the interquartile range of E_{calib}/E_{gen} as a function of $|\eta|$ for electrons in different E_T ranges [122].

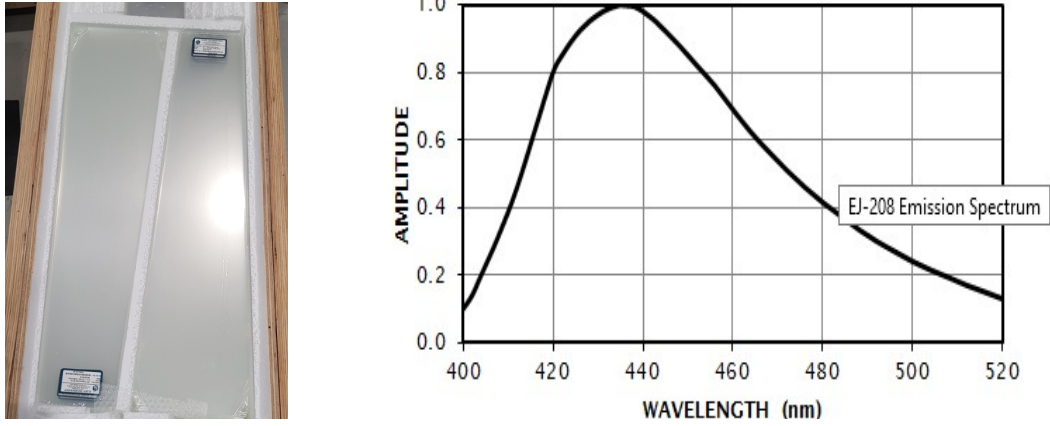


Figure 4.5: High-performance PVT EJ-208 scintillating tiles (left) and their emission spectrum (right) [102].

Kuraray's Y-11 (Multi-cladding, 1MM D., S-type [102]) wavelength shifting fibres are utilized to collect light emitted by the scintillating tiles (blue to green shifters). The collected light is then conveyed by clear fibers to the photomultiplier tubes housed within the TileCal girder, the module's external supporting structure. These fibers are preferred due to their optimal characteristics, such as

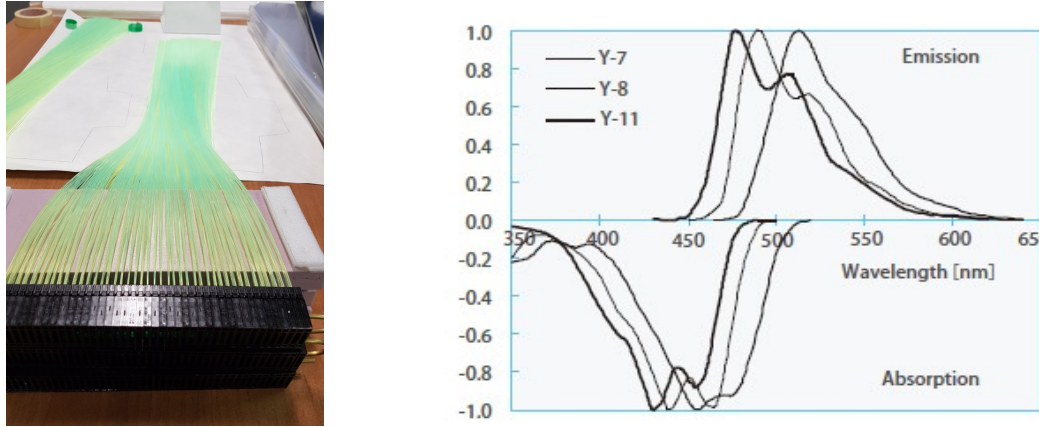


Figure 4.6: Left: Y-11 green WLS optical fibres and Right: Absorption and Emission spectra [102].

a long attenuation length exceeding 3.5 m and high light yield. Additionally, their absorption spectrum aligns with the emission spectrum of EJ-208 scintillators. Figure 4.6 presents a photograph of Y-11 green fibres, along with their absorption and emission spectra.

4.2.2 Minimum Bias Trigger Scintillators (MBTS)

During the investigation of a radiation-resistant plastic scintillator, as documented Refs [111, 112, 113], it was discovered that existing commercial plastic scintillators would still experience significant degradation at the doses in the MBTS region, as outlined in Section 3.4. To counter this effect, several optimizations were proposed. The first involved replacing a single 20 mm thick scintillator plate with a sandwich of four 5 mm scintillators, each individually wrapped with Tyvek®, a material made of 100% high-density polyethylene that acts as a diffuser [124].

The primary reason for using thinner plates was to allow for oxygen diffusion into the scintillators, which is crucial for annealing radiation-induced optical absorption. This phenomenon improves light transmission and helps the scintillator tiles recover after exposure to high-energy particles. The second optimization involved placing the WLS fibres in the grooves on both sides of the large (outer) plates

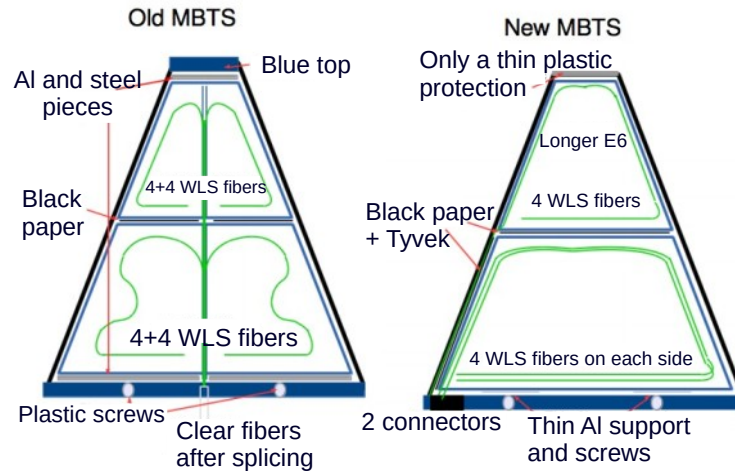


Figure 4.7: Geometry optimization of MBTS scintillator detector module [125].

to enhance their light collection properties, instead of using several fibres in the same groove on one side (see Figure 4.7 and Appendix A).

4.2.2.1 Summary of scintillating materials used in MBTS counters production

The MBTS counters that were used during Run 1 were made of a scintillator UPS-923A material, provided by JINR, Dubna. Later on, before Run 2, the degraded scintillators were replaced by the same non-irradiated material. For Run 3, a more radiation hard green scintillator (PS+BBQ) and more standard (PS+PTP+POPOP) blue scintillator were produced for the inner and outer radius plates, respectively (see Figure 4.8). The scintillator plates were produced from polystyrene granules by melting and baking in a stainless steel form in the oven.

The inner MBTS scintillators (green) have good light yield, which is only 1.5 times less than the same plate from EJ-200 (blue). New WLS orange O-2 (Multi-cladding, 1MM D., S-type [102]) and green Y-11 fibres from Kuraray were mirrored at LIP Portugal and glued to connectors at Michigan State University. Mirroring of fibers involves coating one end of the optical fibers with a reflective material to

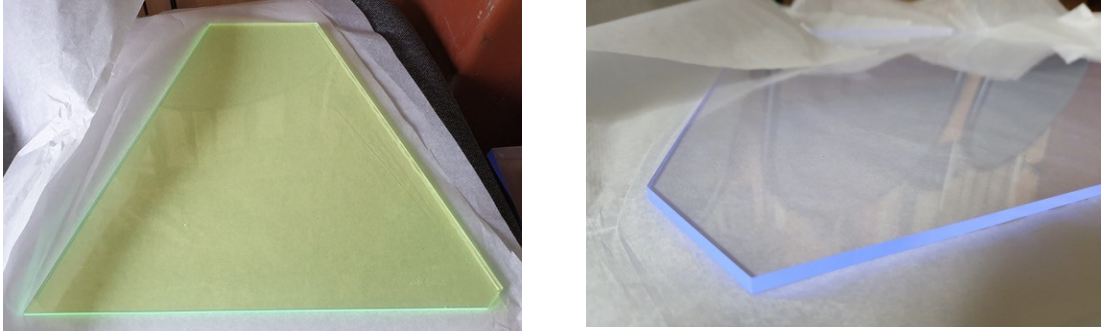


Figure 4.8: Inner MBTS green plate made from PS+BBQ (left) and Outer MBTS blue plate made from PS+PTP+POPOP (right) – right after production, without fibre grooves.

improve light collection efficiency. This reflective coating ensures that any light traveling down the fiber and reaching the mirrored end is reflected back through the fiber, effectively doubling the amount of light that can be transmitted to the detector [126].

Figure 4.9 shows the emission and absorption spectra of dyes used in the production of above mentioned scintillating tiles and fibres. The custom red WLS fibres which were produced by the IHEP consisted of a NOL10 dye having an absorption spectrum matching the emission spectrum of BBQ and was hoped to be used for green scintillator readout. Unfortunately, the NOL10 dye was not radiation hard according to the tests and O-2 fibres were chosen for readout instead [127].

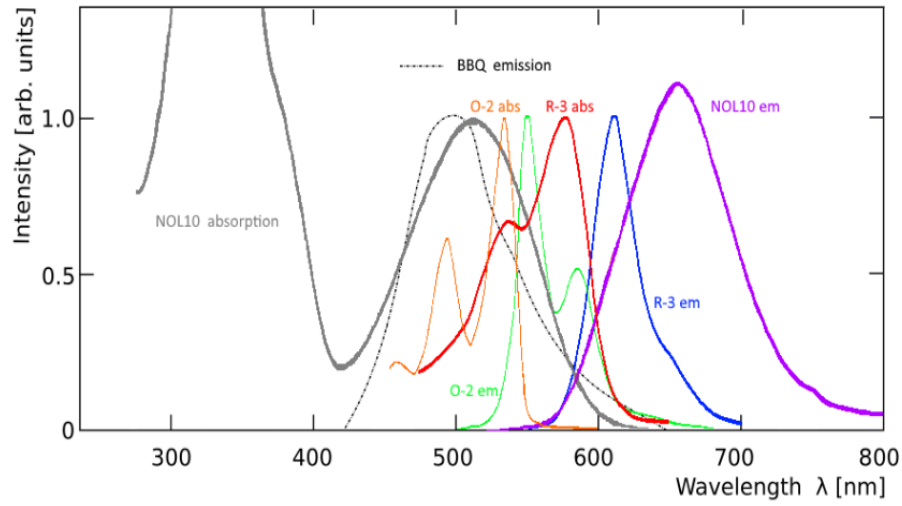


Figure 4.9: Absorption and emission spectra of dyes [127].

4.3 Assembly of detector modules

A special assembly procedure was carefully followed, step by step:

4.3.1 Crack counters

The Tyvek® material was prepared from a standard template provided. It was used for wrapping the scintillator tile as shown in Figures 4.10 and 4.11. Tyvek is designed to trap the scintillation light through internal reflection and also provides mechanical protection.

After wrapping the scintillator tiles with a Tyvek, black tape was placed along the edges of E3 and E4 scintillators [128]. This was done to eliminate the possibility of light escaping E3 region and mixing with light from E4 area. A wrapped E3 tile is shown in Figure 4.12, the unfolded side is where the E3 fibres are coupled. The E4 fibres are aligned along the black tape.

The wrapped scintillator tiles were then placed inside the metallic aluminum can shown in Figure 4.13. These cans are constructed to house the scintillator tiles,

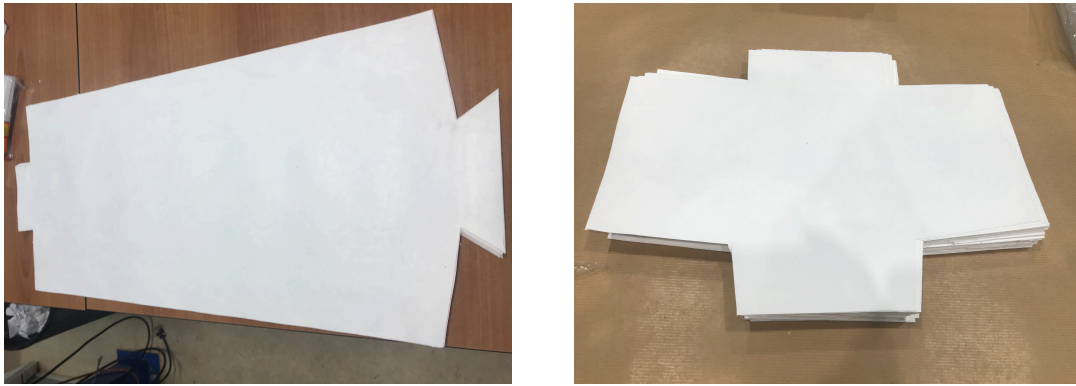


Figure 4.10: Tyvek for E3 (left) and E4 tiles (right).

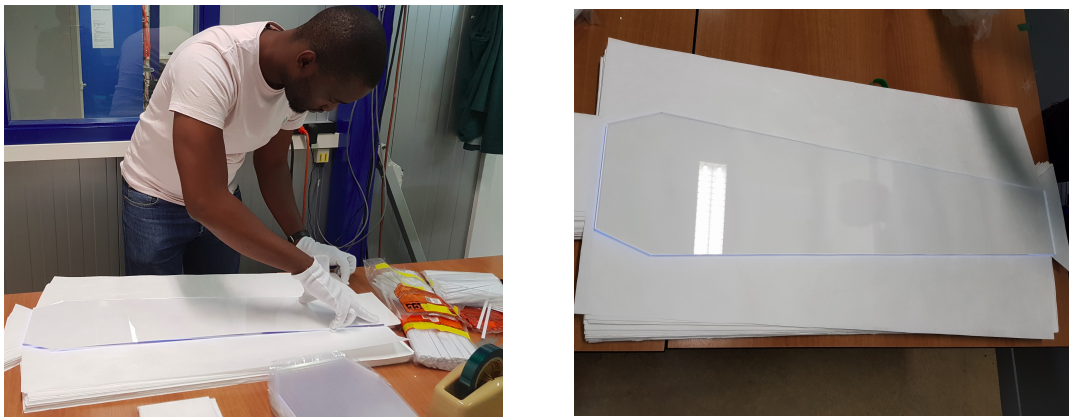


Figure 4.11: Wrapping scintillator tiles with a Tyvek.

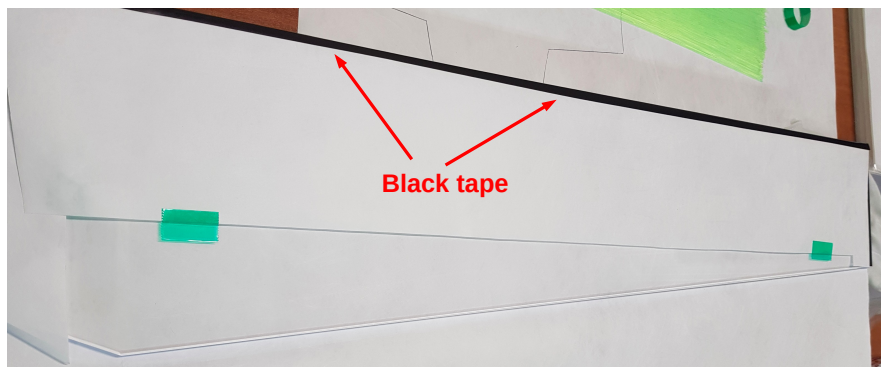


Figure 4.12: A wrapped E3 tile with a black tape placed along the edge.

providing mechanical protection and guarding against light leaks.

The E4 tile was first placed in the aluminum can and its coupled long fibre assem-

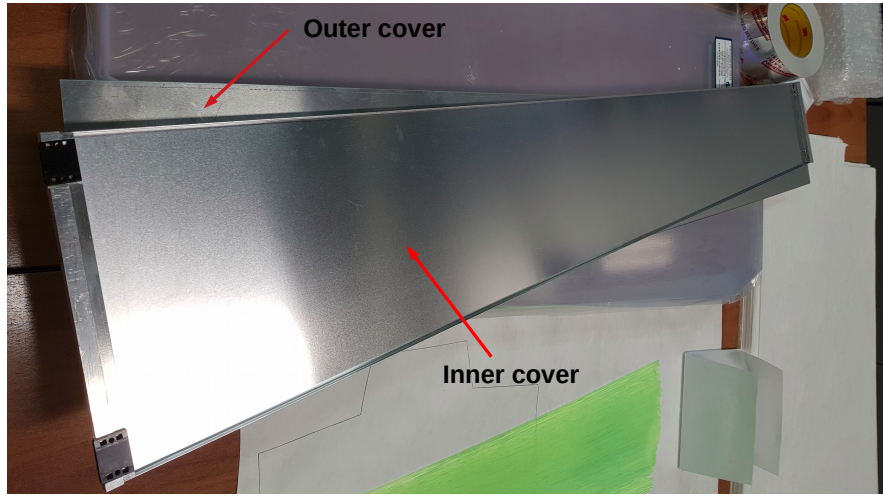


Figure 4.13: Aluminum cans for housing scintillator tiles.

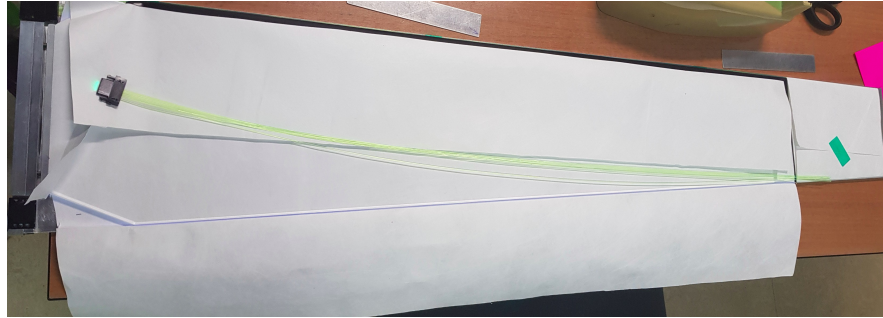


Figure 4.14: WLS fibre placement.

bly (6 fibres) was plugged into the E4 connector barrel. The fibres were aligned and taped to side of the can without overlapping. It was ensured that the scintillator tiles and fibres were packed tightly by placing polystyrene shims in the gaps left on the sides. The E3 tile was lastly placed in the can, with the taped side facing the E4 fibres. Six fibres were also coupled along the edge of E3 scintillator and plugged to the connector.

Finally, everything was enclosed by placing the outer aluminum can. A black tape was used to completely seal the perimeter of the can and was finalised with aluminum tape as shown in Figure 4.15. The purpose of the seal was to ensure that the counter remains intact and light tight.

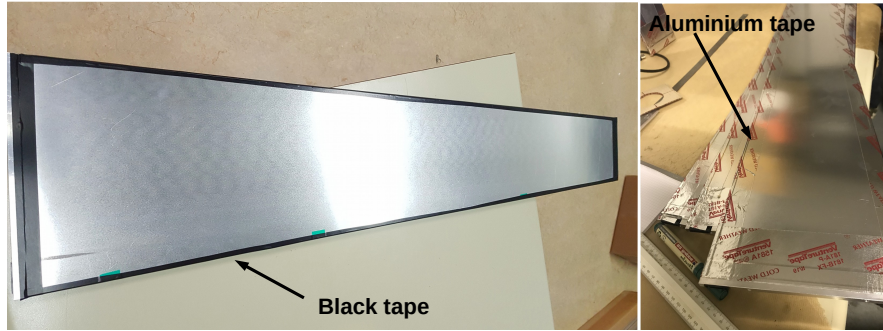


Figure 4.15: A complete assembled Crack counter.

A total of 133 counters and 8 prototypes were assembled for EBA and EBC.

4.3.2 Minimum Bias Trigger Scintillators

The MBTS counters were upgraded with polystyrene scintillator and new fibres, with inner plates (green scintillator) made from IHEP Protvino and O-2 fibres. The aluminum cans were reused from the old counters.

The old cans were opened to remove the old scintillators and fibers, which were then cleaned. Notably, the radiation level of the old components was low, almost at background radiation levels. Tyvek was prepared for wrapping the individual 5 mm thick tiles (32 inner small and 32 large outer tiles). The WLS fibres were placed along the grooves made on each tile (2 fibres per tile), O-2 fibres coupled to green scintillator (inner counter) from IHEP Protvino and new green fibres coupled to polystyrene scintillators (outer counters). The tiles were wrapped, placed in aluminum cans and sealed with black and aluminum tape.

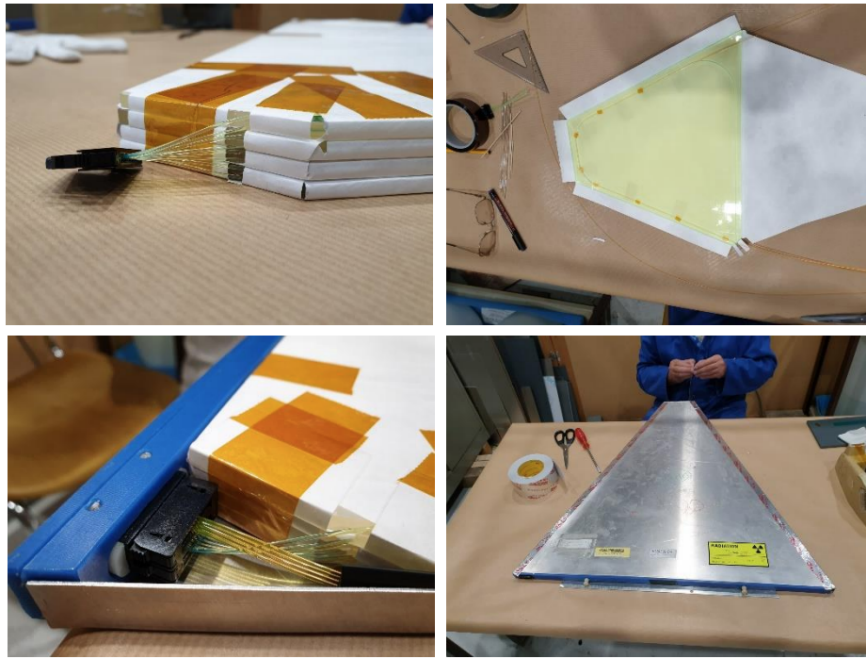


Figure 4.16: Assembly of MBTS detector modules.

4.4 Quality assurance

Before being installed on the ATLAS detector, the assembled detector modules underwent a rigorous quality assurance process. This involved the certification and characterization of the modules, which was carried out in the building 175 at CERN laboratories. Strontium-90 (^{90}Sr) and Cesium-137 (^{137}Cs) radioactive sources were employed for this purpose.

4.4.1 Scanning of Crack counters with ^{90}Sr source

When assessing the quality of E3 and E4 scintillators, the luminescence phenomenon in the plastic scintillators is excited using a ^{90}Sr β -electron source with an activity of 25 MBq, a maximum energy of 2.28 MeV, and a 2 mm collimator. Figure 4.17 shows a schematic representation of light collection and transmission from the scintillating material to the PMT via a WLS.

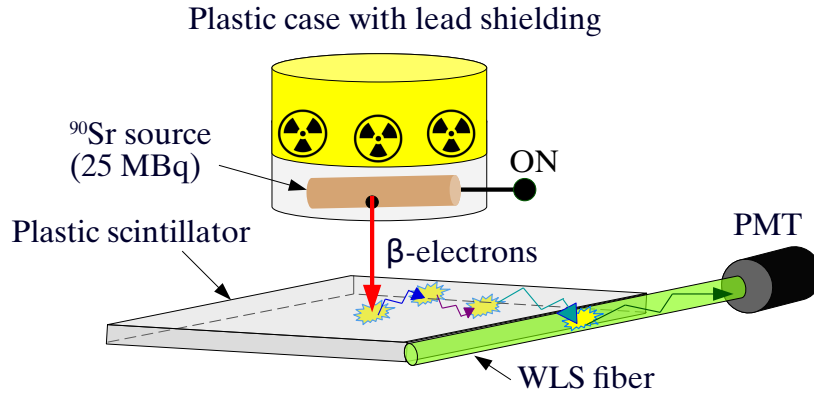


Figure 4.17: Radiation source and scintillation light transmission.

As incident β -electrons traverse the base polymer, they deposit energy along their trajectory path through ionization losses. This deposited energy excites the base molecules, which subsequently transfer their excitation energy to primary fluorophores through processes such as radiative re-absorption or a non-radiative mechanism called Förster resonance energy transfer [129].

The dopant molecules discharge and produce ultraviolet (UV) light at 340 nm. The UV light can only traverse PVT for a maximum of 3-5 mm before being absorbed by PVT or absorbed by POPOP's secondary dopant (fluorophore) molecules. These molecules serve as wavelength shifters by absorbing the shorter wavelengths emitted by the primary fluorophores and re-emitting them at longer wavelengths, around 410 nm (violet), towards the edges of the scintillator material [130]. The emitted light is collected by the WLS fibres and transmitted to the PMT photocathode at an increased wavelength of about 480 nm (green). The performance of a Crack scintillator is determined by its capacity to produce, convert, and transmit light, as well as the optical quality and uniformity of its surfaces throughout the entire module. Any possible misassembly of the detector modules could result in light losses, calculation errors, and ultimately poor calorimeter performance.

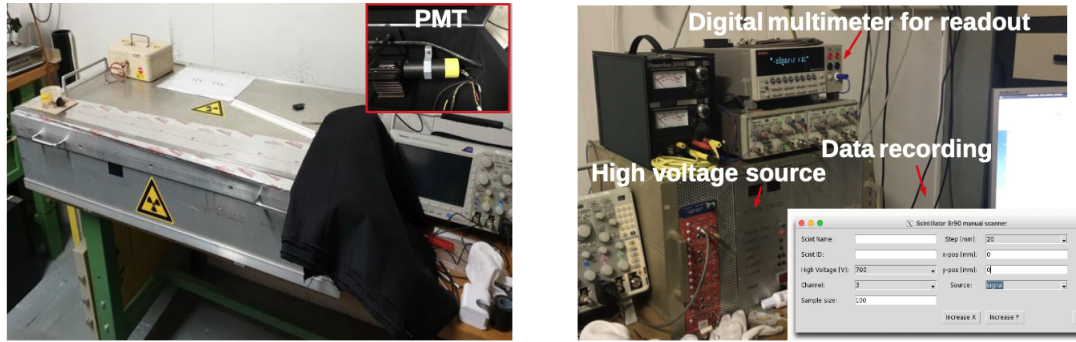


Figure 4.18: Experimental setup of the ^{90}Sr scan.

The experimental setup, illustrated in Figure 4.18, consists of a light-tight scan box housing several components. These include a photomultiplier tube (PMT), which is powered by a high voltage source supplying 700 V. A clear² optical fibre cable comprising six fibres is used to connect the counter to the PMT. A digital multimeter is employed for readout purposes, and a ^{90}Sr beta source with an activity of 25 MBq is utilized. Additionally, a data recording system is incorporated into the setup.

The E3 and E4 segments of the counter underwent assessment to detect any potential light leaks. Prior to conducting the ^{90}Sr scans, the pedestal measurement was performed by recording the signal from the PMT while the counter segments were devoid of a ^{90}Sr source. Once the pedestal measurement was completed, the ^{90}Sr source was introduced, and its position was systematically adjusted along the x -axis of the counter. The voltage reading was recorded at each step during this process.

To collect data, two types of scans were performed, as depicted in Figure 4.19: fine scan and regular scan. During the fine scan, the source was incrementally moved along the x -axis with 10 mm steps, and the voltage readings were recorded at each step. On the other hand, the regular scan involved taking measurements at specific points along each segment. In the E3 counter, four points were selected:

²A fiber specifically designed to transmit the collected light with minimal loss.

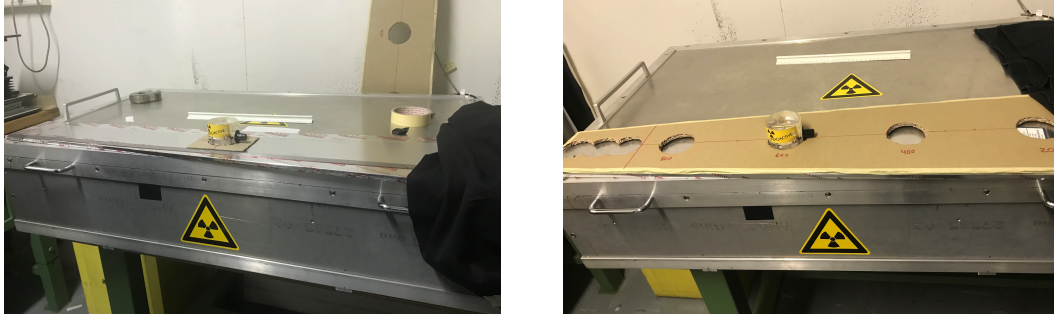


Figure 4.19: The fine scan setup (left) and regular scan setup (right).

200 mm, 400 mm, 600 mm and 800 mm. In the E4 counter, three points were chosen: 900 mm, 950 mm and 1000 mm.

Due to the time-consuming nature of the fine scans, a decision was made to conduct regular scans for all Crack counters. Following this approach, a fine scan was performed after every eight Crack counters, along with four special counters described in Section 4.4.1.2. The measurements for the EBC counters took place between August 14th and August 22nd, 2019, while the measurements for the EBA counters were conducted from October 25th to November 7th, 2019.

4.4.1.1 Response of Crack counters to ^{90}Sr source

Figure 4.20 displays plots depicting the relationship between the PMT average voltage response (aveV) and the source position (x) on the scintillator. Additional plots pertaining to the EBC and EBA counters can be found in Appendix A.1. The average voltage is calculated by averaging the voltage readings taken throughout all the measurements. The voltage readings are acquired from the integrator, which is directly proportional to the integrated current (charge). The utilization of the integrator is necessary because a single electron emitted from the ^{90}Sr source does not produce a discernible signal.

The plots show the response of Crack scintillators to ^{90}Sr source. Channels 3 and 4 transmit signal voltage from the E3 and E4 counter segments, respectively. In

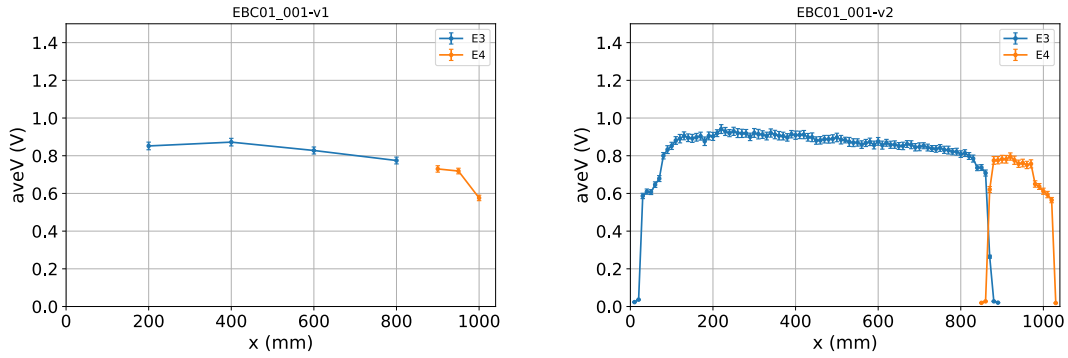


Figure 4.20: PMT voltage response Vs. position of the source for EBC. Regular scan (right) and fine scan (left).

general, all tested counters have a voltage response that lies within the acceptable range and that indicated their readiness for installation into the ATLAS detector.

During the measurements, a significant voltage response drop in the EBC counters was observed (from counter 37 to 64). The low signal output was a result of physically damaged optical fibre cable which transmits light from the counter to photomultiplier tube inside the scan box (see Figure A.6). Since the signal output was still consistent, it was agreed that the measurements continue. However, a new fibre cable was prepared for the new batch of EBA counters.

4.4.1.2 Special counter with orange fibres

Four special counters, namely EBC4, EBC36, EBA67, and EBA68, had their E4 segments coupled to O-2 orange fibres instead of Y-11 green fibres. These orange fibre segments exhibited a lower voltage response, as depicted in Figure 4.21. The reason for this response can be attributed to the fact that orange fibres have a shorter light attenuation length (> 1.5 m) compared to green fibres (> 3.5 m), resulting in higher light attenuation. Furthermore, it should be noted that the PMT (photomultiplier tube) used for the measurements was not specifically designed for orange fibres. During Run 3, the performance of orange fibres will

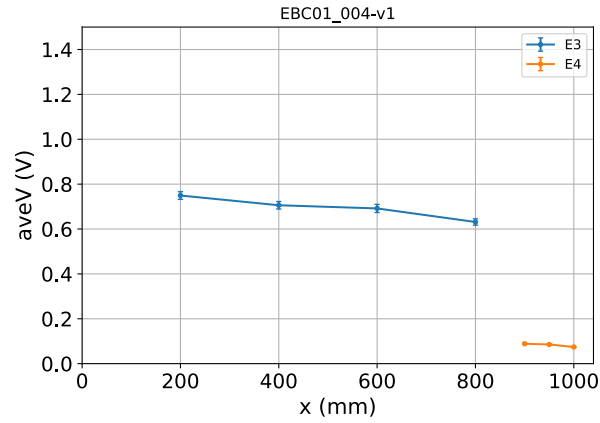


Figure 4.21: Special E4 segment of EBC4 connected to orange fibres.

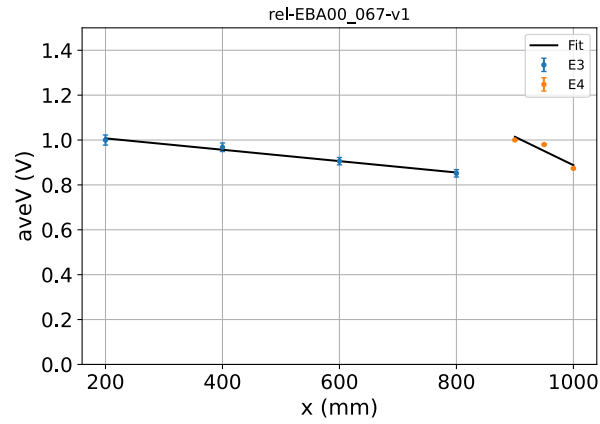


Figure 4.22: Relative voltage Vs. source position and the best fit lines of E3 and E4.

be studied and compared to that of green fibres.

4.4.1.3 Relative voltage slopes

The ratios of voltage values for E3 and E4 segments relative to their respective highest values were calculated. The results were then fitted with a polynomial of first degree to determine the slopes (see Figure 4.22). However, the best fit for the E4s was not satisfactory since the last point (1000 mm) was already covered by the aluminum tape and hence gave a low response.

4.4.1.4 Summary of slopes and highest signals

The slope and highest signal values of all EBA and EBC counters have been compiled in Figures 4.23 and 4.24, respectively. These plots demonstrate a consistent response of the Crack counters to the ^{90}Sr source, with only a few observed outliers, as discussed in Sections 4.4.1.1 and 4.4.1.2.

The issue of low signal output observed after EBC counter 40 has been addressed in Section 4.4.1.1, where it was determined that a defective optical fibre cable connector was causing light leaks. However, it is important to note that this issue does not reflect any inherent poor quality of the counter, as the overall values remain consistent. The lower response values observed in the E4 segment of counters 4, 36, 67, and 68 can be attributed to the use of special counters coupled to O-2 orange fibres. Figure 4.24 highlights that the signal output of EBC counters appears to be superior to that of EBA counters. This discrepancy can be attributed to the utilization of a newly assembled optical fibre cable for EBA measurements, which may not have met the same level of preparation quality as the one used for EBC counters.

4.4.2 Scanning of MBTS with ^{137}Cs

The integrity of the assembled counters was verified using the ^{137}Cs system, utilizing a spare EB module as depicted in Figure 4.25. A ^{137}Cs γ source with an activity of 250 MBq, enclosed within a metal capsule, was transported through the tubes by liquid flow towards the MBTS counter. The counter was positioned at the edge of the EB module, where the tubes extend out of the calorimeter module, leaving uncovered spaces.

As a source approaches the counter, photons with an energy of $E=0.662\text{ MeV}$ induce light emission in the scintillating tiles, enabling the measurement of the optical quality of both the tiles and fibres. The inner counter (E6) and outer

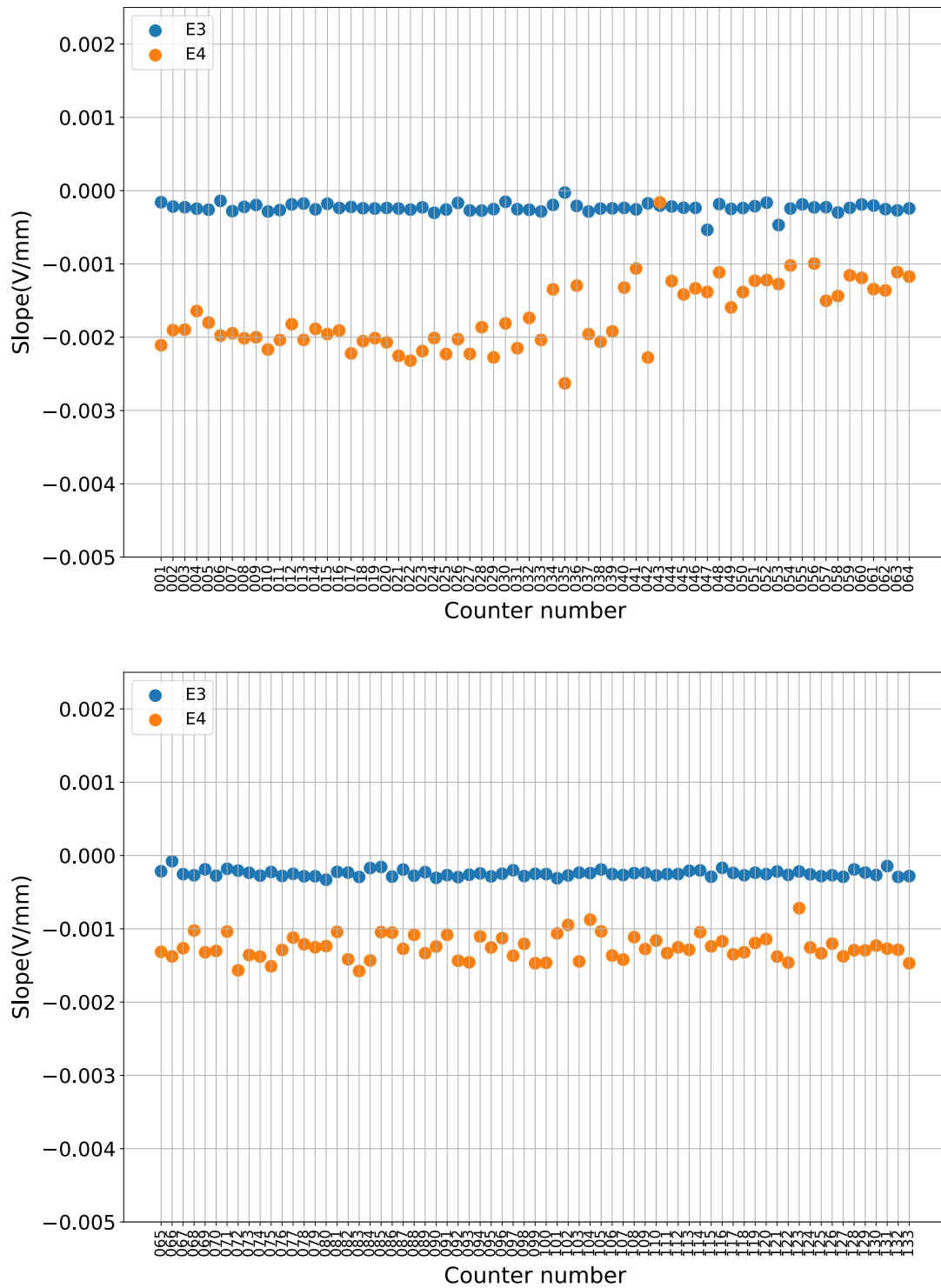


Figure 4.23: The slope for all the counters. Top for EBC and bottom for EBA.

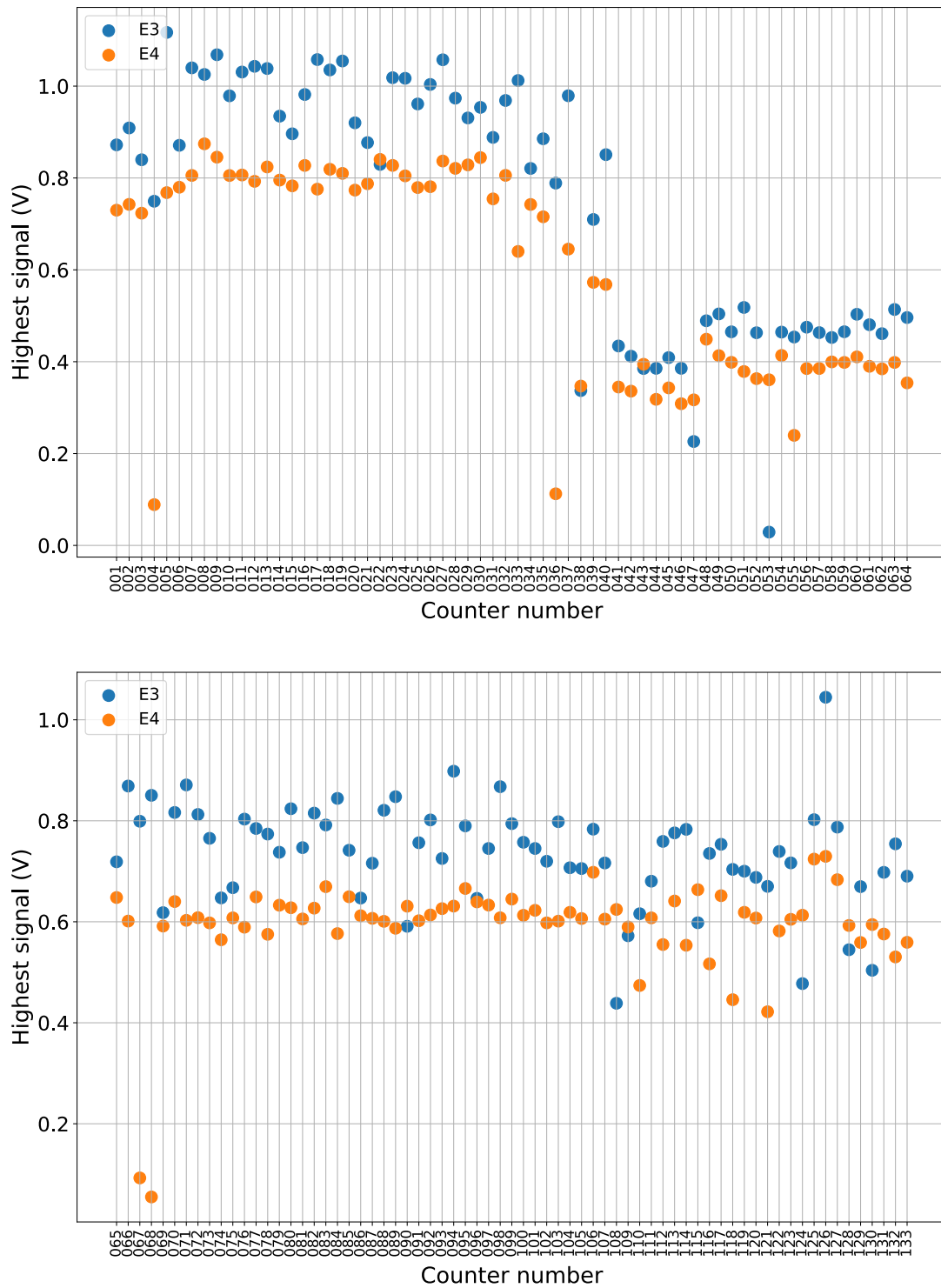


Figure 4.24: The highest signal output for all counters. Top for EBC and bottom for EBA.

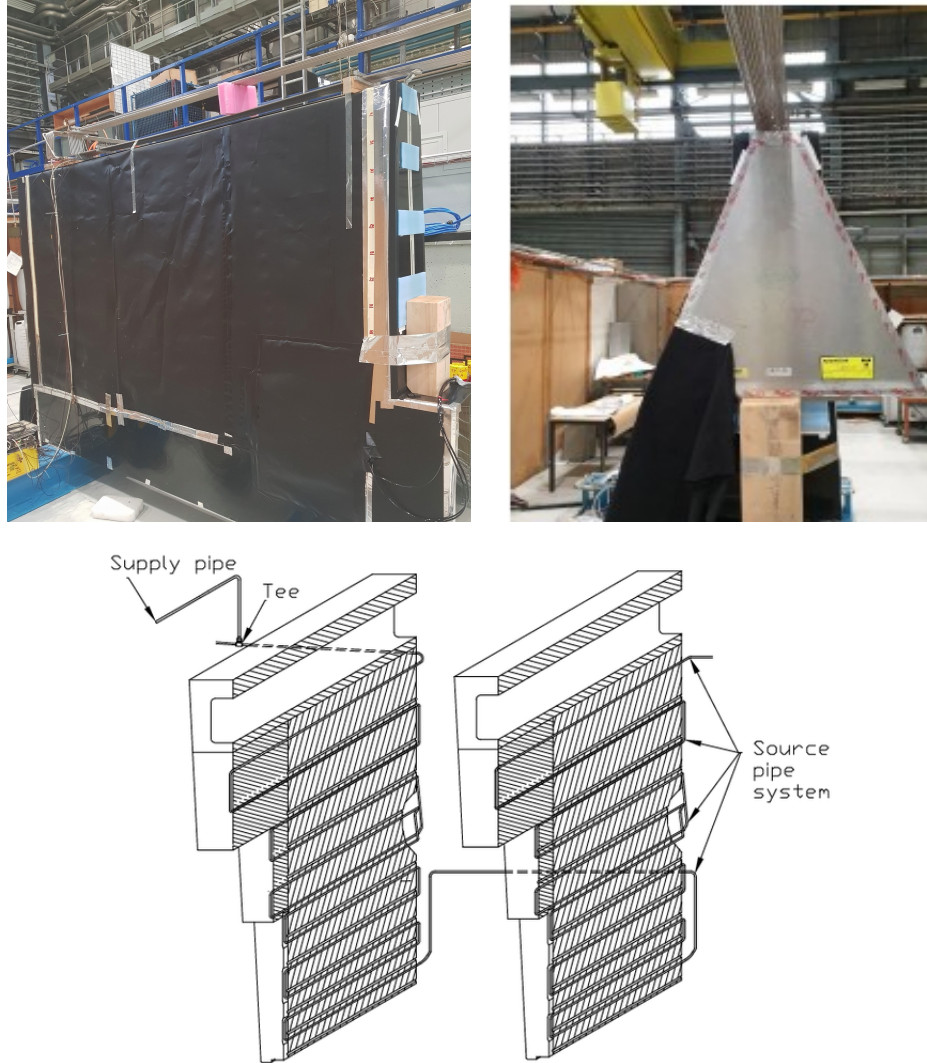


Figure 4.25: Top: ^{137}Cs γ source system (EB module) and Bottom: Schematic of pipes inside the module [131].

counter (E5) were each linked to PMT2 and PMT14, respectively, via a transparent optical fibre cable spanning 3 meters.

4.4.2.1 Response of MBTS to ^{137}Cs

Prior to performing the scans, the baseline value (pedestal) of the photomultiplier tube was measured for each MBTS counter while the ^{137}Cs source was still enclosed in the Cs-garage. Figure 4.26 shows respective PMT pedestal values for counter

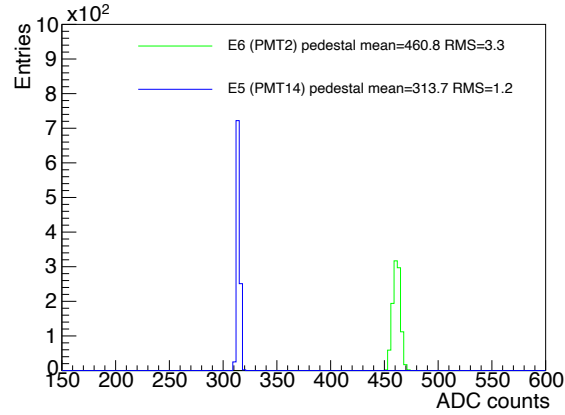


Figure 4.26: Pedestal values of PMT2 and PMT14 measured without the source.

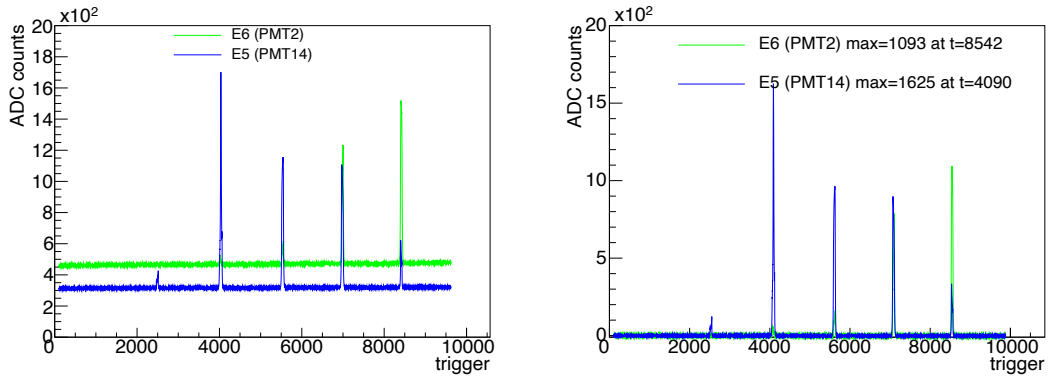


Figure 4.27: ADC counts response including pedestal (left) and ADC counts without pedestal (right) ^{137}Cs travels through the pipe.

number 14 of EBC.

All 16 MBTS counters assembled for A and C sides of ATLAS were tested. The maximum ADC counts for inner and outer counters were calculated by taking the integral of the peaks. The limits for integration on the x -axis (trigger) were defined by fixing the threshold at 50 ADC counts. Since the speed of ^{137}Cs source travelling through the tube would differ from run to run, the maximum ADC integral value obtained was divided by width of the peak to get an average value, hence, better comparison amongst the counters. Figure 4.28 shows zoomed regions of maximum output for PMT14 and PMT2 (cs11316).

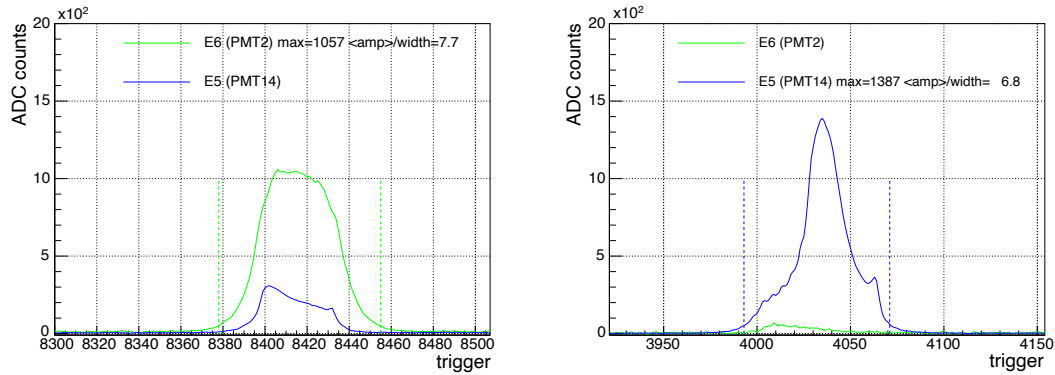


Figure 4.28: Zoomed regions of maximum signal output for PMT14 and PMT2 of run 11316.

Table 4.1: ADC counts from Cs runs for MBTS C-side counters at maximum and average with pedestal subtracted.

MBTS #	C ϕ	Cs run	Inner		Outer	
			Max. amp	Average	Max. amp	Average
14	0	11316	1057	7.7	1387	6.8
04	1	11320	1154	9.2	1499	7.0
06	2	11322	1084	8.8	1457	6.9
05	3	11326	1093	8.8	1625	7.5
01	4	11328	950	7.8	1409	6.8
07	6*	11330	1017	8.5	1354	6.6
02	5	11332	1036	8.5	1477	7.1
03	7*	11334	1028	8.5	1571	7.5

All 16 MBTS counters assembled on sides A and C of the ATLAS detector underwent testing. The maximum ADC counts for the inner and outer counters were determined by integrating the peak signals. Integration limits on the x -axis (trigger) were defined by setting the threshold at 50 ADC counts. To facilitate better comparison among the counters, the maximum ADC integral value was divided by the width of the peak, taking into account variations in the speed of the ^{137}Cs source traveling through the tube during different runs. Figure 4.28 showcases enlarged sections highlighting the maximum output for PMT14 and PMT2 of run 11316.

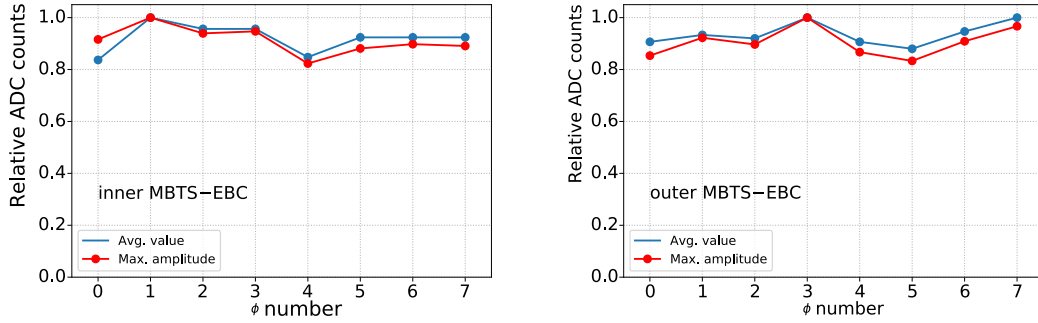


Figure 4.29: Relative ADC counts of maximum amplitude and average for side-C inner counters (left) and outer counters(right).

Table 4.2: ADC counts from Cs runs for MBTS A-side counters at maximum and average with pedestal subtracted.

MBTS #	A ϕ	Cs run	Inner		Outer	
			Max. amp	Average	Max. amp	Average
11	0	11480	532	5.5	1053	5.7
10	1	11482	498	5.3	1037	5.6
15	2	11486	592	5.9	910	5.1
13	3	11490	535	5.5	940	5.1
08	4	11494	541	5.6	895	5.0
16	5	11500	597	6.1	868	5.1
09	6	11504	566	5.7	1035	5.5
12	7	11506	674	6.4	1024	5.5

Counters number 7 and 3 original ϕ position had to be swapped due to wrong assembly of the connectors in counter 7 during refurbishment.

A low signal output was observed for A-side analysis (Table 4.2), however, this is not worrisome since the connecting clear fibres were replaced due to damage. In order to make a meaningful comparison with the C-side, the values of the A-side were scaled. Subsequently, the ratio was calculated from runs 11474 (upgraded $A\phi_0$, old fibres) and 11480 (upgraded $A\phi_0$, new fibres). The ratios are 871/532 and 1488/1053 for the inner and outer counters, respectively (see Figure 4.30). The relative ADC counts are shown in Figure 4.31.

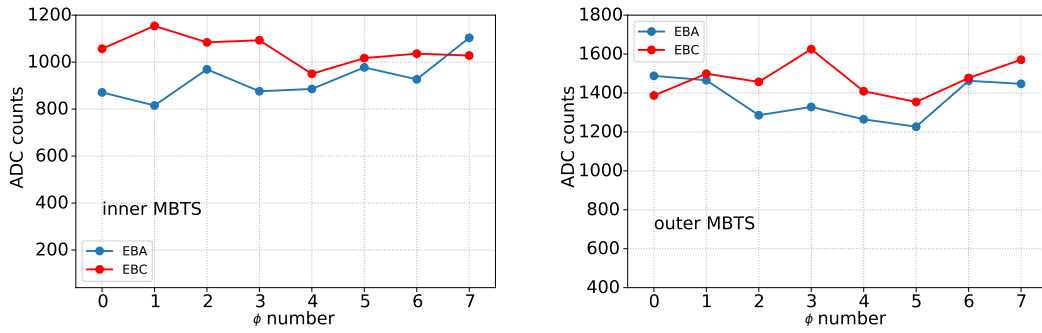


Figure 4.30: Maximum ADC counts comparison for C-side and A-side of inner counters (left) and outer counters (right).

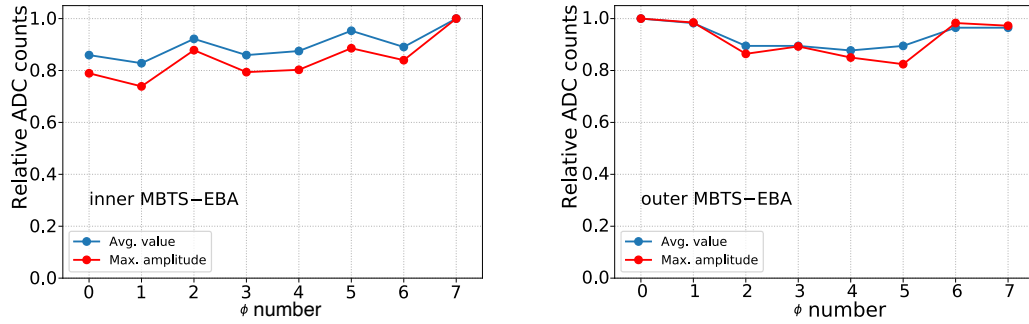


Figure 4.31: Relative maximum and average ADC counts for A-side inner (left) and outer counters (left).

4.5 Installation of detector modules in the ATLAS detector

4.5.1 Crack counters

During the preparations for installation of new counters, all old counters that were used during the LHC Run 2 were uninstalled from both A and C sides of ATLAS.

Following the qualification and characterization of the newly assembled counters, they were transported to Point-1 for installation. The installation process took place in two phases: C-side was installed during the period of August-September 2019, while A-side was installed in October-November 2019. In total, 128 counters,



Figure 4.32: Certified crack counters transported to Point-1 for installation.

including the 4 prototypes, were mounted and connected. Regrettably, a majority of the A-side counters were mistakenly assembled with an incorrect orientation of the optical connector. Consequently, the clear fibres from the calorimeter had to be meticulously twisted during the connection process to compensate for this error.

In addition to the standard counters constructed using EJ-208 scintillator material, four counters utilizing EJ-200 material (prototypes) were installed in positions EBA08, EBA24, EBA40, and EBA56. On the C-side, two special counters featuring orange fibres were installed on EBC4 and EBC64, both situated on E4 plates. Similarly, two special counters on the A-side, previously labeled as EBA67 and EBA68, were installed on EBA29 and EBA61. These special counters required “red” PMTs.

4.5.2 MBTS counters

A total of 16 MBTS counters were successfully mounted and connected. On the 10th and 11th of September 2019, eight counters were installed on the EBC side and properly connected. However, due to an error in connector placement during assembly, the positions of two counters ($\phi 6$ and $\phi 7$) had to be exchanged. As a result, a slight shift of a few millimeters occurred compared to their original intended locations. On the 14th of November 2019, the remaining eight A-side

MBTS counters were installed as planned. Photographs depicting the installed MBTS counters can be seen in Figures [A.11](#) and [A.10](#).

To ensure the proper protection against dust and external light, the installation of counters was completed by applying an aluminum foil cover on both the A-side and C-side. The foil covers were produced in accordance with the standard specifications, consisting of 28 small parts and 4 large parts for each side.

Each foil piece was designed to cover two modules and was shaped as an isosceles trapezium. The small foil pieces had a height of 750 mm, a lower base of 600 mm, and an upper base of 450 mm. Meanwhile, the large foil pieces had a height of 1160 mm, a lower base of 700 mm, and an upper base of 450 mm. This standardized foil coverage effectively protected the installed modules from dust and external light.

4.6 The development of ^{90}Sr Tile scanning table

During Phase-I upgrade of the Tile Calorimeter of the ATLAS experiment, characterization and qualification of the assembled Crack scintillators were conducted through manual scans using a ^{90}Sr radioactive source and a small scan box containing a photomultiplier tube. The Crack scintillator module was too large to fit inside the scan box and had to be connected from the outside using a clear optical fibre cable. Manual scans were possible with this arrangement, in which ^{90}Sr source, with lead shielding, was positioned manually on the surface of the counter during the test. However, because the Crack scintillator and connectors were exposed to external light, this design was not suitable for quality control.

As a result, the imperative for an advanced solution became evident. The development of an automatic scanning system and a suitably sized scan box capable of accommodating all essential components emerged as a critical requirement. This section offers a description of the development, operation, and implementation of

a scan box for the quality control of Crack scintillators that will be deployed after LHC Run 3.

4.6.1 Overview of ^{90}Sr scanning table

The scanning table, schematically shown in Figure 4.33, comprises the following major components: a light-tight box to guard against external light, a fixed main support table, a radiation source holder with a positioning mechanism, a photodetector, and the control and data acquisition system. This section offers insight into the structure of the light-tight scan box.

A 1.4 m long light-tight scan box along the x -axis accommodates the Crack scintillator counter, which consists of two scintillator tiles, E3 and E4. These E3 and E4 scintillators are coupled with readout WLS fibers that connect to photomultiplier tubes PMT1 and PMT2 via clear optical fiber cables for light transmission.

4.6.2 One-coordinate scanning mechanism

The E3 and E4 scintillators are fixed in position and measured with a ^{90}Sr radiation source transported by an automated carriage in a one-coordinate system (x -axis) while emitting radiation in the z direction (see Figure 4.34). The mechanism is constructed from commercially available components and is driven by a powerful Sanyo Denki 103H5210-5240 Bipolar Stepper Motor. This motor has a microstepping resolution of 1/128 steps, ensuring outstanding positioning accuracy and motion smoothness [132].

The motor is controlled by a two-axis stepper motor driver expansion board, X-NUCLEO-IHM02A1, based on the L6470 component. The L6470 device is an advanced, fully integrated microstepping driver for low voltage motor controller applications, operating at a voltage range from 8-45 V with a 7.0 A peak current ($3.0 A_{r.m.s}$) over an SPI connection [133]. This board includes two L6470

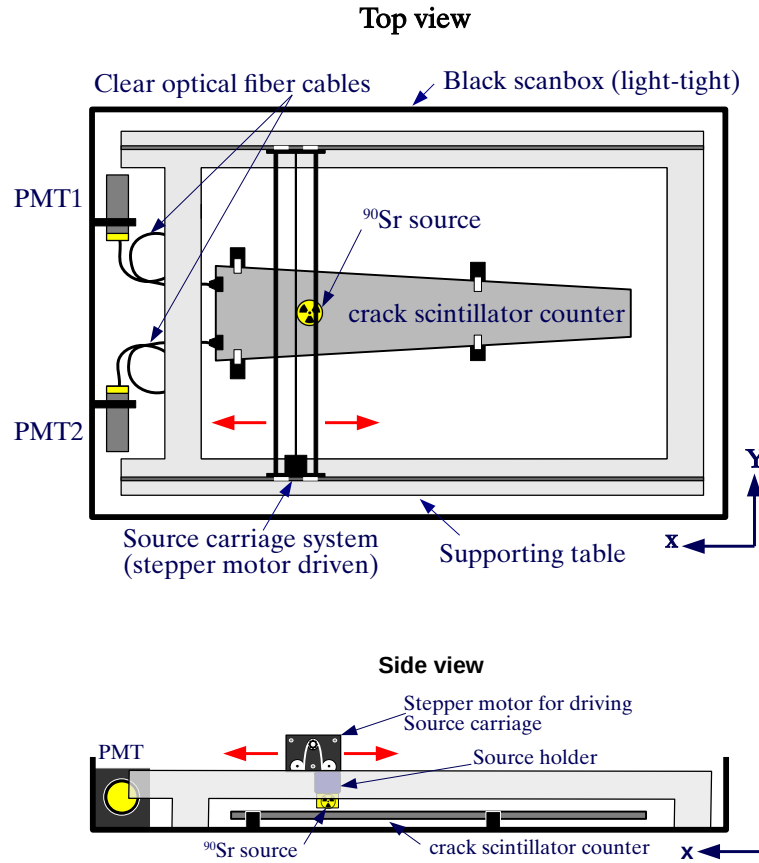


Figure 4.33: The ^{90}Sr scan box: top view (top) and side view (bottom).

microstepping motor drivers.

To enable the correct functionality of the X-NUCLEO-IHM02A1, it is connected to an Arduino UNO R3 microcontroller board [134]. The Arduino, which runs an 8-bit/16 MHz microcontroller (ATmega328), is programmed using the Arduino IDE to develop, compile, and upload code. The SparkFun AutoDriver is a bipolar stepper driver based on the ST Micro L6470 chip. It is used to extend the Arduino's capabilities, providing advanced control functionalities for stepper motors. These include microstepping for smoother movement, configurable acceleration/deceleration profiles, and over-current/temperature protection for the motor.

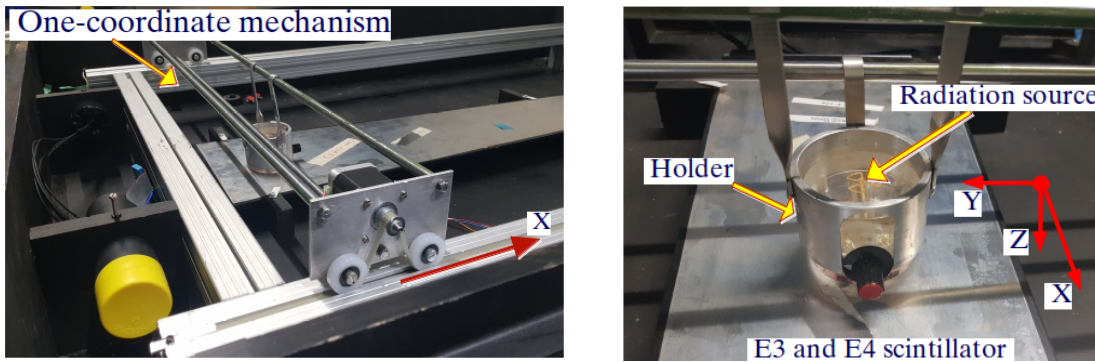


Figure 4.34: Radiation source positioning mechanism.

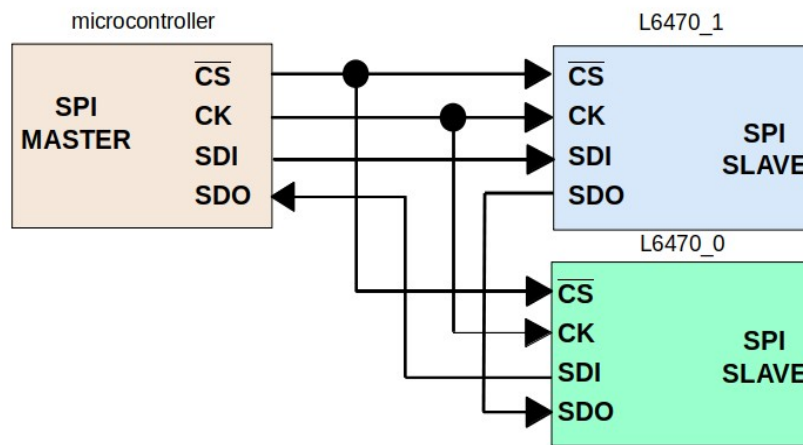


Figure 4.35: Daisy chain configuration.

The Arduino Uno R3 microcontroller uses the Serial Peripheral Interface (SPI) for communication with the L6470 stepper drivers, which are connected in a daisy chain configuration as shown in Figures 4.35 and 4.36. The configuration comprises four digital lines of SPI namely; Chip Select ($\overline{\text{CS}}$), Serial Clock (CK), Serial Data Input (SDI) and Serial Data Output (SDO). The ports and pins for this SPI connection are setup in the stspin6470 sketch that is uploaded into the Arduino microcontroller board. The communication triggers when the $\overline{\text{CS}}$ signal is forced low to enable L6470_0 device selection.

The microcontroller which is the master, generates clock pulses that synchronizes data transmission through the CK input line (D3 wire routed to D13). All the

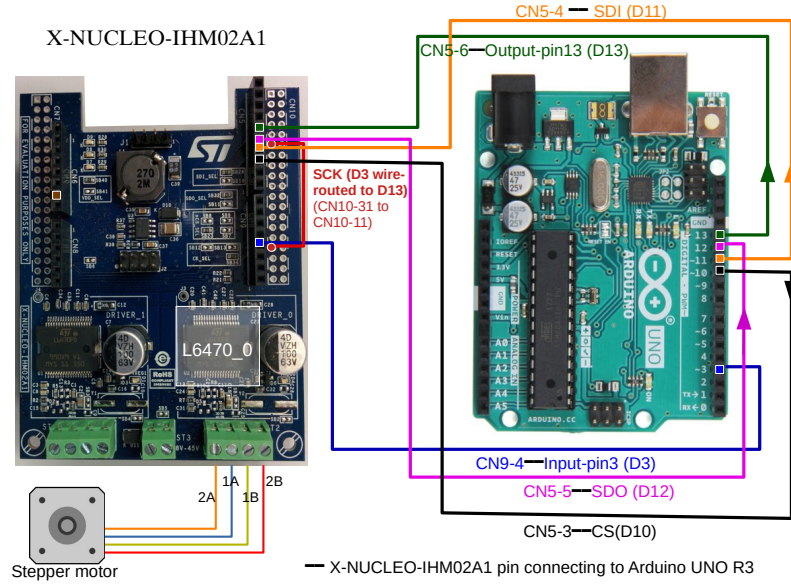


Figure 4.36: Arduino microcontroller connected to X-NUCLEO-IHM02A1 expansion board.

configuration information, movement commands and data registers are sent to and from the L6470_0 device (slave) through the SDI input line (D11), with the Most Significant Bit (MSB) data order first. The same criteria applies to output data bytes when shifting out of L6470_0 through the SDO output line (D12) to the master.

4.6.3 Scanner control and data acquisition

The scanning mechanism is accessible via serial port where the computer connects through the Universal Serial Bus (USB) cable to a serial chip on Arduino microcontroller board. This chip transforms the USB to serial signal and they are connected to the transmission (TX) and receiver (RX) corresponding to digital pin 1 and pin 2, respectively. This form of communication established between the computer and the Arduino is referred to as Universal Asynchronous Receiver-Transmitter (UART) protocol. The Figures 4.37 and 4.38 show a schematic representation of the ^{90}Sr scanning table and the facility setup, respectively, which

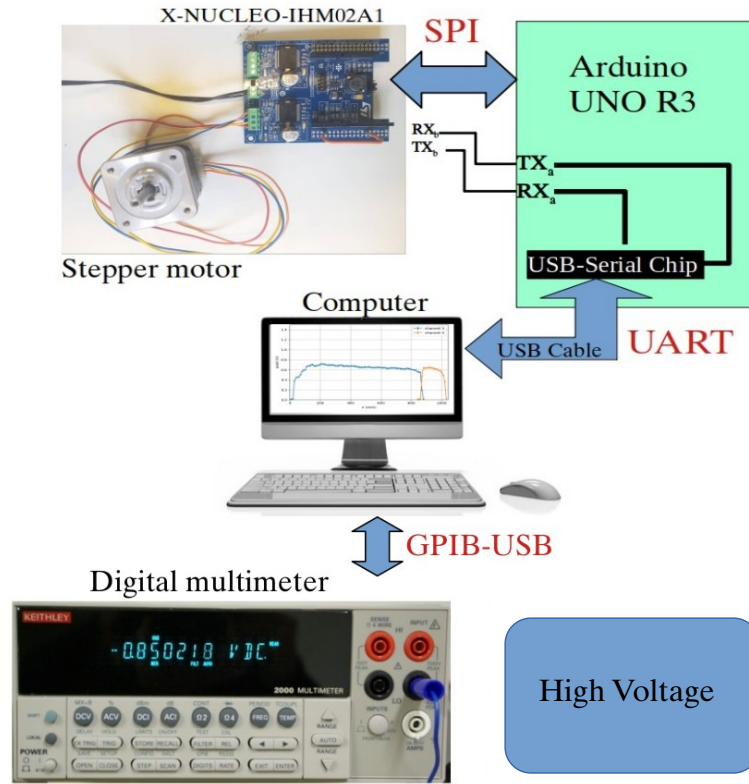


Figure 4.37: Schematic representation of the ^{90}Sr scanbox setup.

consists of scan box, digital multimeter, high voltage power supply unit (HV) 750 V for the PMTs and data acquisition system. The light readout system consists of a WLS fibres, clear optical fibre cable and a very light sensitive Hamamatsu PMT as shown in Figure 4.17 [135]. In order to check the response of E3 and E4 scintillators to ^{90}Sr source, the PMT average voltage response is measured as a function of radiation source position (x) on the module. The scanner underwent testing and validation, affirming its functionality. Figure 4.39 shows the results acquired using the scanner.

The voltage is read from the integrator (modified Tile 3-in-1 board), which is proportional to the integrated current (i.e. charge) [105]. The integrator is used since it is difficult to get a sensible signal from one electron from the ^{90}Sr source, and the activity of the source is too high (25 MBq) to separate them in time.

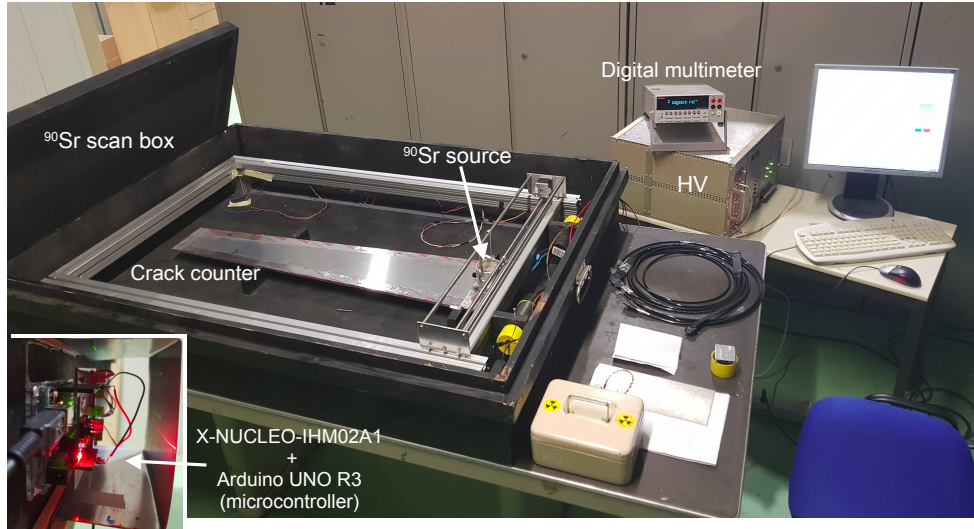
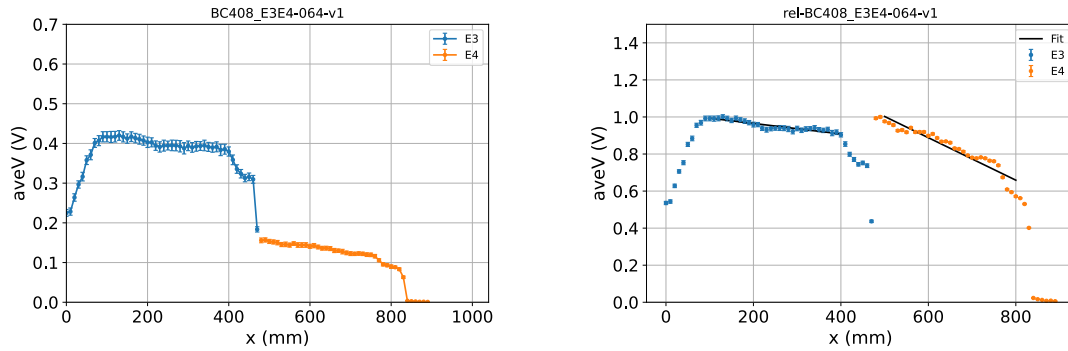
Figure 4.38: A photograph of ^{90}Sr scanning-box facility.

Figure 4.39: Validation plots of the scan box: PMT average voltage response as a function of radiation source position (left) and the relative response (right).

The readout of the integrated current from the PMT is done with the help of high precision (6+ digits) multimeter Keithley-2000, equipped with the SCAN-2000 multiplexer card. The HV monitoring is done by the same multimeter. The data are read out into the personal computer via Keithley KUSB-488A general purpose digital interface system (GPIB-USB). The main control software written in Python programming language with tkInter Graphical User Interface library, and other libraries for serial port and GPIB interface allows for scintillator counter identification, selection of voltage, signal or pedestal source and the sample size.

Physics Objects Reconstruction, Identification and Selection at ATLAS

The ATLAS experiment at the LHC confronts the challenge of transforming vast amounts of raw data from proton-proton collisions into meaningful physics insights. This raw data consists of signals from the detector in the form of tracks and energy deposits. Reconstructing these signals into well-defined physical objects, such as muons, electrons, photons, and jets, is a crucial initial step in physics analyses. The ATLAS collaboration has developed a suite of sophisticated algorithms for event reconstruction, encompassing object reconstruction, identification, and selection.

Following reconstruction, event identification and selection play a vital role in filtering the data for specific physics analyses. These processes involve identifying and selecting events or particles based on predefined criteria, such as momentum, energy, or charge. This filtering helps reduce the data volume for further analysis, enhancing the accuracy and precision of the results. Particle identification techniques and calorimeter isolation methods are utilized to distinguish between different particle types and select the most relevant events for further study.

In the Higgs boson searches, the Higgs invariant mass is calculated using reconstructed particles in their final states. This chapter is devoted to discuss the

methods used for reconstruction, identification, isolation, and selection of electrons, muons and photons for the $H \rightarrow Z\gamma$ analysis in the ATLAS experiment at the LHC. The objects reconstructed by the analysis are divided into two types: basic objects and composite objects. The former includes tracks, vertices, and topological clusters, while the latter includes objects such as electrons. The basic objects act as the foundation for the reconstruction of all composite objects.

5.1 Tracks

Charged particles leave tracks within the silicon-based pixel and SCT systems of the ATLAS ID. Track reconstruction algorithms identify these tracks by analyzing the sensor signals generated as charged particles interact with the detector material. Groups of signals exceeding a certain energy threshold and sharing a common edge or corner are identified using a technique called connected component analysis [136]. These groups provide input for determining the three-dimensional interaction points where charged particles traversed the ID's active material.

A combinatorial Kalman filter is employed as the initial step in track finding. This filter imposes specific requirements on track candidate momenta and impact parameters to refine potential track candidates [137]. Impact parameters refer to the distances between a track and the estimated location of the proton-proton collision vertex. At this stage, a single charged particle might have multiple potential track candidates associated with it.

The best-fitting track is then chosen based on various criteria, including the quality of the track fit, the candidate's momentum, the number of assigned energy deposits (hits), and potential inconsistencies where the track appears to pass through detector regions without registering a hit. A neural network is employed to identify instances where energy deposits originate from multiple charged particles, and an ambiguity-resolving algorithm is used to reassign these deposits to

track candidates, prioritizing those with a higher initial rating.

Compatible measurements from the TRT are used to extend the reconstructed tracks to the outermost regions of the ID [138]. To ensure comprehensive ID coverage, all reconstructed tracks must possess a transverse momentum (p_T) greater than 400 MeV and reside within a pseudorapidity range of $|\eta| < 2.5$. These tracks can be accurately described by a set of five parameters: $(d_0, z_0, \phi, \theta, q/p_T)$. The parameters d_0 and z_0 represent the transverse and longitudinal impact parameters, respectively. ϕ and θ denote the azimuthal and polar angles of the tracks, and the final parameter, q/p_T , signifies the ratio of the particle's charge to its transverse momentum.

5.2 Vertices

Vertices, depicted in Figure 5.1, represent the spatial locations where particle collisions or decays occur within the ATLAS detector. The reconstruction of vertices involves two primary steps: vertex finding and vertex fitting. Both steps utilize reconstructed tracks as input data.

Vertex finding is a crucial step in reconstructing particle interaction events. It aims to identify the locations in space where particle collisions or decays (vertices) transpired, constrained by the position of the beam spot. This process utilizes well-reconstructed tracks and attempts to match them to potential vertex candidates. The z -coordinate of each vertex is then determined through an iterative χ^2 fitting procedure, with tracks deemed inconsistent with the primary vertex used to create additional vertex candidates.

To maintain reliable positional resolution, all reconstructed vertices must be associated with at least two tracks, each possessing a transverse momentum exceeding 400 MeV. However, the presence of pile-up vertices, arising from additional proton-proton interactions within the same bunch crossing as the primary inter-

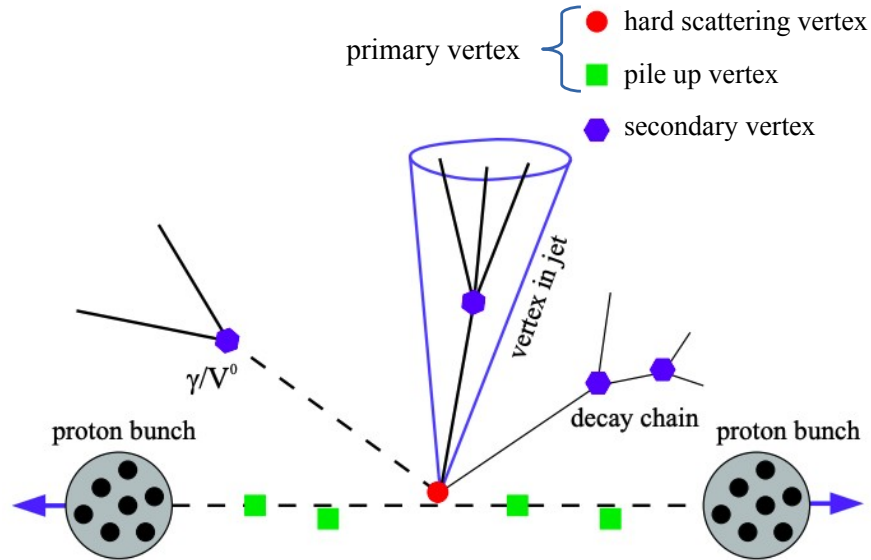


Figure 5.1: Vertex topologies important for physics analyses in ATLAS. PV includes the hardscattering vertex (red round) and pile-up vertex (green square), vertices from conversions and long-lived particles, vertices in jets and vertices from decay chains [139].

action, introduces complexities during event reconstruction and analysis. Overlapping tracks from pile-up vertices can make it challenging to distinguish them from tracks originating from the primary collision vertex. To address this challenge, the vertex with the highest sum of the squared transverse momenta of its associated tracks is designated as the primary vertex (PV) [140].

5.3 Topological Clusters

Topological clustering (topo-clustering) is a technique employed within the ATLAS experiment to group energy deposits in neighboring calorimeter cells. These clusters aim to represent the energy deposited by a single particle within the calorimeter, separating them from noise or contributions from other particles. The formed clusters serve as the foundation for reconstructing hadronic showers initi-

ated by particles interacting with the calorimeter. The process of topo-clustering relies on the concept of a cell's signal significance, denoted as ξ_{cell}^{EM} . This value is calculated as:

$$\xi_{cell}^{EM} = \frac{E_{cell}^{EM}}{\sigma_{noise,cell}^{EM}}, \quad (5.3.1)$$

where E_{cell}^{EM} represents the energy deposited in a particular calorimeter cell, and $\sigma_{noise,cell}^{EM}$ signifies the electronic noise level of that cell, expressed in units of the EM energy scale.

The topo-clustering algorithm utilizes a “growing-volume” approach, which begins by identifying a seed cell with a high signal significance. Three key parameters, S , N , and P , govern the seeding, growth, and boundary definition of the topo-clusters. These parameters establish signal thresholds based on ξ_{cell}^{EM} from Equation 5.3.

To initiate a topo-cluster, a seed cell with a significance exceeding a predefined seed threshold, S , is chosen. Subsequently, all neighboring cells (sharing a direct physical boundary within the same layer, or some overlap in the (η, ϕ) plane for adjacent layers) with a significance greater than a growth threshold, N , are incorporated into the cluster. This step is iterated until no neighboring cells satisfy the criterion of $|\xi_{cell}^{EM}| > N$. If a neighboring cell surpasses the even stricter threshold of $|\xi_{cell}^{EM}| > S$, signifying a potentially distinct particle interaction, the corresponding topo-cluster associated with that cell is merged with the growing cluster. The process continues iteratively on neighboring cells until the final set of neighbors is identified. This final set encompasses all cells with a significance exceeding the lower threshold, $|\xi_{cell}^{EM}| > S$, but not surpassing the stricter growth threshold, $|\xi_{cell}^{EM}| > N$. The ATLAS experiment employs a configuration of $S = 4$, $N = 2$, and $P = 0$ for optimal hadronic final-state reconstruction [79].

5.4 Photons

After being generated at the interaction point, a photon initially travels through the tracker before entering the Electromagnetic Calorimeter (ECAL). Upon entering, it releases all its energy through electromagnetic (EM) showering, which can be widely distributed. The photon's behavior can either be unconverted, passing through the tracker without interaction, or converted into an electron-positron pair before reaching the ECAL. To accurately capture all energy deposits, photons are reconstructed by clustering energy deposits in the ECAL and matching them with track information. This process ensures that all energy deposits are properly accounted for.

To identify photon candidates, energy deposit clusters in the ECAL are reconstructed with a transverse energy (E_T) requirement of at least 2.5 GeV. The reconstruction process begins with a search for energy clusters in the calorimeters, which are divided into a grid of towers, each measuring $\Delta\eta \times \Delta\phi = 0.075 \times 0.123$. The energy deposits from all the layers of the calorimeter are summed to determine the total tower energy. A sliding window algorithm [141] of size 3×5 in $\eta - \phi$ space is then used to select cluster seeds that have a total $E_T > 2.5$ GeV or greater. To remove any duplicate cluster seeds within any 2×2 tower region, an additional algorithm is employed that selects only the seed with the highest E_T [142].

After the removal of duplicate cluster seeds and the merging of the remaining clusters, the resulting photon candidates undergo identification and isolation steps. The Photon Identification (PID) and isolation criteria are usually based on a combination of variables related to shower shape, track association, and isolation requirements. For instance, the shower shape of the photon candidate can be described by variables such as hadronic leakage, energy distributions in the middle-layer and strip layer of the calorimeter system, which can be used to distinguish

between prompt photons and background photons. Additionally, track association is used to identify converted photons, which decay into pairs of oppositely charged particles like electrons or positrons. The ATLAS experiment utilizes an algorithm that provides two levels of identification for photons: the *loose* PID and the *tight* PID. The *loose* PID applies cuts only on the shower shapes depending on the photon candidate's pseudorapidity range, while the *tight* PID implements more stringent cuts, particularly on shower shapes in the first layer of the ECAL.

The isolation requirement is also an important step in photon identification and involves ensuring that the photon candidate is not associated with any other significant energy deposits in the calorimeter or with any charged tracks in the inner detector. Isolation requirements are typically used to reduce the contribution of background processes, such as photons produced from the decay of hadrons or electrons from other processes. The first photon isolation sums the E_T energy of topological clusters with positive energy reconstructed in the calorimeter around each photon candidate in a cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ after correcting for the photon's own energy and leakage. The second isolation variable sums the transverse momenta of tracks with $p_T > 1 \text{ GeV}$ located within a cone of size $\Delta R = 0.2$ around each photon candidate. A detailed description of the optimization of the photon identification and isolation can be found in Refs. [142, 143].

5.5 Electrons

To reconstruct electrons, energy clusters in the ECAL are utilized and linked with tracks in the ID. Similarly, the same methods discussed for photons in Section 5.4 are employed to determine the energy of the electron candidate. After identifying the seed clusters, tracks are associated with them based on factors such as the number of pixels, their proximity to the seed barycenter, and SCT hits. In cases

where there are multiple tracks that meet the criteria, a primary track is defined. The cluster-track pairs are then combined, and the clusters are reconstructed to sizes of 3×7 units in the barrel and 5×5 units in the end-cap regions.

Pattern recognition algorithms are employed to accommodate bremsstrahlung, identifying energy losses caused by track interactions with detector material. Subsequently, track candidates are fitted with either a pion or electron hypothesis using the ATLAS Global χ^2 track fitter [144]. Any tracks unassociated with a cluster are excluded from further analysis and considered as photons.

The last stage of electron reconstruction entails calibrating the cluster energies to match the initial electron energy. This calibration is achieved through multivariate techniques applied to simulated MC samples. By adjusting the cluster energies, the properties of the original electrons, which deposited energy in the ECAL, can be accurately determined.

Electron identification in the ATLAS detector is based on a robust multivariate likelihood approach. This technique combines diverse information sources, including track-based data from the TRT, the characteristics of the EM shower in the calorimeter, bremsstrahlung effects, and the quality of track-to-cluster matching, to generate a unified likelihood value. This value acts as a discriminant, separating the desired signal (electrons) from the background (electrons originating from hadronic jets and photons).

The electron identification algorithm in the ATLAS detector has been optimized to ensure the best possible performance. To achieve this, the algorithm employs three different levels of operating points: *Loose*, *Medium*, and *Tight*. Each of these operating points has its own unique set of parameters and thresholds, which allow researchers to balance the need for high signal efficiency with the requirement for robust background rejection. These operating points are described in detail in Ref. [145], and they provide researchers with the flexibility to tailor the electron

identification algorithm to their specific analysis needs. A brief overview of each operating point is provided below.

- **Loose:** cuts on various variables to distinguish electron showers from other particles. These cuts include variables related to shower shape in the first and second layers of the ECAL, as well as variables related to hadronic leakage.
- **Medium:** requirements are established to uphold precise track reconstruction and ensure accurate alignment between tracks and clusters. These criteria encompass evaluating the track quality within the Inner B-Layer and the Pixel Detector, the proportion of high-threshold hits in the Transition Radiation Tracker, and the transverse impact parameter d_0 .
- **Tight:** criteria guarantee high quality track reconstruction and precise alignment between tracks and clusters. These requirements involve evaluating the track quality within the TRT, the ratio of cluster energy to track momentum, and variables associated with suppressing photon conversions.

To minimize the contribution from background electrons arising from hadronic showers, it is necessary to satisfy isolation requirements. Isolation is determined by dividing the E_T or p_T within a reconstructed cone around the electron by the electron p_T . Isolation can be calculated using calorimeter isolation (p_T^{cone20}) or track isolation ($p_T^{\text{varcone30}}$).

The definition of $p_T^{\text{varcone30}}$ is the total transverse momenta of all tracks in a cone with a size dependent on E_T , where radius $\Delta R = \min(0.3, 10 \text{ GeV}/E_T)$, centered around the electron candidate (excluding the electron track) and originating from the same PV. On the other hand, p_T^{cone20} is the total transverse energies of all calorimeter cells, calibrated at the EM scale, in a fixed-size cone with radius $\Delta R = 0.2$ centered around the electron candidate (excluding the electron cluster).

Through implementation of different cuts on p_T^{cone20} and $p_T^{\text{varcone30}}$, it becomes

feasible to generate a range of isolation working points with varying degrees of strictness tailored to the specific nature of the physics analysis being conducted. For the purposes of this dissertation, a stringent working point has been employed and precisely defined.

5.6 Muons

Reconstructing muons in ATLAS is a multi-step process that leverages information from both the ID and the MS [146]. A search algorithm identifies segments within the MS chambers, and these segments are used to construct track candidates. Tracks reconstructed in the MS are then extrapolated and matched to tracks in the ID. A global χ^2 fit is performed to combine the information from both detectors and determine the type of muon.

The ATLAS experiment defines four primary types of reconstructed muons based on the information used:

- **Combined (CB) Muons:** These muons represent the most precise measurement by utilizing combined track information from both the ID and MS. A global fit incorporating hits from both detectors is performed to establish the final candidate muon track.
- **Segment-tagged (ST) Muons:** When an ID track can be associated with at least one track segment in the MS, an ST muon is reconstructed. This type is particularly useful for low-momentum muons or those traversing regions with limited MS acceptance.
- **Calorimeter-tagged (CT) Muons:** These muons are identified by correlating an energy deposit in the calorimeters with a track in the ID, consistent with a minimum-ionizing particle. While offering the lowest purity compared to other muon types, CT muons are valuable in regions with lim-

ited MS coverage due to cabling and service constraints for the calorimeters and ID. Their identification criteria are optimized for a specific momentum range and pseudorapidity region.

- **Extrapolated (ME) Muons:** Reconstructed solely from tracks extrapolated from the MS to the IP, ME muons provide additional coverage beyond the ID, particularly in the forward pseudorapidity region (typically $2.5 < |\eta| < 2.7$). The reconstruction process for ME muons includes estimating their energy loss within the calorimeters.

The identification of muons in ATLAS relies on several factors, including the compatibility of measurements from the ID and MS, the quality of the track fit, and the outcome of a global χ^2 fit. The ATLAS experiment defines various working points (WPs) for muon identification, each with specific criteria tailored for different physics analyses [146].

Four primary muon identification WPs are commonly used:

- **Loose:** This WP prioritizes maximizing reconstruction efficiency while maintaining high-quality muon tracks. It encompasses all muon types (CB, ST, CT, and ME) and is particularly suitable for analyses targeting Higgs boson candidates decaying into four leptons.
- **Medium:** This WP aims to balance reconstruction efficiency with minimizing systematic uncertainties arising from muon reconstruction and calibration. It corresponds to the standard muon identification criteria employed within the ATLAS experiment and restricts selection to CB and ME muons, applying criteria similar to the Loose WP.
- **Tight:** This WP prioritizes a high purity of selected muons by applying stricter requirements on CB muons. It builds upon the Medium WP criteria and requires a minimum number of hits within the MS, distributed across multiple layers.

- **High- p_T :** This WP is optimized for muons with high transverse momentum (>100 GeV), prioritizing momentum resolution even if it comes at the cost of reduced reconstruction efficiency.

The selection employed within this analysis leverages the Medium WP to optimize signal efficiency for muons.

Similar to electron identification, many ATLAS analyses impose isolation requirements on muons to suppress contamination from background sources like hadrons. The analysis utilizes the calorimetric isolation energy (E_T^{cone20}) and track isolation ($p_T^{\text{varcone20}}$) defined in Section 5.5 for muon isolation as well.

5.7 Jets

Due to color confinement, quarks and gluons produced in proton-proton collisions cannot be directly observed in the ATLAS detector. Instead, they hadronize, forming showers of color-neutral particles. These particles are then reconstructed as jets within the detector.

Jets are reconstructed using information from various detector components. They can be built from topological clusters in the calorimeters (described in Section 5.3), tracks in the ID (described in Section 5.1), or truth particles in MC simulations. The primary jet reconstruction algorithm employed in ATLAS is the anti- k_t algorithm [147]. This algorithm iteratively combines pairs of particles based on a distance measure that considers both the particles' transverse momenta and their angular separation in the detector. Jets are formed until the distance between any two uncombined particles exceeds a predefined threshold, defined by a parameter called the jet radius (R).

The distance measure used in the anti- k_t algorithm depends on the transverse momenta of the two particles being considered, i and j , and their angular separation.

ration in the detector. This angular separation is typically represented by ΔR_{ij} , which is calculated as the square root of the sum of the squares of the differences in azimuthal angle ($\Delta\phi_{ij}$) and pseudorapidity ($\Delta\eta_{ij}$) between the two particles:

$$\Delta R_{ij}^2 = (\Delta\phi_{ij})^2 + (\Delta\eta_{ij})^2. \quad (5.7.1)$$

The distance between a particle i and the beam (denoted by B), d_{iB} , is also considered in the algorithm. The anti- k_t algorithm uses a parameter κ that influences how the algorithm prioritizes the clustering of particles. Here's the complete definition of the distance measures used in the anti- k_t algorithm:

$$d_{ij} = \min(p_{\text{T}}^2 i^\kappa, p_{\text{T}}^2 j^\kappa) \frac{\Delta R_{ij}^2}{R^2}, \quad (5.7.2)$$

$$d_{iB} = p_{\text{T}}^2 i^\kappa. \quad (5.7.3)$$

The choice of κ affects the clustering behavior:

- For $\kappa = 1$, the algorithm prioritizes clustering low p_{T} particles first, which is referred to as the k_t algorithm [148].
- For $\kappa = 0$, the algorithm only considers the geometrical distance between particles, defining the Cambridge/Aachen algorithm [149].
- In ATLAS, the anti- k_t algorithm is employed with $\kappa = -1$, prioritizing the clustering of high p_{T} particles first [150].

Initially, the energy of reconstructed jets is calibrated to the electromagnetic scale, which assumes the energy deposited corresponds to electrons. Subsequently, a further calibration is applied to align the reconstructed jet energy with that of the originating partons using information from MC simulations.

To suppress jets originating from pile-up events (multiple proton-proton interactions within the same bunch crossing), specific selection criteria are applied. These criteria typically involve requiring a minimum transverse momentum threshold and ensuring the jet originates from the PV in the event. The PV is defined as the collision vertex with the highest sum of transverse momenta of its associated charged-particle tracks. Additionally, a jet vertex tagger (JVT) requirement may be imposed, which assesses the fraction of charged tracks in the jet that originate from the PV. Events containing jets identified as arising from detector noise or other non-collision sources are typically rejected using dedicated quality cuts [151].

5.8 Missing transverse momentum

During a pp collision, it is essential for the momenta of all physical objects generated to satisfy momentum conservation in the plane perpendicular to the beam axis. However, there are situations where momentum conservation can break. For instance, neutrinos, which are neutral and weakly interacting, can escape the detector undetected, leading to a momentum imbalance. Additionally, mismodeling of physics objects can also cause a violation of momentum conservation. Hence, understanding the concept of missing transverse momentum is crucial in various physics searches, such as the measurement of Higgs boson and Beyond Standard Model studies.

The missing transverse momentum, denoted as E_T^{miss} or p_T^{miss} , can be computed by summing the p_T of all particles detected in an event and then taking the negative of this vector sum (Equation 5.8). To account for any unassociated activity in the computation, a soft term is added to the E_T^{miss} reconstruction. This soft term can be either track-based or calorimeter-based. The track-based soft term aims to reduce pile-up dependency in E_T , while the calorimeter-based soft term considers all topological clusters not associated with jets in the E_T^{miss} calculation [152].

$$E_{\text{T}}^{\text{miss}} = - \sum_i p_{\text{T},i} \quad (5.8.1)$$

where i runs over all the detected particles. However, to account for any unassociated activity in the event, a soft term is added to the $E_{\text{T}}^{\text{miss}}$ reconstruction:

$$E_{\text{T}}^{\text{miss}} = - \left(\sum_i p_{\text{T},i} + p_{\text{T,soft}}^{\text{miss}} \right) \quad (5.8.2)$$

where $p_{\text{T,soft}}^{\text{miss}}$ is the soft term, which can be either track-based or calorimeter-based, depending on the reconstruction method.

Search of heavy resonances in the $X \rightarrow Z\gamma$ decay channel

6.1 Analysis strategy

This analysis is dedicated to the exploration of potential new heavy bosons (X) within the Beyond Standard Model (BSM) framework. These bosons may arise as additional gauge fields or by expanding the Higgs sector. The focus of the study lies in the detection of the excesses in the $Z\gamma$ final state with Z bosons decaying to $\mu^+\mu^-$ or e^+e^- pairs. The $Z(\rightarrow \ell\ell)\gamma$ final state, where $\ell = e$ or μ , serves as a robust experimental signature, offering several advantages. Firstly, it enables complete reconstruction with high efficiency, facilitating accurate measurement of the invariant mass with good resolution. Additionally, the inclusion of leptonic and photon signatures in this final state ensures minimal interference from hadronic processes, reducing background noise. The initial search for heavy resonances in the $Z\gamma$ decay channel took place through the efforts of ATLAS collaboration in Refs. [79, 153, 154, 155]. Throughout all of these searches, the data consistently demonstrated conformity with the background expectation of the Standard Model. In this specific study, an enhanced exploration of high mass $Z\gamma$ resonances is presented. The investigation incorporates advanced object iden-

tification algorithms employing multivariate analysis techniques and benefits from an augmented integrated luminosity (140 fb^{-1}).

6.2 Data and Monte Carlo simulation samples

The ATLAS detector utilizes hard-scatter pp collision data for multiple physics analyses, with signal and background processes simulated through Monte Carlo (MC) event generators to replicate the detector’s response to generated particles. Section 6.2.1 offers a concise summary of the data samples utilized in the $Z(\rightarrow ee \text{ or } \mu\mu)\gamma$ high-mass search. The associated simulations of signal and background are detailed in Section 6.2.2.

6.2.1 Data samples

The dataset utilized for the analysis was collected by the ATLAS detector during pp collisions at a center-of-mass energy of $\sqrt{s} = 13, \text{TeV}$ from 2015 to 2018, corresponding to an integrated luminosity of 140 fb^{-1} with an uncertainty of 0.83%. Events were captured using unprescaled single-lepton and dilepton triggers with the lowest p_T threshold, along with single high- p_T photon triggers. The list of unprescaled triggers used for the filtering of the events used in the analysis for 2015-2018 data taking is showed in the Table 6.1. Events passing at least one of required triggers are kept.

We utilize events exclusively from runs and luminosity blocks present in the “Good Run List” (GRL), which meet stringent data quality standards as described in Section 2.2.5. This guarantees that all sub-detector systems are functioning optimally, ensuring reliable data-taking efficiency of 95.6% and integrated luminosity of 140.1 fb^{-1} .

The analysis was conducted using the derivations known as DAOD_HIGG1D2. These derivations were generated from Analysis Object Data (AODs) using the

Table 6.1: Trigger strategy for 2015-2018 data and MC.

Trigger name	Type	Year	Offline threshold (GeV)
HLT_e24_lhmedium_L1EM20VH	Single electron	2015	27
HLT_e26_lhtight_nod0_ivarloose	Single electron	2016 2017 2018	27
HLT_e60_lhmedium_nod0	Single electron	2016 2017 2018	61
HLT_e60_lhmedium	Single electron	2015	61
HLT_e120_lhloose	Single electron	2015	121
HLT_e140_lhloose_nod0	Single electron	2016 2017 2018	141
HLT_2e12_lhloose_L12EM10VH	Di-electron	2015	25 25
HLT_2e17_lhvloose_nod0	Di-electron	2016	25 25
HLT_2e24_lhvloose_nod0	Di-electron	2017 2018	25 25
HLT_mu26_ivarmedium	Single muon	2016 2017 2018	27
HLT_mu26_imedium	Single muon	2015	27
HLT_mu50	Single muon	2015 2016 2017 2018	51
HLT_mu22_mu8noL1	Di-muon	2015 2016 2017 2018	10 25
HLT_g120_loose	Single photon	2015	121
HLT_g140_loose	Single photon	2016 2017 2018	141
HLT_g200_loose	Single photon	2018	201
HLT_g200_etcut	Single photon	2015	201
HLT_g300_etcut	Single photon	2016 2017 2018	301

AtlasDerivation release `AthDerivation_21.2.87` for data collected in 2015, 2016, 2017, and 2018 (`ptag 4061`). AODs are data formats containing primary information needed for physics analysis, while Derived Analysis Object Data (DAODs) are more specialized datasets created from AODs by applying specific selections and reductions. The term HIGG1D2 indicates that the samples contain a subset of the total dataset where events have been selected according to the criteria described in this section.

The HIGG1D2 analysis employs a preselection stage to reduce the initial dataset size by three orders of magnitude while maintaining a loose selection compared to the final offline analysis. This skimming process leverages the following criteria:

- **LArError Flag:** Events are required to pass a basic quality check indicated by the absence of errors flagged by the LAr.
- **Trigger Requirements:** Events must satisfy specific trigger conditions, ensuring they align with the physics processes of interest.

- **Physics Object Selection:** Additional criteria are applied based on the identification and properties of reconstructed physics objects within the event:
 - ✓ **Electrons:** Candidates must pass one of the following electron identification criteria: “DFCommonElectronsLoose” or “DFCommonElectronsLHLoose”. Additionally, they are required to have a transverse momentum (p_T) exceeding 4.4 GeV and lie within a pseudorapidity range of $|\eta| < 2.5$.
 - ✓ **Merged Low- p_T Electrons (for $\gamma\gamma^*$ analysis only):** These candidates, relevant specifically for the $\gamma\gamma^*$ search analysis, must have a p_T greater than 18 GeV and fall within the same pseudorapidity range of $|\eta| < 2.5$.
 - ✓ **Muons:** Muon candidates are required to satisfy one of the following identification criteria: “DFCommonGoodMuon” or “DFCommonMuonsPreselection”. Additionally, they must have a p_T exceeding 2.9 GeV and lie within the pseudorapidity region of $|\eta| < 2.7$.
 - ✓ **Photons:** Photon candidates must pass a basic quality check indicated by the “good object quality (OQ)” requirement. They are also required to fulfill the “DFCommonPhotonsIsEMLoose” photon identification criteria. Additionally, they must have a transverse energy (E_T) exceeding 9.9 GeV and be reconstructed within the pseudorapidity acceptance of $|\eta| < 2.5$.
- **Event category selection:** Events are categorized based on the reconstructed physics objects they contain, satisfying at least one of the following criteria:
 - ✓ at least 1 photon and at least 2 electrons;

- ✓ at least 2 muons;
- ✓ at least 1 photon and at least 1 merged electron;
- ✓ at least 1 high p_T photon > 500 GeV and at least 1 electron without identification cuts.

6.2.2 Monte Carlo modeling

For this analysis, we used data and MC samples based on a 25 ns bunch crossing. All MC samples listed in Appendix E were generated using the ATLAS MC for Run 2 settings. Subsequently, they were reweighted to align the profile of mean interactions per crossing with that of the data. Additionally, the derivation of the MC samples mirrors that of the data samples.

6.2.2.1 Signal samples

To evaluate the effectiveness of the final selection criteria and analyze the reconstructed kinematic distributions of the signal process, simulated signal samples were generated. These samples were subsequently processed through the full ATLAS detector simulation and event reconstruction chain. This procedure was carried out to evaluate the effectiveness of the selection criteria and to extract potential signals from the background via a final fitting procedure.

In the high mass search analysis, the nominal signal samples consist of resonances stemming from the gluon-fusion (ggF) spin-0 process with an intrinsic narrow width of 4 MeV and mass range spanning from 200 GeV to 5 TeV. These samples were generated through POWHEG [156] in conjunction with the PYTHIA 8 model [157] for parton shower, hadronization, and underlying event simulations, utilizing the AZNLO set of tuned parameters with the CT10+CTEQ6 L1 PDF [158] for modeling of non-perturbative effects. For most simulated samples, the Z boson decay was restricted exclusively to charged lepton pairs (muons, elec-

trons, and taus), with equal branching ratios for each channel. These samples are commonly referred to as “Zllgam” samples within the context of this analysis.

Spin-2 resonances with mass range spanning from 200 GeV to 5 TeV, with an intrinsic width of 4 MeV, were simulated for gluon–gluon and quark–antiquark initial states. These event samples were generated at leading order (LO) in QCD using the Higgs Characterisation Model [159] with MadGraph5_aMC@NLO2.3.3 [160]. For high-mass spin-0 (spin-2) resonances, parton showering, hadronization, and multi-parton interactions were simulated with PYTHIA 8.186 [157] using the AZNLO (A14) set of tuned parameters and the CTEQ6L1 [161] (NNPDF2.3 [162]) PDF set. The interference between the resonant signal and the non-resonant background was neglected due to the assumed narrow width of the resonance.

6.2.2.2 Background samples

The dominant background contributions in this analysis stem from non-resonant processes involving a Z boson produced in association with either a photon ($Z + \gamma$) or a jet ($Z + \text{jet}$). MC samples for the $Z + \gamma$ process were separately generated for both electron and muon final states, segmented by slices of the three-body invariant mass. Signal samples were generated using SHERPA version 2.2.2 [163, 164]. The simulation employed the NNPDF30NNLO parton distribution function set. Subsequently, the samples were processed through the ATLAS AF-II fast detector simulation.

Derivations (DAOD_HIGG1D2) were then produced using the Athena derivation framework release 21.2.87.0 with a875 (fast simulation) and p4062 tags [165]. The three-body invariant mass slices include 95–110 GeV, 110–175 GeV, 175–250 GeV, 25–400 GeV, 400–1000 GeV, 1000–2000 GeV, 2000–3000 GeV, and 3000 – E_{CMS} . Additionally, fully-simulated $Z + \gamma$ events were generated using the same generator and PDF set as the fast simulation samples for both electron and muon final states, but segmented by slices of the photon’s transverse momentum (p_{T}):

7-15 GeV, 15-35 GeV, 35-70 GeV, 70-140 GeV, 140-E_CMS.

6.3 Analysis Framework

Using the AnalysisBase release 21.2.165, we conducted a search for a high mass resonance that decays into $Z\gamma$ with the H2Zy package (tag version 45a1d8be). This package is a part of the Higgs to Gamma Gamma working group Software, which helps organize analysis with final states in photons. The HGamCore analysis package tools are available in the HGam Software repository and contain important functions for analysis, such as signal parametrization and the selection of physics objects and their calibrations from the CP groups. In this study, we used the es2018_R21_v0 version for the electron-photon calibration. We used the quickFit tool for statistical analysis to obtain limits on the $\sigma \times BR$, and a customized Python script was used to plot the limits against the resonance masses.

6.4 Object and event selections

The event selection process consists of two stages. Firstly, a “preselection” step is performed to identify the objects that will be used in the subsequent overlap removal procedure. Secondly, a set of final selection criteria is applied to the events, following the overlap removal and the identification of a Z boson candidate within each event.

The final selection criteria are applied sequentially after the procedures for removing overlapping events and identifying a Z boson candidate have been completed. In cases where photon candidates pass the preselection but do not meet the stringent criteria, they are still considered for estimating the background composition of the selected sample. This allows for an assessment of the contributions from $Z\gamma$ and Z +jets processes. This section provides an in-depth explanation of the event selection process and the reconstruction of $X \rightarrow Z\gamma$ candidates.

To be considered for further analysis, all events must meet the following basic quality criteria:

- **GRL and event cleaning:** data events that do not pass the standard ATLAS data quality assessment are excluded from further analysis.
- **Vertex selection:** Events are required to contain at least one reconstructed primary vertex (PV) candidate. These candidates are identified by fitting the ID tracks and ensuring a consistent origin point. The PV with the highest sum of the squared transverse momenta (p_T^2) of its associated tracks is designated as the PV of the hard scatter process. To ensure data quality, events with malfunctions in the LAr or TileCal, identified through “event quality” flags, are excluded from further analysis.
- **Trigger match:** the analysis employs a trigger system that necessitates the presence of one or two electrons, muons, or a high-momentum photon within the event. During the highest instantaneous luminosity period, the single-electron trigger requires a minimum p_T threshold of 26 GeV, while the di-electron trigger demands 17 GeV for each of the two electrons. Similarly, the single muon trigger sets a threshold of 26 GeV, whereas the di-muon trigger employs asymmetric thresholds of 22 GeV and 8 GeV. For the single-photon trigger, the lowest threshold for transverse energy is 140 GeV. To complement these lowest threshold triggers, higher threshold triggers with more relaxed lepton identification criteria are also incorporated. Table 6.1 displays a summary of the HLT trigger items and their corresponding offline thresholds.

6.4.1 Object selection

To be considered in the analysis, photons must satisfy the criteria of having a p_T greater than 15 GeV and a pseudo-rapidity falling within specific regions. These

regions are defined as $|\eta| < 1.37$ or $1.52 < |\eta| < 2.37$. The first layer of the ECAL, which exhibits high granularity, plays a crucial role in distinguishing between prompt photons and photons originating from hadron decay within jets. Photons that are reconstructed in areas of the calorimeter impacted by read-out or high-voltage failures are excluded from consideration to ensure data integrity and reliability.

To identify photons, a cut-based selection method is utilized, which involves measuring the shower shapes in the initial two longitudinal layers of the ECAL and assessing the leakage into the hadronic calorimeter. The selection criteria utilize the *Loose* ID working point to ascertain whether a photon meets the criteria. At the object level selection, no isolation requirement is imposed deliberately to aid in studying background composition, as elaborated in subsequent analyses.

Stringent criteria are imposed on electron candidates to ensure high quality and suppress backgrounds. Electrons must possess a significant transverse momentum exceeding 10 GeV and originate from the barrel or end-cap regions of the ECAL, corresponding to a pseudorapidity (η) satisfying either $|\eta| < 1.37$ or $|\eta| > 1.52$. The transition region between these sections ($1.37 < |\eta| < 1.52$) is excluded due to potential inefficiencies. Additionally, the transverse impact parameter significance of the associated ID track, indicative of the electron's distance from the primary interaction point, must be less than 5. This requirement suppresses secondary leptons arising from heavy-flavor hadron decays. Finally, the electron's longitudinal impact parameter, weighted by the sine of its track angle with respect to the beam axis, must satisfy $|z_0 \sin \theta| < 0.5$ mm, ensuring its trajectory originates close to the PV.

In the $X \rightarrow Z\gamma$ high-mass search, a specific issue arises with the electrons identification. Due to their close energy deposits in the ECAL, using *Loose* identification criteria results in a notable loss of signal efficiency. Additionally, the sub-leading electron is mistakenly reconstructed as a photon instead of an electron. In order to

tackle this identification challenge, a specialized criterion called MVA identification, based on Multivariate Analysis (MVA), has been developed. This approach utilizes a combination of shower shape variables and track-based variables to accurately distinguish electrons from photons. By employing the MVA identification criteria, the issue of signal efficiency loss and misidentification of sub-leading electrons is effectively addressed.

The calorimeter shower shape variables used are R_η , R_{had} , R_ϕ , ΔE_s , and E_{ratio} , which are described in detail in Table 1 in Ref. [143]. The track-based variables considered are E/p , eProbabilityHT, $\Delta\eta_1$, d_0 , $n_{\text{innermost}}$, n_{Pixel} , and n_{Si} , also described in Refs. [142, 143]. Additionally, two additional track-based variables are included: n_{TRT} , defined as the number of hits in the TRT detector, and the $\Delta\phi_{\text{rescaled}}$ variable, defined as the $\Delta\phi$ between the cluster energy and associated track in the presampler, first, second, and third layers after rescaling the EM energy deposits. The MVA training is performed on single electrons to separate the signal and background components. This allows for the estimation of the optimal MVA identification cut-point, resulting in improved signal efficiency while maintaining a low background efficiency.

The electron identification system achieves a high level of performance, characterized by a signal efficiency of 99% and a background rejection rate of 76%. Additionally, the compatibility of the invariant mass distributions between selected electrons with the MVA identification in both data and MC is confirmed. To cover the entire explored mass range, the MVA identification is combined (using the logic ‘OR’) with the *Loose* identification criterion, forming the Mixed identification. This Mixed identification enhances the efficiency from 6.2% to 12.7% within the mass range of 200 GeV to 3500 GeV, compared to the *Loose* identification alone.

Similar criteria are necessary for electrons that are mis-reconstructed as photons, with the additional requirement of having at least one track within a cone of radius

Table 6.2: Summary of object selections.

Selection	Muon	Electron	Electron as photon	Photon
p_T	$> 10 \text{ GeV}$	$> 10 \text{ GeV}$	$> 50 \text{ GeV}$	$> 15 \text{ GeV}$
$ \eta $	< 2.7	< 2.47 Exclude $[1.37, 1.52]$	< 2.47 Exclude $[1.37, 1.52]$	< 2.37 Exclude $[1.37, 1.52]$
$ d_0 /\sigma_{d_0}$	< 3	< 5		
$ z_0 \sin \theta $	$< 0.5 \text{ mm}$	$< 0.5 \text{ mm}$		
Identification	<i>Medium</i>	Mixed	MVA	<i>Tight</i>
Isolation	Track-based <i>Tight</i>	Track-based <i>Tight</i>		<i>Loose</i>
$\Delta R(\text{track}, \gamma)$			< 0.1	
ee or $\mu\mu$ pair	≥ 2 , opposite charge			
$e\gamma$ pair			$\Delta R(e, \gamma) < 1$ $ p_T^e - p_T^\gamma /p_T^{e \text{ or } \gamma} > 5\%$	

$\Delta R < 0.1$ around the photon candidate. Both muons and electrons are subjected to a track-based isolation requirement to ensure isolation from additional activity in the detector. Moreover, muon and electron candidates need to be linked with the PV by fulfilling the requirement $|\Delta z_0 \sin \theta| < 0.5 \text{ mm}$, where θ denotes the polar angle of the track. The transverse impact parameter d_0 is assessed concerning the measured beam line position, and its significance must meet the criteria $|d_0/\sigma_{d_0}| < 3$ (5) for muons (electrons), where σ_{d_0} signifies the uncertainty in d_0 . The object selection criteria are summarized in Table 6.2.

6.4.2 Overlap removal

In accordance with the findings presented in Ref. [166], the overlap removal procedure is no longer utilized for events featuring two muon candidates. This decision stems from the improved muon reconstruction techniques employed during Run 2, which enable the accurate distinction of nearby muons within an angular resolution of approximately 0.01-0.02. Consequently, the need for overlap requirement has been rendered unnecessary.

Following the selection criteria for the $Z \rightarrow \ell\ell$ decay mode outlined in Section 6.4.3, an overlap removal procedure is implemented for events containing two identified electrons. Here, a $Z(\ell\ell)\gamma$ candidate has already been reconstructed,

and the overlap removal focuses on the objects constituting this candidate within the event.

For the ee decay channel, the overlap removal criteria address scenarios where two electron candidates share identical track information. In such cases, only the electron with the highest transverse momentum (p_T) is retained. However, enforcing a stricter requirement based on a cone of radius $|\Delta\eta| < 0.075$ and $|\Delta\phi| < 0.125$ around the highest p_T cluster was observed to significantly impact selection efficiency, particularly for high-mass signals. Specifically, this approach resulted in an estimated 17.8% decrease in selection efficiency for a 5 TeV signal mass point.

To mitigate the issue of overlapping electron candidates, a momentum-dependent selection strategy is implemented. For leading electrons with a p_T below 500 GeV, any electron candidate within a cone of $\Delta\eta < 0.075$ and $\Delta\phi < 0.125$ around it is discarded. Conversely, for leading electrons with p_T exceeding 500 GeV, a tighter cone of $\Delta\eta < 0.05$ and $\Delta\phi < 0.05$ is used for overlap removal.

To ensure the quality of the selected candidates, the analysis implements further overlap removal procedures. First, electron candidates that share a track within a cone of $\Delta R < 0.02$ with a reconstructed muon candidate passing all selection criteria are discarded.

Following event categorization and the identification of at least one three-body mass candidate, an event-level overlap removal addresses potential artifacts arising from the loose electron selection criteria. Photon candidates within $\Delta R < 0.3$ of the selected electron or muon pair with an invariant mass closest to the Z boson mass peak are excluded. This step mitigates backgrounds from final-state radiation (FSR) in $Z+\gamma$ processes and reduces the impact of photons misidentified as electrons. Additionally, jets reconstructed within $\Delta R < 0.2$ of any identified photons, electron pairs, or muons are removed.

The overlap removal procedure also considers the $e(\gamma)$ candidate. Similar criteria are employed for the $e(\gamma)$ as for standard electrons, including self-overlap removal, and removal of overlaps with muons, photons, and jets. However, due to the inherent proximity between the $e(\gamma)$ candidate and ordinary electrons, confirmed through MC truth information, no overlap removal is performed between them.

6.4.3 Reconstruction and selection of $Z \rightarrow \ell\ell$ decays

The reconstruction of Z boson candidates relies on selecting pairs of leptons with the same flavor but opposite charges. These lepton pairs are subjected to object selection criteria outlined in Table 6.2. In situations where multiple Z candidates are present within the same event, the candidate with an invariant mass closest to the Z pole is favored. Signal events undergo corrections to the lepton four-momenta in order to enhance the resolution. Specifically, collinear final state radiation (FSR) effects [167] are corrected for in muon momenta, while a Z boson mass constraint [168] is applied to correct the four-momenta of both electrons and muons. The constraint on the mass of Z boson significantly enhances the resolution of the $\ell\ell\gamma$ mass. In the muon channel, the resolution is enhanced by 8% at $m_X = 200$ GeV and by 70% for higher resonance masses, as the precision of momentum measurement diminishes with increasing muon p_T . To ensure the correctness of the dilepton invariant mass, it is required to fall within ± 15 GeV of the m_X boson mass, $m_Z = 91.2$ GeV.

To minimize potential biases introduced by the generator-level filter (dilepton invariant mass, $m_{\ell\ell} > 40$ GeV) in simulated Z +jet samples and the derivation-level requirement (also $m_{\ell\ell} > 40$ GeV) within the HIGG1D2 selection, a higher invariant mass threshold of $m_{\ell\ell} > 45$ GeV is applied without additional corrections. This stricter selection mitigates these biases and enhances the reliability of the analysis results.

In addition to the ee and $\mu\mu$ selections, $e + e(\gamma)$ events are reconstructed to

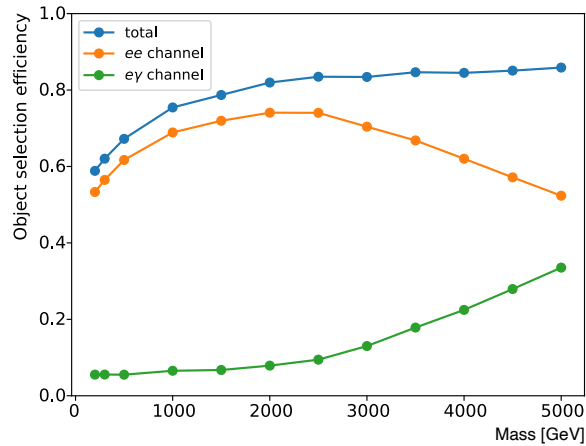


Figure 6.1: $Z \rightarrow ee$ and $Z \rightarrow ee(\gamma)$ selection efficiency for Z bosons produced in $X \rightarrow Z(ee) + \gamma$ and $X \rightarrow Z(ee(\gamma)) + \gamma$ events versus m_X applying acceptance cuts only on the reconstructed objects.

account for cases where electrons are incorrectly identified as photons during the Z reconstruction process. The total object selection efficiencies for $Z \rightarrow ee$ and $Z \rightarrow ee(\gamma)$ events produced in $X \rightarrow Z(ee) + \gamma$ and $X \rightarrow Z(ee(\gamma)) + \gamma$ events, respectively, are illustrated in Figure 6.1. The efficiency is defined as the ratio of $X \rightarrow Z(ee) + \gamma$ and $X \rightarrow Z(ee(\gamma)) + \gamma$ events that pass the object selection criteria to the total number of $X \rightarrow Z(ee) + \gamma$ events detected. The fiducial volume is defined using truth information within the region of $|\eta| < 2.47$, excluding the ECAL barrel/endcap transition region of $1.37 < |\eta| < 1.52$. No truth requirement is imposed on the photons [143].

Finally, the selected Z boson candidate is reconstructed from events with two electrons, in addition to reconstructed $e + e(\gamma)$ events containing one electron and an electron reconstructed as a photon candidate, composing then the ee channel and two muons defining the $\mu\mu$ channel.

The dilepton distributions ($m_{\ell\ell}$) have been constructed using ee or $e + e(\gamma)$ events, as well as their combined dataset. For these events, electrons are required to satisfy acceptance criteria, including the customized electron identification (MixedID) and isolation working point (TightTrackOnly). These distributions serve to verify

that the inclusion of $e + e(\gamma)$ events does not significantly affect the Z mass spectrum.

To model the signal in both data and MC, the distributions have been fitted with a double-sided crystal ball (DSCB) function, while the background is represented by a second-order polynomial function. A detailed description of the DSCB function is provided in Section 6.6.1. Figure 6.2 displays the $m_{\ell\ell}$ data distributions for ee , $e + e(\gamma)$, and $ee + ee(\gamma)$ events. The incorporation of $e + e(\gamma)$ events into the analysis has a minimal influence on the profile of the reconstructed Z boson mass spectrum in data.

6.4.4 $X \rightarrow Z\gamma$ reconstruction and selection

Signal candidates in this analysis are reconstructed by combining a Z boson candidate with the invariant mass closest to the known Z boson mass and a photon candidate with the highest transverse momentum (p_T). However, photon candidates must satisfy stricter selection criteria:

- ***Tight Photon Identification:*** Photon candidates are selected based on their shower profiles within the ECAL. The identification criteria were refined in 2017 utilizing a Toolkit for Multivariate Analysis (TMVA) approach, optimized for the SM Higgs boson search in the $Z\gamma$ decay channel (Ref. [169, 143]). This “tight” identification strategy offers a p_T -dependent selection, allowing for independent optimization of efficiencies for low- and high-momentum photons, resulting in improved overall performance.
- ***FixedCutLoose isolation WP:*** To suppress background contributions from hadronic activity, the analysis employs a stringent “FixedCutLoose” working point for photon isolation. This approach has two components:
 - **Energy-Based Isolation:** It assesses the total transverse energy (E_T^{iso}) within a cone of radius 0.2 around the photon candidate. This

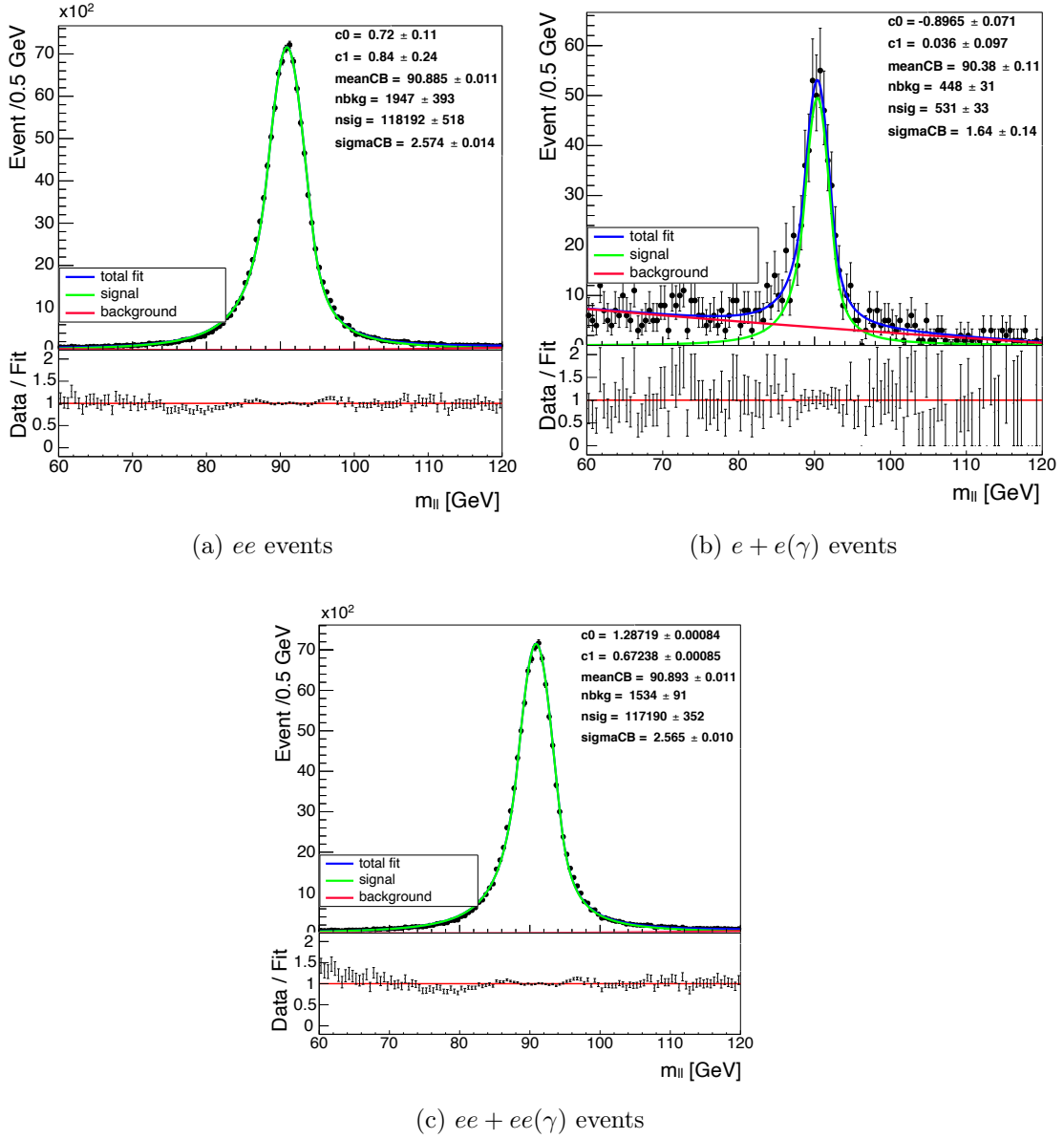


Figure 6.2: Data m_{II} distributions in the ee channel for events containing ee , $ee(\gamma)$ and $ee + ee(\gamma)$ pairs.

energy must be less than $0.065 \times p_T$ GeV

- **Track-Based Isolation:** It evaluates the E_T^{iso} within a cone of radius 0.2, requiring it to be below $0.05 \times p_T$ GeV.

- **Minimum Photon Transverse Momentum:** Additionally, a minimum p_T threshold of 15 GeV is imposed on the photon candidate. Furthermore, as detailed in Section 6.4.4.1, the ratio of the photon's p_T to the reconstructed three-body invariant mass is required to be greater than 0.2.

6.4.4.1 Relative photon p_T optimization

In this analysis, we perform an optimization of the ratio between the photon's p_T and the three-body invariant mass, which is detailed below. To examine the potential impact of using the standard photon p_T , two distributions were generated: one for the photon transverse momentum p_T^γ and another for the ratio of the photon transverse momentum to the three-body invariant mass $p_T^\gamma/m_{\ell\ell\gamma}$. Figure 6.3 presents these distributions for the main background sources, data, and signals with varying resonance masses. As anticipated, the photon p_T distributions exhibit substantial variations corresponding to the mass of the $Z\gamma$ resonance. Consequently, selecting a minimum photon p_T requirement that simultaneously achieves high efficiency across the entire mass range while sufficiently suppressing the background proves challenging. Conversely, the distributions of $p_T^\gamma/m_{\ell\ell\gamma}$ display similarity across all signal samples.

To determine the optimal minimum photon relative transverse momentum, a systematic scan was conducted across various $p_T^\gamma/m_{\ell\ell\gamma}$ values. The value that yielded the highest increase in signal sensitivity ($S/\sqrt{S+B}$) compared to the baseline requirements was selected. The signal (S) and background (B) yields were computed using gluon-gluon fusion-like signal and $Z\gamma$ simulated samples, considering the expected number of events within a 3% mass window around each m_X point. The analysis revealed that the most effective cut values were $p_T^\gamma/m_{\ell\ell\gamma} > 0.3$

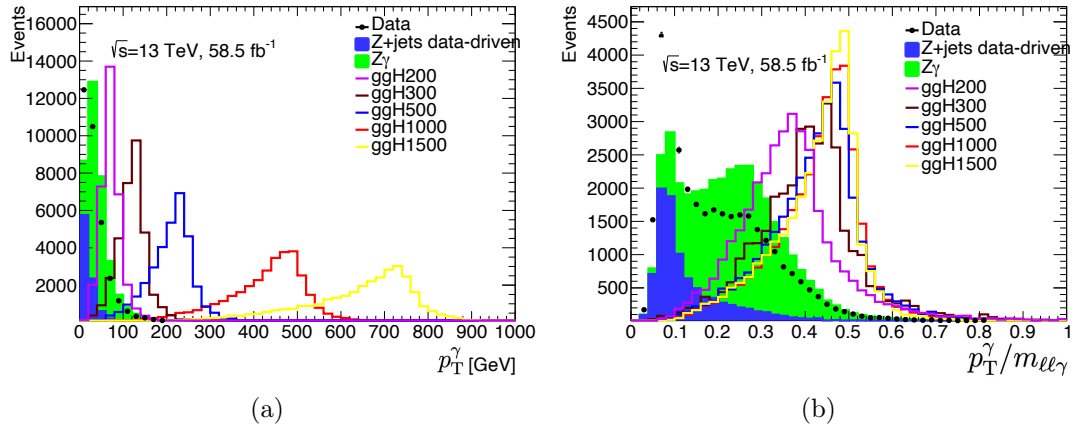


Figure 6.3: Distributions of kinematic properties for photons associated with reconstructed Z boson candidates ($m_{\ell\ell} > 200$ GeV) in both MC and real data. Panel (a) shows the transverse momentum (p_T^γ) of the photons. Panel (b) presents the relative transverse momentum ($p_T^\gamma/m_{\ell\ell\gamma}$). The MC distributions in both panels are normalized to the total number of events in the data to facilitate visual comparison between the simulated and measured photon kinematics.

and $p_T^\gamma/m_{\ell\ell\gamma} > 0.2$. To evaluate the impact of applying these criteria (alongside $p_T^\gamma > 15$ GeV for comparison), the $Z\gamma$ background distribution was examined within the range of 130 GeV to 1000 GeV (see Figure 6.4). It was observed that after applying the $p_T^\gamma/m_{\ell\ell\gamma} > 0.3$ requirement, a turn-on effect appeared around 200 GeV in the $m_{\ell\ell\gamma}$ spectrum. Therefore, $p_T^\gamma/m_{\ell\ell\gamma} > 0.2$ was chosen as the final value, considering its suitability.

The comprehensive event selection for the analysis can be succinctly summarized in the following representative Table 6.3.

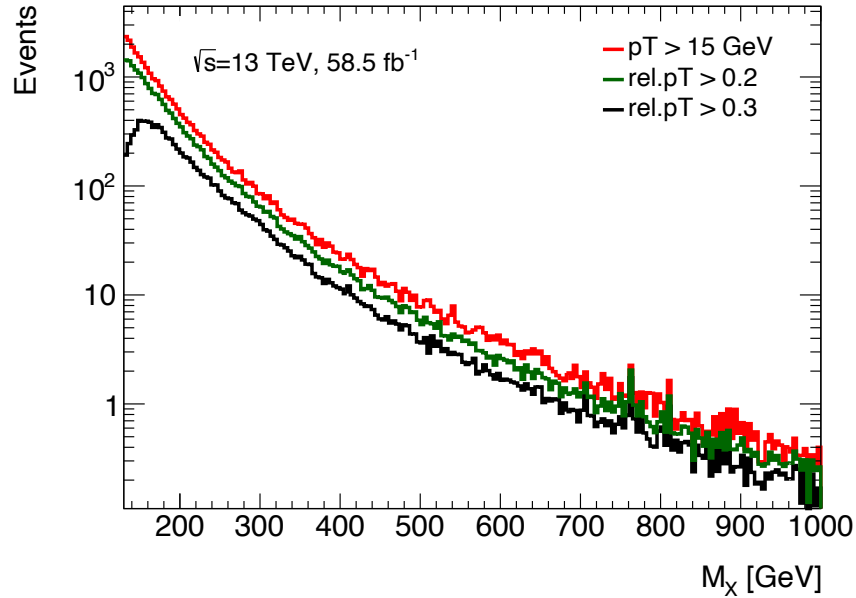


Figure 6.4: 3-body mass distribution $m_{\ell\ell\gamma}$ for background $Z\gamma$ simulated events for either $p_T^\gamma > 15$ GeV, $p_T^\gamma/m_{\ell\ell\gamma} > 0.2$ and $p_T^\gamma/m_{\ell\ell\gamma} > 0.3$ requirements.

Table 6.3: Selection requirements for high-mass $Z(\rightarrow \ell\ell)\gamma$ analysis.

Requirements	Description
Initial event selection:	GRL, PV, Event Quality and Triggers
Object selections:	detailed in Table 6.2. Includes an overlap removal at object level between ee , $\mu\mu$, $e\mu$, $e(\gamma)e(\gamma)$ and $e(\gamma)\mu$
Categorization ($ee\gamma$ and $\mu\mu\gamma$):	≥ 2 good leptons and opposite sign (OS), and one loose photon $ee(\gamma)$ events : $\Delta(e, e(\gamma)) < 1$ and track match Z and $Z\gamma$ selection
Overlap removal (event level):	γ and e , μ and $e(\gamma)$; jets with respect to e , $e(\gamma)$, γ , μ
Trigger Matching:	leptonic and photon triggers used in the analysis
Z -mass constraint:	$76.18 \text{ GeV} < m_{\ell\ell}^{\text{constrained}} < 106.18 \text{ GeV}$
Photon selections:	$p_T^\gamma > 15$ GeV, Tight ID, FixedCutLoose WP (isolation)
High-mass cut:	$m_{\ell\ell\gamma} > 200$ GeV
Photon relative cut:	$p_T^\gamma/m_{\ell\ell\gamma} > 0.2$

6.5 Total selection efficiencies

Once the optimizations for object selection have been implemented, the overall selection efficiencies are calculated for different resonance masses (m_X) using MC

samples at specific mass points. The signal efficiency is calculated as the ratio of the number of events that satisfy all selection criteria to the total expected number of events in the $pp \rightarrow X \rightarrow Z(\rightarrow \ell\ell)\gamma$ process, where $\ell = e, \mu, \tau$. To account for variations in efficiency across different mass intervals between simulated samples, the efficiency is parameterized as a function of the resonance mass. This is achieved by fitting a combination of a first-order polynomial and a logarithmic function to the data, expressed as:

$$f = a + b \cdot m_X + c \cdot \ln(m_X + d), \quad (6.5.1)$$

where $a - d$ are free parameters in the fit. Figure 6.5 illustrates the reconstruction and selection efficiency for spin-0 and spin-2 events plotted against the mass point m_X . The efficiencies are separately parameterized for spin-0 and spin-2 events generated through gluon-gluon fusion processes, as well as for spin-2 events generated through quark-antiquark initial states. The efficiency values range from 21% to 36% over a mass range of 200 GeV to 3500 GeV for spin-0 resonances produced via the gluon-gluon initial state.

The efficiency incompatibility between spin-0 and spin-2 can be attributed to the distinct distributions of p_T and pseudorapidity of the Z boson and photon in the different models. It is worth noting that the efficiencies observed in the electron and muon channels are similar. To gain insights into these discrepancies, kinematic distributions for the γ , Z boson, and $Z\gamma$ system were generated using truth information from events that underwent the full event selection process as shown in Appendix D.

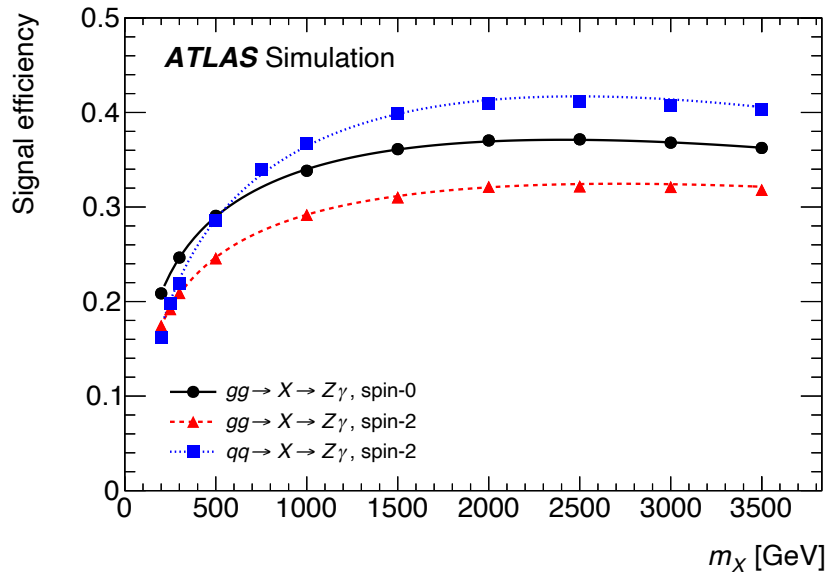


Figure 6.5: The efficiency of reconstructing and selecting the $X \rightarrow Z\gamma$ final state, including kinematic acceptance, is plotted against the mass point m_X [170].

6.6 Modeling signal and background processes

The signal and background yields are determined within the $Z\gamma$ invariant mass spectrum by employing a maximum-likelihood fitting technique. This technique relies on probability density functions (PDFs) for both the signal and background components. The signal PDF parameters are fixed based on dedicated studies performed with simulated signal samples, as detailed in Section 6.6.1. In contrast, the background PDF form is determined through the analysis of spurious signals as described in Section 6.6.3. The specific parameters of the chosen background PDF are subsequently extracted by fitting it directly to the real data.

The composite function describing the high mass resonant m_X spectrum in data can be defined as:

$$\begin{aligned}
f_{S+B} &= N_{\text{sig}} \cdot f_{\text{sig}} + N_{\text{spur}} \cdot f_{\text{sig}} + N_{\text{bkg}} \cdot f_{\text{bkg}} \\
&= \epsilon_{\text{sig}} \cdot \sigma(pp \rightarrow X) \cdot BR(X \rightarrow Z\gamma) \cdot L \cdot f_{\text{sig}} + N_{\text{spur}} \cdot f_{\text{sig}} + N_{\text{bkg}} \cdot f_{\text{bkg}},
\end{aligned}
\tag{6.6.1}$$

where f_{sig} and f_{bkg} represent the normalised analytical function of signal and background respectively. N_{sig} , N_{spur} and N_{bkg} represents the number of events from signal, spurious signal and background, ϵ_{sig} is signal efficiency, the ratio of number of events passing the whole selection criteria over the total number of events.

6.6.1 Signal modeling

The $Z\gamma$ invariant mass distribution for high mass resonances can be effectively characterized using the Double-Sided Crystal Ball function (DSCB). This functional form is employed for various spin-0 and spin-2 production modes and its shape and parameterization are illustrated in Figure 6.6. The DSCB function comprises a central Gaussian component with power-law tails on either side of the distribution peak. The analytic form of this function is presented in Equation 6.6.2:

$$DSCB(x) = N \times \begin{cases} e^{-t^2/2}, & \text{if } -\alpha_{\text{low}} \leq t \leq \alpha_{\text{high}} \\ e^{-\frac{1}{2}\alpha_{\text{low}}^2} \left[\frac{1}{R_{\text{low}}} (R_{\text{low}} - \alpha_{\text{low}} - t) \right]^{-n_{\text{low}}}, & \text{if } t < -\alpha_{\text{low}} \\ e^{-\frac{1}{2}\alpha_{\text{high}}^2} \left[\frac{1}{R_{\text{high}}} (R_{\text{high}} - \alpha_{\text{high}} - t) \right]^{-n_{\text{high}}}, & \text{if } t > \alpha_{\text{high}}, \end{cases}
\tag{6.6.2}$$

where $t = (x - \mu_{\text{CB}})/\sigma_{\text{CB}}$, $R_{\text{low}} = \frac{\alpha_{\text{low}}}{n_{\text{low}}}$, and $R_{\text{high}} = \frac{\alpha_{\text{high}}}{n_{\text{high}}}$. Here N is a normalization

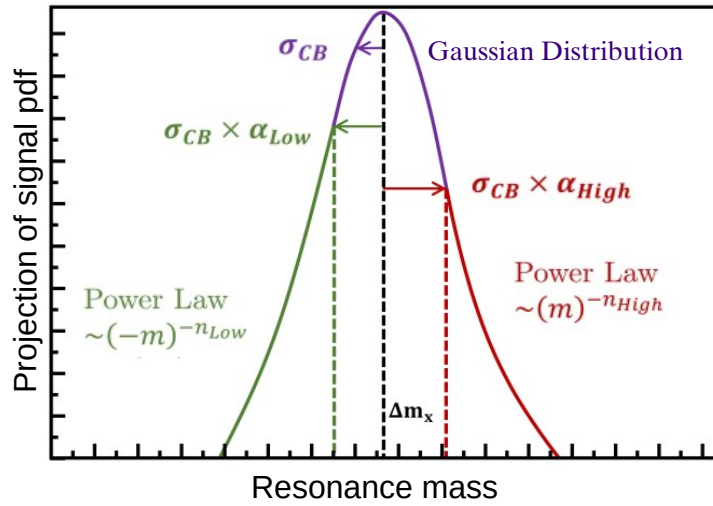


Figure 6.6: The definition of DSCB function.

parameter, μ_{CB} is mean of the Gaussian distribution, σ_{CB} is the width of the Gaussian distribution, α_{low} and α_{high} are the positions of the transitions from the Gaussian core to the exponential tails on the low and high sides, and n_{low} and n_{high} are the exponents of the low and high tails.

In order to obtain the signal shape at any intermediate mass, to which there are not simulated samples corresponding, each of the DSCB parameters is interpolated as a function of m_X and the parameters of such functions are determined by a simultaneous fit to all the high mass signal samples. As the distribution of $m_{Z\gamma}$ would be significantly different when Z boson decays into different type of lepton pair (ee or $\mu\mu$). The signal modeling studied was performed in ee channel with ee events only, ee channel adding the ee and $ee(\gamma)$ events and $\mu\mu$ channels independently. Therefore, all of the results would be presented for the two channels respectively.

The dependence of DSCB parameters on m_X was determined through many tests to keep agreement between parametrisation from simultaneous fit and points from individual fits as good as possible. The final function forms describing the dependence of DSCB parameters on m_X are summarized in Table 6.4, and the corre-

Table 6.4: Parameterization of the DSCB parameters with respect to m_X in the simultaneous fit. x denotes $(m_X - 100\text{GeV})/100\text{GeV}$. Linear function used for μ_{CB} , while parabola used for σ_{CB} , α_{Hi} and α_{Lo} . The remaining 2 parameters n_{Lo} and n_{Hi} are set as constant terms in the simultaneous fit.

Parameter	Fitted function	
	ee channel	$\mu\mu$ channel
μ_{CB}	$a_\mu + b_\mu \times m_X + c_\mu \times m_X^2 + d_\mu \times m_X^3$	$a_\mu \times m_X$
σ_{CB}	$a_\sigma + b_\sigma \times x + c_\sigma \times x^2 + d_\sigma \times x^3$	$a_\sigma + b_\sigma \times x + c_\sigma \times x^2$
α_{Lo}	$a_{\alpha_{\text{Lo}}} + b_{\alpha_{\text{Lo}}} \times x + c_{\alpha_{\text{Lo}}} \times x^2$	$a_{\alpha_{\text{Lo}}} + b_{\alpha_{\text{Lo}}} \times x + c_{\alpha_{\text{Lo}}} \times x^2$
α_{Hi}	$a_{\alpha_{\text{Hi}}} + b_{\alpha_{\text{Hi}}} \times x + c_{\alpha_{\text{Hi}}} \times x^2$	$a_{\alpha_{\text{Hi}}} + b_{\alpha_{\text{Hi}}} \times x + c_{\alpha_{\text{Hi}}} \times x^2$

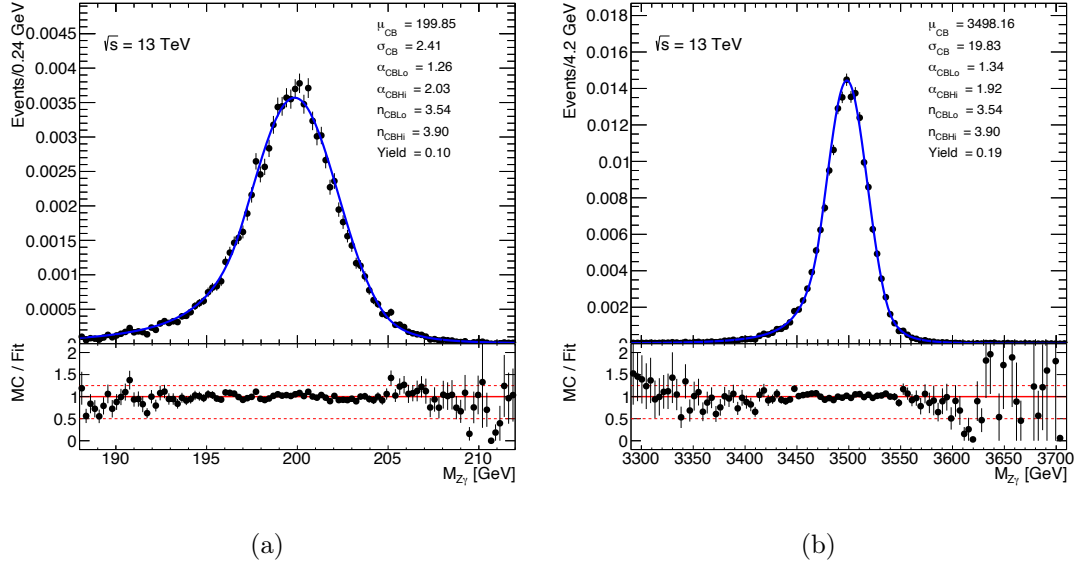


Figure 6.7: Results of simultaneous fits to high-mass ggF spin-0 simulations at 200 GeV (a) and 3500 GeV (b) for ee channel with ee and $e + e(\gamma)$ events.

sponding plots can be found in Appendix B. There are good agreements between parameterized function and predicted points.

The simultaneous fits for the $\mu\mu$ and ee channels in the $m_{Z\gamma}$ region are presented in Figures 6.7 and 6.8 specifically for the ggF spin-0 samples. These figures showcase the signal mass points at $m_X = 200$ GeV and $m_X = 3500$ GeV, while additional plots can be found in Appendix B. Similar parameterization is conducted for other resonances, including ggF spin-2 and $q\bar{q}$ spin-2 samples.

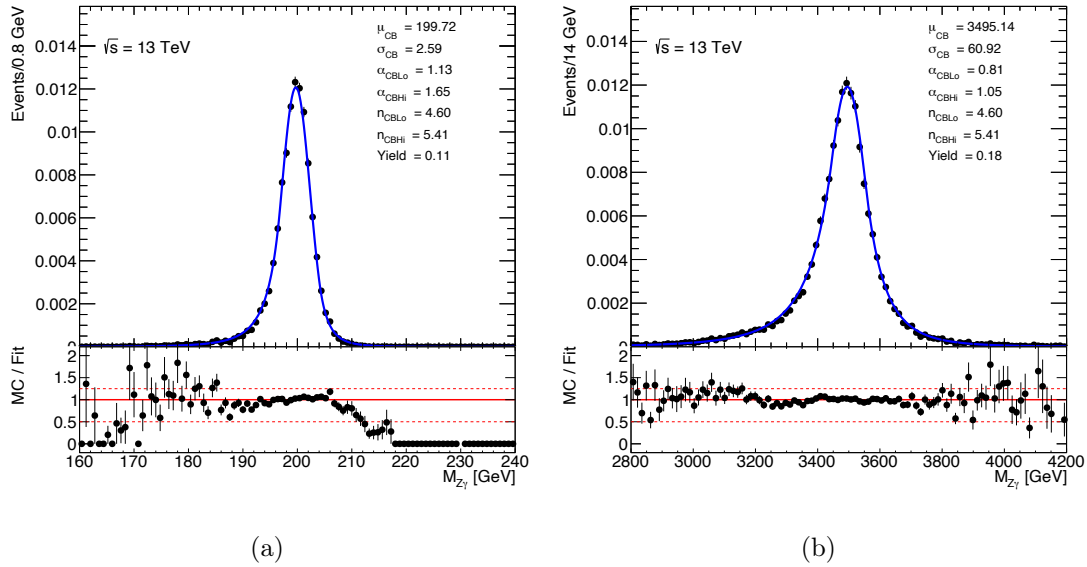


Figure 6.8: Results of simultaneous fits to high-mass ggF spin-0 simulations at 200 GeV (a) and 3500 GeV (b) for the $\mu\mu$ channel.

6.6.2 Background composition

The primary background contributions in this analysis stem from SM processes involving either a genuine $Z + \gamma$ final state or a misidentified Z +jets event. Genuine $Z + \gamma$ production arises from Initial State Radiation (ISR), where a photon is radiated from a quark participating in the hard scattering process as shown in Figure 6.9. The corresponding photon candidate exhibits a narrow energy deposition profile within the ECal and is typically isolated from nearby hadronic activity.

In contrast, the background arising from Z +jets events originates from misidentified jets. These jets can be mistakenly reconstructed as photons when a neutral meson within the jet carries a significant portion of the parton's initial energy. This leads to a broader energy deposition in the ECAL, often accompanied by leakage into the neighboring Hadronic Calorimeter. Additionally, the reconstructed photon candidate in Z +jets events is typically accompanied by substantial hadronic

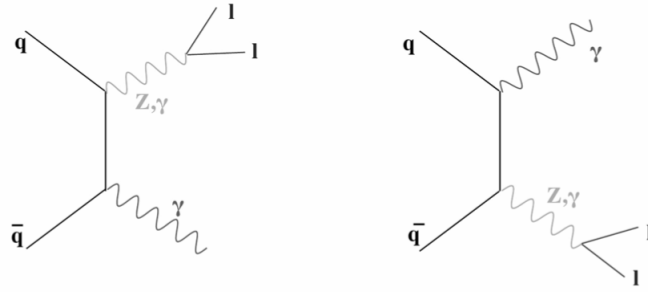


Figure 6.9: Feynman diagrams for $Z + \gamma$ production from Initial State Radiation [171].

activity nearby, unlike the isolated genuine photons from $Z + \gamma$ production.

This section details the application of the data-driven template-fit method to characterize the composition of the selected dataset. This technique has been successfully employed in numerous Run 1 analyses involving final states with prompt photons. Template method is the nominal method used for the extraction of the background fractions and is further cross-checked using the 2D-sideband method as will be shown in Section 6.6.2.1. Compatibility between the purities extracted using both methods is seen within the statistical uncertainties.

The combined background originating from $Z\gamma$ and Z +jets processes contributes a smooth continuum to the $Z\gamma$ invariant mass distribution. The parameters describing this background shape are determined through a direct fit to the real data. While the specific composition of the background plays a secondary role in this process, the measured yields of $Z\gamma$ and Z +jets events are considered when constructing the combined background template used in the subsequent “spurious signal” (SS) studies [172]. For the SS studies (described in Section 6.6.3.2), only the central values of the measured yields are utilized.

6.6.2.1 Data-driven background estimation with template-fit

This subsection describes the data-driven background estimation method employing a binned template fit to the calorimeter isolation distribution. The fit is

performed simultaneously in two distinct regions:

- **Signal Region (SR):** Events satisfying all previously defined selection criteria, including the stringent “tight” photon identification requirements.
- **Control Region (CR):** Events fulfilling all selection requirements except for the tight photon identification. Instead, the CR utilizes looser identification criteria, similar to those employed in the two-dimensional sideband method (“LoosePrime’4”). This looser selection in the CR enriches the background component, particularly Z +jet events where a jet is misidentified as a photon.

The template fit aims to extract both the yield (number of events) and shape (distribution) of the signal ($Z\gamma$) and background (Z +jets) contributions within the signal region. The fit parameters include:

- $N_{\text{SR}}^{\text{Sig}}$: Yield of signal events ($Z\gamma$) in the SR.
- $N_{\text{SR}}^{\text{Bkg}}$: Yield of background events (Z +jets) in the SR.
- $N_{\text{ibin}}^{\text{Bkg}}$: Yield of background events (Z +jets) in each bin of the CR, categorized by transverse energy within a cone of radius $\Delta R = 0.2$ ($E_{\text{T}}^{\text{cone20}}$).

The analysis relies on several key assumptions:

1. The shape of the $Z\gamma$ distribution in the signal region (denoted by $Fraction_{\text{ibin}}$), along with the migration of $Z\gamma$ events between the SR and CR (represented by $Leakage_{\text{ibin}}$), is predicted by the simulated data (MC).
2. The shape of the Z +jets background distribution remains consistent across both the SR and CR.

The template fit method relies on a system of equations to relate the observed number of events in each bin of the transverse energy distribution ($E_{\text{T}}^{\text{cone20}}$). These equations are formulated for both the SR and CR:

$$N_{ibin}^{SR} = N_{SR}^{Sig} * Fraction_{ibin} + N_{SR}^{Bkg} * \frac{N_{ibin}^{Bkg}}{\sum_{ibin=1}^{Nbins} N_{ibin}^{Bkg}}, \quad (6.6.3)$$

and the in background region:

$$N_{ibin}^{CR} = N_{SR}^{Sig} * Fraction_{ibin} * Leakage_{ibin} + N_{ibin}^{Bkg}. \quad (6.6.4)$$

When the number of bins, denoted as N_{bins} , is greater than or equal to 2, a simultaneous fit can be conducted to obtain all the parameters.

Figures 6.10 and 6.11 present the results of the template fit to the calorimeter isolation distribution of photon candidates in the signal and control regions for the ee and $\mu\mu$ channels, respectively. The left panels show the signal region, and the right panels display the jet control region. The stacked histograms represent the fit results, with the lines indicating the contributions from signal (typically $Z + \gamma$ events) and background (primarily Z +jets events).

The template fit results in the high mass resonance search indicate a fraction of $Z + \gamma$ events in the signal region of 0.914 ± 0.004 and 0.908 ± 0.006 for the ee and $\mu\mu$ channels, respectively. Details on the number of signal events (N_S), background events (N_B), and total data events (N_{Data}), for both channels, can be found in Table 6.5.

Furthermore, an analysis was conducted to examine the dependence of the $Z + \gamma$ fraction on the mass range (m_X) for both the ee and $\mu\mu$ channels, as demonstrated in Figure 6.12. The mass binning used for this analysis includes the following values: 180, 190, 200, 210, 220, 230, 240, 250, 280, 300, 350, 400, 500, and 3500 GeV. Notably, the $Z\gamma$ purities remain stable across varying resonance masses. The solid red line represents the average purity observed throughout the resonance mass range, while the assigned error accounts for fluctuations in the purities, approximately 5%. This error is also propagated to the Z +jets fraction, resulting

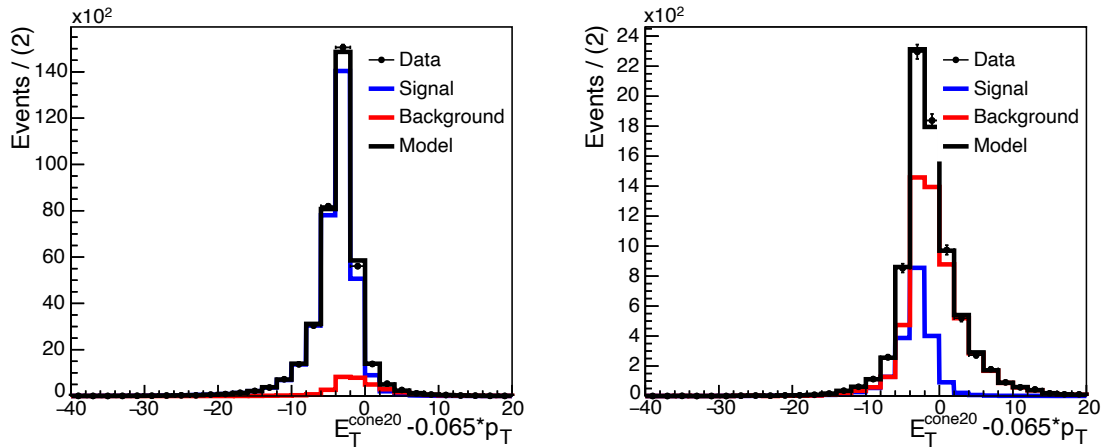


Figure 6.10: Results of the template fit to the calorimeter isolation distribution of photon candidates in the ee channel. The left panel displays the signal region, where tight photon identification criteria (Tight ID) are applied. The right panel shows the control region, which utilizes looser identification criteria (LoosePrime'4). The signal comprises $Z + \gamma$ events, while Z +jets events contribute to the background.

Table 6.5: Extracted $Z + \gamma$ purity using template fit for ee and $\mu\mu$ channels.

Category	Nominal purity	N_S	N_B	N_{Data}
ee channel	0.914 ± 0.004	34206.84 ± 233.66	3200.81 ± 146.96	37407.64 ± 193.34
$\mu\mu$ channel	0.906 ± 0.004	41394.79 ± 262.08	4297.29 ± 169.94	45692.08 ± 213.74

in a relative error of 50%.

Results of the template fit to the calorimeter isolation distribution of photon candidates in the ee channel. The left panel (a) displays the signal region (SR), where tight photon identification criteria (Tight ID) are applied. The right panel (b) shows the control region (CR), which utilizes looser identification criteria (LoosePrime'4). The stacked histograms represent the fit results, with the lines indicating the contributions from signal (typically $Z + \gamma$ events) and background (primarily Z +jets events).

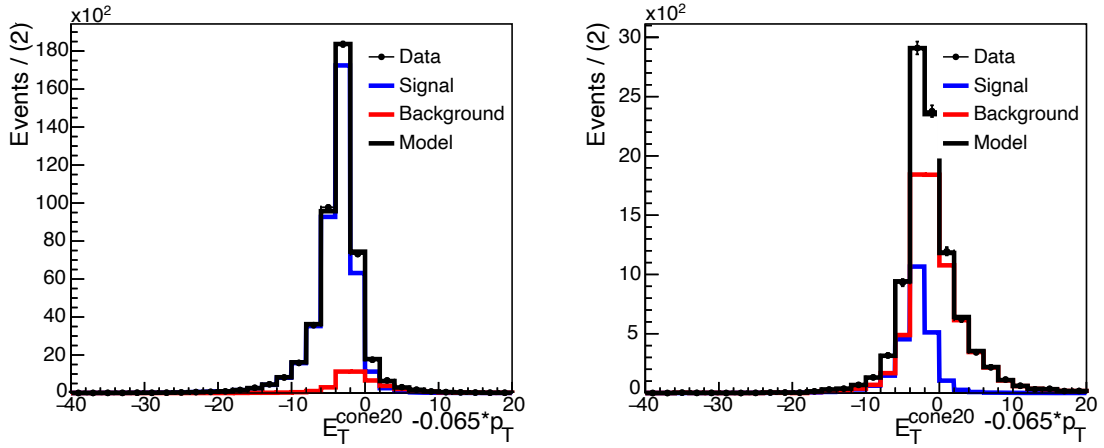


Figure 6.11: Results of the template fit to the calorimeter isolation distribution of photon candidates in the $\mu\mu$ channel. The left panel displays the signal region, where tight photon identification criteria (Tight ID) are applied. The right panel shows the control region, which utilizes looser identification criteria (LoosePrime'4). The signal comprises $Z + \gamma$ events, while Z +jets events contribute to the background.

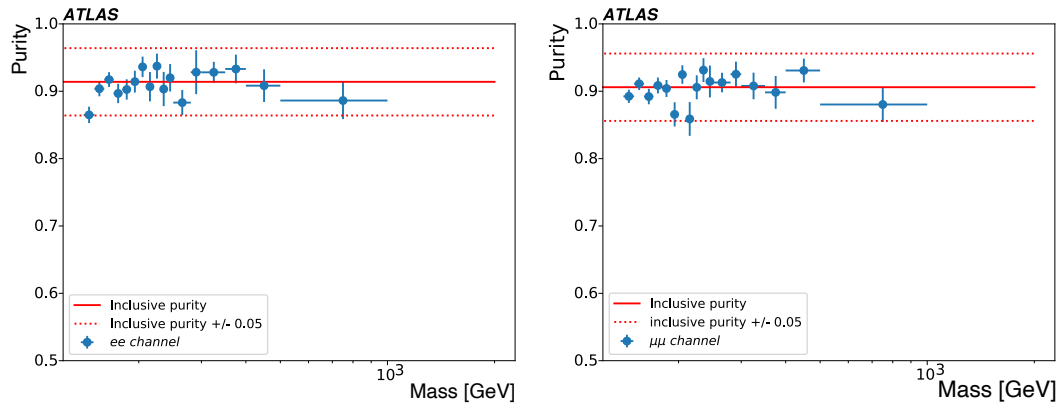


Figure 6.12: $Z + \gamma$ purities versus the resonance mass extracted using the template fit for the ee channel (left) and $\mu\mu$ channel (right). The average purity is indicated by solid red line and in dashed red line the average purity $\pm$ the absolute error is shown.

6.6.2.2 Data versus MC compatibility checks

The data versus MC compatibility distributions in both $Z(ee) + \gamma$ channel (including $ee(\gamma)$ events) and $Z(\mu\mu) + \gamma$ channel using 10 GeV bin width have been prepared as shown in Figure 6.13. Overall, good agreement is observed in the

search mass range explored.

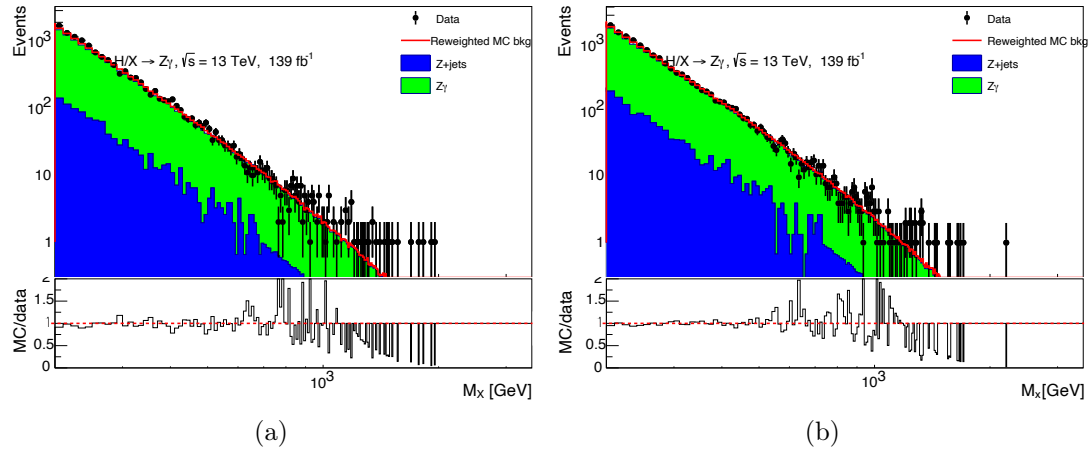


Figure 6.13: $Z\gamma$ mass distributions comparing data to MC expected background for the (a) $Z(ee) + \gamma$ channel (including both $Z(ee)$ and $Z(ee(\gamma))$ events) and (b) $Z(\mu\mu) + \gamma$ channel.

6.6.3 Background modeling

This analysis considers two primary background sources. The first is the non-resonant production of Z bosons in association with a photon, also known as the irreducible background. This process inherently mimics the signal of interest ($Z\gamma$). The second is the reducible background, which arises from inclusive Z boson production where a jet is mistakenly identified as a photon. These backgrounds are characterized by smoothly decreasing distributions and contribute similarly to the overall background profile. The total background's invariant mass distribution is characterized using an analytical function, with its parameters derived directly from data fitting. This method circumvents the need for simulation samples and minimizes systematic uncertainties linked to theoretical normalization of backgrounds and selection efficiencies. The specific functional form chosen for the background representation adheres to criteria outlined in Section 6.6.3.2, ensuring robust investigation of spurious signals.

Table 6.6: Description of Functions

Model	Functional Form
ExpPoly-N	$f_N = \exp\left(\sum_{i=1}^N a_{N-1}x^N\right)$, where $x = \frac{m_{Z\gamma}-100}{100}$
FK0	$f = x^{a_0}(1 - \sqrt[3]{x})^{a_1}$, where $x = \frac{m_{Z\gamma}}{13000}$
FK1	$f = x^{a_0+a_1 \log x}(1 - \sqrt[3]{x})^{a_2}$, where $x = \frac{m_{Z\gamma}}{13000}$
FK2	$f = x^{a_0+a_1 \log x+a_2 \log^2 x}(1 - \sqrt[3]{x})^{a_3}$, where $x = \frac{m_{Z\gamma}}{13000}$
Bern-N	$f_{\text{BernN}}(a_0, a_1, \dots, a_{N-1})$, N order Bernstein polynomial
Pow	$f = x^{a_0}$, where $x = \frac{m_{Z\gamma}}{100}$
Pow2	$f = x^{a_0} + a_1 x^{a_2}$, where $x = \frac{m_{Z\gamma}}{100}$

Table 6.7: Description of Dijet Models

Model	Functional Form
Dijet	$f = x^{a_0}(1 - x)^a$, where $x = \frac{m_{Z\gamma}}{13000}$
DijetHighMass	$f = x^{a_0}(1 - \sqrt[3]{x})^{a_1}$, assuming $a_0 < 0$, where $x = \frac{m_{Z\gamma}}{13000}$
Dijet2HighMass	$f = x^{a_0}(1 - x)^{a_1}$, assuming $a_0 < 0$, where $x = \frac{m_{Z\gamma}}{13000}$
Dijet3HighMass	$f = x^{a_0+a_1 \log x}(1 - x)^{a_2}$, where $x = \frac{m_{Z\gamma}}{13000}$

6.6.3.1 Choice of background modeling function

The background models for the high mass search are chosen from analytical functions presented in Table 6.6.

Additionally, to effectively depict the extensive range of high mass distribution, a tailored set of functions has been devised as potential candidates. These functions have been shown to perform exceptionally well in the evaluation of spurious signals:

$$f_{k;d}(x; b, \{a_k\}) = (1 - x^d)^b x^{\sum_{j=0}^k a_j \log(x)^j}, \quad (6.6.5)$$

where $x = \frac{m_{Z\gamma}}{\sqrt{s}}$, $k = (0, 1, 2)$ and the d is usually set to 1 or 1/3. In this thesis, the functions presented in Table 6.7 were used.

6.6.3.2 Spurious signal study

The term “spurious signal” refers to the bias introduced in the signal yield due to the selection of a specific background function. In order to evaluate this bias, a high-statistics background-only distribution, scaled to the data luminosity but without statistical fluctuations, is fitted using a signal plus background model [173]. The resulting fitted signal yield represents the bias resulting from the chosen background function and is termed the spurious signal (SS) in this study. The error in the fitted signal yield, denoted as δS , is used as a criterion to assess the suitability of the background function.

The background distribution is formed by merging the SM $Z\gamma$ (Sherpa_CT10) MC shape and Z +jets shape obtained from a control region in data, SM $Z\gamma$ MC sample and purities depending on $m_{ll\gamma}$ mass. The data in control region can describe the Z +jets shape in the low $m_{ll\gamma}$ mass region, but since the statistical error in the high $m_{ll\gamma}$ mass is very large, the ratio of Z +jets and $Z\gamma$ becomes very large in some certain $m_{ll\gamma}$ mass bins.

In the low $m_{ll\gamma}$ mass region the Z +jets shape is extracted from data control region events by applying selection criteria defining the signal region but inverting isolation and particle ID requirements. In the high $m_{ll\gamma}$ mass region the Z +jets shape is estimated with SM non-resonant $Z\gamma$ MC events applying selection criteria defining the signal region and purities depending on $m_{ll\gamma}$ mass bin-by-bin:

$$N_{Z+jets} = \frac{N_{Z\gamma}(1 - \text{purity})}{\text{purity}}. \quad (6.6.6)$$

The high and low mass region are defined as the output $N_{Z+jets} < 1$ and $N_{Z+jets} > 1$. Since the purities are stable as the $m_{ll\gamma}$ mass varies, the average purities estimated in Section 6.6.2.1 are used for ee channel (92%) and $\mu\mu$ channel (91%). An 0.05 absolute error is assigned on the purities to cover the differences between

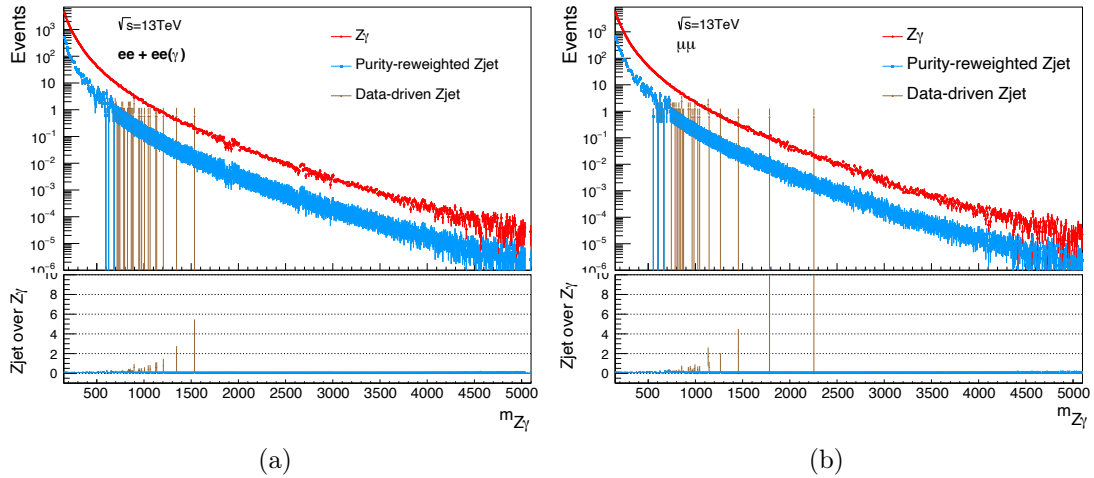


Figure 6.14: The $m_{ll\gamma}$ distributions of $Z\gamma$, $Z + \text{jets}$ and purity-reweighted $Z + \text{jets}$ events. (a) $ee\gamma$ (b) $\mu\mu\gamma$. The $Z\gamma$ and $Z + \text{jets}$ histograms in the top pad have been scaled to the luminosity of data. The bottom pad draws the ratio of $Z + \text{jets}/Z\gamma$.

results from all mass windows. The MC $Z\gamma$, data-driven $Z + \text{jets}$ and purity-reweighted $Z + \text{jets}$ mass distributions are shown in the Figure 6.14.

To mitigate the impact of statistical uncertainties arising from the limited number of events in the $Z + \text{jets}$ control region, a smoothing technique is employed. This method leverages a reweighted $Z\gamma$ distribution to represent the combined background from both $Z\gamma$ and $Z + \text{jets}$ processes. The reweighting procedure accounts for the relative contributions of each background source:

1. **Mass Binning:** The $Z\gamma$ invariant mass distribution ($m_{Z\gamma}$) is first divided into discrete bins.
2. **Signal Region Efficiency:** The yield of simulated $Z\gamma$ Monte Carlo (MC) events in each mass bin is weighted by the signal region selection efficiency. This weighted yield, denoted as $B_{Z\gamma\text{-SR}}$, reflects the expected number of signal events in the final analysis.
3. **$Z + \text{jets}$ Extraction:** The $Z + \text{jets}$ background events are extracted from data using the previously described method. The event yield for $Z + \text{jets}$ in

each mass bin of the control region is represented as $B_{Zj-\text{CR}}$.

4. **Relative Background Ratio:** The ratio, $R_{Zj/Z\gamma}$, is calculated for each mass bin by dividing the Z +jets yield ($B_{Zj-\text{CR}}$) by the weighted $Z\gamma$ yield ($B_{Z\gamma-\text{SR}}$). This ratio quantifies the relative contribution of Z +jets compared to $Z\gamma$ within a given mass bin.
5. **Exponential Fit:** An exponential function is fitted to the $R_{Zj/Z\gamma}$ ratios across the $m_{Z\gamma}$ mass bins. This functional form captures the trend of how the Z +jets background scales relative to $Z\gamma$ as a function of invariant mass.
6. **Background Estimation in Signal Region:** Finally, the estimated Z +jets background contribution in the signal region for each mass bin, denoted as $B_{Zj-\text{SR}}$, is obtained by multiplying the weighted $Z\gamma$ yield ($B_{Z\gamma-\text{SR}}$) by the corresponding $R_{Zj/Z\gamma}$ ratio from the exponential fit. This approach provides a statistically robust estimate of the Z +jets background within the signal region.

The total background yield in each mass bin is defined as $B = pB_{Z\gamma-\text{SR}} + (1 - p)B_{Zj-\text{SR}}$ scaled to the luminosity of the data, where p is purity of $Z\gamma$ component in the total background, measured in Section 6.6.2.1 as 92% for $ee\gamma$ and 91% for $\mu\mu\gamma$ channel. The comparison of $m_{Z\gamma}$ distributions from $Z\gamma$, $Z + \text{jets}$ and reweighted- $Z\gamma$ events has been presented in Figure 6.15. The distributions of $Z\gamma$ and $Z + \text{jets}$ have been rescaled to the luminosity of data after taking into account the mentioned purities.

The reweighted- $Z\gamma$ distributions is used as total background in spurious signal study. The lower and upper boundary of $m_{ll\gamma}$ histogram is 190 GeV and 3600 GeV with a granularity of 1 GeV/bin. In the spurious signal test, $m_{ll\gamma}$ serves as the scan variable, which is chosen from a mass window narrower than full mass range, then the parameters of signal function would be determined according to the value of $m_{ll\gamma}$. After that, a serial of $S + B$ fits are performed to measure the information

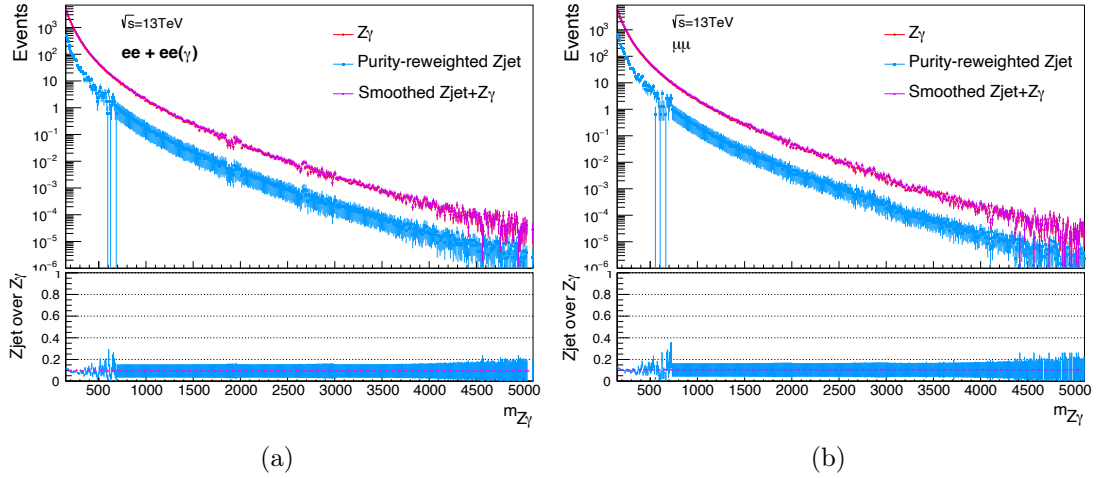


Figure 6.15: The $m_{ll\gamma}$ distributions of $Z\gamma$, $Z + \text{jets}$ and reweighted- $Z\gamma$ events. (a) $ee\gamma$ (b) $\mu\mu\gamma$. The $Z\gamma$ and Zjet histograms in the top pad have been scaled to the luminosity of data. The reweighted- $Z\gamma$ histogram denotes $(1 + R_{Zj/Z\gamma}) \cdot Z\gamma$, used to describe total background. The bottom pad shows the ratio of $Z + \text{jets}/Z\gamma$ and where the exponential function is used to fit it.

of spurious signal as function of $m_{ll\gamma}$.

The scan points are selected in the range of 220–3400 GeV with a step size of 20 GeV, which is slightly narrower than the full mass window. This ensures that the signal region of the first and last fit can be covered by the total background spectrum.

Regarding the choice of the background function, a criterion of $\frac{S}{\delta S} < 50\%$ is applied. The function with the fewest number of free parameters is preferred. The following are the selections for the background function:

- $S/\delta S < 50\%$
- minimum number of free parameters

Table 6.8 provides a list of all functions that satisfy the criterion of $S/\delta S < 50\%$. The plots in Figure 6.16 illustrate the values of $S/\delta S$ as a function of $m_{ll\gamma}$ for the ee and $\mu\mu$ channels within the mass range of 220–3400 GeV. For the final fit to

Table 6.8: The background models satisfying the criteria of spurious signal study.

Category	1.0 GeV per bin, 139 fb ⁻¹					
	Background model	Free parameters	S	max. $ \frac{S}{\delta S} $	χ^2/DoF	$P(\chi^2)$ [%]
$Z \rightarrow ee$	DijetHighMass	2	-11.5	-37.8%	18.1	0.00
	Dijet2HighMass	2	9.65	27.5%	1.52	0.00
	FK0	2	-11.5	-37.8%	17.8	0.00
	Dijet	2	9.63	23.3%	1.51	0.00
$Z \rightarrow \mu\mu$	Dijet2HighMass	2	10.0	38.3%	1.46	0.00
	Dijet	2	10.1	38.2%	1.47	0.00
	DijetHighMass	2	7.69	28.7%	5.91	0.00
	FK0	2	7.68	28.7%	5.87	0.00

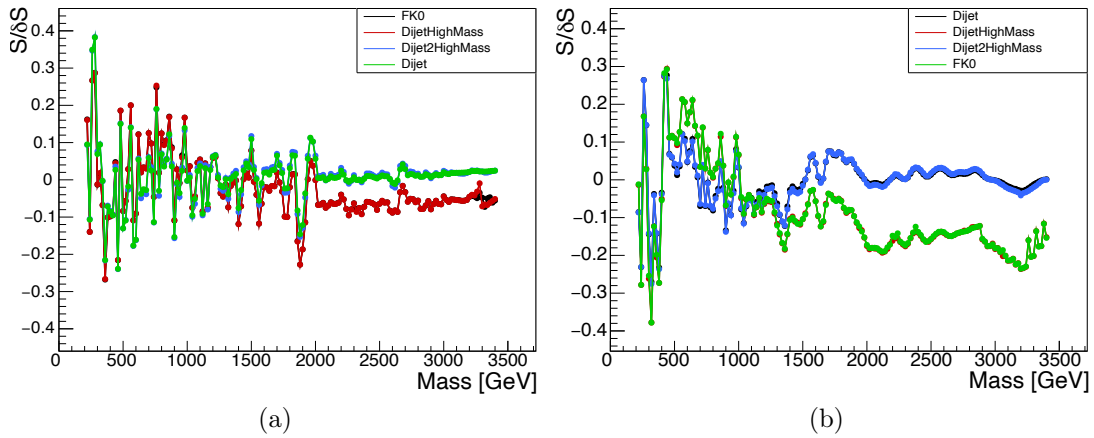


Figure 6.16: The ratio of the expected signal yield (S) to its uncertainty due to the background model (δS) as a function of the resonance mass (m_X). Separate panels are presented for the Z boson decaying to either an electron-positron pair (ee) in (a) or a muon-antimuon pair ($\mu\mu$) in (b). A higher $S/\delta S$ ratio indicates a more precise measurement of the signal strength.

data, the **Dijet** function is selected for both the ee and $\mu\mu$ channels.

6.7 Experimental systematic uncertainty

Two main categories of systematic uncertainties impact this analysis. The first concerns the background modeling. Our choice of a specific background model can introduce a bias in the estimated signal yield, known as the “spurious signal” uncertainty. The second category involves uncertainties in signal modeling, in-

cluding those related to the momentum, energy scale, and resolution of leptons and photons for both the $\mu\mu\gamma$ and $ee\gamma$ channels. A brief description of these uncertainties is provided below. Additionally, the integrated luminosity uncertainty for the combined 2015-2018 dataset is 0.83%, as reported in [174]. This measurement is based on the ATLAS primary luminometer, the LUCID-2 detector [175], supplemented by measurements from the ID and calorimeters. Understanding these uncertainties is crucial for accurately assessing the expected signal events.

Pileup re-weighting To account for the overlay of simulated pile-up on the simulated process, the level of pile-up in MC data is determined relative to the average number of interactions per bunch crossing. However, the reference distribution may not perfectly align with the measured distribution. Consequently, scale factors are applied to re-weight the simulated events, aiming to enhance the agreement between the simulated and measured distributions of pile-up.

Electrons The e/γ energy scale, resolution, and electron reconstruction (Reco), identification (Id), and isolation (Iso) efficiencies in simulated events are adjusted to better match the experimental data. Each electron undergoes energy scale and resolution corrections, while event re-weighting is employed to correct Reco/Id/Iso efficiencies.

- **Energy resolution all:** an uncertainty related to electron energy smearing in simulated events is introduced to enhance the consistency in resolution between MC data and experimental data.
- **Energy scale all (AFS):** an uncertainty related to the calibration of the electron energy scale during the simulation process pertains to a specific set of calibrations and associated uncertainties. These are applied to MC data generated using the `Atlfast-II` (AF2) parametrization, rather than GEANT4.

- **Electron efficiency (Reco, Iso, ID):** Uncertainties arise from adjusting simulated events through re-weighting to align the reconstruction, isolation, and identification efficiencies in simulation with those observed in data. The uncertainty in identification efficiency is approximately $\pm 4\%$ on the signal region yield and constitutes the primary source of systematic uncertainty.
- **Customized electron ID:** uncertainty associated with the customized electron identification employed in this high-mass analysis is assessed using the $Z \rightarrow ee$ data and MC samples via the tag-and-probe method. Events where the electrons exhibit an angular separation $\Delta R(e, e) < 0.5$ are utilized to emulate scenarios where the electrons are closely situated, as observed in the high-mass analysis. Due to this requirement $\Delta R(e, e)$, the $Z \rightarrow ee$ event yield becomes limited, necessitating the definition of an inclusive p_T bin in both the barrel ($|\eta| < 1.37$) and endcap ($1.52 < |\eta| < 2.47$) regions. The efficiencies are evaluated within an inclusive electron p_T range of 27 to 3000 GeV for electrons with $\Delta R(e, e) < 0.5$.

Muons Corrections are applied to the momentum scale, e/γ resolution, and track-to-vertex association (ttva)/reconstruction (Reco)/isolation efficiencies of muons in simulation. Each muon undergoes corrections for resolution and momentum scale [146], while corrections for ttva/reconstruction/isolation efficiency are implemented via event re-weighting.

- **Muon ID:** uncertainty linked to the charge-agnostic adjustment of MC muon p_T within the inner detector, aiming to enhance the agreement in muon identification p_T resolution between experimental data and MC data.
- **Muon scale:** Uncertainty related to the calibration of the simulated

muon momentum scale.

- **Muon efficiency Reco(ttva)(Iso) stat(sys) low- p_T** : Comparable to the efficiency uncertainties observed for electrons, however, segmented into statistical and systematic errors pertaining to the weights.
- **Muon sagitta rho**: This uncertainty pertains to adjusting muon momenta to rectify sagitta biases dependent on charge in MC data. Geometric distortions in the detectors impact the sagitta measurement and therefore affect the momentum.
- **Muon sagitta resbias**: uncertainty related to adjusting muon momenta to account for residual sagitta bias in MC data.
- **Muon MS**: uncertainty linked to the charge-agnostic adjustment of MC muon p_T within the MS, aiming to enhance the agreement in muon MS p_T resolution between experimental data and MC data.
- **Extra Smearing on muon p_T** : uncertainty introduced to address the effect of poorly measured resolution in high- p_T muons (typically above 300 GeV) that satisfy the *medium* identification criterion but not the high- p_T identification criterion [176].

Photons Photon ID/Isolation/Trigger efficiency uncertainties pertain to the uncertainties associated with accurately identifying, isolating, and triggering photons in experimental studies. These uncertainties arise from the inherent difficulties in precisely determining the properties and characteristics of photons, including their energy, position, and momentum. Accounting for these uncertainties is vital to ensure the reliability and accuracy of photon-related measurements and analyses.

To quantify the influence of the mentioned sources on the signal position (μ_{CB}) and width (σ_{CB}), the invariant mass distribution ($m_{\ell\ell\gamma}$) is recalculated by vary-

ing each uncertainty source by $\pm 1\sigma$. The value of σ corresponds to the uncertainty provided by the Muon Combined Performance Working Group (MCP) in Refs. [177, 178, 179]. A comparison is then made between the nominal fitted shape distribution of $m_{\ell\ell\gamma}$ and the fitted shape distribution obtained by varying these parameters within their simulation-based uncertainties.

The fitting procedure employs a sum of a first-order polynomial and logarithmic function, as detailed in Section 6.5 (Equation 6.5.1). The relative difference between these distributions allows for estimation of the influence of these sources on the signal shape. A comprehensive tabulation of the systematic uncertainties considered in this analysis is provided in Table C.1. The corresponding plots illustrating the impact of these uncertainties on the final results are presented in Appendix C. Among these uncertainties, the dominant contributor to the systematic uncertainty on σ_{CB} is associated with the uncertainties in e/γ momentum resolution. For the $\mu\mu\gamma$ channel, these uncertainties range from 2.5% to 10%, while for the $ee\gamma$ channel, they range from 7% to 60%.

To evaluate the systematic uncertainties in the signal efficiency, the reconstruction, identification, isolation, and trigger efficiencies for both leptons and photons are considered. The uncertainties associated with these quantities are evaluated by calculating the relative difference between the nominal signal efficiency (the efficiency obtained using the central values for the quantities) and the efficiency obtained when these quantities are varied within their one-sigma uncertainties based on simulations. The dominant contributors to the uncertainties in signal efficiency are the electron identification efficiency, which ranges from 2.8% to 4.0%, and the muon reconstruction efficiency, which ranges from 0.2% to 6.4%.

It is important to note that all the systematic uncertainties impacting the signal efficiency are estimated solely using spin-0 resonance samples, which are then applied to the spin-2 resonance results. To assess any potential bias resulting from this uncertainty assignment, the largest systematic uncertainty affecting the signal

efficiency (muon reconstruction efficiency) is determined using spin-2 resonance samples. The estimation of this systematic uncertainty demonstrates a favorable agreement between the spin-0 and spin-2 samples within the statistical uncertainty. Given that the systematic uncertainties for spin-0 resonances are greater than those for ggX spin-2 samples, adopting the spin-0 systematic uncertainties for estimating the signal efficiency across all samples is considered a conservative approach.

6.8 Statistical analysis

To detect localized excesses over a smoothly falling background in the $m_{Z\gamma}$ distribution of the data, a profile-likelihood-ratio method is utilized [180]. This method serves various objectives, such as identifying potential excesses, assessing their significance, estimating production cross sections, and determining signal strengths. The signal strength, defined as the ratio of observed event yield to the expected yield in the SM, is particularly crucial. Employing this approach, the analysis endeavors to identify and characterize significant deviations from the anticipated background in the $m_{Z\gamma}$ distribution.

6.8.1 Likelihood definition

The extended likelihood function $\mathcal{L}(\alpha, \theta)$ is expressed as the product of several terms. Firstly, a Poisson term is included to account for the observed event counts. The PDF $f_{\text{tot}}(m_{Z\gamma}^i, \alpha, \theta)$ represents the distribution of the invariant mass $m_{Z\gamma}^i$ for each candidate event i and depends on the parameters α and θ . Additionally, constraint terms $G(\theta)$ are incorporated to impose restrictions or priors on the parameters θ . Overall, the extended likelihood function encapsulates the statistical description of the data, incorporating both the observed event counts and the underlying probability distributions for the invariant mass, while considering any

relevant constraints on the parameters.

Mathematically, the extended likelihood function is expressed as:

$$\mathcal{L}\left((\alpha, \theta) \middle| \{m_{Z\gamma}^i\}_{i=1..n}\right) = \frac{e^{-N(\alpha, \theta)} N^n(\alpha, \theta)}{n!} \left(\prod_{i=1}^n f_{\text{tot}}(m_{Z\gamma}^i, \alpha, \theta) \right) \times G(\theta), \quad (6.8.1)$$

where α represents the parameter of interest, θ corresponds to the nuisance parameters, and n represents the observed number of events. The expected event yield N is the sum of the signal events N_{sig} , which is calculated as the product of the integrated luminosity L_{int} , the production cross-section σ , the branching ratio BR , and the signal efficiency ϵ . Additionally, the expected event yield includes the number of background events N_{bkg} , as well as any spurious signal events $N_{\text{spur}}\theta_{\text{spur}}$, where θ_{spur} corresponds to the nuisance parameter associated with the spurious signal. In the context of the high mass search, the parameter of interest is defined as $\alpha = \sigma(pp \rightarrow X) \times BR(X \rightarrow Z\gamma)$.

The PDF for the invariant mass, $f_{\text{tot}}(m_{Z\gamma}^i, \alpha, \theta)$, is constructed by combining the PDFs for the signal and background invariant mass distributions, represented by f_{sig} and f_{bkg} , respectively. The total PDF is given by:

$$f_{\text{tot}}(m_{Z\gamma}^i, \alpha, \theta) = \frac{1}{N} \sum_c \left\{ \left[N_{\text{sig}}^{(c)}(m_X, \alpha, \theta_{\text{sig}}) + N_{\text{spur}}^{(c)}(m_X, \theta_{\text{spur}}) \right] \times f_{\text{sig}}^{(c)}(m_{Z\gamma}^i, \theta_{\text{sig}}) + N_{\text{bkg}}^{(c)} \times f_{\text{bkg}}^{(c)}(m_{Z\gamma}^i, \theta_{\text{bkg}}) \right\}. \quad (6.8.2)$$

The category is indicated by the index c . The nuisance parameters θ_{bkg} are responsible for determining the shape of the background distribution. On the other hand, the nuisance parameters θ_{sig} are associated with uncertainties in the signal parametrization, efficiency, and acceptance. The uncertainties related to the event

yield or the resolution of $m_{Z\gamma}$ are assigned log-normal PDFs. For the nuisance parameters associated with the peak position of the $m_{Z\gamma}$ signal, Gaussian PDFs are used. Similarly, the nuisance parameters θ_{spur} related to the spurious signal are also assigned Gaussian PDFs.

6.8.2 The p -value calculation

The level of agreement between the observed data and the hypothesis where α is assumed to equal μ can be assessed statistically using the p -value. The p -value signifies the probability of obtaining a dataset, under the premise of $\alpha = \mu$, that demonstrates equal or lower compatibility with the proposed hypothesis compared to the data actually observed.

A high p -value indicates strong concordance between the observed data and the hypothesis. Following ATLAS recommendations, we employ the test statistic $q(\mu)$ to determine the p -value of the null hypothesis (where $\alpha = \mu$). This test statistic is defined as:

$$q(\mu) = -2 \ln \lambda(\mu) = -2 \ln \left(\frac{L(\mu, \hat{\theta}(\mu))}{L(\hat{\mu}, \hat{\theta})} \right), \quad (6.8.3)$$

where:

- L represents the likelihood function, a function that expresses the probability of observing the data given a set of model parameters.
- $\hat{\mu}$ and $\hat{\theta}$ denote the maximum likelihood estimates for all parameters of interest (α in this case) and nuisance parameters (parameters affecting the analysis but not directly of interest), respectively. These estimates are found by allowing their values to vary freely.
- $\hat{\theta}(\mu)$ represents the maximum likelihood estimate of the nuisance parameters under the specific hypothesis where the signal strength is assumed to be μ .

The p -value, $p(\mu)$, is calculated by integrating the probability distribution function (PDF) of the test statistic, $f(q_\mu|m_H, \mu, \hat{\theta}(\mu))$, over the tail region beyond the observed value, $q_{\mu,\text{obs}}$:

$$p(\mu) = \int_{q_{\mu,\text{obs}}}^{\infty} f(q_\mu|m_H, \mu, \hat{\theta}(\mu)), dq_\mu. \quad (6.8.4)$$

The test statistic $q(\mu)$ allows us to construct two-sided confidence intervals for the parameter of interest (μ) due to its sensitivity in both directions. A low p -value can result from the estimated signal strength ($\hat{\mu}$) being either significantly higher or lower than the hypothesized value (μ). Therefore, the set of μ values rejected based on a pre-defined p -value threshold will encompass values on both sides of those not rejected.

6.8.3 Limit setting

When analyzing models where the presence of a new signal can only increase the event rate above the expected background (e.g., searches for new heavy particles), a modified test statistic, $\tilde{q}_\mu$, is often employed. This statistic addresses the scenario where the estimated signal strength, $\hat{\mu}$, might be negative.

In such cases, the best agreement between the data and any physically valid value of the parameter of interest (μ) occurs when μ is set to zero. To account for this, we define the modified log-likelihood ratio, $\tilde{\lambda}(\mu)$, as:

$$\tilde{\lambda}(\mu) = \begin{cases} \ln \frac{L(\mu, \hat{\theta}(\mu))}{L(\hat{\mu}, \hat{\theta})} & \text{for } \hat{\mu} \geq 0 \\ \ln \frac{L(\mu, \hat{\theta}(\mu))}{L(0, \hat{\theta}(0))} & \text{for } \hat{\mu} < 0 \end{cases} \quad (6.8.5)$$

Here, $\hat{\theta}(0)$ and $\hat{\theta}(\mu)$ represent the maximum likelihood estimates of the nuisance parameters under the specific hypotheses where the signal strength is μ and 0,

respectively. This definition ensures that when the estimated signal strength is negative, the best fit is achieved by setting μ to zero.

The modified test statistic, $\tilde{q}_\mu$, is then defined to establish upper limits on the parameter of interest, specifically $\sigma(pp \rightarrow X) \times BR(X \rightarrow Z\gamma)$ in your case, for the high mass region:

$$\tilde{q}_\mu = \begin{cases} -2\ln\tilde{\lambda}(\mu) & \hat{\mu} \leq \mu \\ 0 & \hat{\mu} > \mu \end{cases} = \begin{cases} -2\ln\frac{L(\mu, \hat{\theta}(\mu))}{L(0, \hat{\theta}(0))} & \hat{\mu} < 0 \\ -2\ln\frac{L(\mu, \hat{\theta}(\mu))}{L(\hat{\mu}, \hat{\theta})} & 0 \leq \hat{\mu} \leq \mu \\ 0 & \hat{\mu} > \mu \end{cases} \quad (6.8.6)$$

The rationale behind setting $\tilde{q}_\mu = 0$ for data with an estimated signal strength exceeding the hypothesized value ($\mu > \hat{\mu}$) is that such data points are not considered less compatible with the given μ compared to the observed data. As a result, they are excluded from the rejection region of the test statistic. Higher values of $\tilde{q}_\mu$ indicate a stronger level of incompatibility between the data and the hypothesized value of μ .

It is important to note that while the asymptotic approach described above is commonly used, for establishing limits in the high mass region (typically exceeding 2.5 TeV in your case), employing MC toys is crucial. This method provides a more accurate determination of the upper limit in this specific regime.

6.9 Results

The Figures 6.17 and 6.18 depict the $m_{Z\gamma}$ of data events that satisfy the high mass selection criteria, for the $ee\gamma$ and $\mu\mu\gamma$ channels. The data exhibits the highest mass events of 2.0 TeV in the $ee\gamma$ channel and 2.2 TeV in the $\mu\mu\gamma$ channel. An unbinned fit of the data to the background model is represented by the dashed

blue line. Notably, no significant excess is observed beyond the background-only hypothesis. However, two notable deviations are evident: in Figure 6.17, a deviation at 250 GeV is observed with a local significance of 2.1 standard deviations (σ), which is in the area of interest. Additionally, the most substantial deviation is observed at 420 GeV with a local significance of 2.3σ (see Figure 6.18). These figures demonstrate an example of a 250 GeV and 420 GeV signals (indicated by the dashed dark cyan line) and present the outcomes of a fit of the data to a hypothesis involving both signal and background (illustrated by the solid red line).

The computation of the p -value is elaborated in Section 6.8.2, which examines the agreement between the data and the background-only hypothesis. Figure 6.19 displays the local p -value as a function of $m_{Z\gamma}$ for the $\mu\mu\gamma$, $ee\gamma$, and $\mu\mu\gamma + ee\gamma$ channels.

This analysis establishes 95% confidence level (CL) upper limits on the product of the production cross section times branching ratio (BR) for a narrow scalar boson, X , decaying to a Z boson and a photon ($Z\gamma$), denoted as $\sigma(pp \rightarrow X)BR(X \rightarrow Z\gamma)$. Expected limits are presented in Section 6.9.1, while observed limits are shown in Section 6.9.2.

6.9.1 Expected only limits

This section establishes expected upper limits at a 95% CL on the production cross section times branching ratio for a hypothetical narrow scalar boson, denoted as X , decaying to a Z boson and a photon. The targeted mass range for the X boson is from 200 GeV to 3500 GeV.

We consider two scenarios: a spin-0 resonance produced via gluon-gluon fusion (ggF) and spin-2 resonances produced via both ggF and quark-antiquark annihilation ($q\bar{q}X$). The expected limits for the spin-0 resonance, incorporating contri-

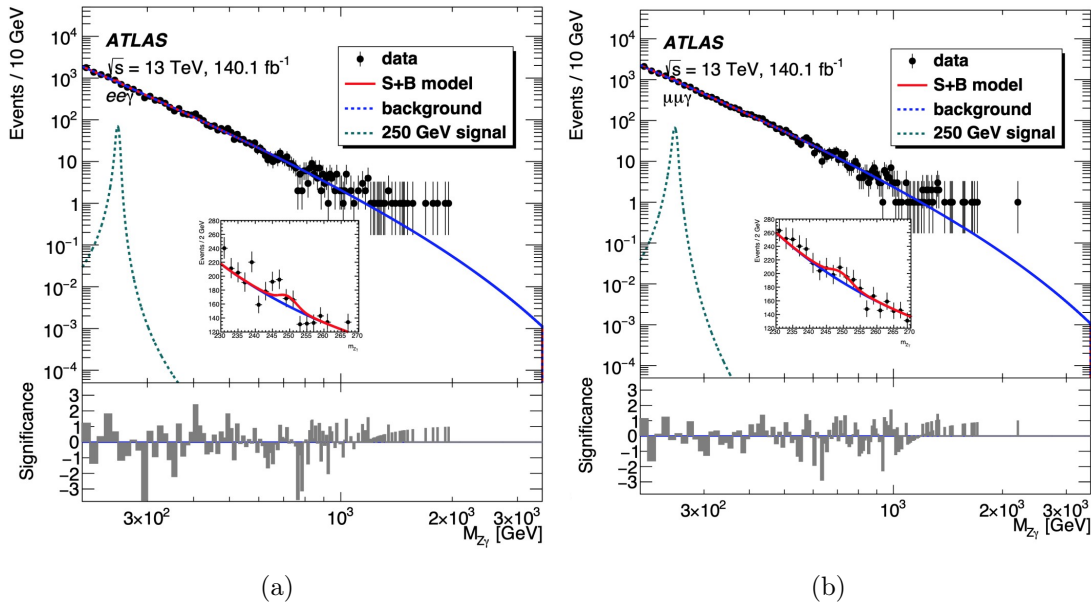


Figure 6.17: A graphical representation of the invariant mass distributions of the $Z\gamma$ system for events passing the high-mass selection criteria in data. Separate distributions are shown for the two decay channels: (a) $ee\gamma$ and (b) $\mu\mu\gamma$. Data points with error bars represent the measured invariant mass spectrum and its associated statistical uncertainties. The overlaid curves illustrate the results of unbinned maximum likelihood fits performed independently in each channel. The solid red line indicates the total fit, which is a combination of a background component (dashed blue line) and a hypothetical signal component (dashed dark cyan line). The bottom panel displays the significance, defined as the difference between the observed data and the background-only fit divided by the data's statistical uncertainty. An inset highlights the lower mass region of the distribution, revealing a potential excess around 250 GeV with a significance of 2.1σ [170].

butions from both electron and muon decay channels of the Z boson (including reconstructed $e + e(\gamma)$ events as shown in Figure 6.20), range from 34.22 fb to 0.42 fb for a boson mass from 200 GeV to 3500 GeV. The expected limits for individual electron and muon channels, along with all systematic uncertainties, are also presented for comparison. Figure 6.21 illustrates how including reconstructed $e + e(\gamma)$ events improves the expected limits, particularly in the high-mass region (up to 9.5% improvement).

Furthermore, the results are extrapolated to set expected limits for spin-2 res-

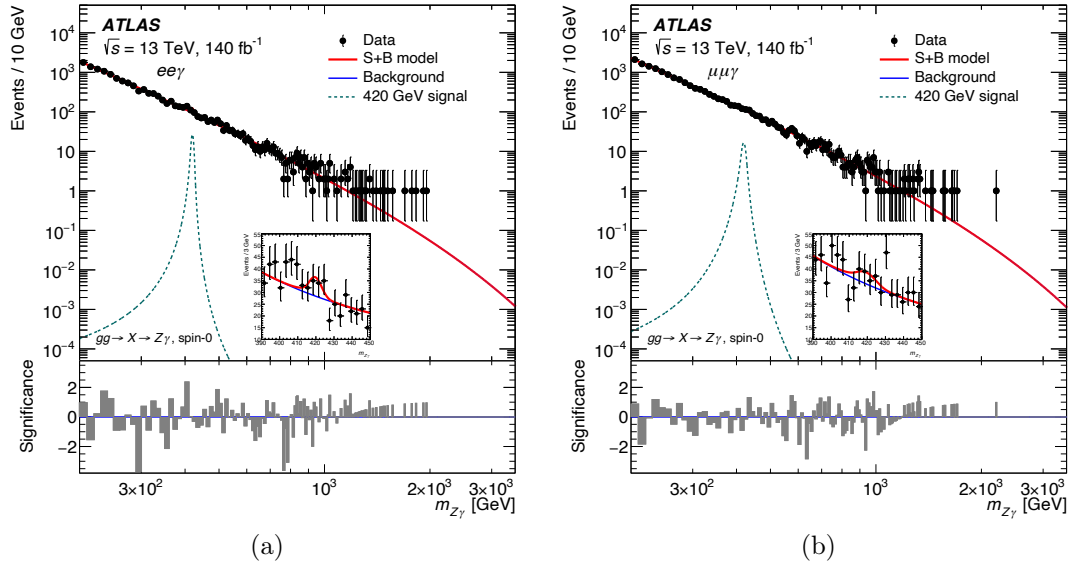


Figure 6.18: A graphical representation of the invariant mass distributions of the $Z\gamma$ system for events passing the high-mass selection criteria in data. Separate distributions are shown for the two decay channels: (a) $ee\gamma$ and (b) $\mu\mu\gamma$. Data points with error bars represent the measured invariant mass spectrum and its associated statistical uncertainties. The overlaid curves illustrate the results of unbinned maximum likelihood fits performed independently in each channel. The solid red line indicates the total fit, which is a combination of a background component (dashed blue line) and a hypothetical signal component (dashed dark cyan line). The bottom panel displays the significance, defined as the difference between the observed data and the background-only fit divided by the data's statistical uncertainty. An inset highlights the lower mass region of the distribution, revealing a potential excess around 420 GeV with a significance of 2.3σ [170].

onances in the same mass range. Figure 6.22 presents the limits, ranging from 40.4 fb to 0.38 fb for $q\bar{q}X$ spin-2 and 41.0 fb to 0.48 fb for ggF spin-2 resonances, respectively.

Table C.2 presents the influence of various systematic uncertainty sources on the anticipated limits. It is evident that the spurious signal contributes the most significant relative impact on the expected limits, while the overall systematic uncertainties range from 0.12% to 14.5% in relative impact.

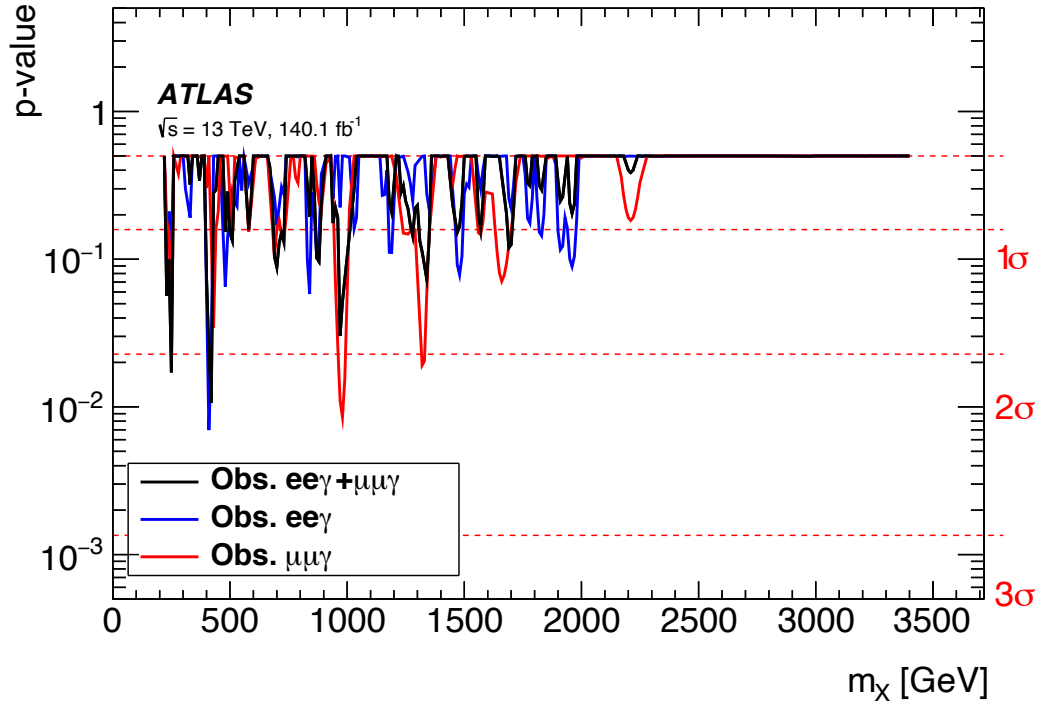


Figure 6.19: Observed local p -value versus the distribution of the invariant mass $m_{Z\gamma}$ in the search for a high mass $X \rightarrow Z\gamma$ resonance, using Z bosons reconstructed in decays to electrons and muons.

6.9.2 Observed limits

This section presents the observed upper limits at a 95% CL for the production cross section times branching ratio ($\sigma(pp \rightarrow X) \times BR(X \rightarrow Z\gamma)$) of a narrow scalar boson (X) decaying to a Z boson and a photon. The mass range explored extends from 220 GeV to 3400 GeV.

The observed limits are determined for both spin-0 and spin-2 resonances produced via gluon-gluon fusion (ggF) and quark-antiquark annihilation ($q\bar{q}X$) processes. Figures 6.23 and 6.24 display the observed limits for these scenarios, respectively. The observed limits are presented alongside the expected limits (previously discussed in Section 6.9.1) for comparison.

The observed limits generally follow the trend of the expected limits, with some

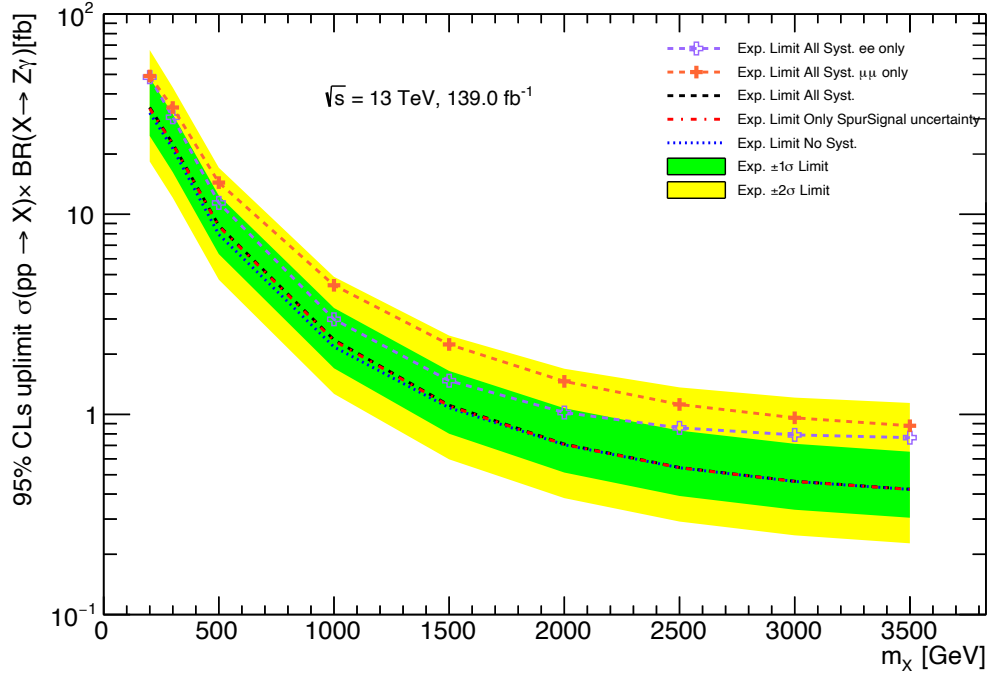


Figure 6.20: Expected upper limits at 95% CL in the mass range between 200 GeV and 3500 GeV for ggF spin-0 resonance for individual ee and $\mu\mu$ channels (with all systematic uncertainties included) and $ee + \mu\mu$ channels for no systematic uncertainties, spurious signal uncertainty only and all systematic uncertainties included.

deviations due to statistical fluctuations. The specific values for both observed and expected limits are provided within the figures for each resonance type across the explored mass range (220 GeV to 3400 GeV). The observed limits (expected limits) range between 65.5 fb to 0.6 fb (43.3 fb to 0.6 fb) for the ggH spin-0 resonance, 71.6 fb to 0.5 fb (50.3 fb to 0.5 fb) for $q\bar{q}X$ spin-2 resonance and 77.4 fb to 0.6 fb (50.8 fb to 0.6 fb) for ggF spin-2 resonance in the mass range m_X from 220 to 3400 GeV.

The observed (expected) limits for spin-0 and spin-2 resonances from $m_X = 1.9$ TeV to 3.4 TeV obtained from the asymptotic formulae are underestimated by 5% to 32% (7% to 25%) compared to those from ensemble tests.

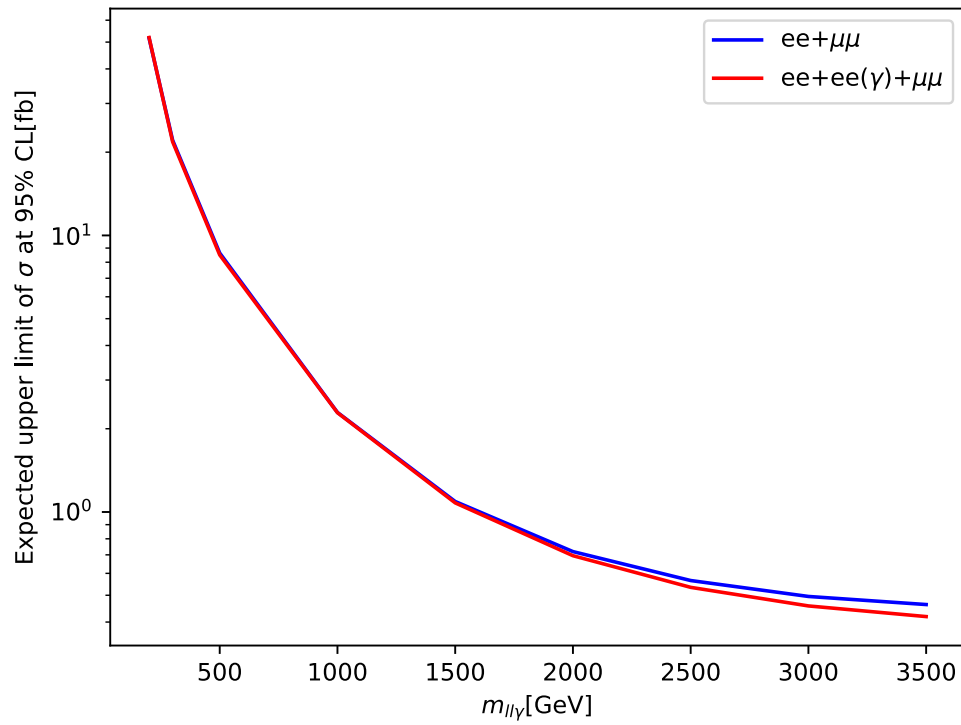
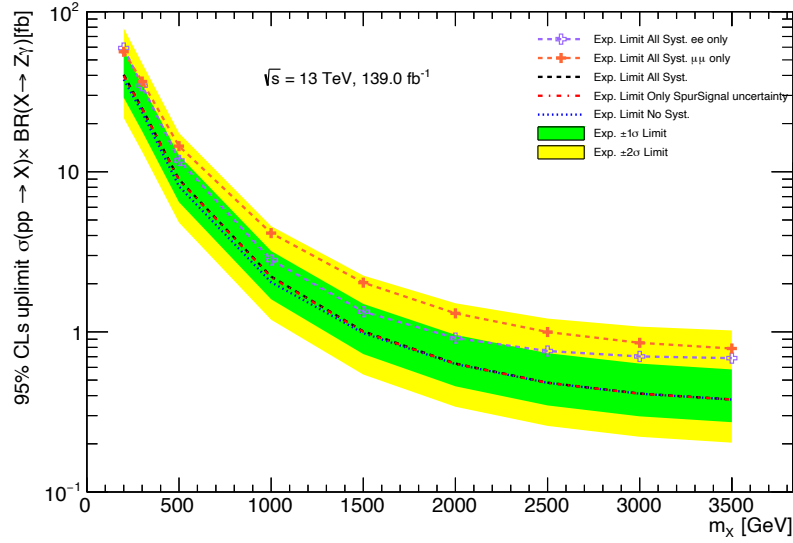
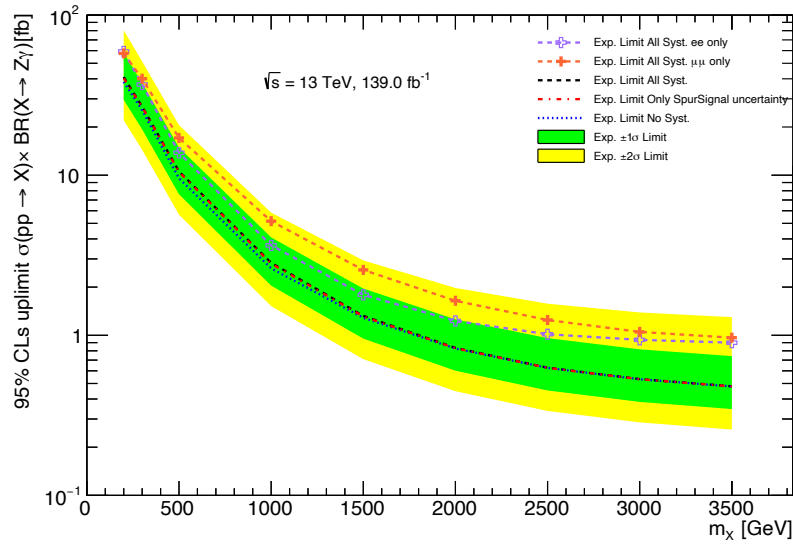


Figure 6.21: Comparison between the expected upper limits at a 95% CL of high mass resonance production cross sections as a function of $m_{ll\gamma}$ for $ee + \mu\mu$ channels (blue line) and $ee + \mu\mu$, including the $e + e(\gamma)$ events (red line).



(a)



(b)

Figure 6.22: A graphical representation of the expected upper limits at a 95% CL on the product of the production cross section times branching ratio (BR) for a spin-2 resonance, X , decaying to a Z boson and a photon ($Z\gamma$). The limits are shown for two production processes: (a) quark-antiquark annihilation ($q\bar{q}$) and (b) gluon-gluon fusion (ggF). The mass range for the expected limits spans from 200 GeV to 3500 GeV.

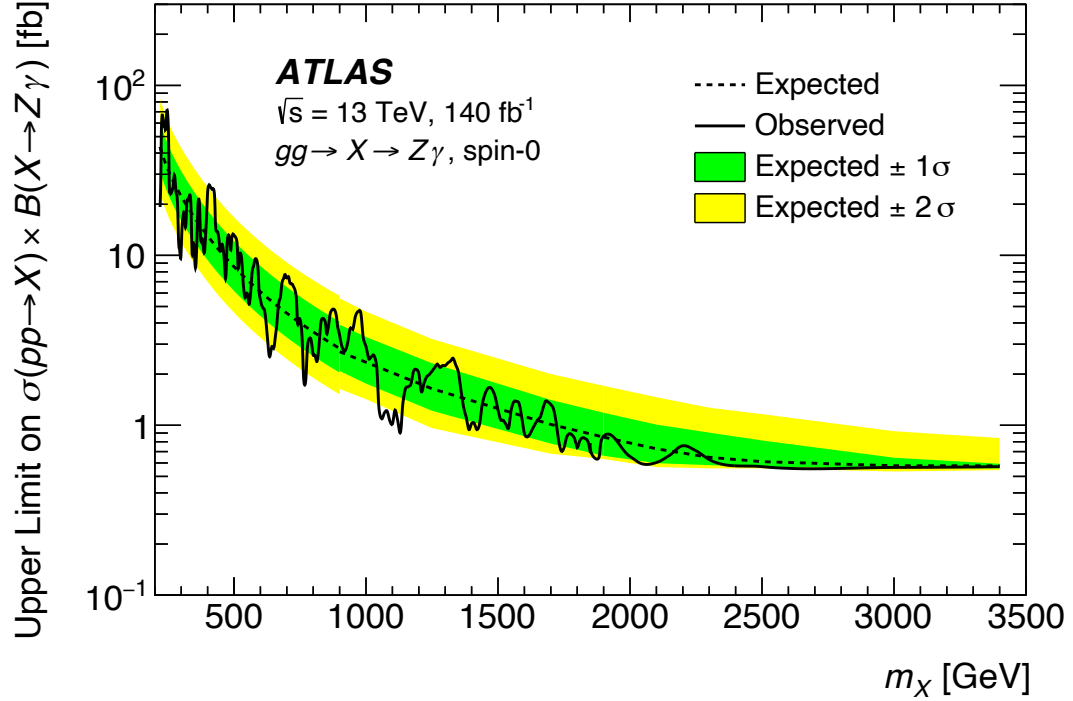
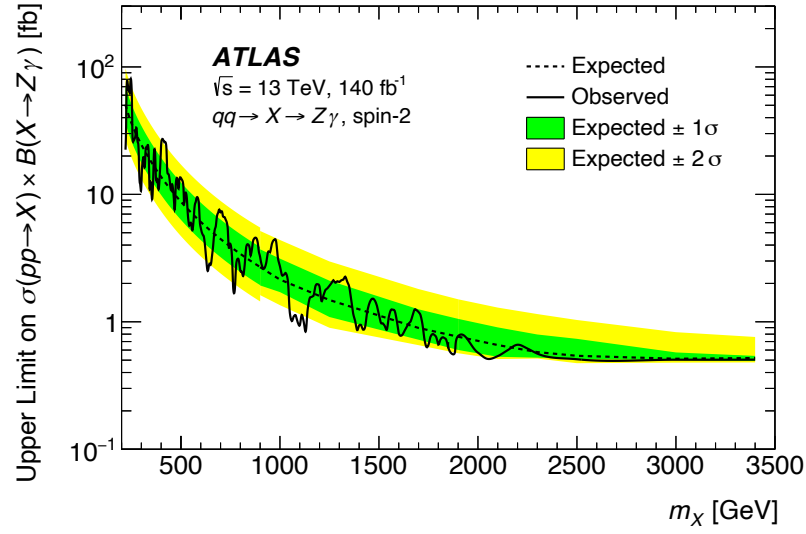
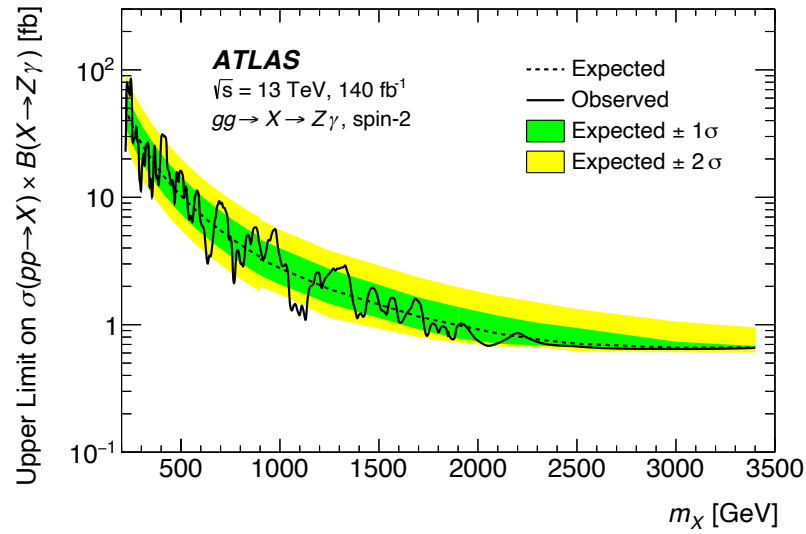


Figure 6.23: A graphical representation of the 95% CL upper limits on the product of the production cross section times branching ratio (BR) of a narrow-width spin-0 resonance, X , decaying to a Z boson and a photon ($Z\gamma$). Observed limits (solid line) and expected limits (dashed line) are shown for X production via gluon-gluon fusion (ggF). Ensemble tests were employed to derive limits for resonance masses exceeding 1.9 TeV. The green and yellow bands represent the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties for the expected limits, respectively. These limits are set within a mass range of 220 GeV to 3400 GeV for the combined electron-positron and muon-antimuon decay channels ($ee\gamma$ and $\mu\mu\gamma$) [170].



(a)



(b)

Figure 6.24: A graphical representation of the 95% CL upper limits on the production cross section times branching ratio (BR) of a narrow-width spin-2 resonance, X , decaying to a Z boson and a photon ($Z\gamma$). Solid lines represent observed limits, while dashed lines depict expected limits. These limits are presented for X production via two initial states: (a) quark-antiquark annihilation ($q\bar{q}$) and (b) gluon-gluon fusion (ggF). Ensemble tests were used to determine limits for resonance masses exceeding 1.9 TeV. The green and yellow bands around the expected limits represent the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainty bands, respectively. These limits are set for resonance masses ranging from 220 GeV to 3400 GeV and are obtained by combining data from the electron-positron ($ee\gamma$) and muon-antimuon ($\mu\mu\gamma$) decay channels [170].

Conclusions

This thesis presents a comprehensive and rigorous search for high-mass resonances decaying into the $Z(\rightarrow ee \text{ or } \mu\mu)\gamma$ final state, with a focus on spin-0 and spin-2 particles. By analyzing a substantial dataset of 140 fb^{-1} of proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$, recorded by the ATLAS detector at the LHC, the invariant mass distribution of the $\ell\ell\gamma$ system was thoroughly investigated. The comparison with the expected smoothly falling background, predicted by the standard model, revealed a remarkable agreement, indicating no significant excess in the search range of 220-3400 GeV. A small excess is observed at 250 GeV within the area of interest, with a combined significance of 2.1 standard deviations for spin-0 heavy resonances in the $ee\gamma$ and $\mu\mu\gamma$ channels.

To assess the production of these resonances, upper limits at a 95% confidence level (CL) were derived for the production cross section of $pp \rightarrow X$ multiplied by the branching fraction for the decay $X \rightarrow Z\gamma$. The observed limits demonstrated the absence of substantial signals, with values ranging from 65.5 fb to 0.6 fb for the spin-0 resonance produced via gluon-gluon fusion, from 76.1 fb to 0.5 fb for the spin-2 resonance produced via quark-antiquark initial state, and from 77.4 fb to 0.6 fb for the spin-2 resonance produced via gluon-gluon fusion, all within the mass range m_X from 220 to 3400 GeV. Furthermore, the expected limits were obtained, yielding valuable insights into the anticipated bounds for different resonance sce-

narios. The expected limits varied from 43.3 fb to 0.6 fb for the spin-0 resonance produced via gluon-gluon initial state, while for spin-2 resonances generated via quark-antiquark and gluon-gluon fusion initial states, the expected limits ranged from 50.3 fb to 0.5 fb and from 50.8 fb to 0.6 fb, respectively.

Notably, this research was complemented by various improvements to the analysis methodology. The utilization of the full Run 2 dataset collected during 2015 and 2018 provided a wealth of valuable data. Additionally, a dedicated electron identification algorithm was developed, resulting in an extended search mass range of up to 3400 GeV. Furthermore, enhancements were made to the reconstruction of electron (e) and photon (γ) object candidates, bolstering the accuracy and reliability of the analysis.

Furthermore, the successful completion of the Tile Calorimeter Phase-I upgrade signifies a major advancement in the ongoing development of the ATLAS detector at CERN. This upgrade, initiated during the LHC long shutdown 2 (LS2), involved the complete replacement and refurbishment of the E3E4 and MBTS counters in the TileCal. These counters had experienced degradation due to high radiation levels during LHC Run 2 and required replacement with more radiation-hard and high-performing scintillators prior to Run 3. Extensive improvements were implemented in both the E3E4 and MBTS counters, building upon the lessons learned from LHC Run 1 and Run 2, to enhance their light yield and overall performance efficiency.

The assembly process involved the construction of 133 crack counters, 8 prototypes, and 16 Minimum Bias Trigger Scintillator (MBTS) counters for both the A and C sides of the ATLAS detector. Prior to their installation on the ATLAS detector, rigorous evaluations were conducted to assess the light tightness and quality of these counters. Radioactive sources such as ^{90}Sr and ^{137}Cs were utilized in the laboratory in building 175 at CERN to perform these evaluations. This ensured that the counters met the required standards and would operate

effectively in the challenging environment of the ATLAS detector. The installation of 128 crack counters, including 4 prototypes, and 16 MBTS counters was successfully carried out during the period from August to November 2019. This installation phase involved meticulous planning and coordination to ensure the seamless integration of the upgraded counters into the ATLAS detector.

The completion of the Tile Calorimeter Phase-I upgrade represents a significant achievement for the ATLAS collaboration. The new Crack and MBTS scintillator detector modules not only address the radiation-induced degradation but also enhance the overall performance and reliability of the Tile Calorimeter. This upgrade sets the stage for future data-taking periods, including Run 3, enabling the ATLAS experiment to continue its exploration of fundamental particles and phenomena at the forefront of HEP. The successful implementation of this upgrade highlights the dedication and expertise of the researchers, engineers, and technicians involved in this project, ensuring the continued success of the ATLAS detector in its pursuit of scientific discovery.

Overall, this PhD thesis has made a significant and valuable contribution to the field of HEP, specifically in the investigation of high-mass resonances decaying into the $Z\gamma$ final state. The observation of a small excess at 250 GeV warrants further investigation with more data. Moreover, the successful completion of the Tile Calorimeter Phase-I upgrade, along with the obtained results and implemented enhancements, has not only provided important insights but also established a solid foundation for future research in this domain. These accomplishments have played a pivotal role in advancing our understanding of fundamental particles and interactions at the electroweak scale, pushing the boundaries of knowledge in the field.

TileCal Phase-I upgrade

Photographs of the inner MBTS (green plate) and outer MBTS (blue plate) with grooves.

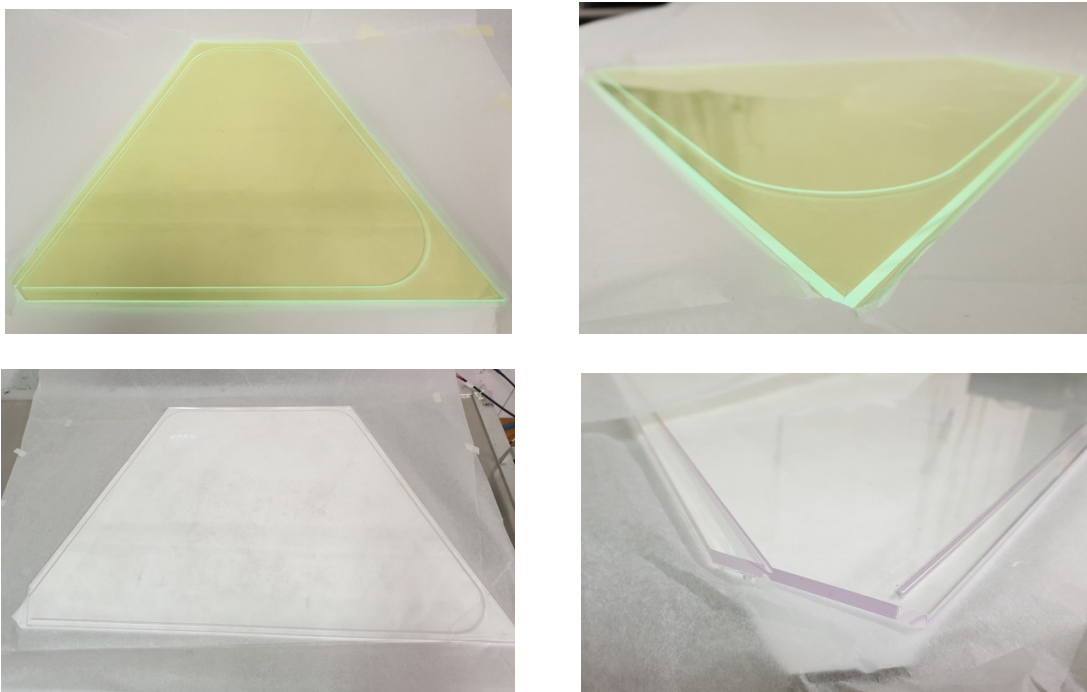
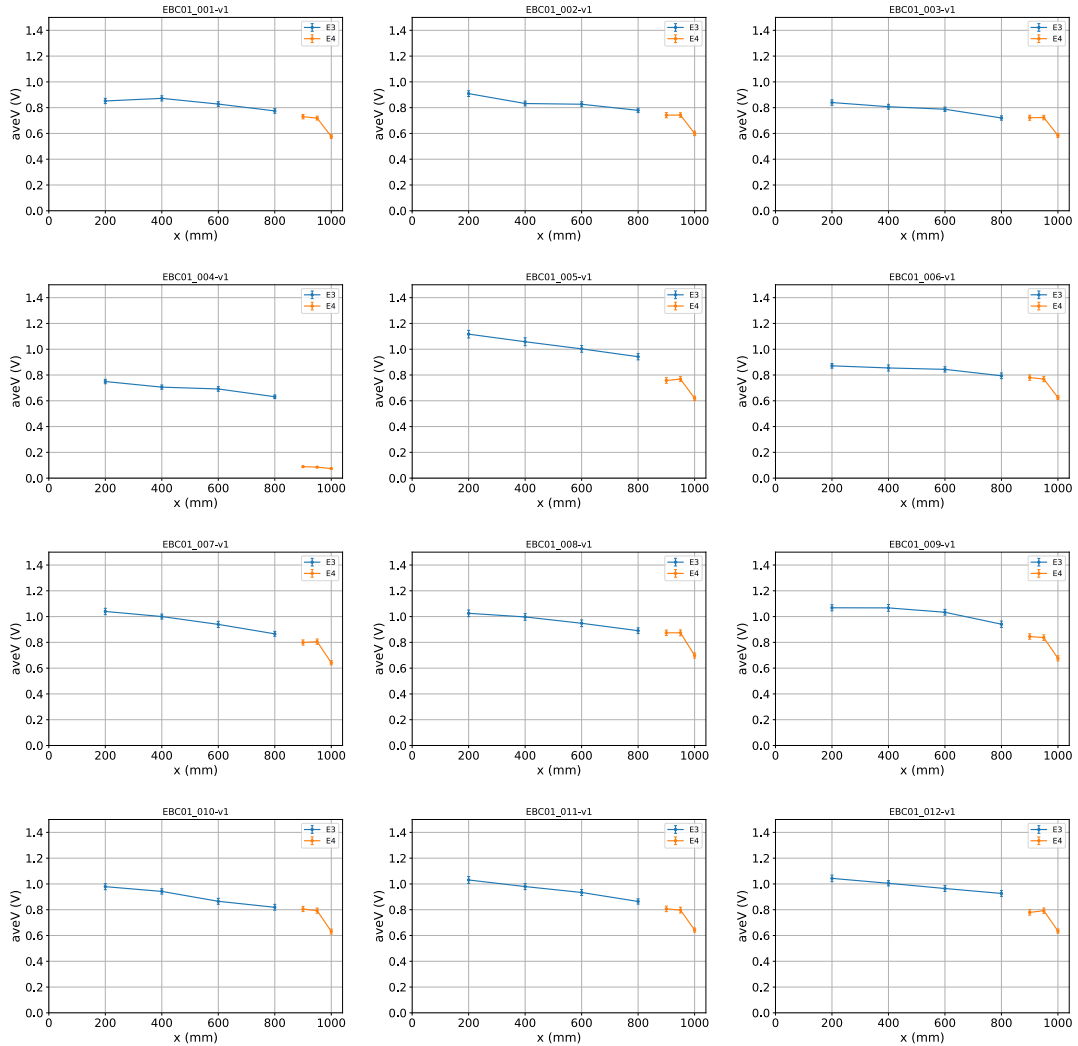


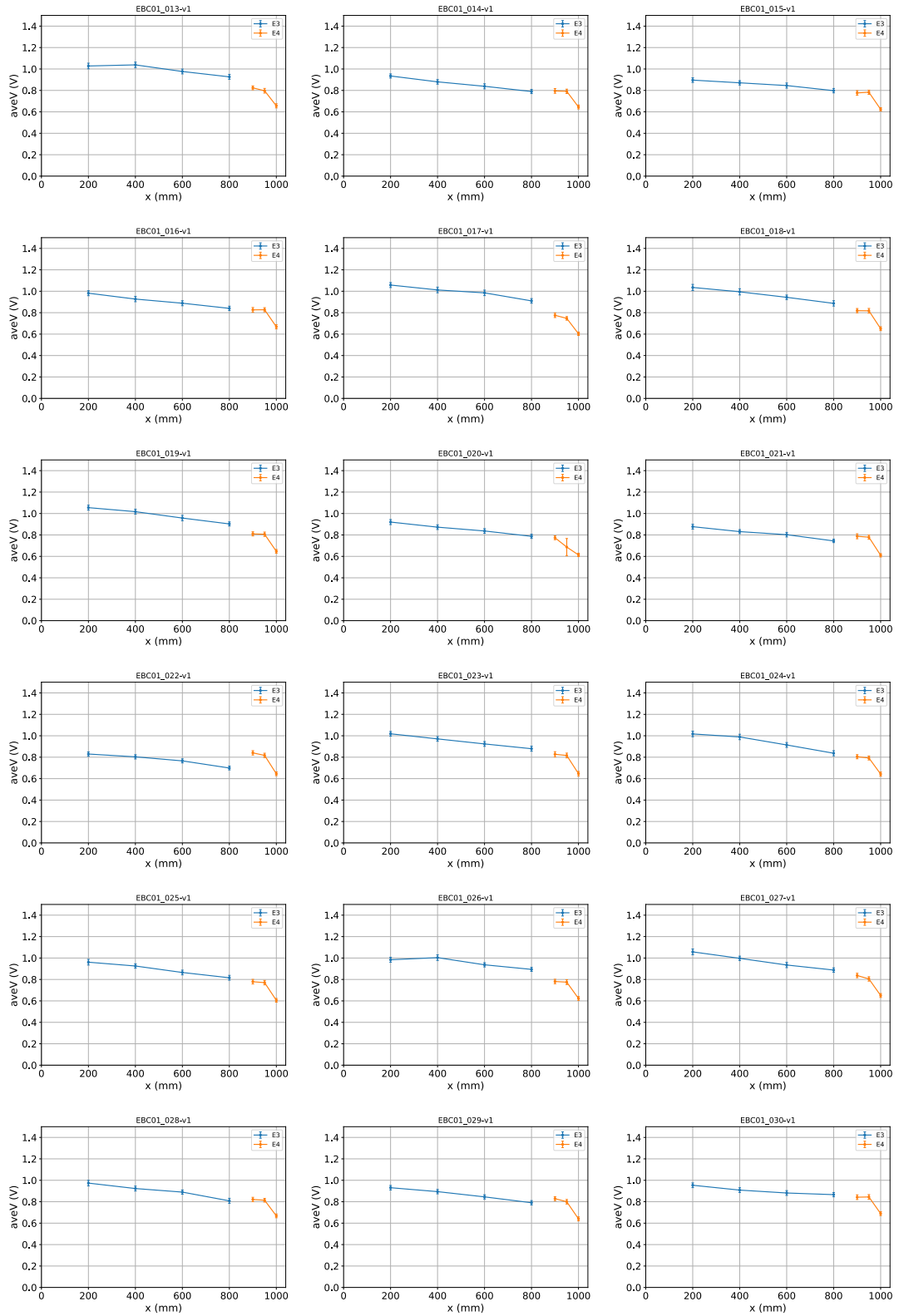
Figure A.1: Inner MBTS plates (top row) and outer MBTS plates (bottom row).

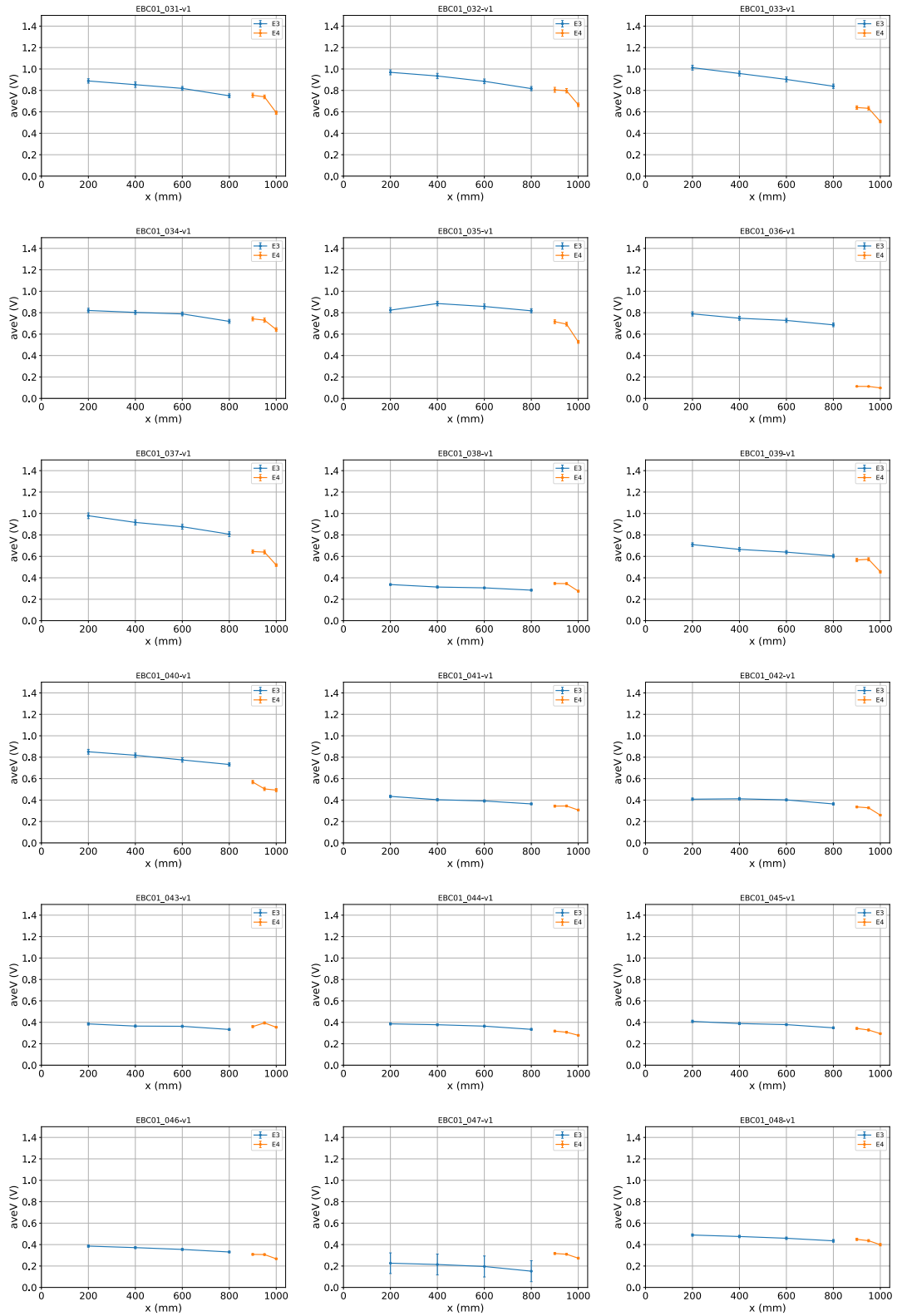
A.1 Response of Crack counters to ^{90}Sr source

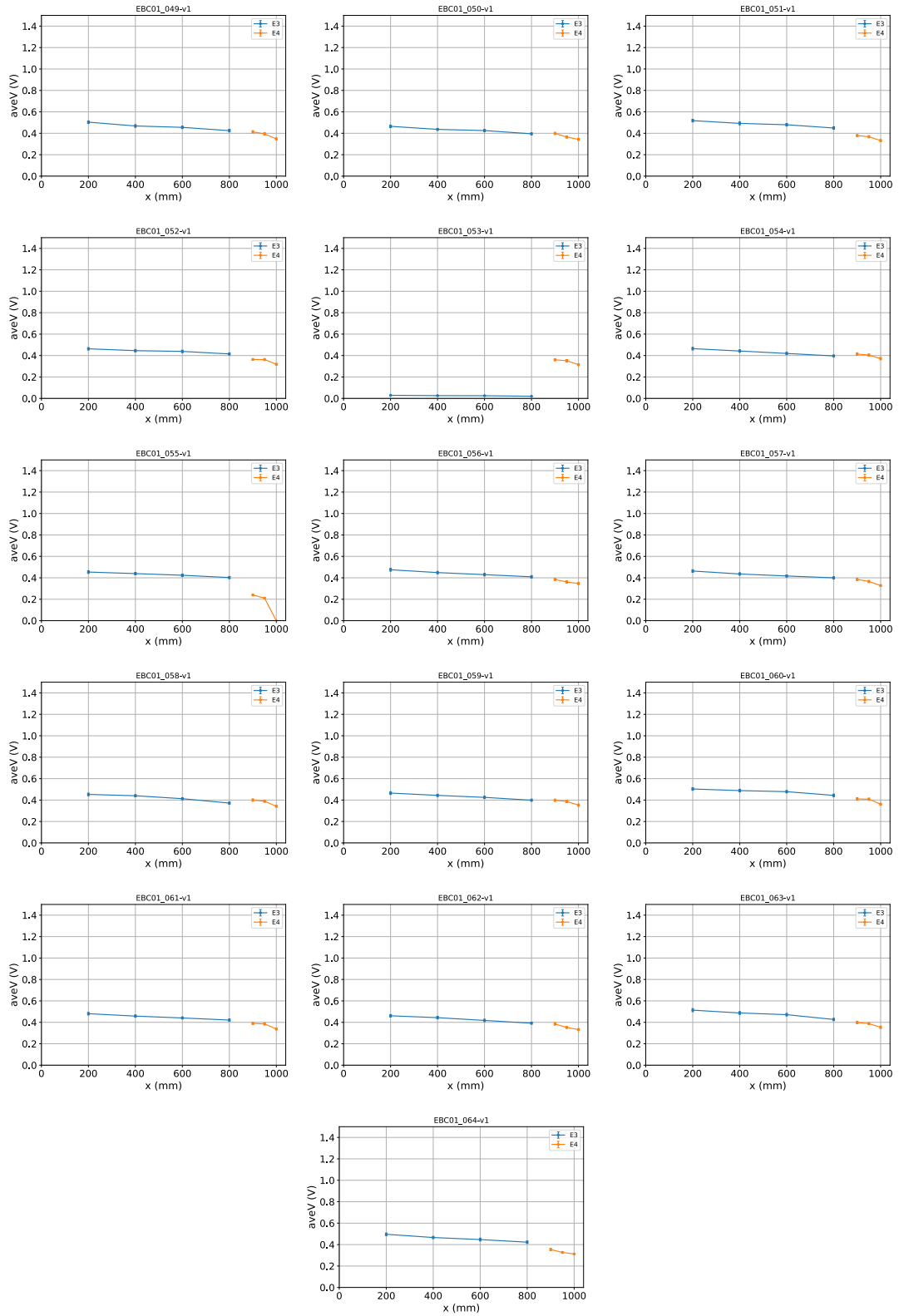
The plots in Appendix A.1.1 provide a thorough view of how Crack counters respond to the ^{90}Sr source, as discussed in Section 4.4.1.1. They depict the counters' voltage response, offering key insights into their performance. Results show that all tested counters fall within an acceptable voltage range, confirming their readiness for integration into the ATLAS detector.

A.1.1 Regular scans (EBC counters)









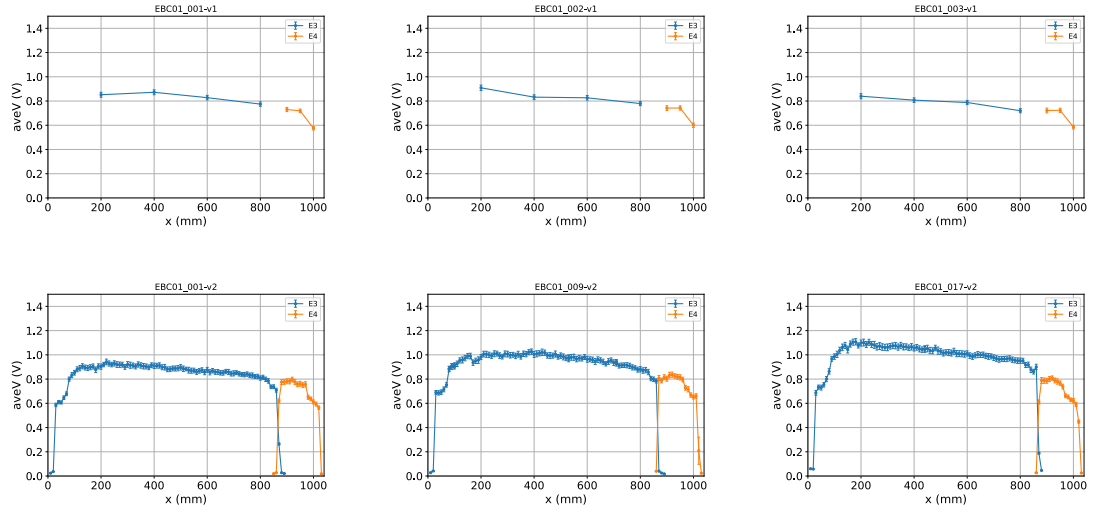


Figure A.2: PMT voltage response Vs. position of the source for EBC. Top row: regular scans and bottom row: fine scans.

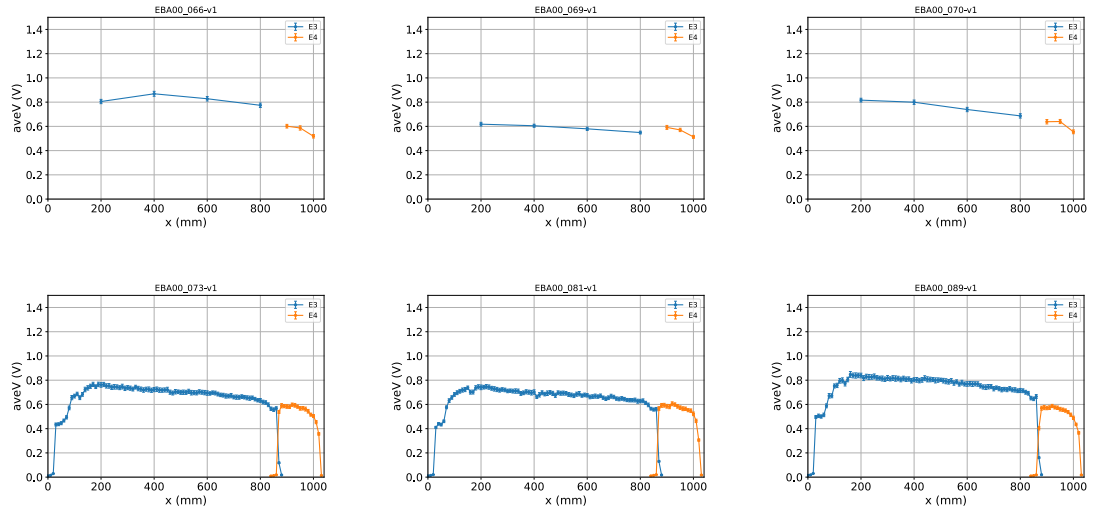


Figure A.3: PMT voltage response Vs. position of the source for EBA. Top row: regular scans and bottom row: fine scans.

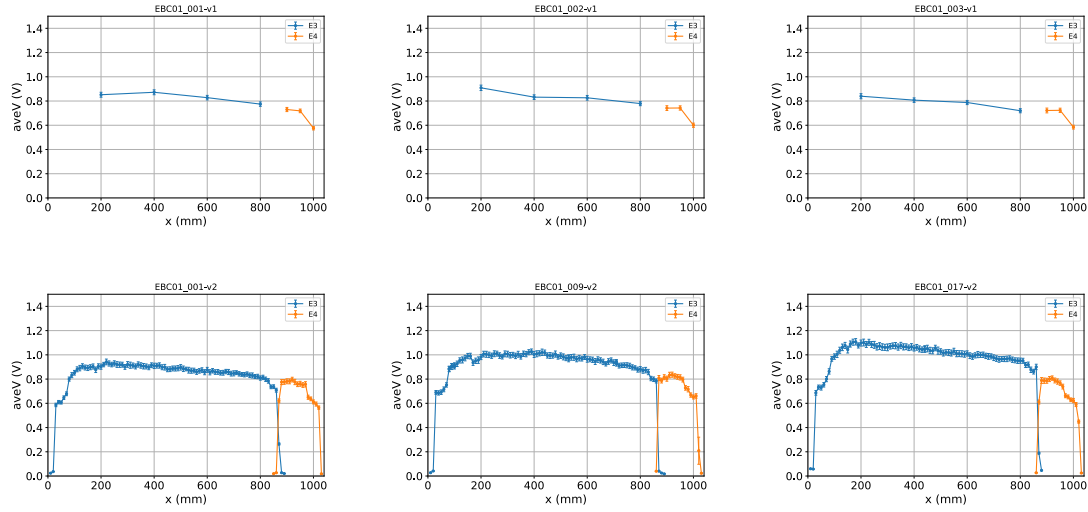


Figure A.4: PMT voltage response Vs. position of the source for EBC. Top row: regular scans and bottom row: fine scans.

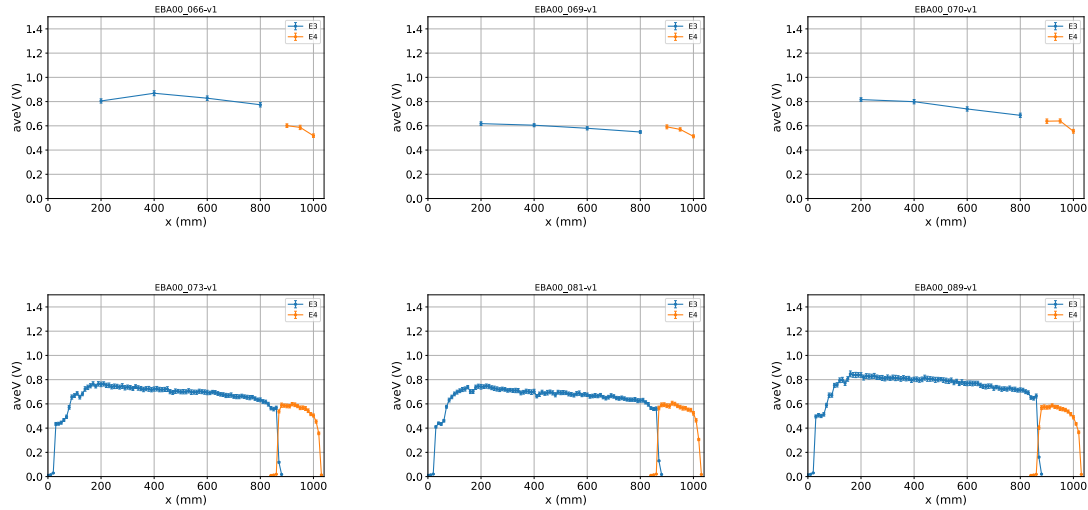


Figure A.5: PMT voltage response Vs. position of the source for EBA. Top row: regular scans and bottom row: fine scans.

During the measurements, a significant voltage response drop in the EBC counters was observed (from counter 37 to 64). The low signal output was a result of physically damaged optical fibre cable which transmits light from the counter to photomultiplier tube inside the scan box. Some of the plots are shown in

Figure A.6. Since the signal output was still consistent, it was agreed that the measurements continue. However, a new fibre cable was prepared for the new batch of EBA counters.

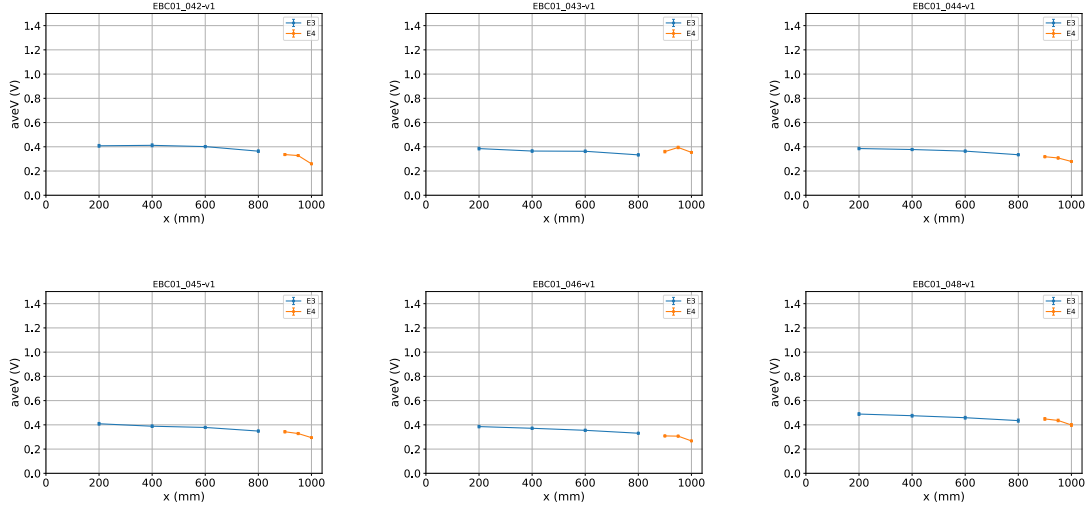


Figure A.6: PMT voltage response Vs. the position of the source. The readings are lower but they are still reliable for assuring the quality.

Figure A.7 shows three strange plots from the measured EBC counters. In Figure A.7a, E3 of counter 47 shows a low voltage response and large error bars, this was attributed to a problem with the experimental setup such as fibre connection defect causing light leaks. A near zero voltage response was observed in E3 of counter 53 (EBC053), see Figure A.7b. The scan was probably performed with the closed source on the counter by mistake. The low output values of E4 for EBC055 in Figure A.7c was also accounted for by the defective optical fibre connector.

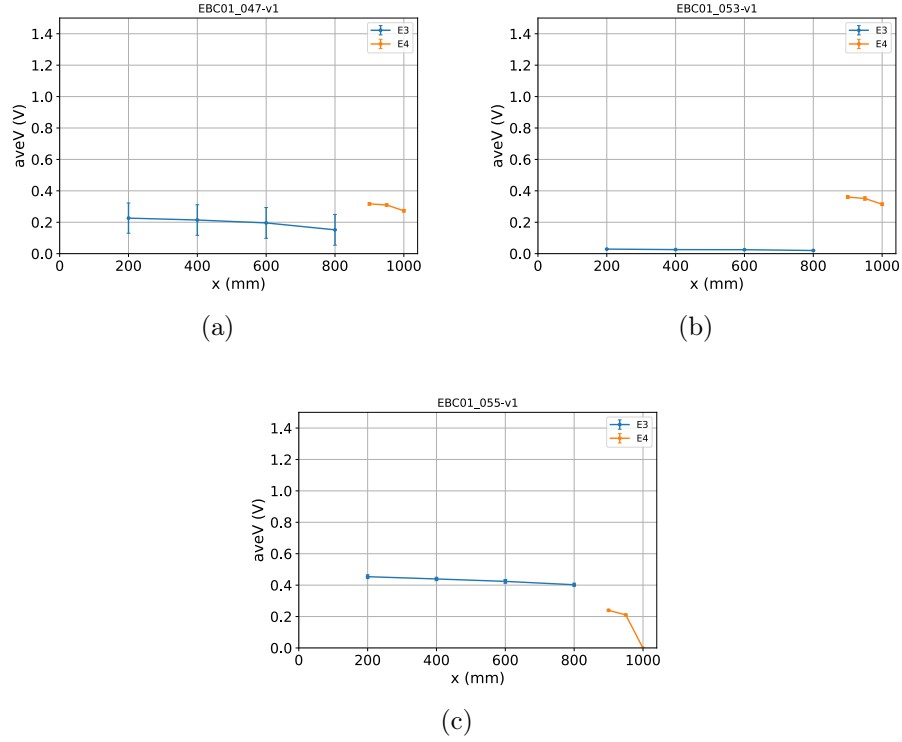


Figure A.7: The three strange graphs.

A.1.1.1 Special counter with orange fibres

There were 4 special counters (EBC4, EBC36, EBA67 and EBA68) in the sense that, their E4 segments were coupled to O-2 orange fibres instead of Y-11 green fibres. These segments have low voltage response and the plots are shown in Figure A.8. Orange fibres attenuate more light because they have short light attenuation length ($> 1.5\text{ m}$) in comparison with green fibres ($> 3.5\text{ m}$), hence the response was expected. In addition to this, the PMT that was used for measurements is not designed for orange fibres. The performance of orange fibres would be studied during Run 3 and compared to green fibres.

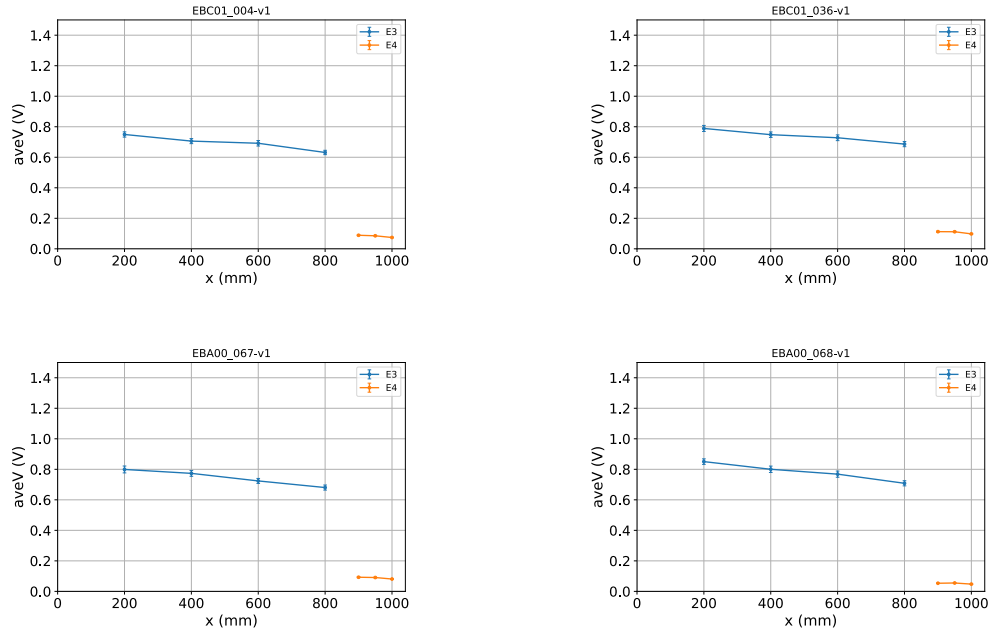


Figure A.8: Special E3E4 counters connected to orange fibres.

A.2 Photographs during Installation of detector modules

The photographs below (Figures A.9 to A.12) provide a captivating glimpse into a pivotal moment during the Phase-I upgrade of the ATLAS Tile Calorimeter. These images showcase the intricate process of installing Crack scintillators and MBTS counters, essential components in the heart of the ATLAS experiment. The shots capture the great work of the scientists and engineers involved, as they carefully position and secure these advanced detectors. The installation is a testament to the dedication and precision required to uphold and improve the functionality of the ATLAS detector, a vital instrument at CERN's LHC, contributing to groundbreaking discoveries in particle physics. These photographs offer a rare behind-the-scenes view of the technical expertise and collaborative efforts that drive the frontiers of scientific research.

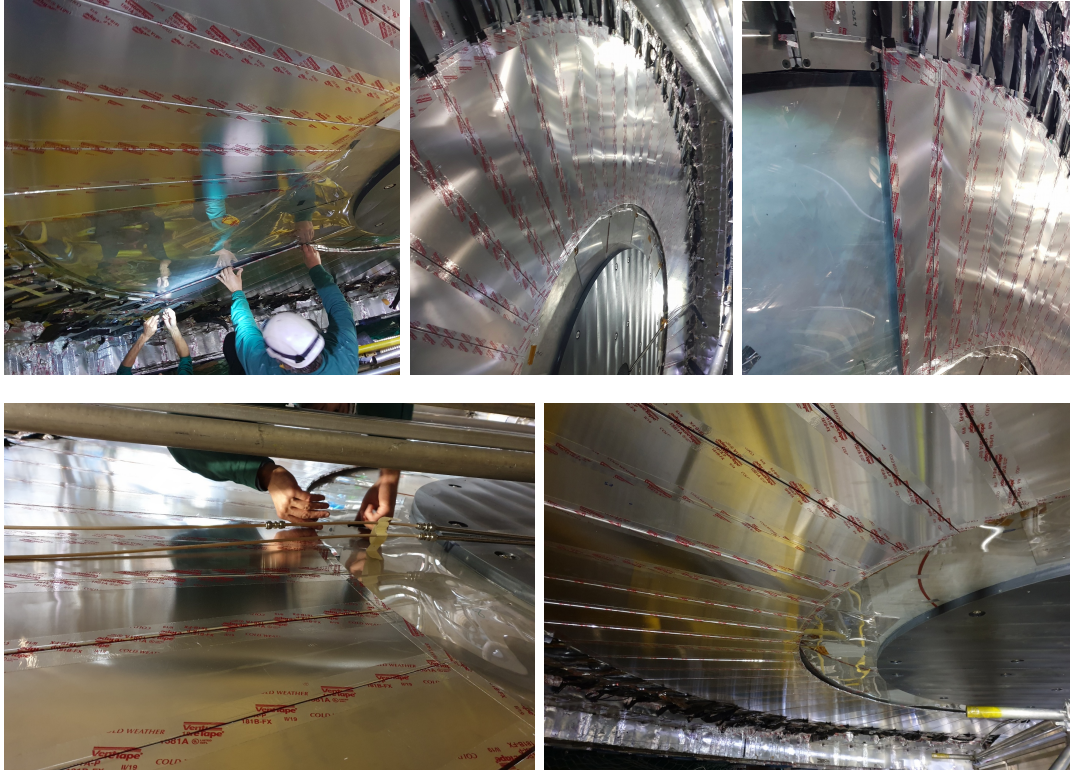


Figure A.9: Installation of crack counters on the ATLAS detector.



Figure A.10: A photograph of clear optical cable connecting MBTS counters to the calorimeter.

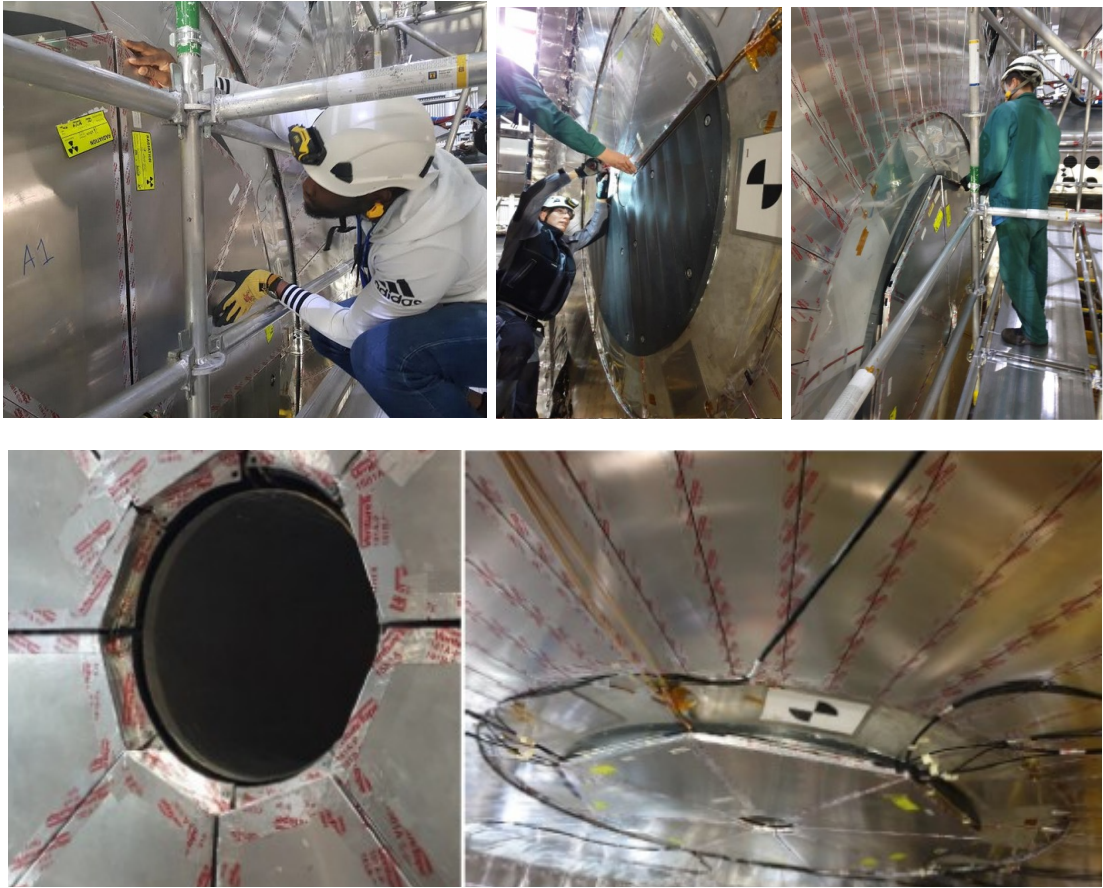


Figure A.11: Installation of MBTS counters on the ATLAS detector.

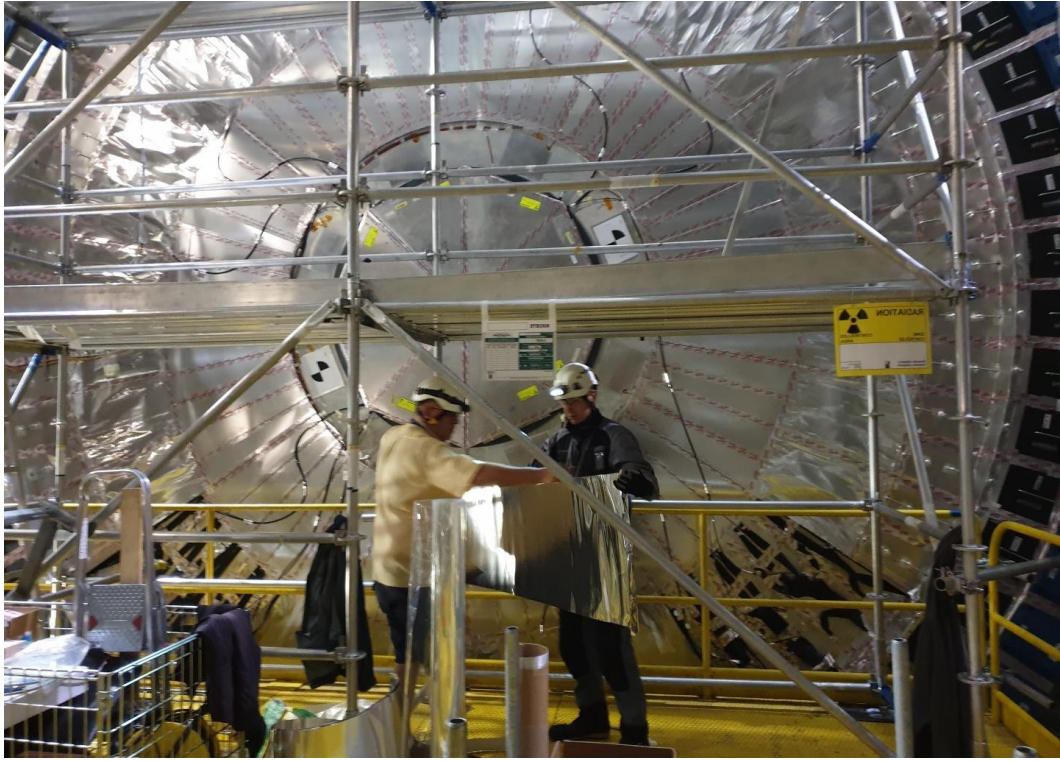


Figure A.12: Finalization of the installation with the aluminium foil.

Signal modeling

Figures B.1 to B.6 display the parameters of the Double-sided Crystal Ball (DSCB) function as a function of m_X obtained from the simultaneous fit. These figures specifically focus on the ee channel, considering events that exclusively belong to the ee category (ggF spin-0).

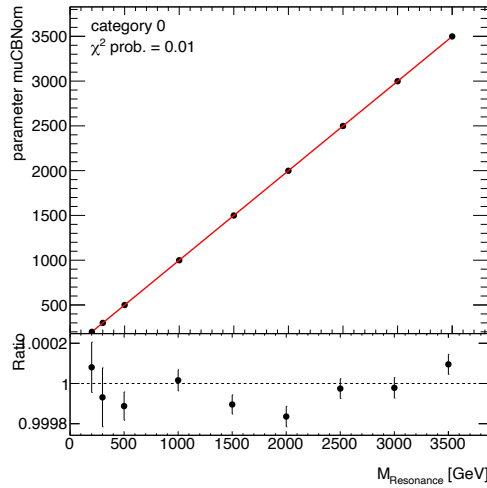


Figure B.1: μ_{CB}

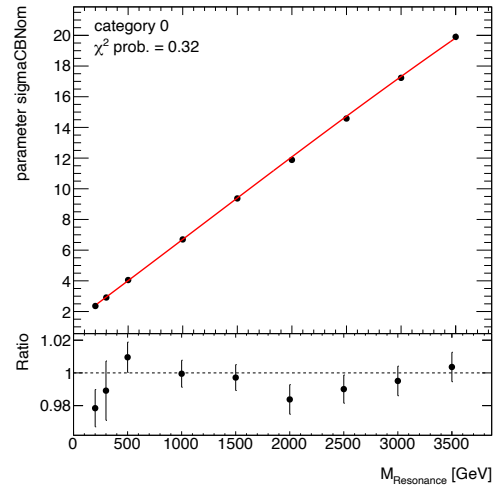
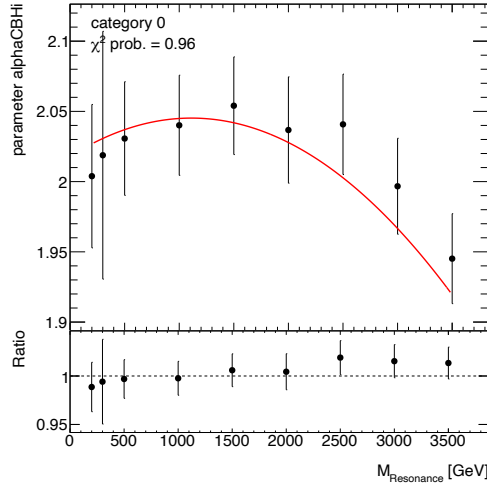
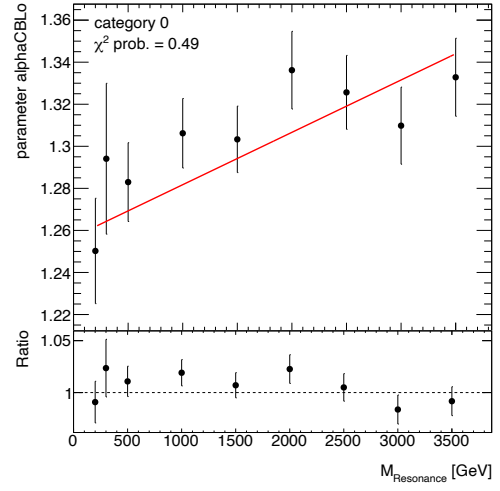
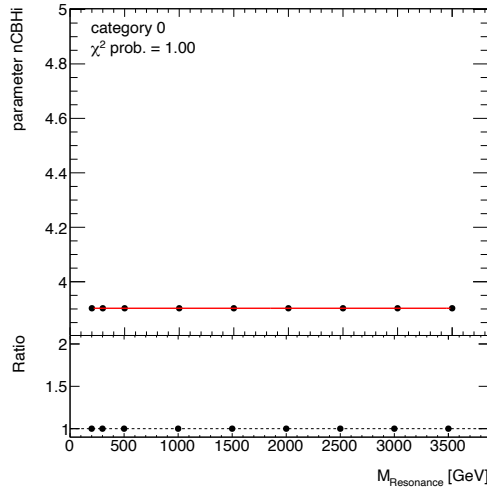
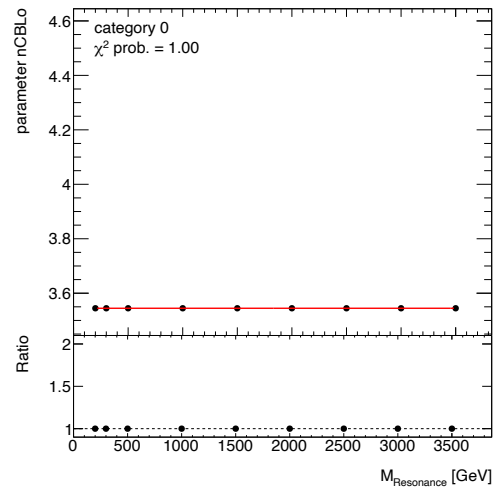
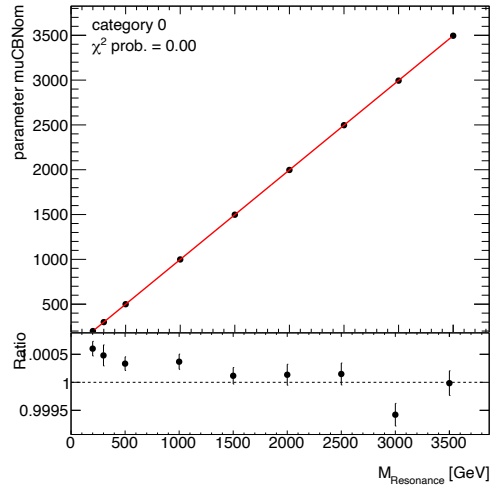
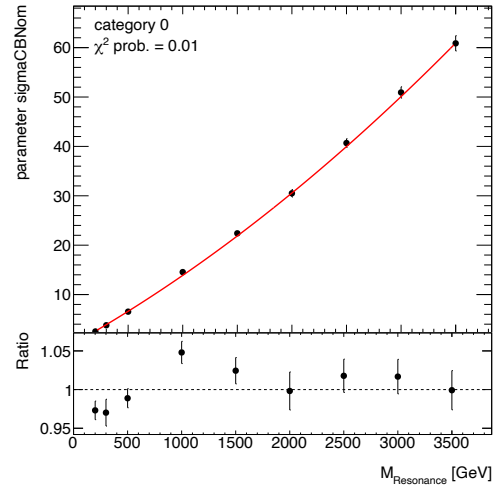
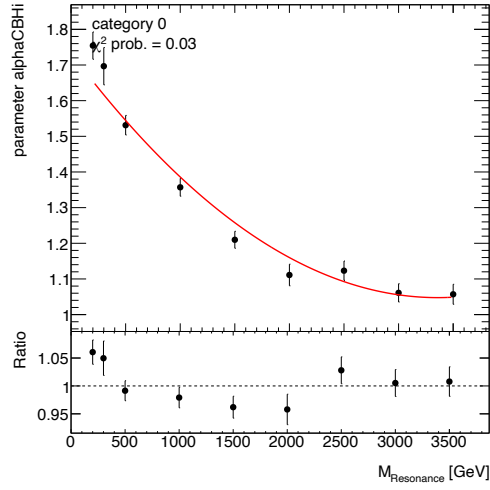
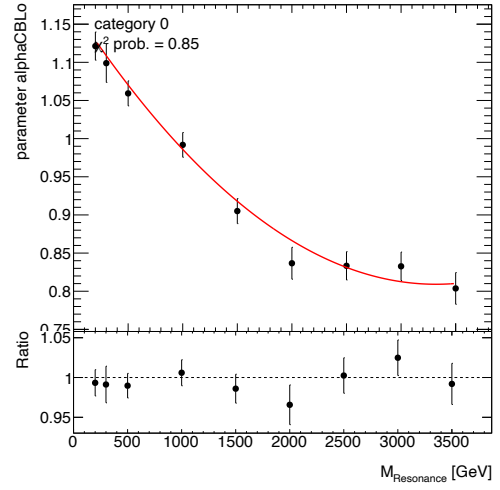
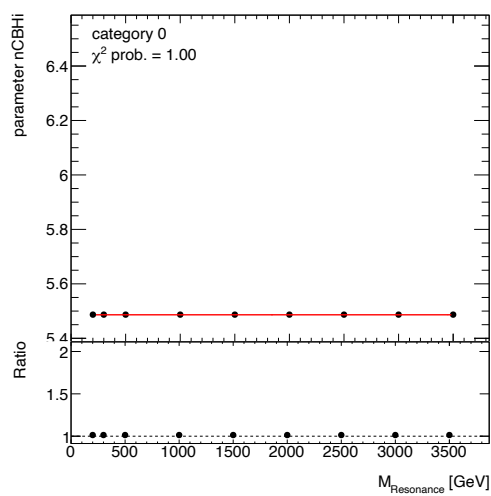
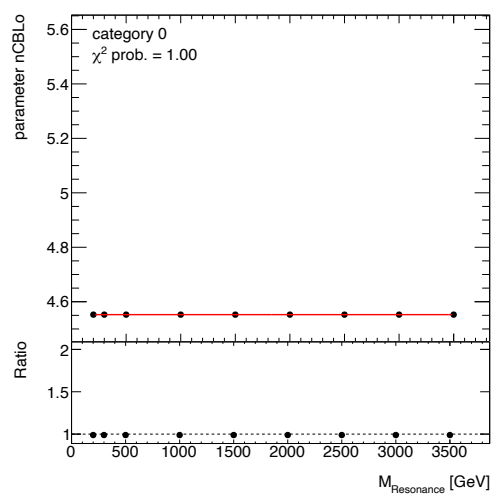


Figure B.2: σ_{CB}

Figure B.3: $\alpha_{CB_{H_i}}$ Figure B.4: $\alpha_{CB_{L_o}}$ Figure B.5: $n_{CB_{H_i}}$ Figure B.6: $n_{CB_{L_o}}$

Figures B.7 to B.12 display the parameters of the Double-sided Crystal Ball (DSCB) function as a function of m_X obtained from the simultaneous fit. These figures specifically focus on the $\mu\mu$ channel, considering events that exclusively belong to the $\mu\mu$ category (ggF spin-0).

Figure B.7: μ_{CB} Figure B.8: σ_{CB} Figure B.9: $\alpha_{CB_{Hi}}$ Figure B.10: $\alpha_{CB_{Lo}}$

Figure B.11: n_{CBHi} Figure B.12: n_{CBLo}

B.1 Double Sided Crystal Ball fits (DSCB)

Figures B.13 to B.30 show the results of individual DSCB fits performed for both ee and $\mu\mu$ channels of ggF spin-0.

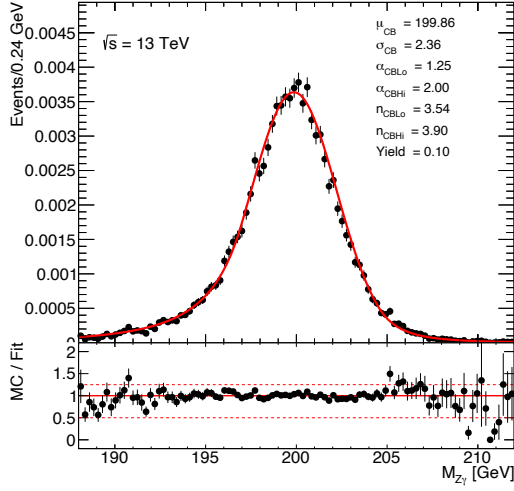


Figure B.13

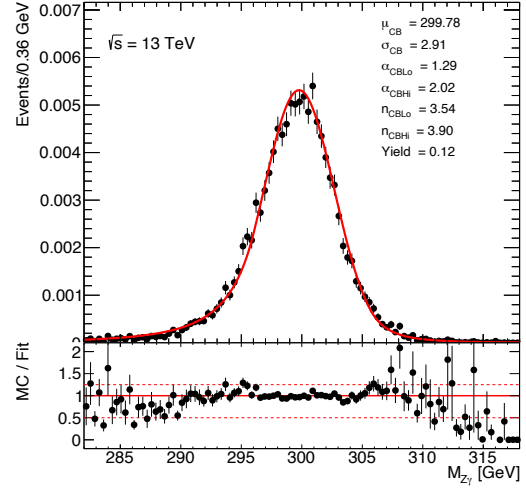


Figure B.14

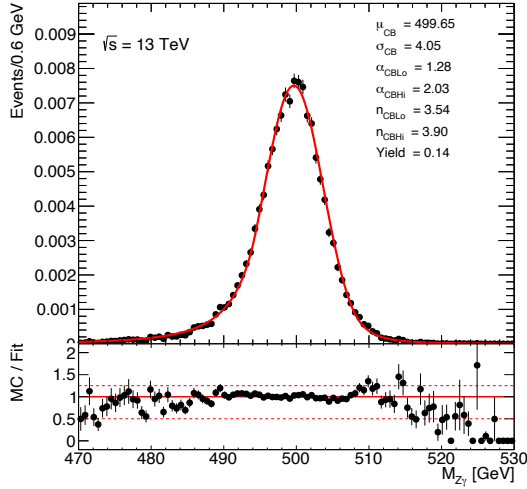


Figure B.15

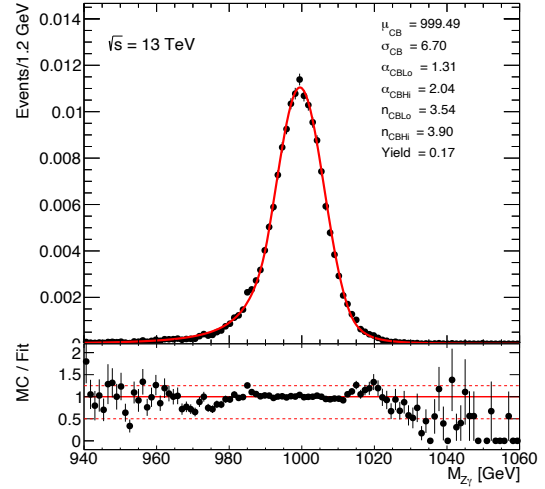


Figure B.16

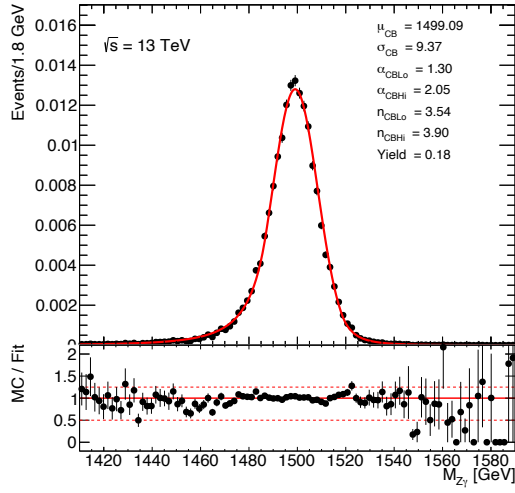


Figure B.17

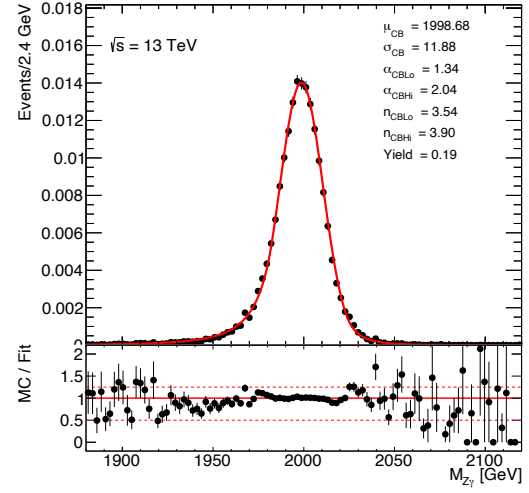


Figure B.18

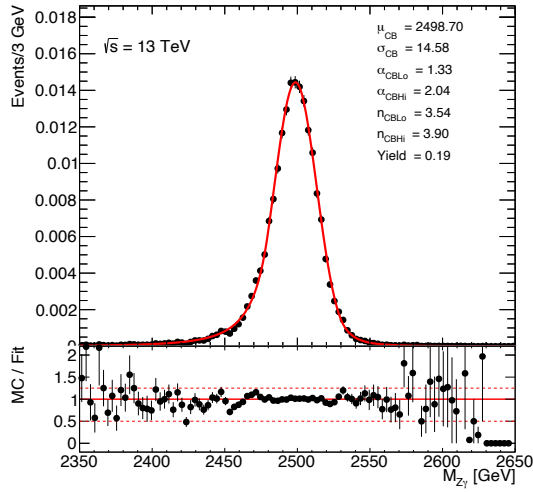


Figure B.19

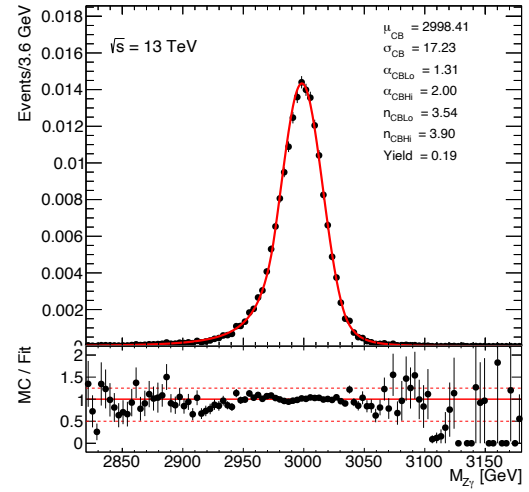


Figure B.20

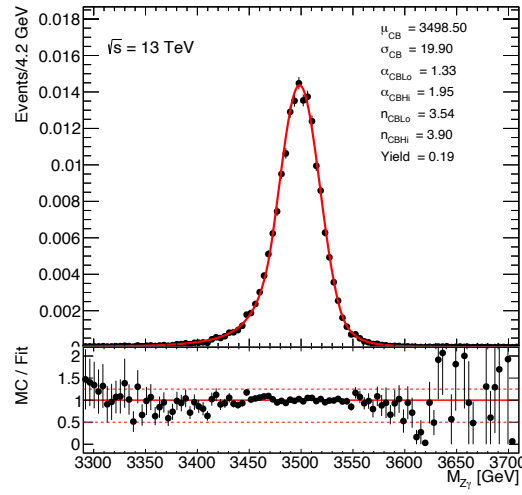


Figure B.21

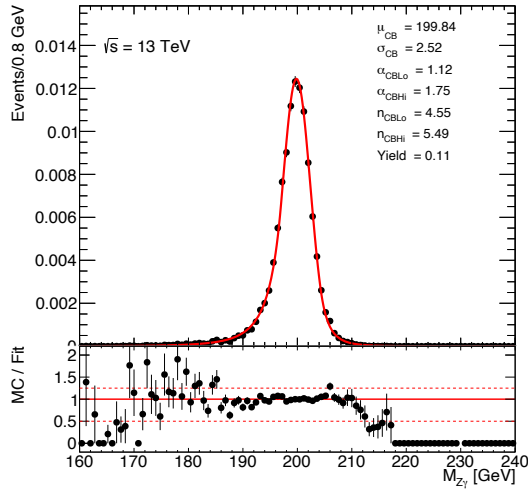


Figure B.22

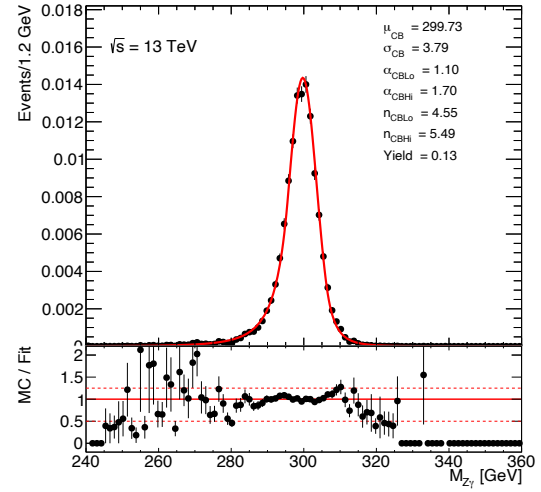


Figure B.23

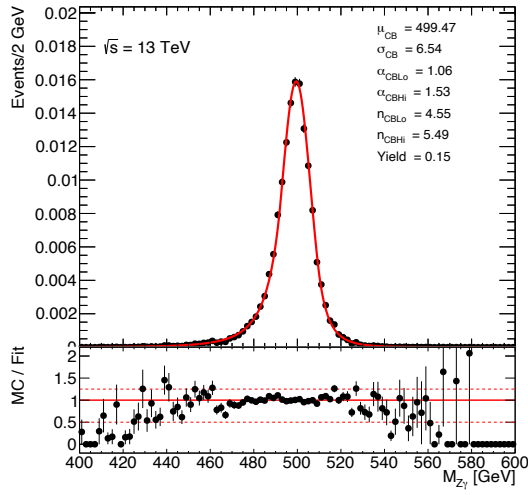


Figure B.24

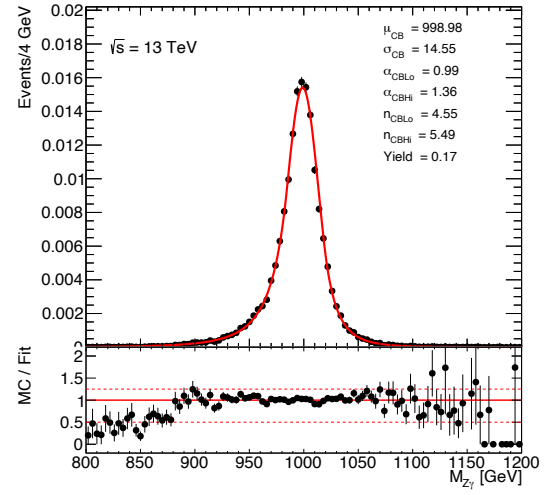


Figure B.25

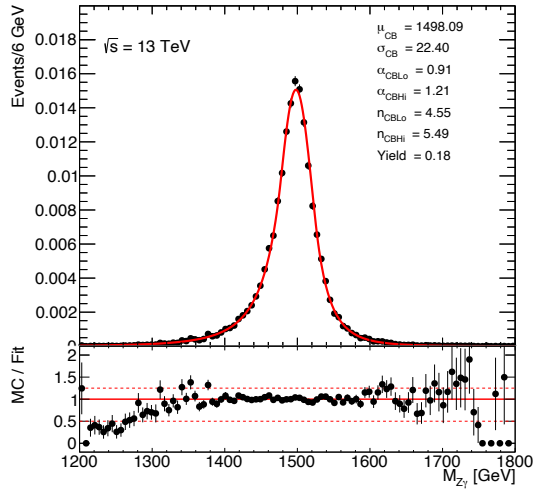


Figure B.26

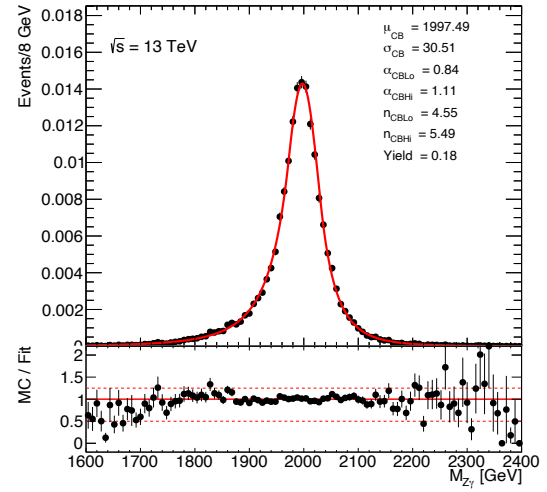


Figure B.27

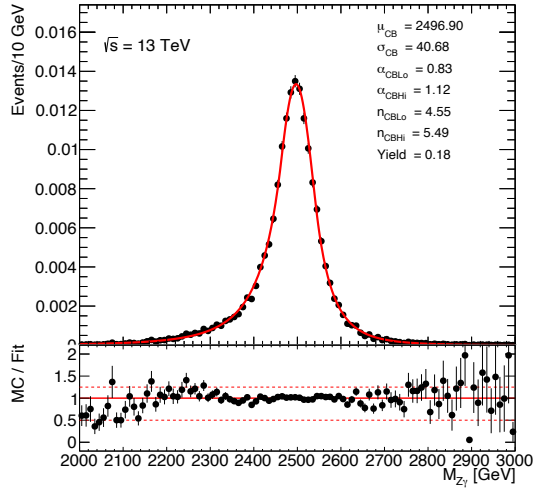


Figure B.28

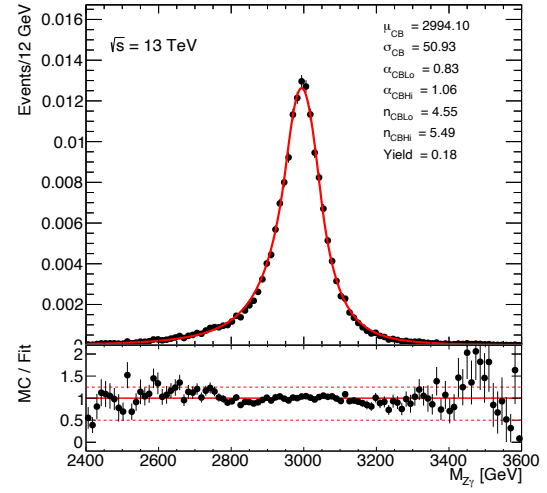


Figure B.29

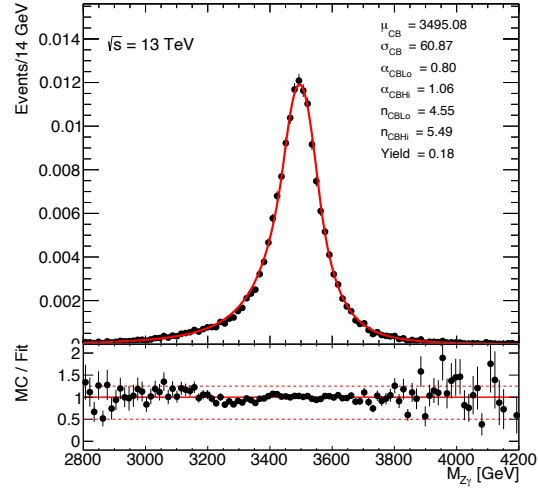


Figure B.30

Figures B.31 to B.48 show the results of simultaneous DSCB fits performed for both ee and $\mu\mu$ channels of ggF spin-0.

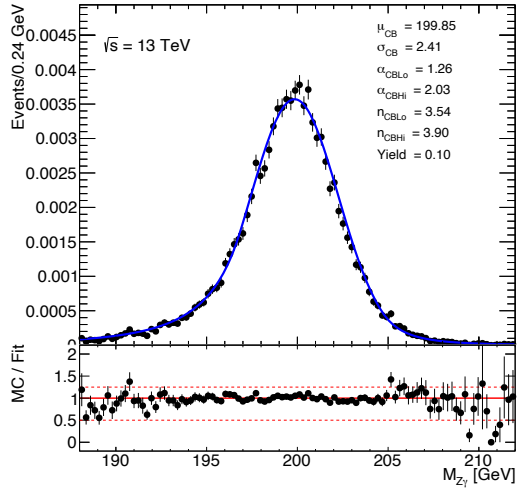


Figure B.31

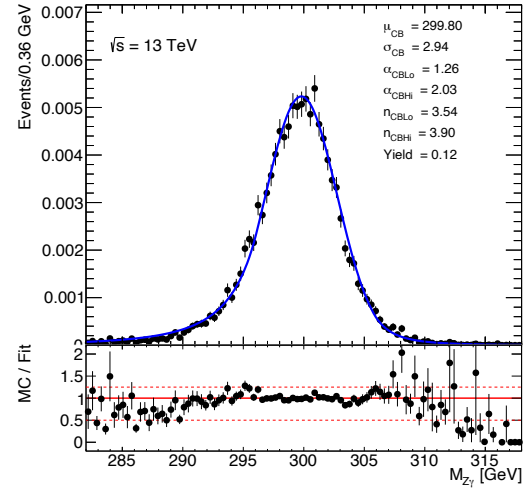


Figure B.32

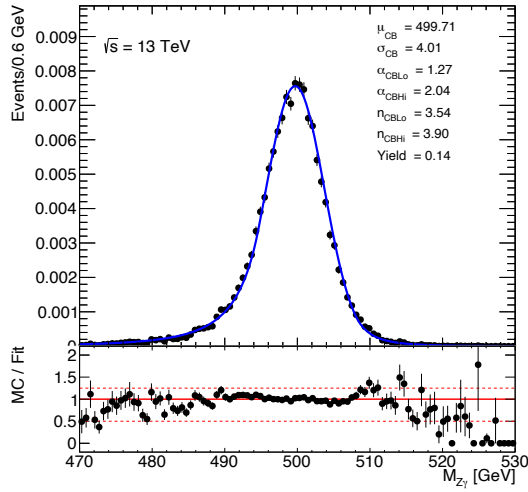


Figure B.33

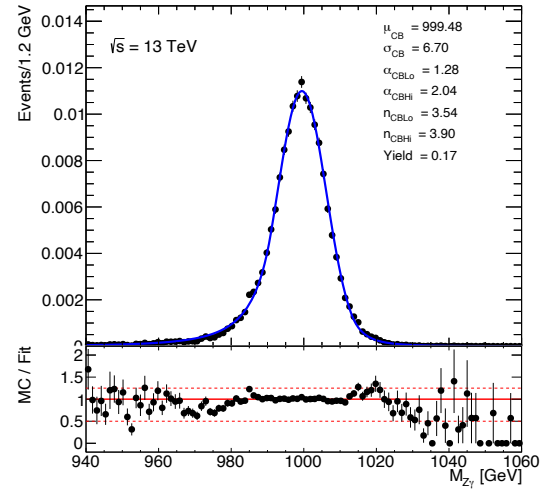


Figure B.34

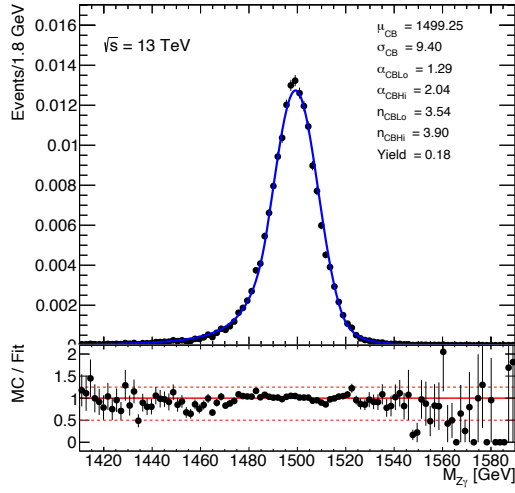


Figure B.35

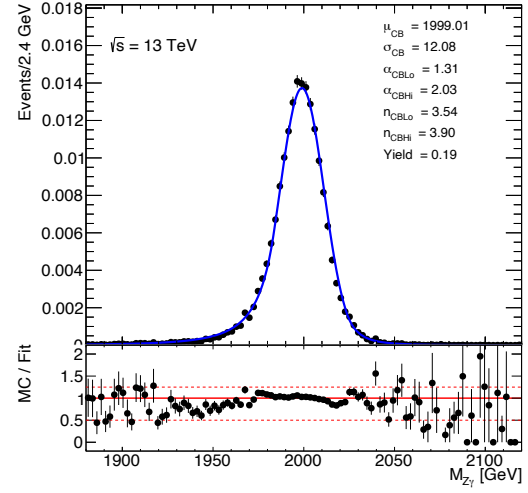


Figure B.36

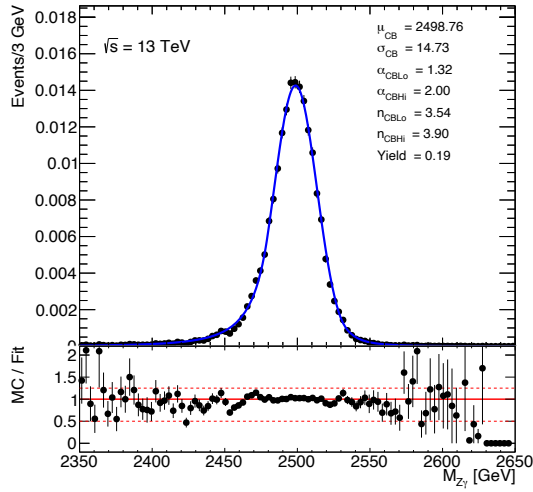


Figure B.37

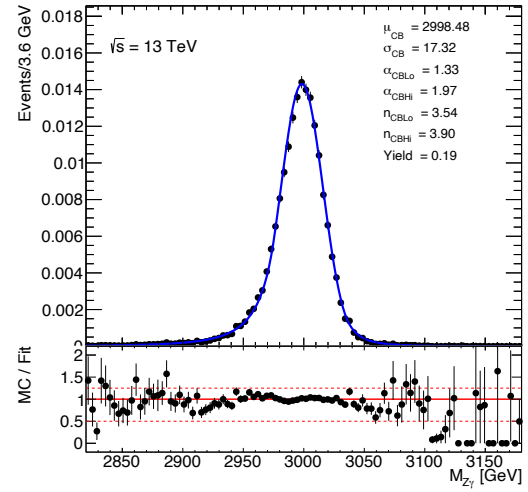


Figure B.38

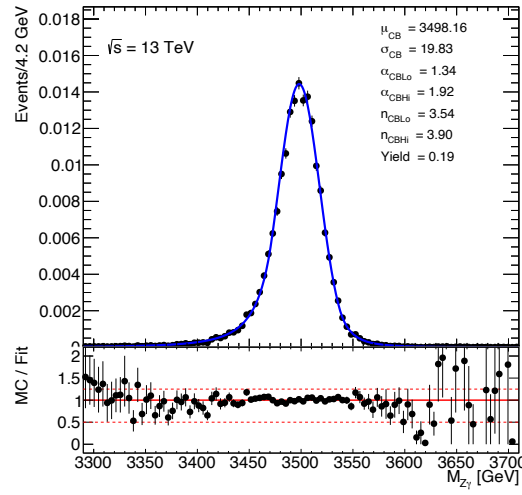


Figure B.39

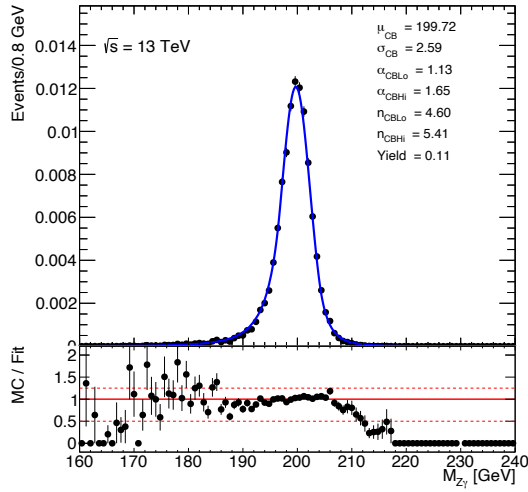


Figure B.40

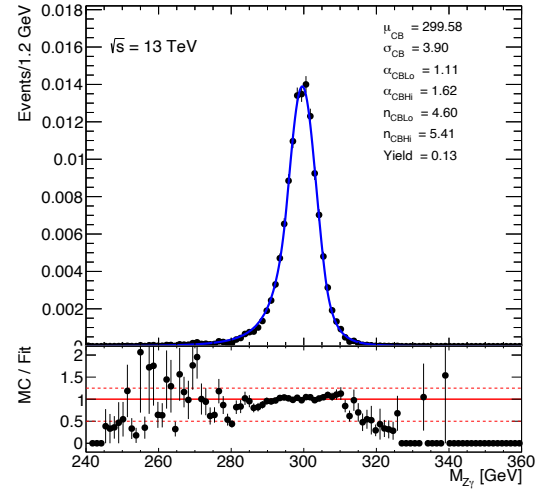


Figure B.41

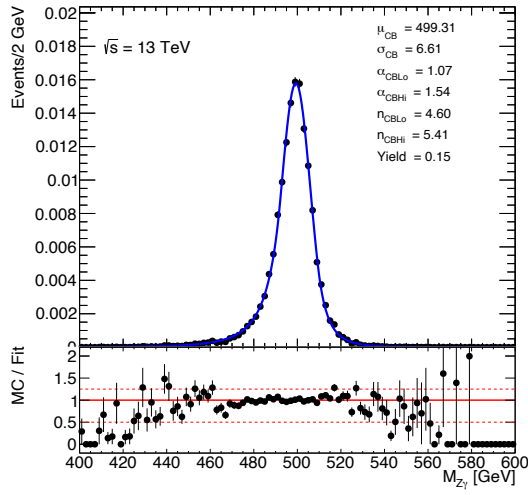


Figure B.42

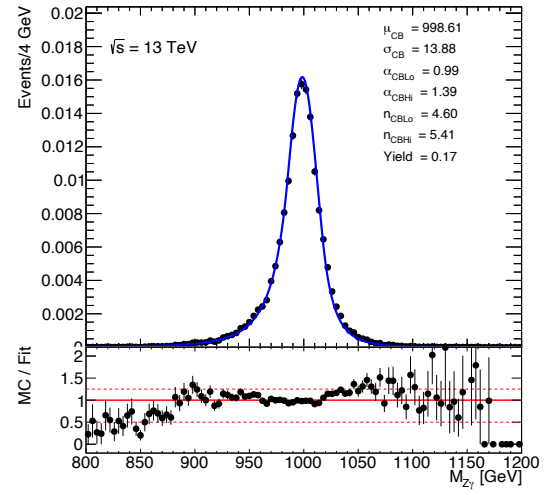


Figure B.43

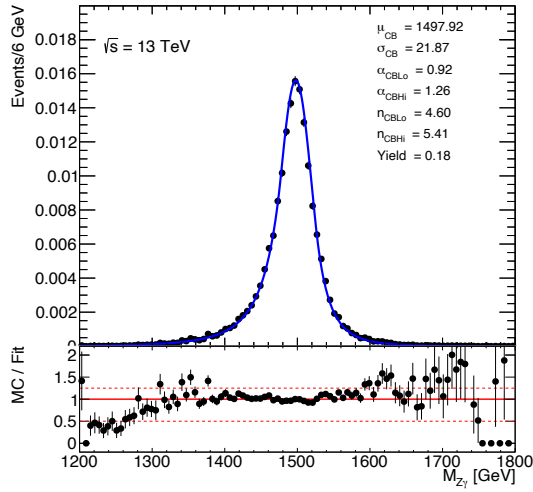


Figure B.44

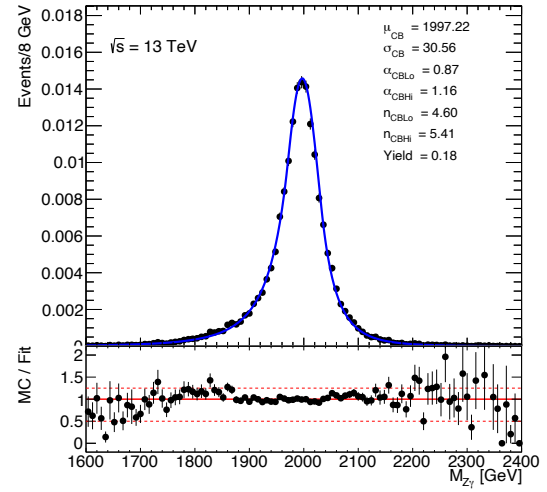


Figure B.45

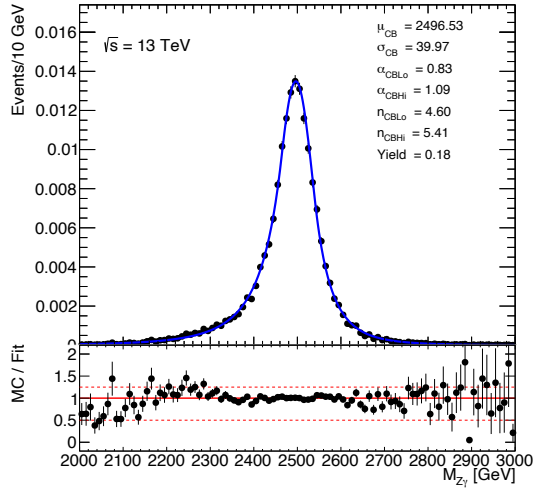


Figure B.46

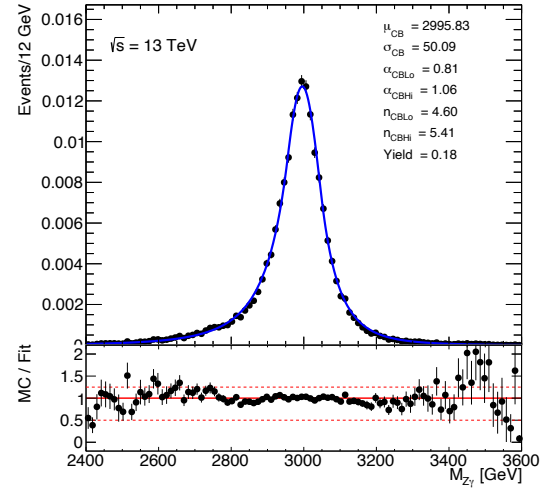


Figure B.47

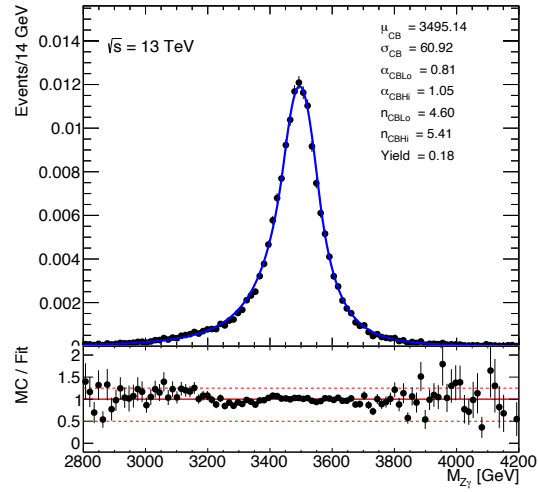


Figure B.48

Systematic Uncertainties

C.1 Systematic uncertainty on the signal $m_{\ell\ell\gamma}$ distribution

Figures C.1 to C.4 show the uncertainty effect on the signal shape parameters (μ_{CB} and σ_{CB}) of the DSCB function employed to characterize the signal invariant mass distribution due to systematic uncertainties on the lepton and photon energy or momentum scale and resolution. The values of the shape parameters used for computing are obtained using the nominal value of the source of systematic uncertainty under study and the values after varying the source by $\pm 1\sigma$ as described in Section 6.7. The two curves on the plots (red and green) correspond to relative difference between the signal shape parameters after source variation and the nominal ones. The up(down) variation corresponds to uncertainty in the upper(lower) position and the absolute maximum(minimum) value in the bottom pad is taken as an estimate.

Table C.1: Sources of systematic uncertainty influencing the measurement of $\sigma(pp \rightarrow X \rightarrow Z\gamma)$ and their corresponding effects on the measurement uncertainty.

Category	$\mu\mu\gamma$	$ee\gamma$
Luminosity	0.83%	
<i>Signal Efficiency</i>		
Photon ID efficiency uncertainty	0.643 – 0.648%	0.636 – 0.753%
Photon isolation efficiency uncertainty	0.734 – 1.350%	0.731 – 1.570%
Photon trigger efficiency uncertainty	0.000 – 0.016%	–
Pile-up	0.000 – 0.016%	–
Muon isolation efficiency (stat.)	0.114 – 0.528%	–
Muon isolation efficiency (sys.)	0.996 – 1.090%	–
Muon reconstruction efficiency (stat.)	0.110 – 0.128%	–
Muon reconstruction efficiency (sys.)	0.191 – 6.370%	–
Muon reconstruction efficiency (stat. lowpt)	0.002 – 0.021%	–
Muon reconstruction efficiency (sys. lowpt)	0.002 – 0.041%	–
Muon efficiency (ttva stat.)	0.096 – 0.126%	–
Muon efficiency (ttva sys.)	0.096 – 0.187%	–
Muon efficiency (trig. stat. uncertainty)	0.115 – 0.140%	–
Muon efficiency (trig. sys. uncertainty)	0.546 – 0.997%	–
Electron ID efficiency (total)	–	2.880 – 4.010%
Electron Iso. efficiency (total)	–	0.148 – 0.494%
Electron Reco. efficiency (total)	–	0.294 – 0.587%
Electron Trig. efficiency (total)	–	0.043 – 0.091%
Electron TrigEff. efficiency (total)	–	0.001 – 0.002%
<i>Signal modeling on μ_{CB}</i>		
Electron and photon energy scale (all)	0.330 – 0.380%	0.150 – 0.690%
Muon momentum scale	0.003%	–
Muon Sagitta pho [181]	0.02%	–
Muon Sagitta Resbias [181]	0.01%	–
<i>Signal modeling on σ_{CB}</i>		
Electron and photon energy resolution (all)	2.53 – 10.38%	6.57 – 61.22%
Muon ID resolution	0.397 – 1.747%	–
Muon MS resolution	0.559 – 1.867%	–
Extra Smearing on muon p_T	2.4%	–
<i>Background modeling</i>		
Spurious signal	0.007 – 10.0	0.003 – 9.44
<i>Customized electron ID (syst. on signal efficiency)</i>		
MVA ID only	–	0.2 – 0.5%
Mixed ID	–	1.0%

Table C.2: Impacts of grouped dominant systematic uncertainties. The impact corresponds to the relative variation of the expected upper limit of $\sigma(pp \rightarrow X) \times BR(X \rightarrow Z\gamma)$ from $m_X = 220 \text{ GeV}$ to $m_X = 3.4 \text{ TeV}$ when re-evaluating the quantity by fixing the corresponding nuisance parameters to the best-fit values, while keeping others free to float. The impact of total systematic uncertainties are performed in the last row.

Source	Relative impact
<i>Signal Efficiency</i>	
Electron/Photon efficiency	$< 0.26\%$
Muon efficiency	$< 0.31\%$
<i>Signal modeling</i>	
Electron/Photon energy scale/resolution	$< 1.74\%$
Muon momentum scale/resolution	$< 1.11\%$
<i>Background modeling</i>	
Spurious signal	$< 12.1\%$
Total systematic	$0.12\% - 14.54\%$

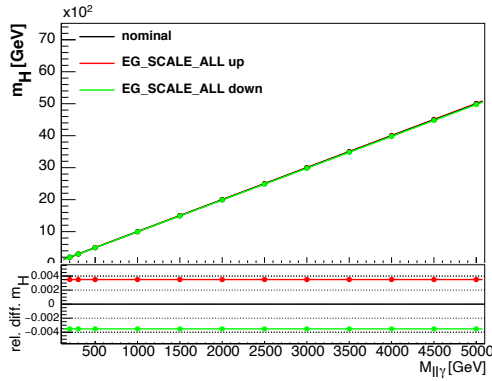


Figure C.1: Shape systematic uncertainties on μ_{CB} due to the e/γ energy scale uncertainty – $\mu\mu\gamma$.

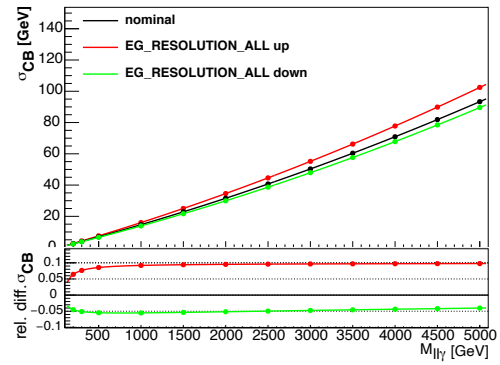


Figure C.2: Shape systematic uncertainties on σ_{CB} due to the e/γ energy resolution uncertainty – $\mu\mu\gamma$.

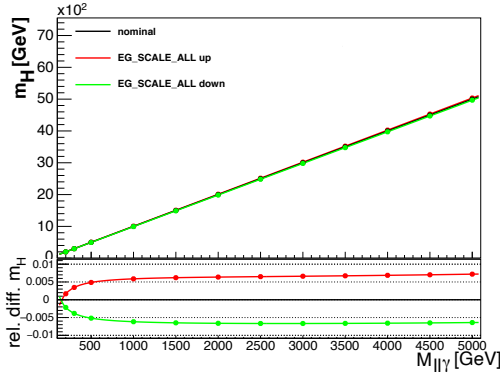


Figure C.3: Shape systematic uncertainties on μ_{CB} due to the e/γ energy scale uncertainty – $e\gamma$.

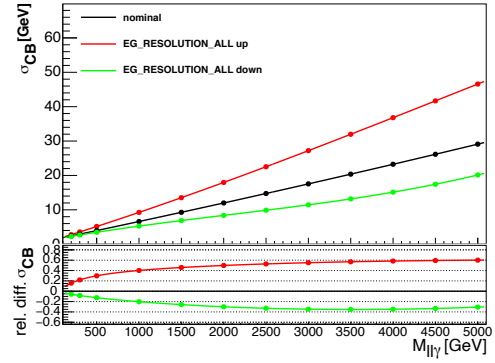


Figure C.4: Shape systematic uncertainties on σ_{CB} due to the e/γ energy resolution uncertainty – $e\gamma$.

C.2 Systematic uncertainty on the signal efficiency

Figures C.5 – C.18 illustrate the impact of the systematic uncertainties on the signal efficiency as a function of m_x . The procedure for estimating uncertainty is described in Section 6.7.

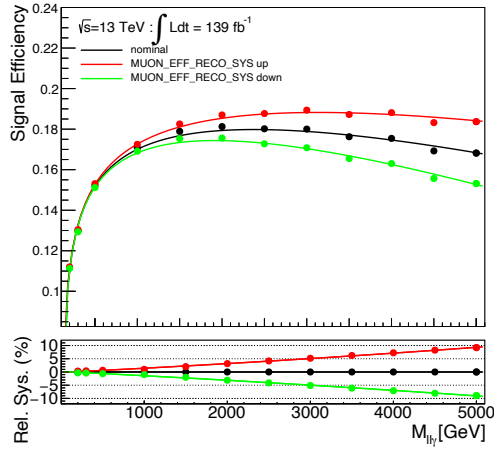


Figure C.5: Systematic uncertainty on the signal efficiency from the uncertainty on the muon reconstruction efficiency (due to the systematic uncertainty on the scale factors).

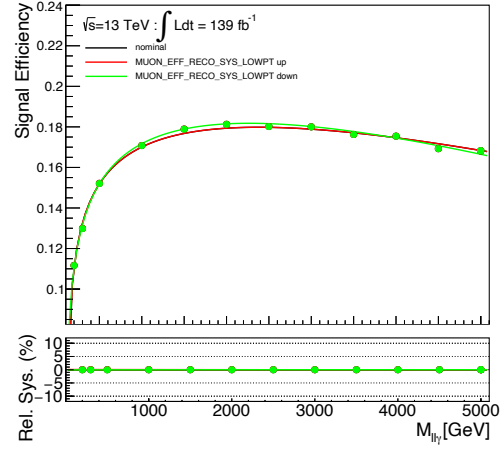


Figure C.6: Systematic uncertainty on the signal efficiency from the uncertainty on the muon reconstruction efficiency at low transverse momentum (due to the systematic uncertainty on the scale factors).

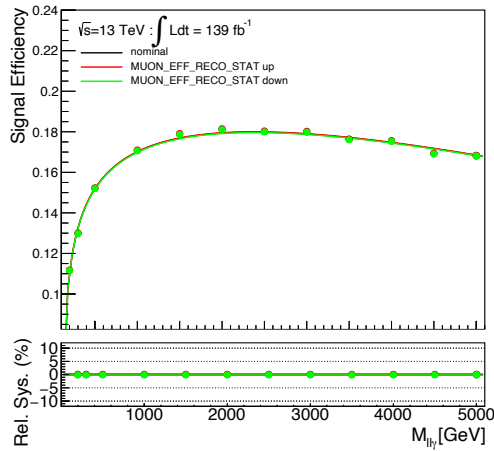


Figure C.7: Systematic uncertainty on the signal efficiency from the uncertainty on the muon reconstruction efficiency (as a result of the statistical uncertainty regarding the scale factors).

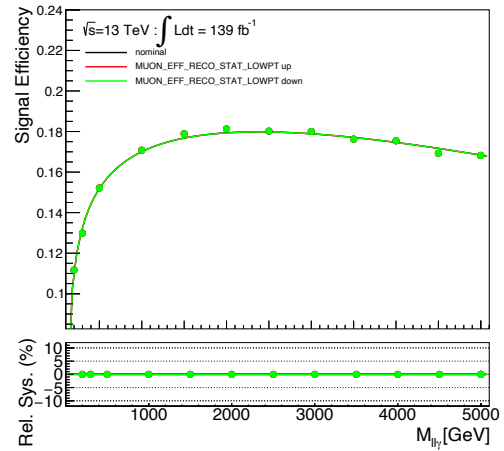


Figure C.8: Systematic uncertainty on the signal efficiency from the uncertainty on the muon reconstruction efficiency at low transverse momentum (as a result of the statistical uncertainty regarding the scale factors).

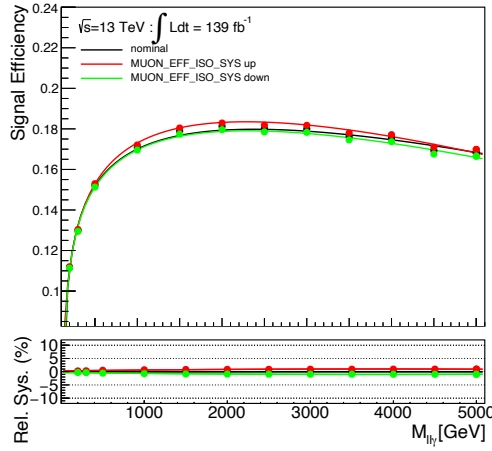


Figure C.9: Systematic uncertainty on the signal efficiency from the uncertainty on the muon isolation efficiency (due to the systematic uncertainty on the scale factors).

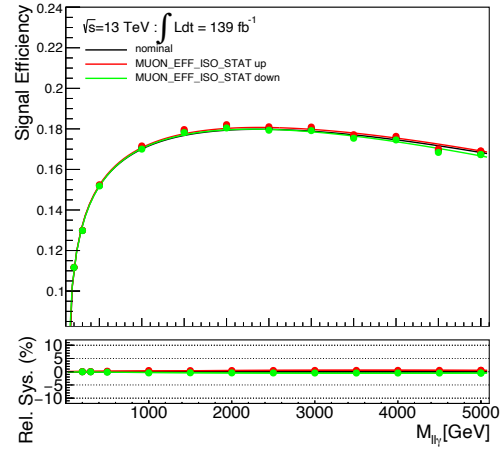


Figure C.10: Systematic uncertainty on the signal efficiency from the uncertainty on the muon isolation efficiency (as a result of the statistical uncertainty regarding the scale factors).

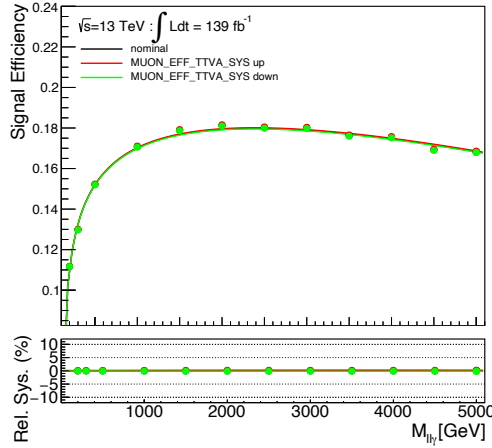


Figure C.11: Systematic uncertainty on the signal efficiency from the muon track to vertex association.

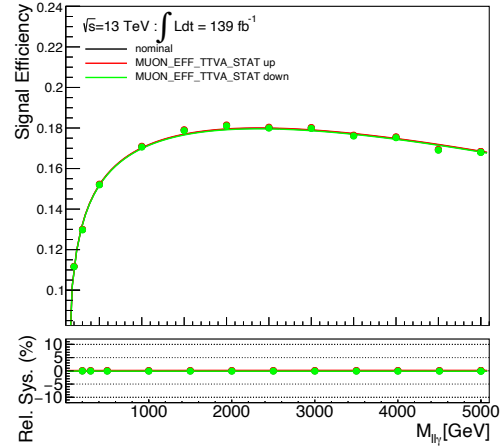


Figure C.12: Statistical uncertainty on the signal efficiency from the muon track to vertex association.

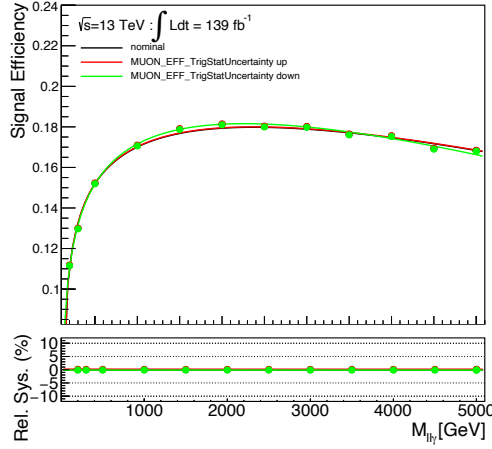


Figure C.13: Systematic uncertainty on the signal efficiency from the uncertainty on the muon trigger efficiency (as a result of the statistical uncertainty regarding the scale factors).

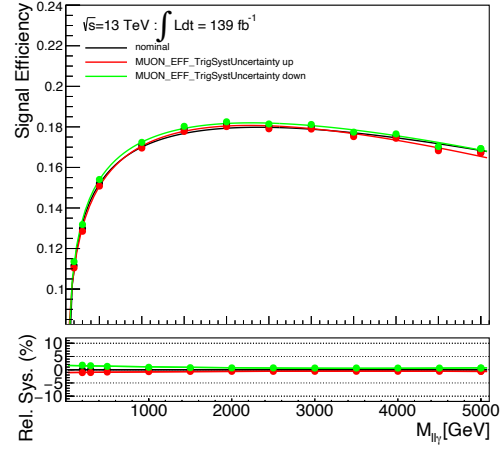


Figure C.14: Systematic uncertainty on the signal efficiency from the uncertainty on the muon trigger efficiency (due to the systematic uncertainty on the scale factors).

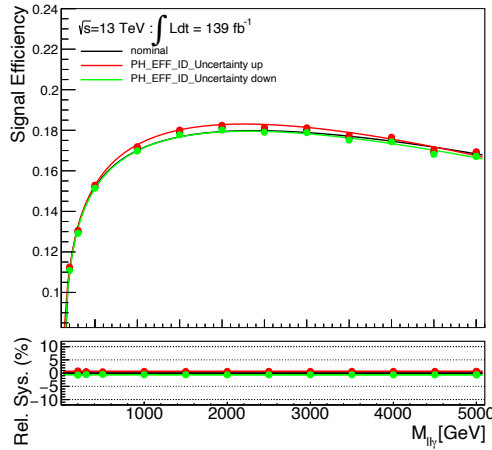


Figure C.15: Systematic uncertainty on the signal efficiency from the uncertainty on the photon ID efficiency.

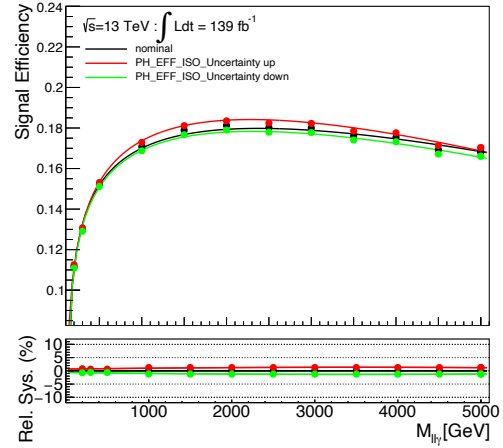


Figure C.16: Systematic uncertainty on the signal efficiency from the uncertainty on the photon calorimeter isolation efficiency.

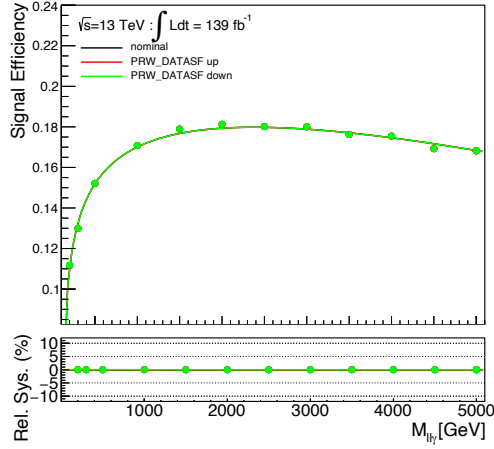


Figure C.17: Systematic uncertainty on the signal efficiency from the pileup distribution.

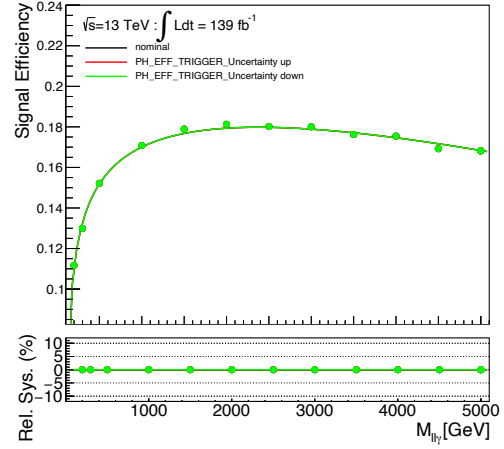


Figure C.18: Systematic uncertainty on the signal efficiency from the uncertainty on the muon trigger efficiency.

Figures C.19 – C.34 show the effect due to the systematic uncertainties on electron identification, isolation, reconstruction, trigger efficiency and photon objects in the $ee\gamma$ -channel.

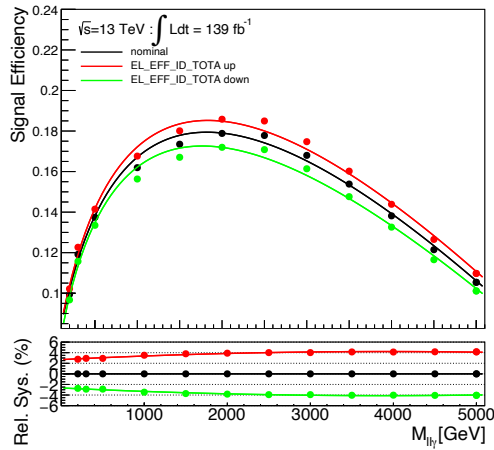


Figure C.19: Systematic uncertainty on the signal efficiency from the uncertainty on the electron ID efficiency.

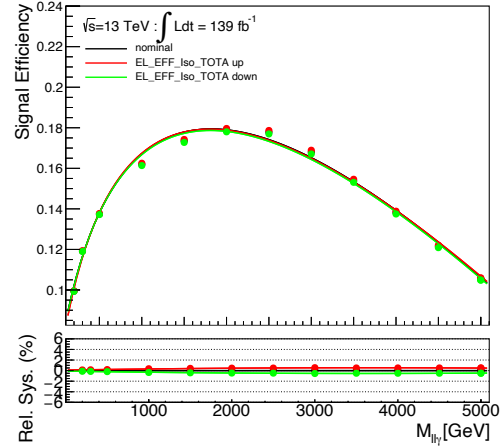


Figure C.20: Systematic uncertainty on the signal efficiency from the uncertainty on the electron isolation efficiency.

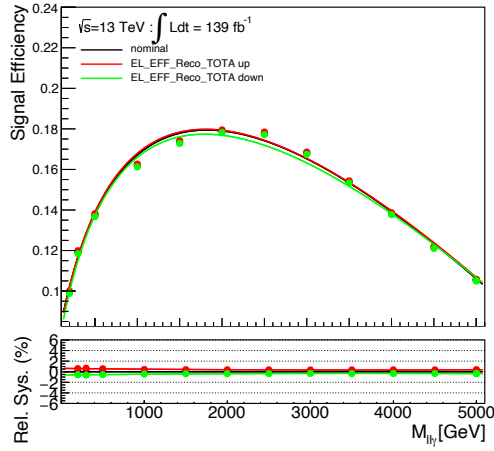


Figure C.21: Systematic uncertainty on the signal efficiency from the uncertainty on the electron reconstruction efficiency.

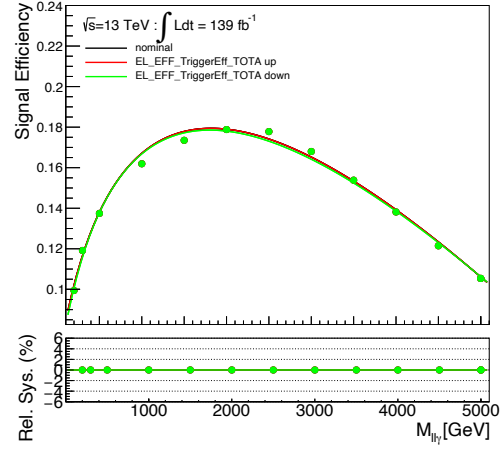


Figure C.22: Systematic uncertainty on the signal efficiency from the uncertainty on the electron trigger efficiency.

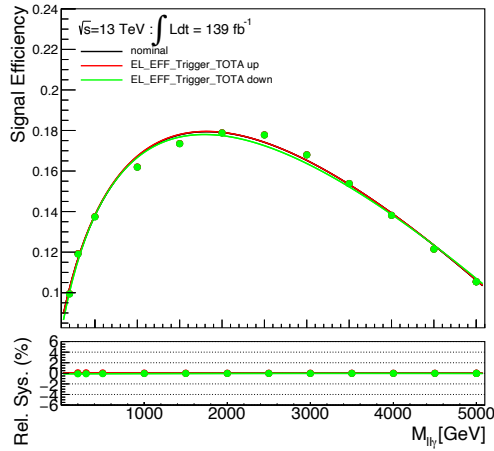


Figure C.23: Systematic uncertainty on the signal efficiency from the uncertainty on the electron trigger efficiency.

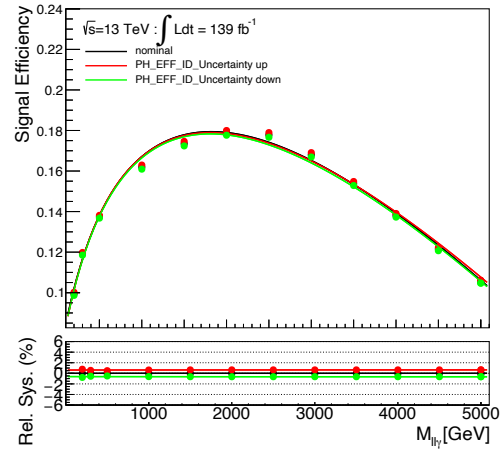


Figure C.24: Systematic uncertainty on the signal efficiency from the uncertainty on the photon ID efficiency.

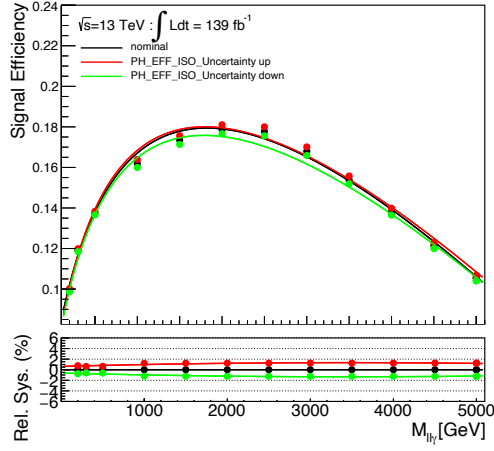


Figure C.25: Systematic uncertainty on the signal efficiency from the uncertainty on the photon calorimeter isolation efficiency.

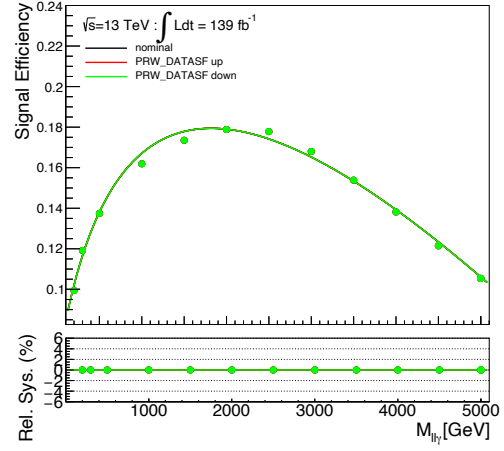


Figure C.26: Systematic uncertainty on the signal efficiency from the pileup distribution.

Figures C.27 – C.34 show the effect due to the systematic uncertainties on electron identification, isolation, reconstruction, trigger efficiency and photon objects in the $e\gamma$ -channel.

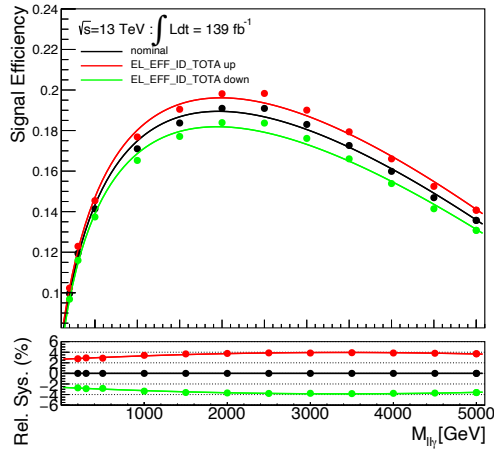


Figure C.27: Systematic uncertainty on the signal efficiency from the uncertainty on the electron ID efficiency.

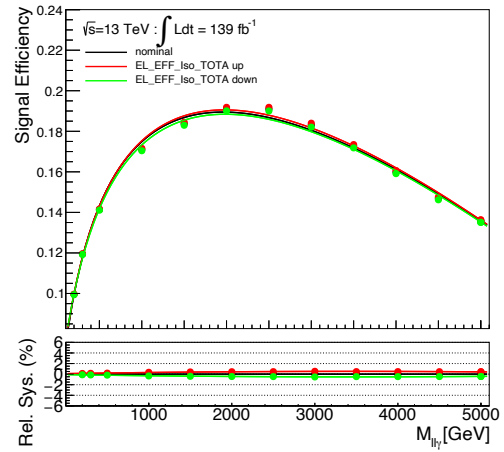


Figure C.28: Systematic uncertainty on the signal efficiency from the uncertainty on the electron isolation efficiency.

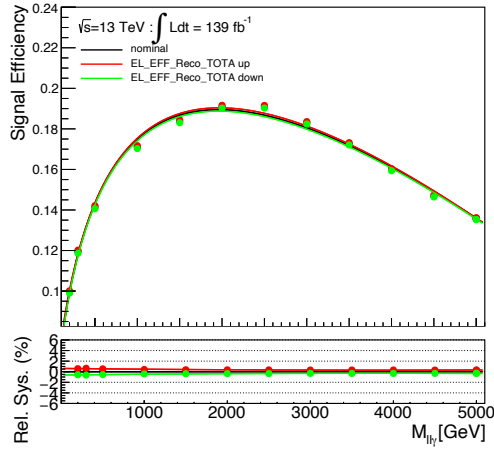


Figure C.29: Systematic uncertainty on the signal efficiency from the uncertainty on the electron reconstruction efficiency.

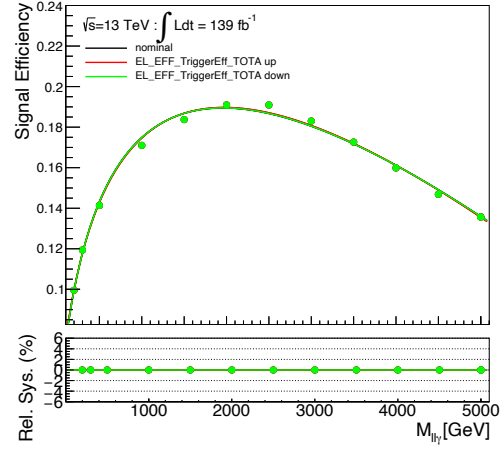


Figure C.30: Systematic uncertainty on the signal efficiency from the uncertainty on the electron trigger efficiency.

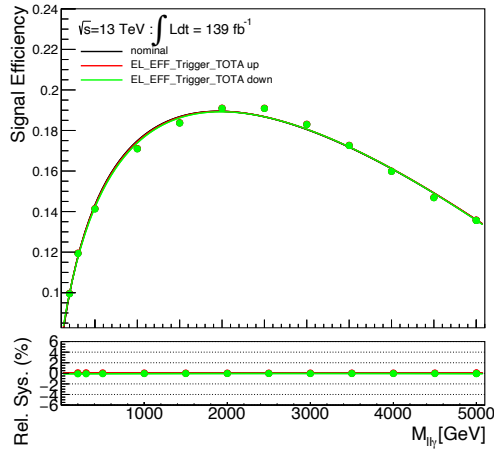


Figure C.31: Systematic uncertainty on the signal efficiency from the uncertainty on the electron trigger efficiency.

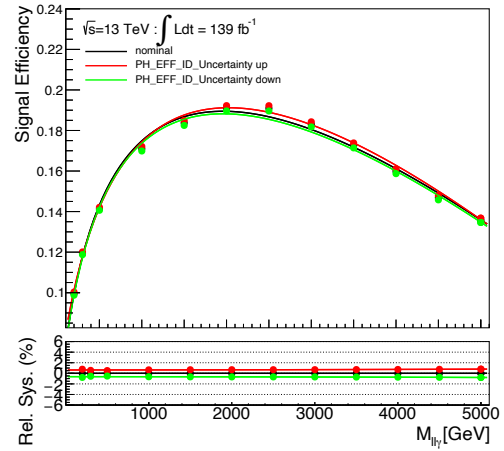


Figure C.32: Systematic uncertainty on the signal efficiency from the uncertainty on the photon ID efficiency.

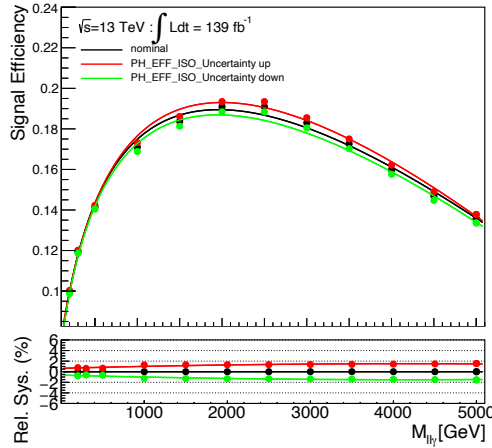


Figure C.33: Systematic uncertainty on the signal efficiency from the uncertainty on the photon calorimeter isolation efficiency.

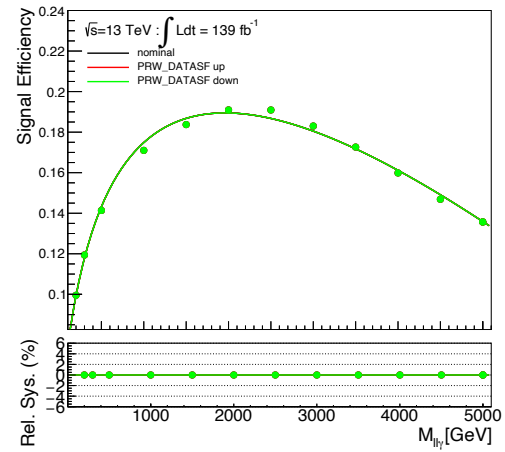


Figure C.34: Systematic uncertainty on the signal efficiency from the pileup distribution.

C.2.1 Systematic uncertainty on background modeling

In the case of the non-resonant background model, the parameters are obtained through a fitting process. As a result, the sole systematic uncertainty associated with the background is the possibility of a spurious signal arising from the selection of the background model, as detailed in Section 6.6.3. To describe the shape of the envelope encompassing the spurious signal, an exponential function is employed with the form $f(x) = 10^{ax+b}$. Specifically, for the ee channel, the values of the parameters are $a = -0.0011$ and $b = 1.25$, while for the $\mu\mu$ channel, the values are $a = -0.0011$ and $b = 1.29$. A systematic uncertainty is determined by considering the envelope that bounds the fitted spurious signal yield from above, as depicted in Figure C.35. The systematic uncertainties for both the $ee\gamma$ and $\mu\mu\gamma$ channels are presented in Table C.3, covering the mass range from 220 GeV to 3400 GeV.

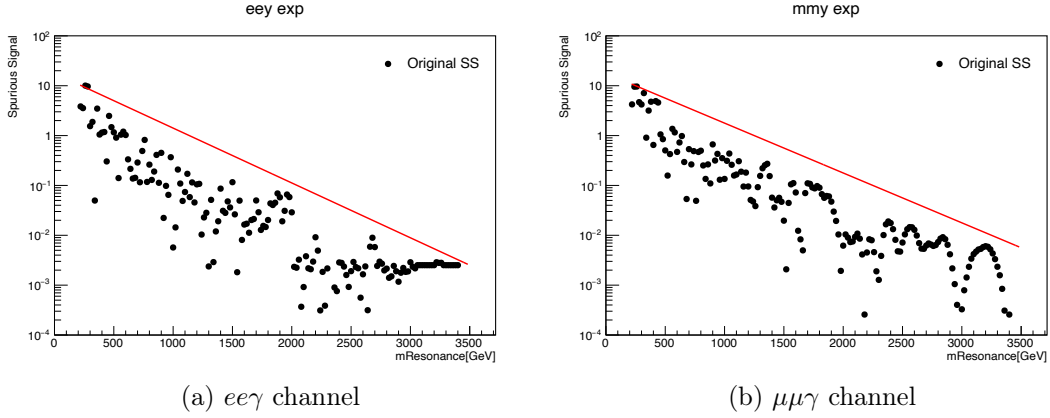


Figure C.35: The fitted spurious signal yields with variations including pdf eigenvector, different background mixture fraction and different parametrization function for the shape ratio between $Z + \text{jets}$ and $Z + \gamma$. The left plot is for the $ee\gamma$ channel and the right plot is for the $\mu\mu\gamma$ channel. The red lines are the parametrized shape for the envelop of the spurious signal yield dependence on the resonance mass.

Table C.3: Absolute value of spurious signal for both $ee\gamma$ and $\mu\mu\gamma$ channels within the mass range of 220–3400 GeV.

Mass [GeV]	$ee\gamma$ channel SS	$\mu\mu\gamma$ channel SS
220	10.186	10.715
300	8.318	8.913
500	5.012	5.623
1000	1.413	1.778
1500	0.398	0.562
2000	0.112	0.178
2500	0.032	0.056
3000	0.009	0.018
3400	0.003	0.007



Kinematic distributions

The kinematic distributions for the γ , Z boson and $Z\gamma$ system have been produced using truth information from events with the full event selection applied for the $M_X = 2 \text{ TeV}$ as shown in Figure D.1 and Figure D.2 for $M_X = 3 \text{ TeV}$. As can be seen from both signal mass points, the $q\bar{q}X$ spin-2 distributions for photon and Z boson are harder than the spin-2 ggF process. Also, larger p_T spectrum is seen for $q\bar{q}X$ spin-2 process below 100 GeV. The η distributions for the photon and Z boson are also quite different between the spin-2 $q\bar{q}X$ and spin-2 ggF processes.

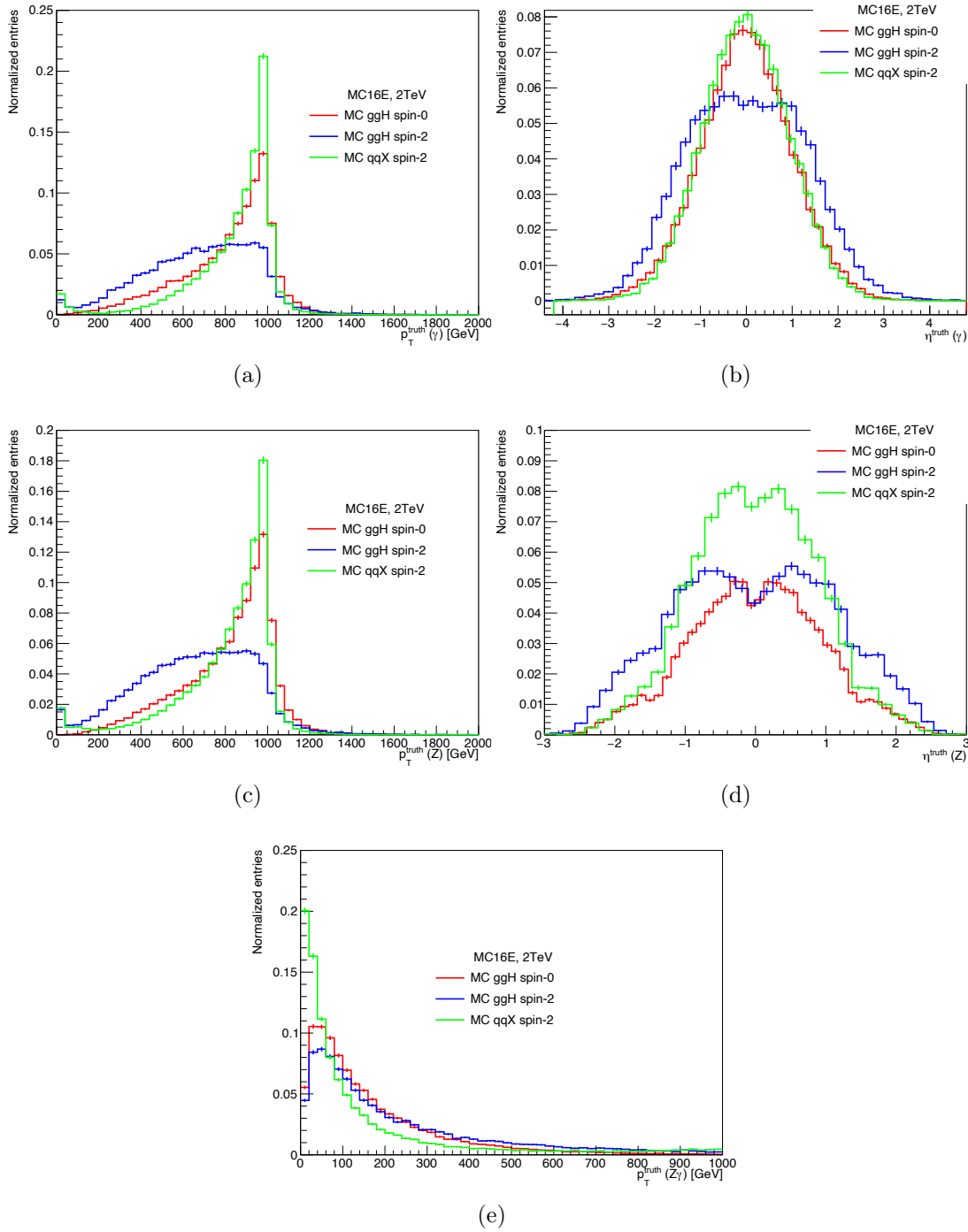


Figure D.1: Kinematics for truth photon (a) p_T (b) η , truth Z boson (c) p_T (d) η and $Z\gamma$ system (e) p_T for 2 TeV signal mass point (MC16E).

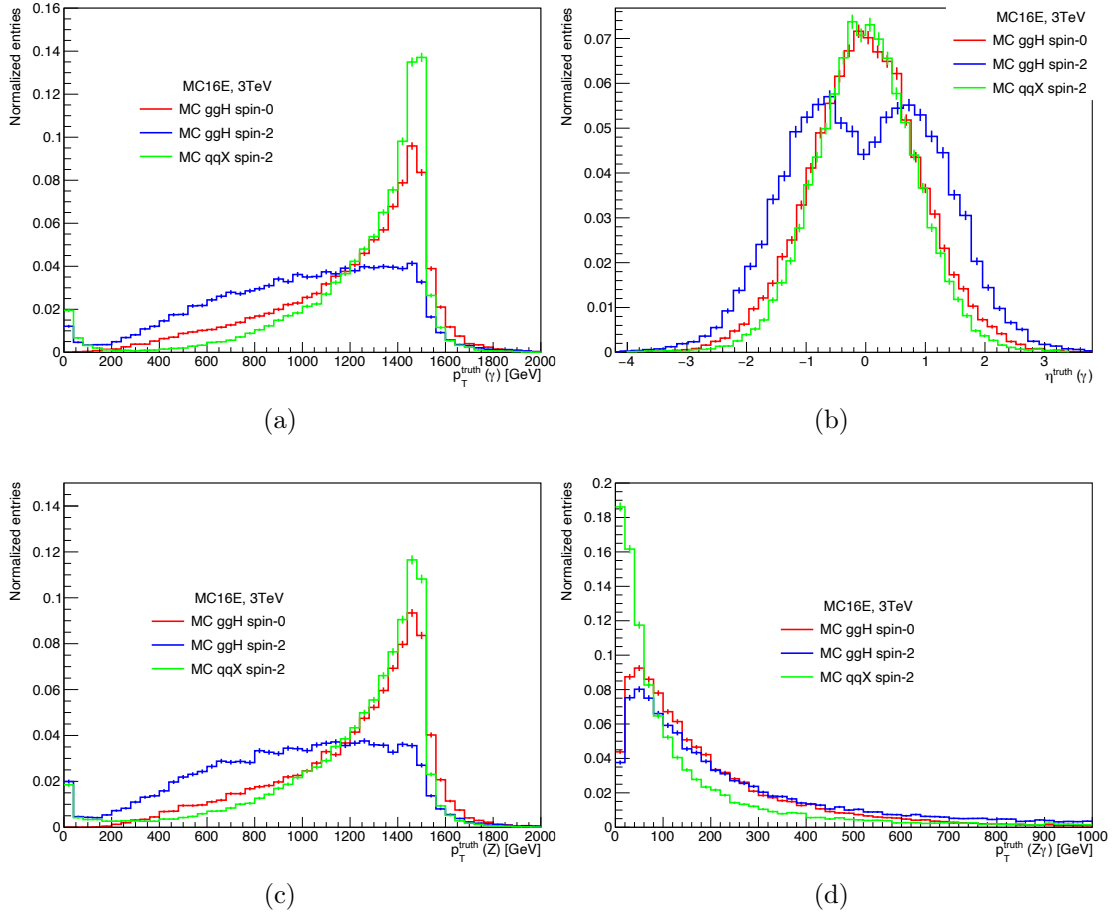


Figure D.2: Kinematics for truth photon (a) p_T (b) η , truth Z boson (c) p_T and (d) $Z\gamma$ system for 3 TeV signal mass point (MC16E).

A list of MC samples

The tables below provide a comprehensive list of MC samples for both fast and full simulation MC $Z + \gamma$ background samples. A list of MC generated signal samples is also provided: ggF spin-0, ggF spin-2 and $q\bar{q}X$ spin-2 production modes.

Table E.1: The fast simulation MC $Z + \gamma$ background samples in three-body invariant mass slices.

Channel	DSID	Dataset name
fastSim: $ee\gamma$	346196	Sherpa_222_NNPDF30NNLO_eegamma_M_95_110
	345887	Sherpa_222_NNPDF30NNLO_eegamma_M_110_175
	345888	Sherpa_222_NNPDF30NNLO_eegamma_M_175_250
	345889	Sherpa_222_NNPDF30NNLO_eegamma_M_250_400
	345890	Sherpa_222_NNPDF30NNLO_eegamma_M_400_1000
	345891	Sherpa_222_NNPDF30NNLO_eegamma_M_1000_2000
	345892	Sherpa_222_NNPDF30NNLO_eegamma_M_2000_3000
	345893	Sherpa_222_NNPDF30NNLO_eegamma_M_3000_E_CMS
fastSim: $\mu\mu\gamma$	346197	Sherpa_222_NNPDF30NNLO_mumugamma_M_95_110
	345894	Sherpa_222_NNPDF30NNLO_mumugamma_M_110_175
	345895	Sherpa_222_NNPDF30NNLO_mumugamma_M_175_250
	345896	Sherpa_222_NNPDF30NNLO_mumugamma_M_250_400
	345897	Sherpa_222_NNPDF30NNLO_mumugamma_M_400_1000
	345898	Sherpa_222_NNPDF30NNLO_mumugamma_M_1000_2000
	345899	Sherpa_222_NNPDF30NNLO_mumugamma_M_2000_3000
	345900	Sherpa_222_NNPDF30NNLO_mumugamma_M_3000_E_CMS

Table E.2: The full simulation MC $Z + \gamma$ background samples in slices of the transverse momentum of the photon.

Channel	DSID	Dataset name
fullSim: $ee\gamma$	364500	Sherpa_222_NNPDF30NNLO_eegamma_pty_7_15
	364501	Sherpa_222_NNPDF30NNLO_eegamma_pty_15_35
	364502	Sherpa_222_NNPDF30NNLO_eegamma_pty_35_70
	364503	Sherpa_222_NNPDF30NNLO_eegamma_pty_70_140
	364504	Sherpa_222_NNPDF30NNLO_eegamma_pty_140_E_CMS
fullSim: $\mu\mu\gamma$	364505	Sherpa_222_NNPDF30NNLO_mumugamma_pty_7_15
	364506	Sherpa_222_NNPDF30NNLO_mumugamma_pty_15_35
	364507	Sherpa_222_NNPDF30NNLO_mumugamma_pty_35_70
	364508	Sherpa_222_NNPDF30NNLO_mumugamma_pty_70_140
	345897	Sherpa_222_NNPDF30NNLO_mumugamma_pty_140_E_CMS

Table E.3: ggF spin-0 signal samples from 200 GeV to 5000 GeV.

Process	DSID	Dataset name
ggX spin-0	342208	PowhegPythia8EvtGen_CT10_AZNLOCTEQ6L1_ggH200_Zllgam
	342209	PowhegPythia8EvtGen_CT10_AZNLOCTEQ6L1_ggH300_Zllgam
	342210	PowhegPythia8EvtGen_CT10_AZNLOCTEQ6L1_ggH500_Zllgam
	342211	PowhegPythia8EvtGen_CT10_AZNLOCTEQ6L1_ggH1000_Zllgam
	343580	PowhegPythia8EvtGen_CT10_AZNLOCTEQ6L1_ggH1500_Zllgam
	344744	PowhegPythia8EvtGen_CT10_AZNLOCTEQ6L1_ggH2000_Zllgam
	344745	PowhegPythia8EvtGen_CT10_AZNLOCTEQ6L1_ggH2500_Zllgam
	344746	PowhegPythia8EvtGen_CT10_AZNLOCTEQ6L1_ggH3000_Zllgam
	344747	PowhegPythia8EvtGen_CT10_AZNLOCTEQ6L1_ggH3500_Zllgam
	344748	PowhegPythia8EvtGen_CT10_AZNLOCTEQ6L1_ggH4000_Zllgam
	344749	PowhegPythia8EvtGen_CT10_AZNLOCTEQ6L1_ggH4500_Zllgam
	344750	PowhegPythia8EvtGen_CT10_AZNLOCTEQ6L1_ggH5000_Zllgam

Table E.4: ggF spin-2 signal samples from 200 GeV to 5000 GeV.

Process	DSID	Dataset name
ggX spin-2	306262	MadGraphPythia8EvtGen_A14NNPDF23LO_HC_ggX2toZy_lly_200_NW
	306263	MadGraphPythia8EvtGen_A14NNPDF23LO_HC_ggX2toZy_lly_250_NW
	306264	MadGraphPythia8EvtGen_A14NNPDF23LO_HC_ggX2toZy_lly_300_NW
	306268	MadGraphPythia8EvtGen_A14NNPDF23LO_HC_ggX2toZy_lly_500_NW
	306273	MadGraphPythia8EvtGen_A14NNPDF23LO_HC_ggX2toZy_lly_750_NW
	306276	MadGraphPythia8EvtGen_A14NNPDF23LO_HC_ggX2toZy_lly_1000_NW
	306277	MadGraphPythia8EvtGen_A14NNPDF23LO_HC_ggX2toZy_lly_1500_NW
	306278	MadGraphPythia8EvtGen_A14NNPDF23LO_HC_ggX2toZy_lly_2000_NW
	306279	MadGraphPythia8EvtGen_A14NNPDF23LO_HC_ggX2toZy_lly_2500_NW
	306280	MadGraphPythia8EvtGen_A14NNPDF23LO_HC_ggX2toZy_lly_3000_NW
	306281	MadGraphPythia8EvtGen_A14NNPDF23LO_HC_ggX2toZy_lly_3500_NW
	306282	MadGraphPythia8EvtGen_A14NNPDF23LO_HC_ggX2toZy_lly_4000_NW
	306283	MadGraphPythia8EvtGen_A14NNPDF23LO_HC_ggX2toZy_lly_4500_NW
	306284	MadGraphPythia8EvtGen_A14NNPDF23LO_HC_ggX2toZy_lly_5000_NW

Table E.5: $q\bar{q}$ spin-2 signal samples from 200 GeV to 5000 GeV.

Process	DSID	Dataset name
$q\bar{q}X$ spin-2	306220	MadGraphPythia8EvtGen_A14NNPDF23LO_HC_qqX2toZy_lly_200_NW
	306221	MadGraphPythia8EvtGen_A14NNPDF23LO_HC_qqX2toZy_lly_250_NW
	306222	MadGraphPythia8EvtGen_A14NNPDF23LO_HC_qqX2toZy_lly_300_NW
	306226	MadGraphPythia8EvtGen_A14NNPDF23LO_HC_qqX2toZy_lly_500_NW
	306231	MadGraphPythia8EvtGen_A14NNPDF23LO_HC_qqX2toZy_lly_750_NW
	306234	MadGraphPythia8EvtGen_A14NNPDF23LO_HC_qqX2toZy_lly_1000_NW
	306235	MadGraphPythia8EvtGen_A14NNPDF23LO_HC_qqX2toZy_lly_1500_NW
	306236	MadGraphPythia8EvtGen_A14NNPDF23LO_HC_qqX2toZy_lly_2000_NW
	306237	MadGraphPythia8EvtGen_A14NNPDF23LO_HC_qqX2toZy_lly_2500_NW
	306238	MadGraphPythia8EvtGen_A14NNPDF23LO_HC_qqX2toZy_lly_3000_NW
	306239	MadGraphPythia8EvtGen_A14NNPDF23LO_HC_qqX2toZy_lly_3500_NW
	306240	MadGraphPythia8EvtGen_A14NNPDF23LO_HC_qqX2toZy_lly_4000_NW
	306241	MadGraphPythia8EvtGen_A14NNPDF23LO_HC_qqX2toZy_lly_4500_NW
	306242	MadGraphPythia8EvtGen_A14NNPDF23LO_HC_qqX2toZy_lly_5000_NW

Searching for heavy scalar resonances in the LHC Run 2 dataset in the $Z\gamma$ final states using machine learning techniques

Motivated by the statistically significant excesses in the multi-lepton final states compatible with physics at the electroweak scale, here we attempt a direct search for a high mass resonance in the $Z\gamma$ final states using MC simulated samples corresponding to 2017 dataset recorded by the ATLAS experiment in proton-proton collisions during the LHC Run 2. The study aims to extract the signal process using the state-of-the-art machine learning algorithms.

F.1 Introduction

The groundbreaking discovery of a new boson by the ATLAS and CMS collaborations at the Large Hadron Collider (LHC) in 2012 marked a significant milestone in particle physics. This newly observed particle exhibited properties remarkably consistent with the Higgs boson, a cornerstone prediction of the Standard Model (SM) that explains the origin of mass for fundamental particles. The successful detection of the Higgs boson has opened a new chapter in our understanding of the universe, igniting extensive research efforts. These endeavors focus on pre-

cisely characterizing the Higgs boson's properties, exploring its interactions with other particles, and utilizing the vast amount of LHC data to search for potential physics beyond the Standard Model (BSM) [24].

Several independent anomalous features were observed in LHC Run 1 datasets and lead to the introduction of BSM additional scalars H and S to explain this phenomenon. This postulation was inspired by the deformity of Higgs boson transverse momentum p_T^h spectrum accompanied by elevated associated jet activity and rates of leptons in association with b -tagged jets, all of which indicate some excesses around resonance masses of 270 GeV, constituting indirect evidence of new physics at the electroweak scale [66, 4].

A study detailed in Reference [182] was conducted in order to investigate the excesses of four leptons (e, μ) and two muons between 240 and 280 GeV mass range. The excesses provide narrow resonances as no missing energy escapes from ATLAS the detector. The combination of all excesses are reaching a statistical significance of 4σ for a boson of a mass around 265 GeV, which is very close to the original estimate of 2015. The data are an indicative of the presence of a wide resonance.

These results open the window for a systematic search of new resonances. The study aims at developing a search for high-mass $Z\gamma$ resonances in the 240-280 GeV mass range. Here we consider a hypothetical heavy scalar H decaying to $Z\gamma$ in association with missing transverse energy ($H \rightarrow Z\gamma + E_T^{\text{miss}}$), where only events in which the Z boson decays to di-electrons or di-muons are used.

The $Z\gamma$ channel is considered because in the high mass region, a Higgs like boson (H) has relatively higher possibility of decaying into a $Z\gamma$ final state in comparisons with the di-photon final state. In addition, its vertex is well reconstructed than di-photon events, hence making it possible to search for excesses. However, the signal which is searched for can not be easily extracted since it's still mixed

and overlaid by background processes with similar signatures.

F.2 Methodology

We are setting up a search based on machine learning techniques to assist with the separation of signal and background in the 240-280 GeV mass range. Machine Learning (ML) is capable of exploiting large datasets in order to minimise complexity and discover new features in data, hence significantly improving classification problems in High Energy Physics [183]. Here we implement and compare the performance of two types of ML, namely, weakly supervised learning and full supervised learning for signal/background classification, in conjunction with Deep Neural Networks (DNNs).

F.2.1 Full supervised learning

In supervised learning, ML algorithms learn from labelled dataset [184]. It requires a distinct signal and background samples. Since we attempt to unearth a signal, the characteristics of which are not yet known in details, this method becomes a challenge and compel us to compare it with another methodology that would allow extraction of information from the data.

F.2.2 Weakly supervised learning

It is a new ML paradigm for classification problems where training is performed using a dataset which is not completely labeled [185]. It requires a background sample and a sample from data that contains background and an unknown mixture of signal (unlabelled data), hidden in the real data. Here we let the ML algorithm to decide in splitting the unknown mixture of signal and background.

F.2.3 Toolkit for Multivariate Data Analysis (TMVA)

TMVA is a ML software developed by CERN to apply a variety of ML algorithms for high-energy physics application challenges. It has been a mature softwarepackage for multivariate data analysis. TMVA provides ROOT-intergrated environment for application of large set of advanced multivariate classification for signal/background. The software package comprises training, testing and performance evaluation of the algorithm [186]. Some commonly used classification methods are usually prone to reaching their limitations due to separating a very small signal mixed with large background processes of the similar signature. However, TMVA toolkit is capable of exploiting available features from the typical datasets more efficiently.

One of the TMVA packages implemented in this study is the artificial neural networks (three different multilayer perceptron implementations).

F.2.4 Signal and Background samples

The Monte Carlo (MC) samples used in this analysis correspond to 2017 data condition. The signal samples used for $H \rightarrow Z\gamma$ were generated using the RSH and AZH models shown in Figure F.1.

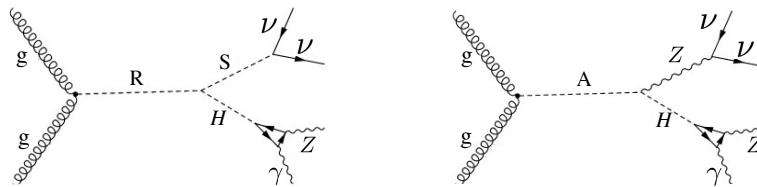


Figure F.1: A schematic Feynman diagrams of the production and decay of scalars in the RSH (left) and AZH (right) models.

The RSH model suppose the production of a heavy mass particle R through gluon fusion (ggF), decaying into Higgs-like scalar H in association with CP even scalar S . The decay progresses where H decays to a $Z\gamma$ final state. In addition,

the decay of S boson into a pair of neutrinos provide scope for studying the behaviour of $Z\gamma$ final states in association with E_T^{miss} . The RSH model follows a similar production and decay principle as the AZH model; A is a pseudo-scalar boson in a 2HDM model, Z is a Z boson and H is a heavy scalar H . On the other hand, background samples are generated from full simulated $Z+\gamma$, and $Z+\text{jet}$ events obtained through data-driven method by reversing one photon (2D-sideband method).

F.3 Invariant mass spectrum of $Z + \text{photon resonance}$ ($M_{Z\gamma}$)

Figure F.2 shows a plot of mass system of $Z\gamma$ in association with E_T^{miss} . The resonance search focuses in 200-400 GeV mass range, which is divided into background sideband and mass-window regions. In the mass-window region $240 \leq m_{Z\gamma} \leq 280$ GeV, there are mixture of signal and background (blue) and a pure signal (green). The sideband which contains only pure background is in $200 \leq m_{Z\gamma} \leq 240 \parallel 280 \leq m_{Z\gamma} \leq 400$ GeV mass region.

For a weakly supervised study, the training samples are categorised as sample-1 (M1) and sample-2 (M2). M1 is used as a background sample containing pure background in the sideband region and M2 is a signal sample consisting of an unknown mixture of signal and background in the mass-window region. The testing of the model is done using pure signal and pure background. In full supervision study, pure signal in the mass-window and background in the sideband are used for training and testing of the model. Both studies use 50% of data for training and 50% for testing.

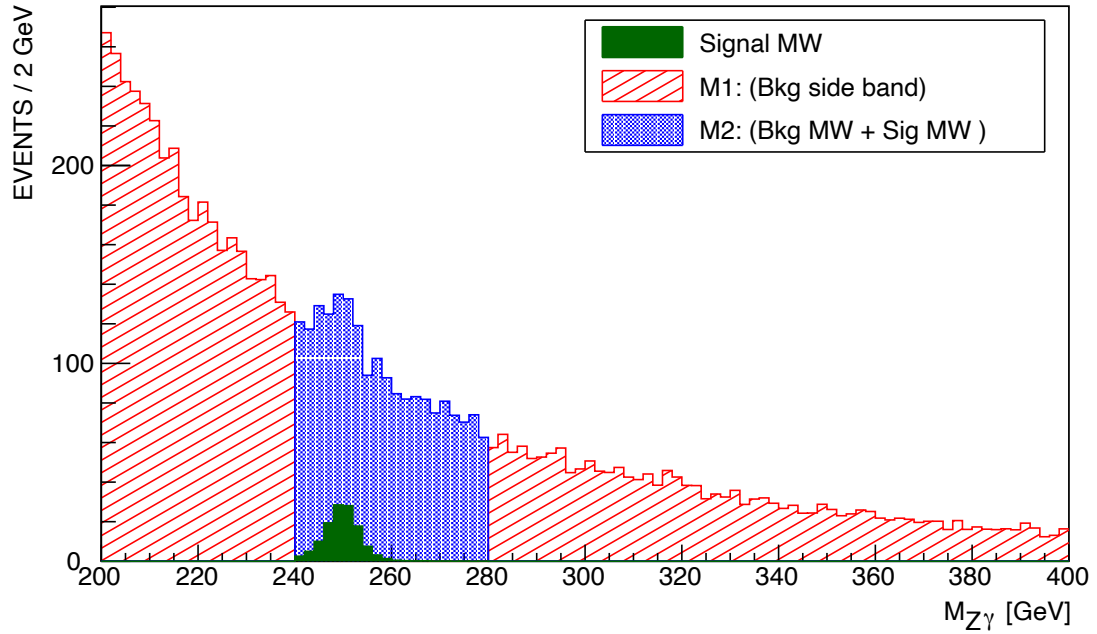


Figure F.2: Invariant mass distribution of the $Z\gamma$ in association with E_T^{miss} .

F.3.1 Preselection

The preselection for this analysis is defined in Figure F.3, where the total number of signal and background events in the mass-window and sideband are shown. There are 125 signal events mixing with 1811 background events in the mass-window as well as 5676 background events in the sideband. A selection on the missing transverse momentum was also defined by applying a preselection on the $E_{T, \text{sig}}^{\text{miss}}$ variable, where $E_{T, \text{sig}}^{\text{miss}}$ is defined as the E_T^{miss} divided by the square root of the scalar sum of all visible objects in an event (sum of E_T). The selection was fixed at $E_{T, \text{sig}}^{\text{miss}} \geq 2.5\sqrt{\text{GeV}}$, to maximise the signal events and minimise the background events as much as possible.

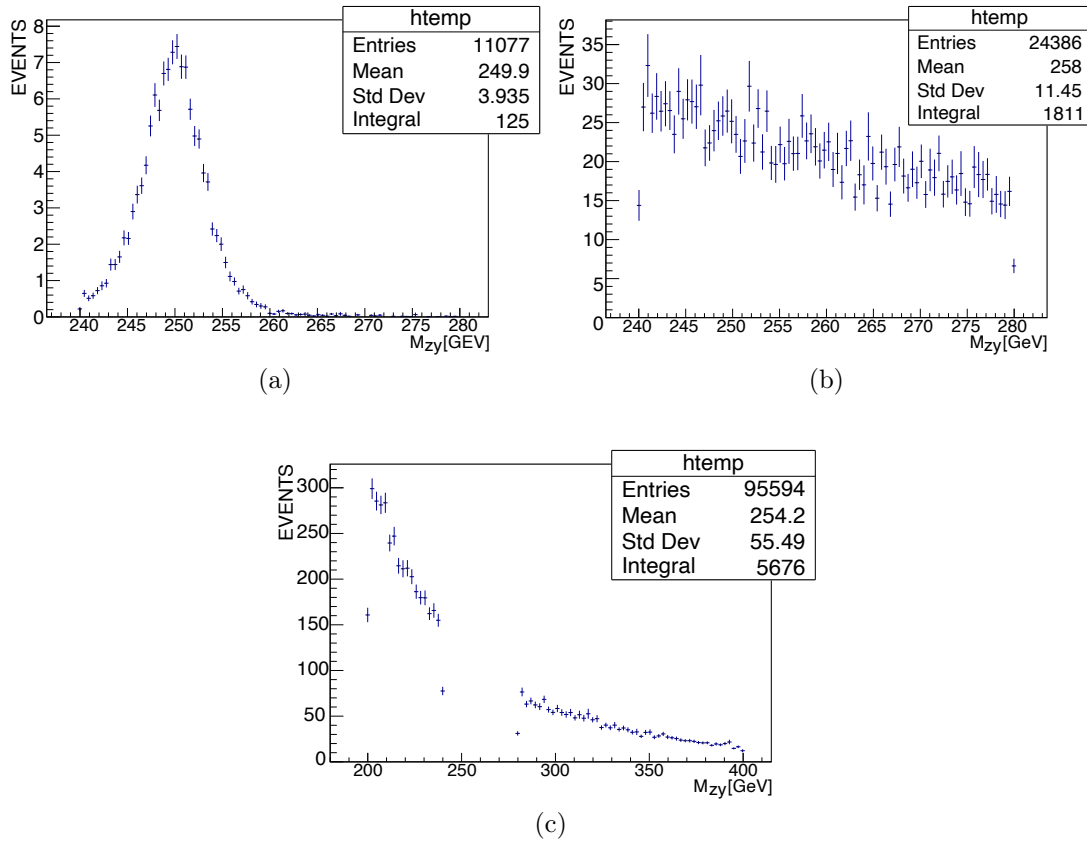


Figure F.3: Preselection for the pure signal F.3a and pure background F.3b in the masswindow, and pure background in the sideband F.3c.

F.4 Input variables used for S/B classification

The input variables utilized to train the DNN model are described below. The corresponding one-dimensional distributions of these variables are depicted in histograms in Section F.7, for both weakly supervised learning and full supervision learning scenarios:

- μ (μ): represents the average number of inelastic proton-proton interactions per bunch crossing. This parameter is commonly referred to as the pileup parameter.
- lsumpt2 (Leading vertex $\sum p_T^2$): represents the scalar sum of the squared

transverse momenta p_T of all the tracks associated with the leading vertex.

- **ssumpt2** (Subleading vertex $\sum p_T^2$): represents the scalar sum of the squared transverse momenta (p_T) of all the tracks associated with the subleading vertex.
- **dsumpt2** (Leading vertex $\sum p_T^2$ - Subleading vertex $\sum p_T^2$): The scalar difference between the squared transverse momentum p_T of the leading vertex and the squared p_T of the subleading vertex.
- **dphifjmet** ($\Delta\phi_{(\text{forward-jets}, E_T^{\text{miss}})}$): The variable $\Delta\phi$ represents the angular distance between forward jets and E_T^{miss} . Forward jets are jets with a high transverse momentum (p_T) located in the region $2.4 < |\eta| < 4.4$. In cases where there are no forward jets present, a default value of -1 is assigned. This variable is specifically designed to mitigate the occurrence of fake E_T^{miss} signals originating from events with non-JVT tagged jets.
- **dphisjmet** ($\Delta\phi_{(\text{soft-jets}, E_T^{\text{miss}})}$): The $\Delta\phi$ between soft jets and E_T . The soft jets are defined as jets with $20 < p_T < 30$ GeV and $|\eta| < 2.4$. Events that do not contain any soft jets are assigned a default value of -1. This variable is used to suppress fake E_T^{miss} signal arising from miscalibration of soft jets.
- **dphirefjetmet** ($\Delta\phi_{(\text{RefJets}, E_T^{\text{miss}})}$): The angular distance ($\Delta\phi$) between RefJets and E_T^{miss} . RefJets are defined as the vectorial sum of the p_T of all the jets considered in the reconstruction of E_T^{miss} .
- **djpt** (RefJets - p_T^{jj}): Scalar difference between RefJets and the vectorial sum of the p_T of the leading and subleading central jets (p_{jj}). In cases where there is only one central jet, p_{jj} is taken to be the p_T of the leading central jet. This variable quantifies the extent to which the jets not originating from the hard scattering vertex overlay with jets originating from the hard scattering vertex and enhance the fake E_T^{miss} signal.

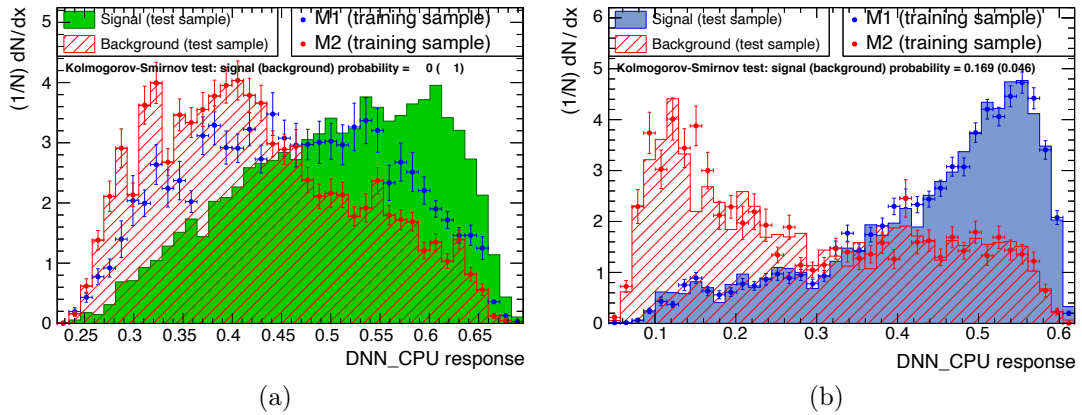


Figure F.4: Evaluation of classifier training output for weakly supervised F.4a and full supervised F.4b.

F.5 Results

F.5.1 Overtraining check for DNN classifier

Figures F.4a and F.4b show evaluation of DNN classifier training for weakly supervised and full supervised learning, respectively. The classifier output for test and training samples are checked for overtraining, which occurs when a classifier training has too many degrees of freedom due to many adjustable parameters for too few training events. Here the performance between training and testing samples was compared to detect obvious overtraining. A Kolmogorov Smirnov test is used to check if two sample distributions are compatible with coming from the same parent distribution, where a statistical KS-test should give a uniformly distributed value between 0 and 1.

F.5.2 Performance evaluation of the DNN classifier

The performance of the DNN classifier for both ML methods is evaluated using Receiver Operator Characteristic (ROC) curves, which is basically a generic scan of the classifier output distribution for both signal and background events. Fig-

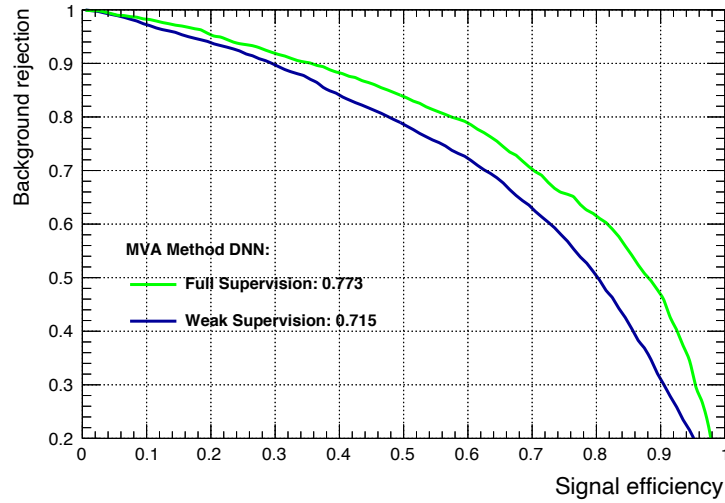


Figure F.5: Background rejection versus signal efficiency plot.

Figure F.5 shows a plot of background rejection versus signal efficiency for weakly supervised and full supervised classifier. One performance metric is the Area Under the Curve (AUC) which is the integral of the ROC curve. The ROC integral for weakly supervised classifier is 0.715 and 0.773 for fully supervised one. To determine the improvement in significance of the ROC curves, signal efficiency is divided by the square-root of background efficiency ($S_{eff}/\sqrt{B_{eff}}$) versus 1. The weak and full supervision curves have a significance improvement of 6% and 25%, respectively, measured at 50% of signal efficiency.

F.6 Conclusion

The aim of this study was to search for high-mass $Z\gamma$ resonances in 240-280 GeV mass range, in the view of compelling statistically significant excesses in multi-lepton final states compatible with physics at the electroweak scale. We have presented a search approach based on machine learning techniques, for classification of signal and background events. The combination of Deep Neural Networks, advanced weakly supervised and full supervised methodology can help for finding new particles in High Energy Physics. What we have tested so far in the $Z\gamma$ decay

channel already showed some improvements and a proof that the methodology is working.

F.7 1D distributions of input variables

In this study on weakly supervised learning, we present the one-dimensional distributions of input variables used for training and testing the DNN model. These distributions are depicted in Figures F.6 to F.23. In the context of the input variable distribution, it is important to clarify a distinction from the description provided in Section F.3. Here, M1 is used to represent a signal sample that encompasses an unidentified combination of signal and background events within the mass-window region, while M2 is designated as a background sample comprising exclusively pure background events within the side-band region. It is important to note that this labeling distinction is solely for identification purposes and does not impact the study itself.

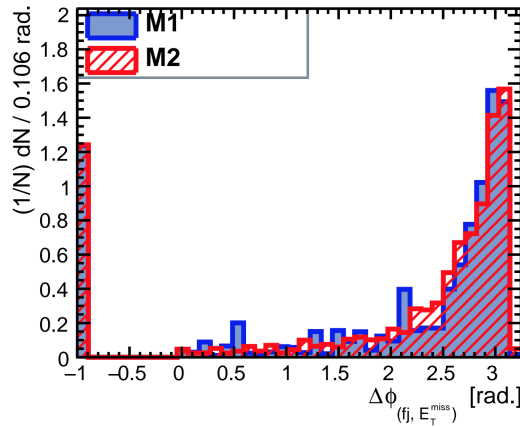


Figure F.6: $\Delta\phi_{(\text{forward-jets}, E_T^{\text{miss}})}$

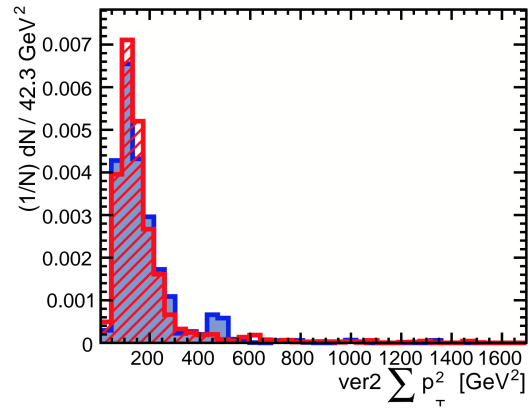
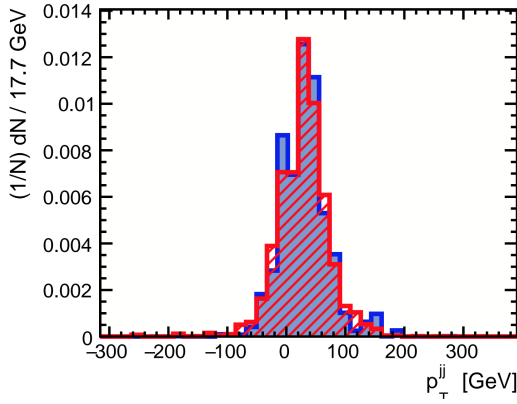
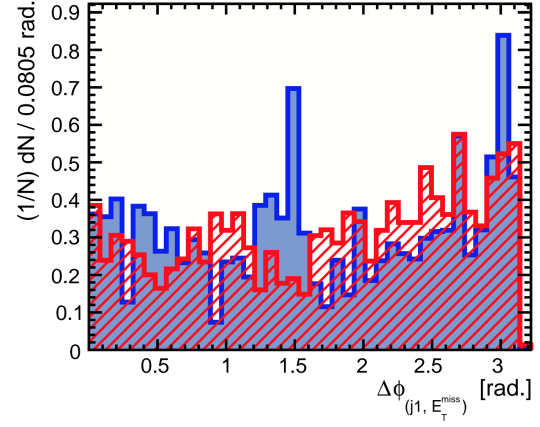
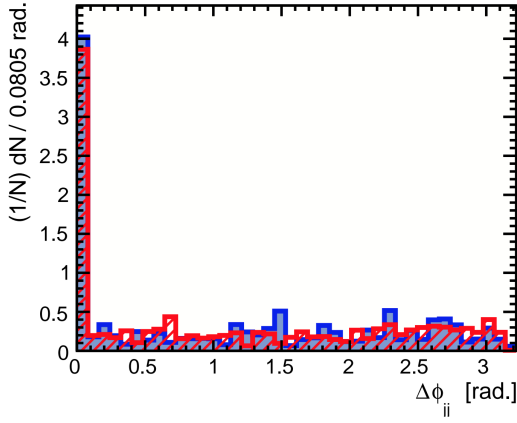
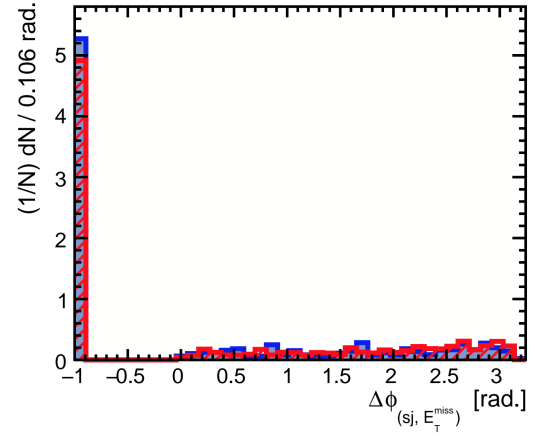
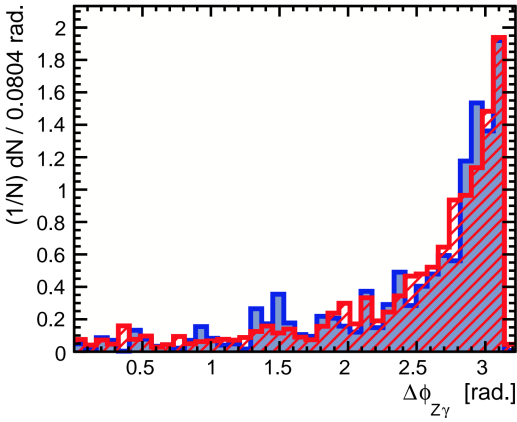
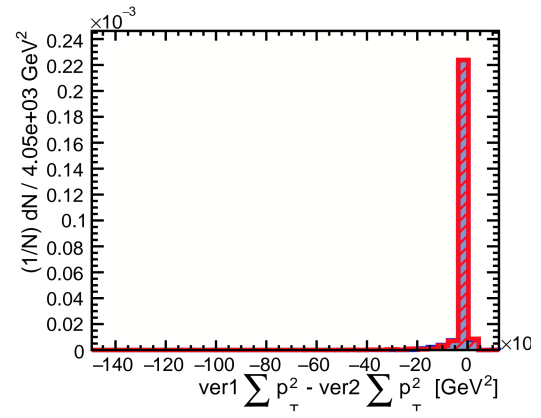
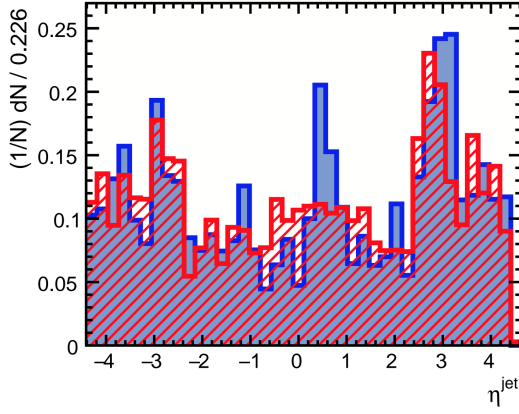
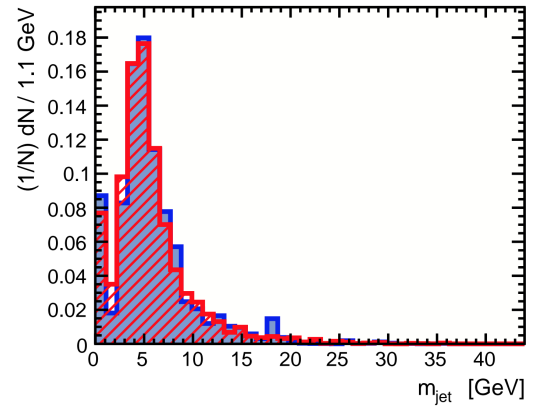
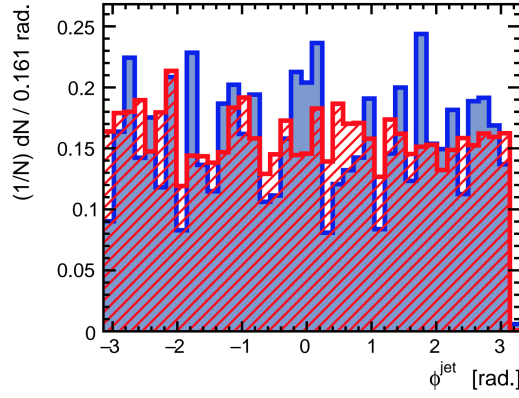
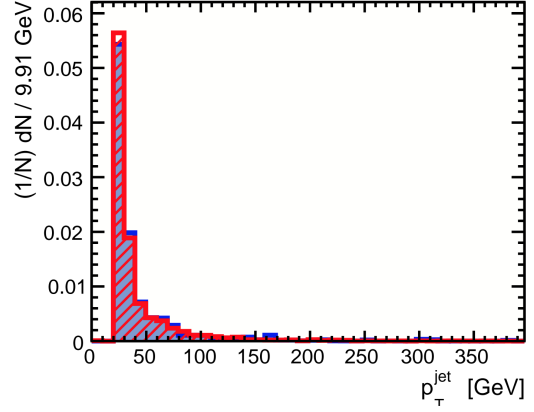
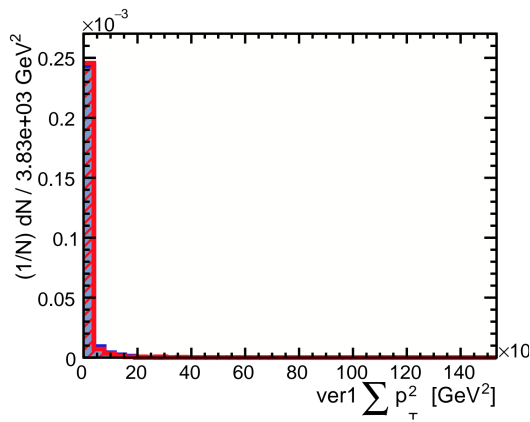
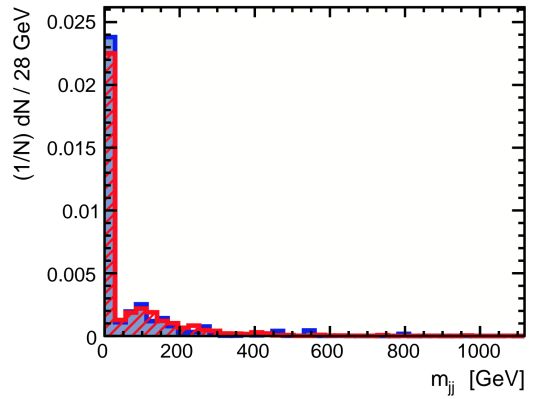
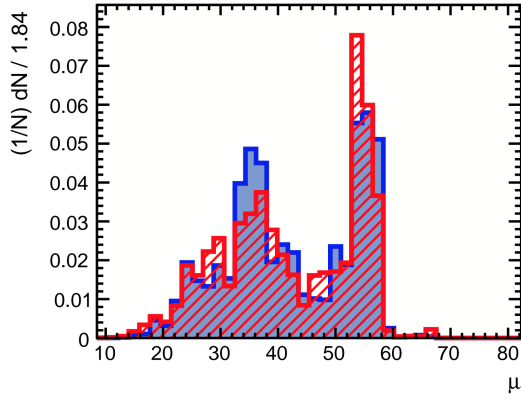
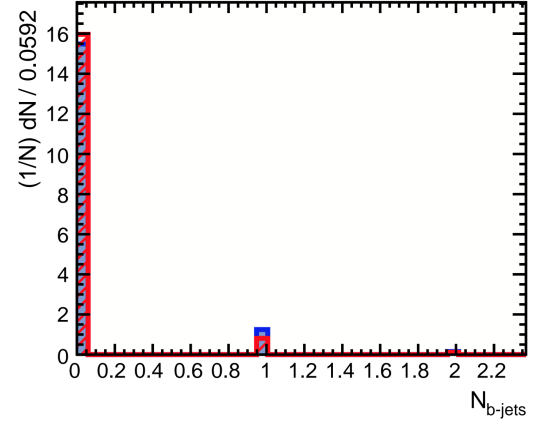
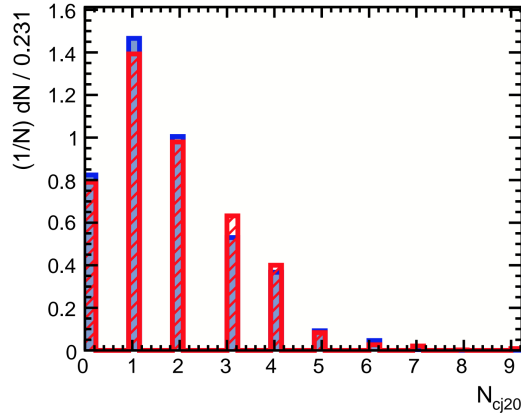
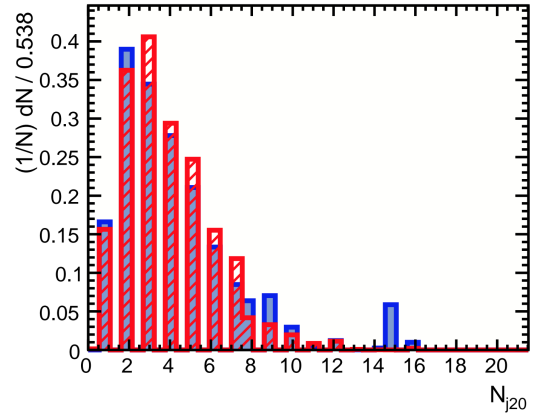


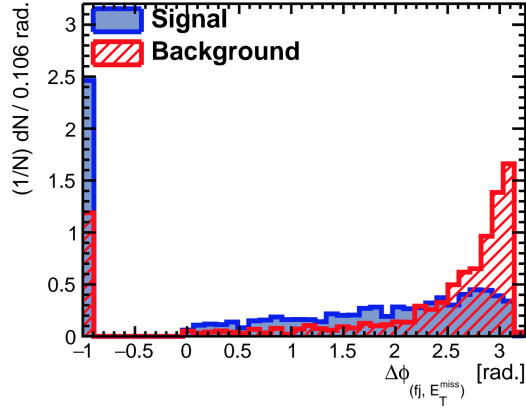
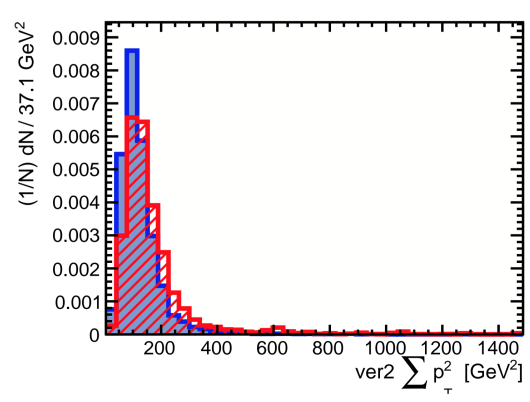
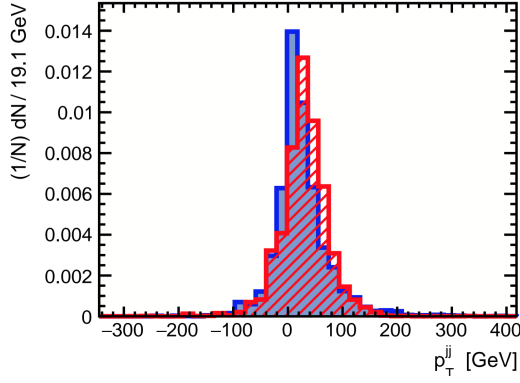
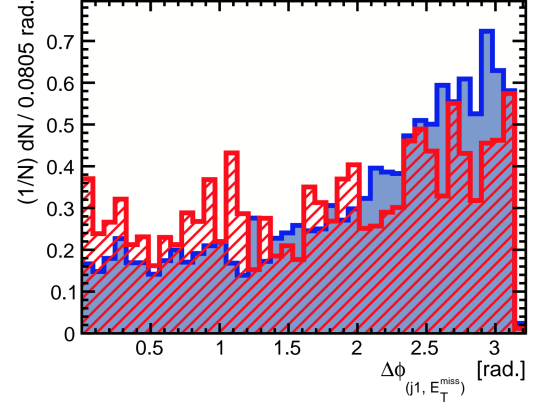
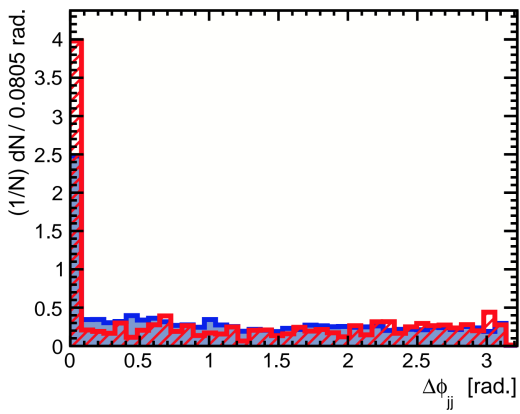
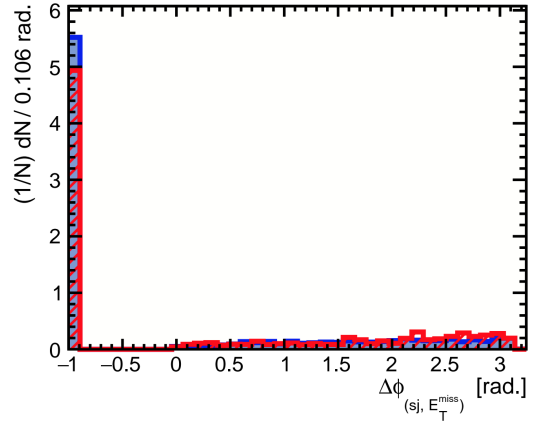
Figure F.7: Subleading vertex $\sum p_T^2$

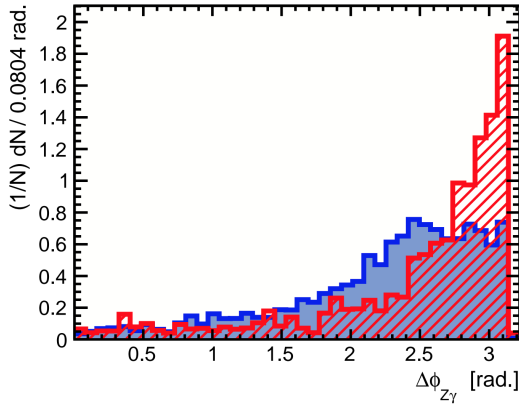
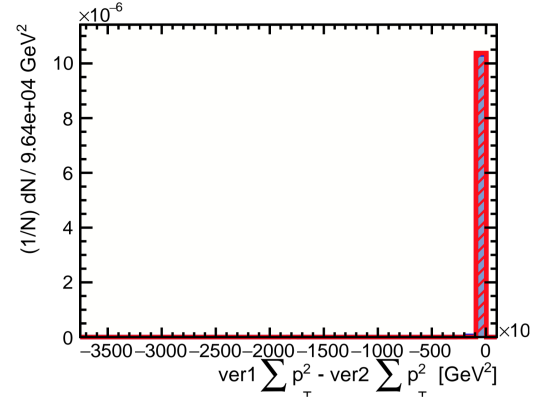
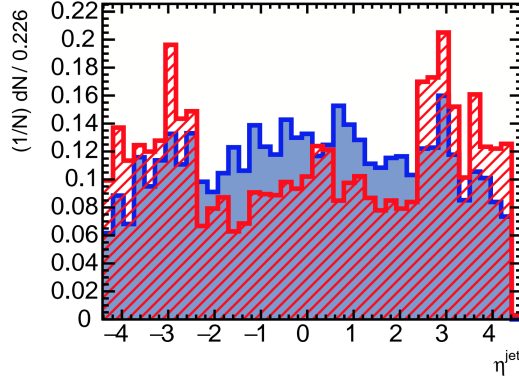
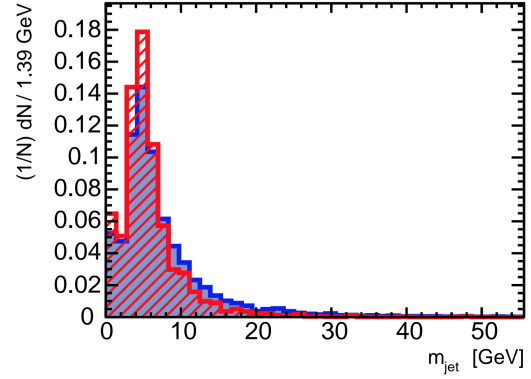
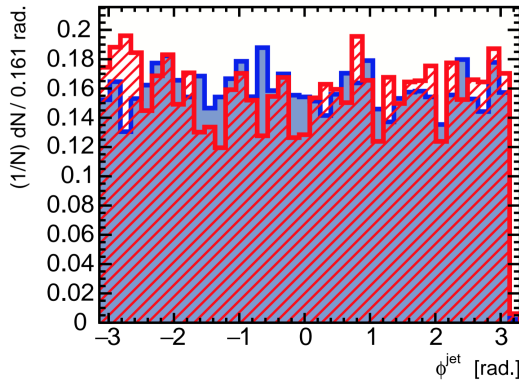
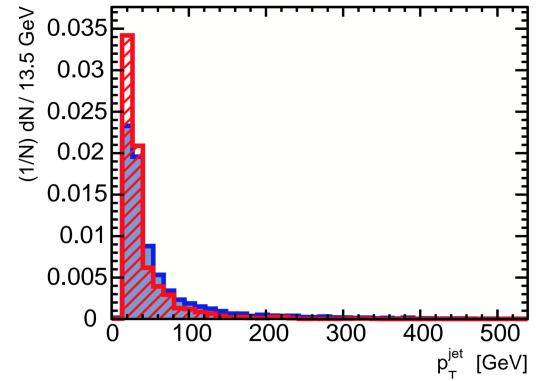
Figure F.8: RefJets - p_T^{jj} Figure F.9: $\Delta\phi_{(\text{jet1}, E_T^{\text{miss}})}$ Figure F.10: $\Delta\phi_{jj}$ Figure F.11: $\Delta\phi_{(\text{soft-jets}, E_T^{\text{miss}})}$ Figure F.12: $\Delta\phi_{Z\gamma}$ Figure F.13: Leading vertex $\sum p_T^2$ - Subleading vertex $\sum p_T^2$

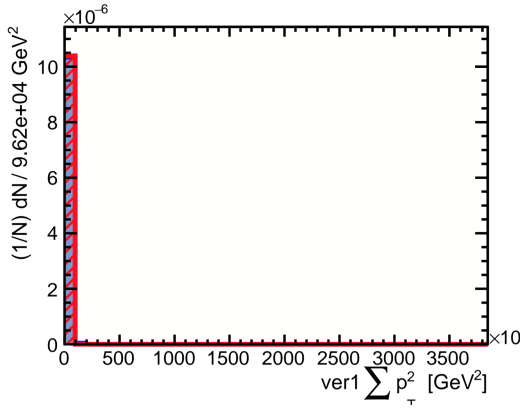
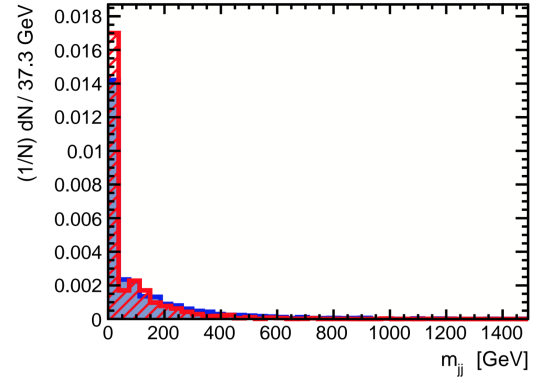
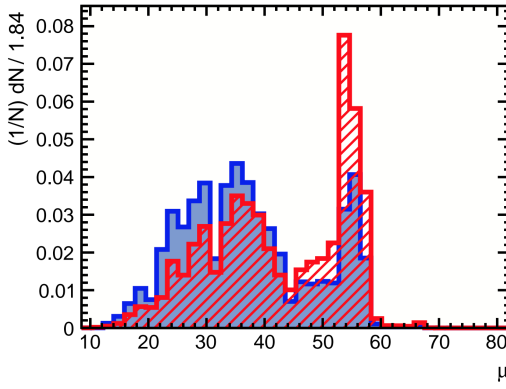
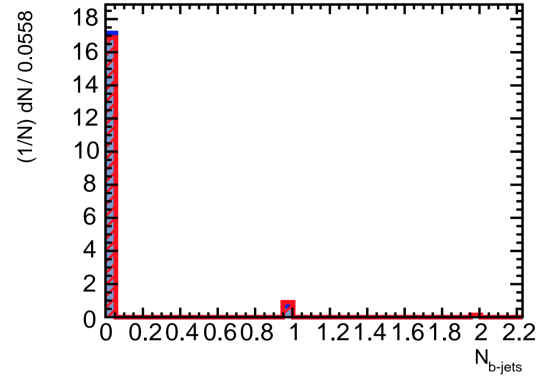
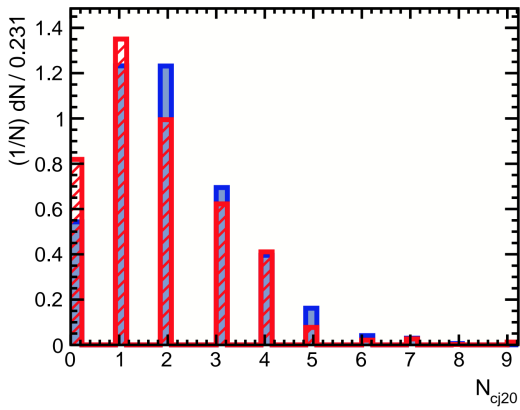
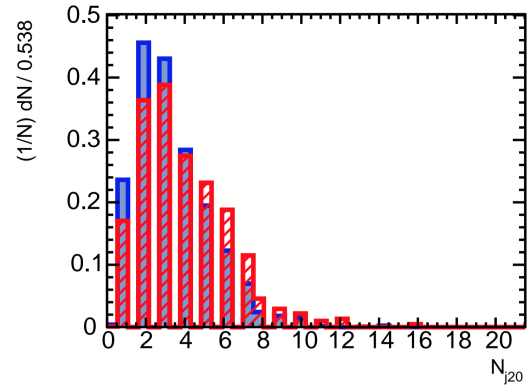
Figure F.14: η_{jet} Figure F.15: m_{jet} Figure F.16: ϕ_{jet} Figure F.17: p_T^{jet} Figure F.18: Leading vertex $\sum p_T^2$ Figure F.19: m_{jj}

Figure F.20: μ Figure F.21: $N_{b\text{-jets}}$ Figure F.22: N_{cj20} Figure F.23: N_{j20}

The Figures [F.24](#) to [F.41](#) illustrate the one-dimensional distributions of input variables employed for training the DNN model in the context of full-supervised learning. The histogram in blue illustrates the signal distribution, while the red histogram corresponds to the background distribution.

Figure F.24: $\Delta\phi_{(\text{forward-jets}, E_T^{\text{miss}})}$ Figure F.25: Subleading vertex $\sum p_T^2$ Figure F.26: RefJets - p_T^{jj} Figure F.27: $\Delta\phi_{(\text{jet1}, E_T^{\text{miss}})}$ Figure F.28: $\Delta\phi_{jj}$ Figure F.29: $\Delta\phi_{(\text{soft-jets}, E_T^{\text{miss}})}$

Figure F.30: $\Delta\phi_{Z\gamma}$ Figure F.31: Leading vertex $\sum p_T^2$ - Subleading vertex $\sum p_T^2$ Figure F.32: η_{jet} Figure F.33: m_{jet} Figure F.34: ϕ_{jet} Figure F.35: p_T^{jet}

Figure F.36: Leading vertex $\sum p_T^2$ Figure F.37: m_{jj} Figure F.38: μ Figure F.39: $N_{b\text{-jets}}$ Figure F.40: N_{cj20} Figure F.41: N_{j20}

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