
SEARCH FOR A HEAVY RESONANCE DECAYING INTO
TWO PHOTONS IN ASSOCIATION WITH B-JETS WITH THE
ATLAS DETECTOR AND CONSTRAINTS ON A 2HDM+S
MODEL

BY

ESRA MOHAMMED SHRIF MOHAMMED SALIH

SUPERVISOR: DR XIFENG RUAN

CO-SUPERVISOR: PROF BRUCE MELLADO



INSTITUTE FOR COLLIDER PARTICLE PHYSICS
UNIVERSITY OF THE WITWATERSRAND

*A thesis submitted to the Faculty of Science, the University of the Witwatersrand
for the degree of Doctor of Philosophy*

October 28, 2022

DECLARATION

I, Esra Mohammed Shrif (Student number 1467592) declare that this thesis is my own, unaided work except where I have explicitly indicated otherwise. It is submitted for award the Degree of Doctor of Philosophy of Science in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.



ABSTRACT

This thesis consists of two parts. The first part, a two-Higgs doublet model extended with an additional singlet scalar (2HDM+S) is motivated and discussed. A brief introduction to the model and its parameters space is provided. Constraints are applied to the parameter space of this model in order to accommodate a number of discrepancies in the data that have been interpreted in [1] as the result of the $H \rightarrow Sh$ decay produced via gluon-gluon fusion and in association with top quarks. Implications on the phenomenology of the heavy pseudo-scalar (A) and charged scalar (H^+) are discussed. In particular, the decays $A \rightarrow ZH$ and $H^+ \rightarrow W^+H$ become prominent. This leads to final states with multiple leptons and b -quarks. The decay $A \rightarrow ZH \rightarrow ZSh$ results in the production of a high transverse momentum Z produced in association with a lepton and two b -quarks with little additional jet activity. These predictions are compared to the data with the model's benchmark points. With the parameters obtained here, the model is able to accommodate the features at the LHC reported in [1]. Without varying these parameters additional excesses in the $Zb\bar{b}$ and $t\bar{t}$ invariant mass spectra, and the production of 3 leptons plus two b -tagged jets can be explained assuming $m_A \approx 600$ GeV. In the second part of this thesis, a search for a heavy resonance decaying into two photons in association with b -tagged jets is presented. The search uses proton-proton collision data taken at centre-of-mass energy of 13 TeV with the ATLAS detector at the LHC during 2015 to 2018. The dataset used corresponds to a total of 139 fb^{-1} integrated luminosity. Three different models are tested in this search. A Higgs boson like heavy scalar X produced with top quarks, b quarks or Z boson decaying into $b\bar{b}$ are examined. Limits on these models are set at 95% CL on the production cross-section times branching ratio into two photons, for masses ranging from 160 GeV-1.6 TeV.

ACKNOWLEDGEMENTS

First and foremost, all thanks and praise be to Almighty Allah, the Most Gracious, and the Most Merciful for His blessing given to me during my studies. I would like to express my profound gratitude and sincere appreciation to my supervisor Dr Xifeng Ruan who provided me with valuable advice, insight, technical and analytical skills throughout my degree. I would also like to show my greatest appreciation to Prof Bruce Mellado for his guidance, mentoring and hosting me at Institute for Collider Particle Physics (ICPP) group at the University of the Witwatersrand.

I thank my entire colleagues at the ICPP group for their help, support, and advice during my PhD undertakings. I am most grateful to Dr Shell-May and Dr Stefan for sharing their deep knowledge about particle physics at the beginning of my PhD. Special thanks to my friend and colleague Abdualazem, for his guidance and support throughout my PhD. Perhaps, this acknowledgment is incomplete without thanking Prof Deepak Kar for inviting me to attend his lectures on particle physics and ROOT framework and for his experimental particle physics book, which teaches me a lot. Many thanks are extended to Dr Mukesh Kumar, Prof Alan Cornell for their contribution in calibration studies.

I will forever be indebted to my beloved mother for her love, support, encouragement and understanding throughout my academic journey. To my dearest brother, Noural-daem, thank you for your love, support and for soldering the responsibility of taking care of our mother during my stay in South Africa.

I acknowledge the financial assistance I received from the Schlumberger foundation the faculty for the future towards this research. I also acknowledge the assistance from the SA-CERN consortium and iThemba LABS for sponsoring my trip to CERN and to conferences and workshops throughout South Africa and abroad. Their assistance is well received and truly appreciated.

To everyone and all those that we cross-path and I have not mentioned: Lots of love and thank you.

*To my Mother
For her endless love and support.*

CONTENTS

Declaration	i
Abstract	ii
Acknowledgements	iii
List of Figures	viii
List of Tables	xiv
List of Abbreviations	xvi
1 Introduction	1
2 Theoretical background	4
2.1 The Standard Model of particle physics	4
2.2 The BEH mechanism and Yukawa interactions	7
2.3 Theoretical constraints on the Higgs boson mass	10
2.3.1 The unitarity bounds	10
2.3.2 The triviality constraint	11
2.3.3 The vacuum stability constraint	11
2.3.4 The fine-tuning constraint	13
2.4 Physics Beyond the SM	14
2.4.1 Limitations of the SM	14
2.4.2 Two Higgs doublet models	16
2.5 The SM Higgs Boson	20
2.5.1 The Higgs production modes	20
2.5.2 The Higgs decay modes	21
2.5.3 Discovery of the SM Higgs boson at the LHC	23
3 Experimental apparatus	26
3.1 The Large Hadron Collider	26
3.1.1 LHC performance	28
3.1.2 LHC parameters of interest	29
3.1.3 Experiments at the LHC	30
3.2 The ATLAS detector	31

3.2.1	The Inner Detector	33
3.2.2	The Calorimeters System	35
3.2.3	Muon Spectrometer	37
3.2.4	Trigger System	39
4	Constraints on a 2HDM+S and implications in the search for heavy bosons at the LHC	41
4.1	Introduction	41
4.2	The Model	43
4.3	Tools and phenomenology	48
4.4	The MC Studies	54
4.4.1	$A \rightarrow Zh$ search	55
4.4.2	Three leptons in association with two b -tagged jets	58
4.4.3	Measurement of Vh production signal strength	60
4.5	Summary	62
5	Search for a resonance decaying into two photons in association with b-jets	65
5.1	Introduction	65
5.2	Data and simulated samples	66
5.2.1	Data	66
5.2.2	Signal	67
5.2.3	Backgrounds	67
5.3	Object selection	69
5.3.1	Photons	69
5.3.2	Leptons	69
5.3.3	Jets	70
5.3.4	B -tagging Jets	70
5.3.5	Primary vertex	71
5.3.6	Overlap removal	71
5.4	Event optimization	71
5.5	Event selections	77
5.6	Signal Parameterization	87
5.7	Diphoton purity measurement	92
5.8	Background Parameterization	93
5.8.1	The ratio method	93
5.8.2	The spurious signals	97
5.9	Statistical Interpretation of Results	102
5.9.1	Systematic Uncertainties	102

5.9.2	Statistical models	106
5.9.3	Results	109
6	Conclusions	116
	Appendices	118
	Appendix A: Additional parameter correlations for Section 4.3	119
	Appendix B: Additional plots for Sections 5.4 and 5.5	121
	Appendix B.1: Event optimization	121
	Appendix B.2: Event selection	121
	Appendix C: Additional Plots for Section 5.6 to 5.8	129
	Appendix C.1: Signal parametrization	129
	Appendix C.2: The Ratio Method	129
	Appendix C.3: Spurious Signal	130
	Appendix D: Additional plots for Sections 5.9	154
	Appendix D.1: Systematic uncertainties	154
	Appendix D.2: Statistical model	154
	References	171

LIST OF FIGURES

2.1	The fundamental particles of the standard model	5
2.2	The Higgs potential $V(\Phi)$ for different signs of the parameter μ^2	8
2.3	Feynman diagrams for one-loop self-coupling of the Higgs boson	12
2.4	The triviality (upper) and vacuum stability (lower) bounds on m_H as a function of Λ for some SM parameters.	12
2.5	Feynman diagrams for the one-loop fermion (F) and gauge boson (V) to contribution λ	13
2.6	The significant quadratically divergent contributions to the m_H in the SM	13
2.7	Higgs production Feynman diagrams	21
2.8	SM Higgs boson production cross-section and decay branching ratios .	23
2.9	The discovery plots for the invariant mass for the 4ℓ and $\gamma\gamma$ channels by ATLAS and CMS	24
2.10	The ATLAS and CMS observed local p-value as a function of m_H in the low mass range for 7 and 8 TeV data	25
2.11	Combined Higgs mass measurements in the $\gamma\gamma$ and 4ℓ channels obtained by the ATLAS and CMS experiments in Run-1 and Run-2.	25
3.1	The CERN accelerator complex	27
3.2	A cut-away view of the ATLAS detector	31
3.3	The ATLAS right-handed Cartesian and cylindrical coordinate systems.	32
3.4	An illustration of the ATLAS Inner Detector and its sub-systems	33
3.5	A cut-away view of the ATLAS calorimeter system	35
3.6	Schematic drawing of the ATLAS ECAL and HCAL modules	36
3.7	Transverse and longitudinal view of the ATLAS Muon Spectrometer . .	38
4.1	Allowed values of the mixing angles α_1, α_2 and α_3 for the benchmark considered here in the 2HDM+S	47
4.2	Correlation plots between the mixing angles α_1, α_2 and α_3 against $\tan\beta$ for the benchmark considered here in the 2HDM+S	47
4.3	Correlation plots between the BRs of different h production vs $h \rightarrow Z\gamma$	49
4.4	Correlation plots between the BRs of different productions of S vs $h \rightarrow Z\gamma$	50
4.5	The BRs of S, H, A and $H^\pm$ in the differnt ranges of their masses . . .	53
4.6	The jet multiplicity for the decay $A \rightarrow ZH \rightarrow ZSh$ produced via ggF .	56

4.7	Distribution of the invariant mass of the Zh system from the $A \rightarrow ZH \rightarrow Zh\bar{h}$ (left) and $A \rightarrow ZH \rightarrow ZSh$ (right) decays, where $m_H = 270$ GeV and $m_S = 145$ GeV.	58
5.1	Feynman diagrams for the production of the Higgs like boson in association with a pair of top quarks, bottom quarks and with the Z boson. .	66
5.2	The optimization result for the $t\bar{t}X$ $m_X = 180$ GeV in each region with two significance's formulas	74
5.3	All background distribution with relative photon p_T cuts for (a) category-1, (b) category-3 and (c) category-11.	76
5.4	Kinematic distributions corresponding to different variables after the event preselection in the control region ($m_{\gamma\gamma}$ in 130-160 GeV)	78
5.5	Distributions of $\Delta\phi_{\gamma\gamma}$ with different event cuts	79
5.6	Distributions of m_{bb} with different event cuts.	80
5.7	Description of the double-sided Crystal Ball function shape and parameters, The different parameters are described in the text.	87
5.8	The results of a single fit of a DSCB function and the width of the resonance peak (σ_{CB}) as a function of the resonance mass for the simulated signal sample $t\bar{t}X$ in category 3	89
5.9	An example of the acceptance times efficiency fit process for $t\bar{t}X$	91
5.10	1 signal and 15 control regions in 2x2D sideband method, this data-driven method is based on photon tight ID and photon isolation.	92
5.11	The ratios of the simulated background samples γj and $\gamma\gamma$ in signal and control region for category 3.	96
5.12	The smoothed and raw shape of γj and $\gamma\gamma$ in category 3 compared with the merged template of all background in category 3.	96
5.13	Example of fitting on the background MC template category 3, using a signal plus background function.	98
5.14	The $N_{spur}/\delta N_{spur}$ as a function of mass for each functional form using raw and smoothed background.	98
5.15	Fitting on the background MC template for category 3, using background functions.	101
5.16	The systematic uncertainty in the signal yields corresponding different objects for category 3 given as a function of the resonance mass	104
5.17	The systematic uncertainty of $e - \gamma$ scale and $e - \gamma$ resolution in the signal shape as a function of the resonance mass in category 3	105
5.18	The scale uncertainty and the PDF+ α_S uncertainty in the migration of the signal yields as a function of the resonance mass in category 3. . . .	105

5.19	The fit on the background only Asimov data based on the MC background template in the $t\bar{t}X$ channel (a) with 800 GeV signal and (b) with 1200 GeV signal.	110
5.20	The correlation matrix for all the systematics for $t\bar{t}X$ (first row), $b\bar{b}X$ (second row), ZX (last row) samples for 300 GeV mass (left) and 1200 GeV mass (right).	111
5.21	The ranking for all the systematics for $t\bar{t}X$, samples for 300 GeV mass (top) and 1200 GeV mass (bottom).	112
5.22	The ranking for all the systematics for $b\bar{b}X$, samples for 300 GeV mass (top) and 1200 GeV mass (bottom)	113
5.23	The ranking for all the systematics for ZX , samples for 300 GeV mass (top) and 1200 GeV mass (bottom)	114
5.24	The expected CLs limits on the production cross-section of the resonance X times its branching fraction to $\gamma\gamma$ as a function of the resonance mass m_X for each model.	115
A.1	Allowed values of α_1, α_2 and α_3 against m_{12}^2 for the benchmark considered in section 4.3.	119
A.2	Allowed values of α_1, α_2 and α_3 against v_S for the benchmark considered in section 4.3.	120
A.3	Correlation of allowed values between (a) m_{12}^2 and $\tan\beta$, (b) m_{12}^2 and v_S , (c) $\tan\beta$ and v_S for the benchmark considered in section 4.3.	120
B.1	The optimization result for the $t\bar{t}X$ $m_X = 250$ GeV in each region with two significance's formulas	122
B.2	The optimization result for the ZX $m_H = 200$ GeV with different $\Delta\phi_{\gamma\gamma}$ cuts with two significance's formulas.	123
B.3	The optimization result for the ZX $m_H = 200$ GeV with different $\Delta\phi_{\gamma\gamma}$ cuts with two significance's formulas.	124
B.4	The optimization result for the $b\bar{b}X$ with (a) $m_X = 180$ GeV and (b) $m_X = 180$ GeV.	124
B.5	Distributions of the jet multiplicity with different event cuts	125
B.6	Distributions of the central jet multiplicity with different event cuts	126
B.7	Distributions of the transverse momentum of the leading photon with different event cuts	127
B.8	Distributions of the transverse momentum of the subleading photon with different event cuts	128
C.1	The results of a single fit of a DSCB function (lines) for $t\bar{t}X$ signal sample with $m_H = 180$ GeV in the categories 0, 3-10, 14 and 15	131

C.2	Width of the resonance peak as a function of the resonance mass for $t\bar{t}X$ signal in the categories 0, 3-10, 14 and 15.	132
C.3	Width of the resonance peak as a function of the resonance mass for $b\bar{b}X$ signal in each category.	133
C.4	Width of the resonance peak as a function of the resonance mass for the ZX signal in each category.	133
C.5	The DSCB parameter α_{low} as a function of the resonance mass for $t\bar{t}X$ signal in the categories 0, 3-10, 14 and 15.	134
C.6	The DSCB parameter α_{high} as a function of the resonance mass for $t\bar{t}X$ signal in the categories 0, 3-10, 14 and 15.	135
C.7	Acceptance times efficiency at different mass points of the $b\bar{b}X$ signal in categories 0-2.	136
C.8	Acceptance times efficiency at different mass points of the $t\bar{t}X$ signal in the categories 0, 14 and 15.	136
C.9	Acceptance times efficiency at different mass points of the ZX signal in categories 0, 14 and 15.	136
C.10	Acceptance times efficiency at different mass points of the $t\bar{t}X$ signal in the categories 16-18.	137
C.11	Acceptance times efficiency at different mass points of the ZX signal in categories 16-18	137
C.12	Fraction of events for the $t\bar{t}X$ signal in the categories 3-10 as a function of the resonance mass.	138
C.13	Fraction of events for the ZX signal in the categories 11-13 as a function of the resonance mass.	138
C.14	Acceptance times efficiency for the $t\bar{t}X$ signal in the categories 3-10 as a function of the resonance mass.	139
C.15	Acceptance times efficiency for the ZX signal in the categories 11-13 as a function of the resonance mass.	139
C.16	The ratio of γj sample in signal and control region. The fit is also shown.	140
C.17	The ratio of $\gamma\gamma$ sample in signal and control region. The fit is also shown.	141
C.18	The smoothed shape and the raw shape of γj sample in categories 0-7.	142
C.19	The smoothed shape and the raw shape of γj sample in categories 8-15.	143
C.20	The smoothed shape and the raw shape of $\gamma\gamma$ sample in categories 0-7.	144
C.21	The smoothed shape and the raw shape of $\gamma\gamma$ sample in categories 8-15.	145
C.22	The smoothed merged shape and the raw merged shape of all the background samples in categories 0-7.	146
C.23	The smoothed merged shape and the raw merged shape of all the background samples in categories 8-15.	147

C.24 Example of fitting on the background MC template for category 1-15 using a signal plus background function.	148
C.25 The $N_{spurious}/\delta N_{spurious}$ as a function of mass for each functional form using raw background.	149
C.26 The $N_{spurious}/\delta N_{spurious}$ as a function of mass for each functional form using smoothed background.	150
C.27 The $N_{spurious}$ envelop for each functional form.	151
C.28 Fitting on the background MC template for categories 0-7 using background functions.	152
C.29 Fitting on the background MC template for categories 8-15 using background functions.	153
D.1 The systematic uncertainty due to $e - \gamma$ scale and resolution affecting the signal yields as a function of the resonance mass in each category. .	155
D.2 The systematic uncertainty due to the b -tagging as a function of the resonance mass in each category.	156
D.3 The systematic uncertainty due to muon selection efficiency as a function of the resonance mass in each category.	157
D.4 The systematic uncertainty due to electron selection efficiency as a function of the resonance mass in each category.	158
D.5 The systematic uncertainty due to photon selection efficiency as a function of the resonance mass in each category.	159
D.6 The systematic uncertainty due to jet energy resolution, energy scale and selection efficiency as a function of the resonance mass in each category.	160
D.7 The systematic uncertainty due to pile-up reweighting as a function of the resonance mass in each category.	161
D.8 The systematic uncertainty of $e - \gamma$ resolution in the signal shape as a function of the resonance mass in each category.	162
D.9 The systematic uncertainty of $e - \gamma$ scale in the signal shape as a function of the resonance mass in each category.	163
D.10 The scale uncertainty in the migration of the signal yields as a function of the resonance mass in each category.	164
D.11 The PDF+ α_S uncertainty in the migration of the signal yields as a function of the resonance mass in each category.	165
D.12 The fit on the background only Asimov data based on the MC background template in the $t\bar{t}X$ channel with 300 GeV signal.	166
D.13 The fit on the background only Asimov data based on the MC background template in the $t\bar{t}X$ channel with 800 GeV signal.	167

D.14	The fit on the background only Asimov data based on the MC background template in the $t\bar{t}X$ channel with 1200 GeV signal.	167
D.15	The fit on the background only Asimov data based on the MC background template in the $b\bar{b}X$ channel with 300 GeV signal.	168
D.16	The fit on the background only Asimov data based on the MC background template in the $b\bar{b}X$ channel with 1200 GeV signal.	168
D.17	The fit on the background only Asimov data based on the MC background template in the ZX channel with 300 GeV signal.	169
D.18	The fit on the background only Asimov data based on the MC background template in the ZX channel with 800 GeV signal.	170
D.19	The fit on the background only Asimov data based on the MC background template in the ZX channel with 1200 GeV signal.	170

LIST OF TABLES

2.1	The SM Higgs boson production cross-sections and decay branching ratios for different processes	22
3.1	Evolution of the LHC beam parameters.	30
3.2	Calorimetry energy resolution, as obtained from beam-test results . . .	37
4.1	The coupling coefficient $c(Hiff)$ as defined in eq. (4.2.19).	46
4.2	The fraction of events with exactly two or more than two b -tagged jets with respect to the ggF production of $A \rightarrow Zh$ in a 2HDM	57
4.3	The fraction of events after the application of the event selections described in section 4.4.1 with respect to at least and exactly two b -tagged jets final states for the signal sample $A \rightarrow ZH \rightarrow Zhh$	59
4.4	The fraction of events after the application of the event selections described in section 4.4.1 with respect to at least and exactly two b -tagged jets final states for the signal sample $A \rightarrow ZH \rightarrow ZSh$	59
4.5	The fraction of events after the application of the event selections described in the text with respect to three lepton final states for both $A \rightarrow ZH \rightarrow Zhh$ and $A \rightarrow ZH \rightarrow ZSh$ signals.	60
4.6	The potential contamination from the BSM production mechanisms, in the measurement of the signal strength of the Vh , $Z = Z, W$ in the SM	62
5.1	The $t\bar{t}X$, $b\bar{b}X$, ZX signal samples used in this analysis.	68
5.2	Non-resonant background processes relevant in this analysis.	68
5.3	The optimization results for the $t\bar{t}X$ and $b\bar{b}X$ models. The significance corresponding to the optimal $\Delta\phi(\gamma, \gamma)$ and N_{cjet} cuts for each region.	72
5.4	The optimization result for the ZX model in the two b -tagged jets region. The significance corresponding to the optimal cuts on the high and low values of m_{bb} with different $\Delta\phi(\gamma, \gamma)$	72
5.5	Relative p_T cut on the $t\bar{t}X$ samples with $m_X = 180, 250$ and 500 GeV for category $N_{bjet} \geq 1 \& N_{leps} \& N_{cjet} \geq 4$	75
5.6	Relative p_T cut on the $t\bar{t}X$ samples with $m_X = 180, 250$ and 500 GeV for category $N_{bjet} \geq 1 \& N_{leps} \& N_{cjet} \geq 4$	75
5.7	Relative p_T cut on the ZX samples with $m_X = 200$ and 400 GeV for category 11.	75
5.8	The definition of each category, for different models and mass range. . .	77

5.9	The background cut flow table in the control region with $m_{\gamma\gamma} = 130$ - 160 GeV.	81
5.10	The background cut flow table in all region.	82
5.11	The cutflow for the $t\bar{t}X$, $b\bar{b}X$ and ZX signal samples normalized to 1fb with $m_{\gamma\gamma} > 130$ GeV.	83
5.12	Significance in each category for $t\bar{t}X$ in each mass points with some selected categories	84
5.13	Significance in each category for ZX in each mass points with some selected categories.	85
5.14	Significance in each category for $b\bar{b}X$ in categories 0-3 in each mass points .	86
5.15	The temporarily defined category dedicated for the signal efficiency pa- rameterisation.	89
5.16	The statistical and systematic uncertainties in the estimation of the signal efficiencies.	90
5.17	Purities with 2x2D sideband method with at least one bjet selection. .	93
5.18	The treatment of each MC background template for their shape and normalisations.	94
5.19	The definition of the control regions and the ratio method of the $\gamma\gamma$ and γj samples.	95
5.20	Parameterized functions form to describe the Spurious signal for cate- gories 0-7. The yields of the spurious signal correspond to 2015-2018 139 fb^{-1} luminosity.	99
5.21	Parameterized functions form to describe the Spurious signal for cate- gories 8-15. The yields of the spurious signal corresponds to 2015-2018 139 fb^{-1} luminosity.	100
5.22	The selected functional forms for each category.	101
5.23	Breakdown of the dominant systematic uncertainties.	108

LIST OF ABBREVIATIONS

Acronyms

2HDM	Two-Higgs doublet model
ATLAS	A Toroidal LHC Aparatus
BEH	Brout-Englert-Higgs
BR	Branching Ratio
BSM	Beyond the Standard Model
CDC	Cathode Strip Chambers
CERN	The European Organization for Nuclear Research
CL	Confidence Level
CMS	Compact Muon Solenoid
CP	Charge conjugation and Parity
DSCB	Double-sided crystal ball
EB	Event Builder
ECal	Electromagnetic Calorimeter
ESS	Event Selection Software
ET	Event Filter
EW	Electroweak interaction
EWSB	Electroweak Symmetry Breaking
FCal	Forward Calorimeter
FCNC	Flavour Changing Neutral Currents
GeV	Gegaelectronvolt
ggF	gluon-gluon-Fusion

HCal	Hadronic Calorimeter
HEC	Hadronic End-cap Calorimeter
HL-LHC	High Luminosity LHC
HLT	High-Level Trigger (HLT)
IBL	Insertable B-Layer
ICPP	Institute for Collider Particle Physics
ID	Inner Detector
IP	Interaction Point
JVT	Jet Vertex Tagger
L1	Level-1 trigger
L2	Level-2 trigger
LAr	Liquid Argon
LED	Light Emitting Diode
LEP	The Large Electron-Positron Collider
LHC	The Large Hadron Collider
LINAC	Linear Accelerator
LO	Leading Order
LS	Long Shutdown
MC	Monte Carlo
MDT	Monitored Drift Tube chambers
MeV	Megaelectronvolt
NLO	Next-to-leading Order
NNLO	Next-to-next-to-leading Order
PD	Pixel Detector
PDF	Parton Distribution Function
PMTs	Photo-Multiplier Tubes

PS	Proton Synchrotron
PSB	Proton Synchrotron Booster
QCD	Quantum Chromodynamics
QED	Quantum Electrodynamics
Run-1	The LHC data taking period from 2009 to 2013
Run-2	The LHC data taking period from 2015 to 2018
Run-3	The LHC data taking period from 2022 to 2024
SCT	Semi-Conductor Tracker
SM	Standard Model
SPS	Super Synchrotron Booster
TeV	Teraelectronvolt
TGC	Thin Gap Chambers
TileCal	Tile Hadronic Calorimeter
TRT	Transition radiation tracker
VBF	Vector Boson Fusion
vev	Vacuum expectation value

Symbols

$\mathcal{L}$	Instantaneous luminosity
$\mathcal{L}$	Lagrangian density
η	Pseudorapidity
$\sqrt{s}$	centre-of-mass energy
ϕ	Azimuthal angle
γ	Photon
g	Gluon
ℓ	Leptons ($\mu, e, \tau, \nu_\mu, \nu_e, \nu_\tau$)
q	Quarks (u, d, c, s, t, b)

b	Bottom quark
c	Charm quark
d	Down quark
s	Strange quark
t	Top quark
u	Up quark
μ	Muon
e	Electron
τ	Tau lepton
ν_μ	Muon neutrino
ν_e	Electron neutrino
ν_τ	Tau neutrino
h	Standard Model Higgs boson
H	Heavy boson, heavier than h
σ	Significance or Cross section
S, X	Higgs-like scalar bosons
E_{T}	The transverse energy
$E_{\text{T}}^{\text{miss}}$	The missing transverse energy
p_{T}	The transverse momentum of a particle
H_{T}	The scalar sum of the transverse momenta
fb^{-1}	Inverse femtobarns (Unit of integrated luminosity)

INTRODUCTION

In the last several decades, great achievements have been made in the field of particle physics, through the work of many visionary scientists around the world with the help of giant technological developments. Many interesting ideas were proposed and developed successfully in quantum field theories for describing strong, electromagnetic and weak interactions. Those new ideas were combined into a simple and beautiful theory known as the Standard Model (SM) of particle physics, a theory of symmetries in nature [2, 3, 4]. The SM developed in the late 1960's, and was formulated in the framework of non-Abelian gauge theory that successfully describes with great accuracy the fundamental particles and their interactions. Since then, a wide range of experiments have tested and confirmed most of the SM predictions with extraordinary precision.

The Higgs boson, being the last missing particle predicted by the SM, the Higgs boson has been extensively searched for during the last decades by the Large Electron Positron collider (LEP) at CERN, followed by the Tevatron proton-antiproton collider at Fermilab which ceased operation in 2011. In 2010, the Large Hadron Collider (LHC), a proton-proton and heavy-ion collider, started to take data at unprecedented centre-of-mass energies with the primary goal of searching for this boson. In July 2012, the physics community witnessed a breakthrough with the discovery of a particle like the SM Higgs with a mass of approximately 125 GeV by both ATLAS and CMS collaborations [5, 6]. This discovery was made possible using the proton-proton collision data collected at centre-of-mass energies of 7 and 8 TeV during the first data-taking period (Run-1) of the LHC. Since then, measurements of the new particle's properties were performed by the ATLAS and CMS experiments, exploiting the LHC Run-1 (2011-2012), and Run-2 (2015-2018), datasets. These include the measurements of its mass, couplings, spin and parity as well as production cross-section and decay branching ratios. So far, all measurements show excellent compatibility of the properties of the new boson with the predictions of the SM.

Although the SM has been very successful in providing theoretical predictions that have been well-supported by experimental observations, its limitations are also very apparent thus making it an incomplete theory. The limitations have invited the theorists to make speculations about the nature of physics Beyond the SM (BSM). Over the years, several

BSM theories have been proposed which are able to provide answers to some of the SM problems. Typically, each new physics model has its own characteristic predictions. Among these models, there are some that include extended Higgs sector, where new multiple scalar bosons are predicted. The two-Higgs-Doublet-Model (2HDM), is one of the most popular extended Higgs sector. The 2HDM has been explored extensively in the literature. Various facets related to the theory, phenomenology and constraints on these models have been explored using the experimental data from different collider environments [7, 8, 9]. I give more details about this model in Section 2.4.2.

Of particular interest in this thesis is the BSM scenario considered in Refs. [10, 11, 12] the scalars H and S were introduced via an effective model to explain multiple features in the Run-1 data. These include distortions of the Higgs boson transverse momentum spectrum, accompanied by elevated associated jet activity, elevated rates of leptons in association with b -tagged jets used for the search of the associated production of the Higgs boson with top quarks, and results from the search for double Higgs boson and weak boson production. As pointed out in Refs. [11, 12, 13, 14], the 2HDM alone is not able to accommodate the above-mentioned features of the data. Therefore, a scalar singlet S is introduced in conjunction with the 2HDM in Ref. [12], referred to here as a 2HDM+S model. In addition, this type of model may also be able to explore scenarios with dark matter. Ref. [12] demonstrates how the multi-lepton anomalies are accommodated by using the 2HDM+S model. It was discussed that a 2HDM+S model would result in the anomalous production of multiple leptons. This hypothesis has been compared to data [1], where large discrepancies between the data and SM Monte Carlo (MC) are observed that cannot be resolved with the current understanding of systematic uncertainties. The features of the data examined in Ref. [1] have been studied with additional data in Ref. [15]. This study indicates that these features have become more pronounced with more data.

Here, in this thesis, I expand on the phenomenology described in Refs. [1, 12]. Firstly, I identify the parameter space of the 2HDM+S model that accommodates the features in the data studied in Ref. [1]. Secondly, I also evaluate the implications of this choice of parameter space for the heavy pseudo-scalar and the charged scalar. I am especially interested in investigating the CP-odd scalar in the 2HDM+S model. In particular, I study the production of A through the gluon-gluon-Fusion (ggF) mode, and its decay into $A \rightarrow ZH$ channels, where the decay modes $H \rightarrow hh, Sh, SS$ are considered. This setup leads to a number of interesting final states with leptons and b -tagged jets.

The second and main topic I presented in this thesis is the search for a heavy resonance decaying into two photons and produced in association with at least one b quark ($b\gamma\gamma$). This analysis uses proton-proton (pp) collision data at a centre-of-mass energy of 13 TeV

at 139 fb^{-1} recorded with the ATLAS detector during the LHC’s second run from 2015 to 2018. Similar analyses have been performed by ATLAS and CMS in the $\mu^+\mu^-$ and $b\bar{b}$ final states. Three production modes are tested in this search, the $t\bar{t}X$, $b\bar{b}X$ and ZX , where the Z boson decays into two b -quarks. Aside from its mass, X is assumed to be a Higgs-like heavy resonance. The search examines the diphoton invariant mass spectrum from 130 GeV to 1.6 TeV with one b -tagged jet, two b -tagged jets and one b -tagged jet plus one lepton final states. Limits at 95% Confidence Level (CLs) on the production cross-section times the branching ratio to diphoton final state are set on the resonance range from 180 GeV to 1.6 TeV. Only the narrow width assumption is tested.

This thesis is organised as follows. Chapter 2 gives a brief overview of the SM, the theoretical constraints on the Higgs boson mass. This is followed by the discovery of the Higgs boson and its production mechanisms and decay modes at the LHC. This Chapter, as well, discusses some of the SM’s limitations and introduces the 2HDM in a general way, as a possible extension of the SM that can overcome these problems. Chapter 3 presents a general description of the CERN accelerator complex including the LHC with its main parts and operation conditions. The performance of the LHC is discussed in terms of the luminosity. This is followed by a detailed description of the ATLAS detector together with its several sub-systems. Chapter 4 provides a brief introduction to the 2HDM+S and its parameters and describes the tools used and constraints imposed on the parameter scan. It also shows the allowed region of the parameter space and report on the implications on the branching ratios of the heavy pseudo-scalar (A) and charged scalar (H^+). In addition, it also includes a comparison of the data with the model’s benchmark points in the parameter space. Chapter 5 presents the main analysis in this thesis, the search for new resonance decaying into diphoton. The Chapter started with an introduction to the analysis followed by the description of the MC simulated samples and the recorded data used for this analysis along with the reconstruction techniques and identification criteria of the physics objects. This is followed by a discussion of the event optimization, selection and categorization. The rest of the chapter gives details about the modelling of the signal and the estimation of the background and finally presents the statistical procedure used to analyse the data together with the analysis results. In Chapter 6, a conclusion is drawn to summarise important aspects of this thesis. Finally, four appendices A-D provide additional information and results related to the presented studies.

THEORETICAL BACKGROUND

2.1 THE STANDARD MODEL OF PARTICLE PHYSICS

The Standard Model [2, 3, 4] of Particle Physics is a relativistic quantum field theory which describes the dynamics and interactions of all currently known elementary particles. It succeeded in unifying three of the four fundamental forces in nature: the electromagnetic, weak and strong nuclear forces. Gravity is not described by the SM. It is by far the weakest and its effect is assumed to be negligible at energies below the Planck scale.

Elementary particles in the SM are divided into two groups: fermions and gauge bosons. Fermions are half-spin particles that obey the Fermi-Dirac statistics and come as 6 quarks: (up, down, charm, strange, bottom, and top) and 6 leptons (electron, muon, tau, and their corresponding neutrinos). Bosons are integer spin particles that obey the Bose-Einstein statistics. Within the SM all the interactions are mediated by the exchange of four vector bosons. The electromagnetic interactions between the charged particles is mediated by the exchange of a single boson called the photon (γ) and the weak force, that couples to all fermions, employs the $W^\pm$ and Z bosons. While the strong interaction between the colour charged particles is mediated by eight bosons known as gluons. Gluons are the only bosons that have non-zero colour charge and thus interact with each other. Figure 2.1 shows an overview of the standard model particles and their properties. In addition to the particle content in this table, each particle has a corresponding antiparticle with same mass, spin and opposite electric charge.

Quarks have colours that have the same role as a charge in electromagnetic interactions. However, coloured particles have never been observed due to the confinement property of Quantum Chromodynamics (QCD). Quarks and gluons combined in colourless particles with integer charges referred to as hadrons. These hadrons are typically a combination of two or three quarks. However, theorists have discovered the existence of states with four and five anti-quarks, these are called exotic hadrons namely tetra- and pentaquarks respectively. Hadrons composed by three quarks with different colour

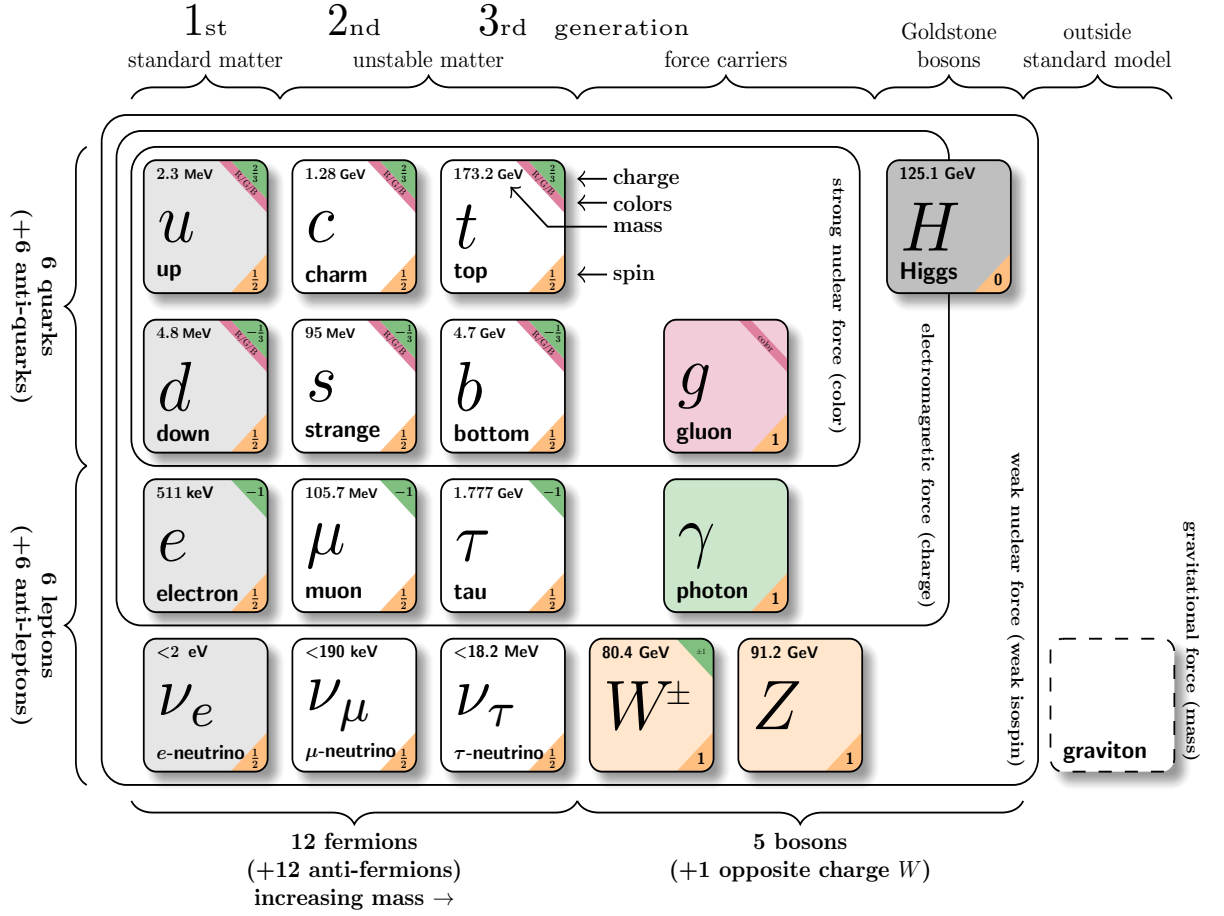


Figure 2.1: Summary of the SM particles (fermions and bosons) and their properties, as well as the Higgs boson. Anti-fermions have identical properties, except for the charge which is inverted, and are denoted with an over-bar, i.e. $\bar{f}$ [16].

charges (blue, green, red) are called baryons, and hadrons formed by three anti-quarks with different anti-charges are called anti-baryons. Hadrons composed by a quark combined with an anti-quark has colour and anti-colour charge, respectively are known as mesons. All fermions interact with the weak force. Leptons do not undergo strong interactions, since they do not carry a colour charge. The electron, muon, and tau carry the electric charge $Q/e = -1$ (e is the elementary charge). They interact therefore both, electromagnetically and weakly, whereas neutrinos do not carry an electric charge and thus interact only weakly. Quarks carry a charge and interact via all three forces, since they also carry a colour charge. They can be separated into six different flavours. Fermions can be divided into three sets of leptons and quarks called generations, where each generation contains two types of leptons and two types of quarks as shown in Figure 2.1. The fermions of the second and third generation can decay

via the weak force into fermions of the lower generations. Only the light particles of the first generation (electron, up and down quarks) are stable and make up all matter around us. A complete listing of known elementary particles and their properties can be found in Ref. [17].

The SM represents the mathematical theory based on quantum field theory to describe all fundamental particles. All information about the dynamics of the fields involved is encompassed in the Lagrangian density ($\mathcal{L}$). The SM is based on gauge symmetries, where a gauge symmetry postulates, that $\mathcal{L}$ is invariant under a local phase transformation on the field. The Quantum Chromodynamics (QCD) [18] is a non-abelian gauge theory that describes the strong interactions and it is represented by a $SU(3)_C$ symmetry group, where C indicates the colour charge. It is derived by requiring gauge invariance under local $SU(3)_C$ gauge transformations on quark colour fields. $SU(3)_C$ is made up of eight generators that correspond to eight force carriers, the colour-charge massless gluons.

Electromagnetic and weak interactions are unified in the SM and are described in a common symmetry group $SU(2)_L \otimes U(1)_Y$. They are therefore summarized as ElectroWeak (EW) interactions, where $U(2)_L$ is a non-abelian gauge group associated with the weak interactions, and the subscript L stands for the fact that only left handed particles undergo weak interactions. The $U(1)_Y$ is a chirally¹ independent gauge group associated with the weak hypercharge Y , in which Quantum Electrodynamics (QED) is embedded. Analogous to the Gell-Mann-Nishijima formula obtained in the quark model of hadrons, the combination of the $U(1)$ weak hypercharge and the third component of the weak isospin can be used to determine the electric charge: $Q = T_3 + Y/2$ [19, 20].

Experiments show that the weak force-carriers, the $W^\pm$ and Z bosons are massive. However, gauge symmetry forbids massive fermions and gauge bosons. This problem is solved via the Brout-Englert-Higgs (BEH) mechanism through which the EW symmetry is spontaneously broken [21, 22, 23, 24, 25, 26, 27]. Thereby, $W^\pm$ and Z bosons become massive and the BEH mechanism introduces a new fundamental scalar, the Higgs Boson. Furthermore, Fermions acquire their mass by coupling to the scalar Higgs field, called Yukawa-coupling [28, 29].

Imposing these gauge symmetries, the complete Lagrangian of the SM can be factorised in terms that describe the strong interactions, the electroweak interactions, the Higgs sector and the Yukawa terms for the fermion masses:

$$\mathcal{L}_{SM} = \mathcal{L}_{QCD} + \mathcal{L}_{EW} + \mathcal{L}_H + \mathcal{L}_{Yukawa}. \quad (2.1.1)$$

¹Chirality is a property defined by the particle behaviour under a mirror transformation

The SM Lagrangian shown in Equation [2.1.1](#) is invariant under local transformations of the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$.

2.2 THE BEH MECHANISM AND YUKAWA INTERACTIONS

The BEH mechanism introduces a complex scalar field Φ which is a weak isospin doublet (called Higgs field) of the $SU(2)_L$ symmetry group [[21](#)]:

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}_L = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}. \quad (2.2.1)$$

where ϕ^+ is a charged field, ϕ^0 is a neutral field and ϕ_i are real scalar fields. The doublet has weak isospin $T = \frac{1}{2}$, hypercharge $Y = 1$ and $T_3 = \pm \frac{1}{2}$ for upper and lower members of the doublet. The Lagrangian to describe the dynamics of this scalar field is written as:

$$\mathcal{L}_H = (\mathcal{D}_\mu \Phi)^\dagger \mathcal{D}^\mu \Phi - V(\Phi^\dagger \Phi), \quad (2.2.2)$$

with,

$$V(\Phi^\dagger \Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2. \quad (2.2.3)$$

Here, $V(\Phi^\dagger \Phi)$ is the self interaction potential of the field. This Lagrangian is invariant under $SU(2)_L \times U(1)_Y$ with the covariant derivative $\mathcal{D}_\mu$ which couples the scalar Φ to the electroweak gauge bosons and defined as:

$$\mathcal{D} = \partial_\mu - \frac{1}{2}ig\sigma_a W_\mu^a + \frac{1}{2}ig'Y_W B_\mu. \quad (2.2.4)$$

in which g and g' are the coupling constants determine the strengths of the interactions of both gauge groups $SU(2)_L$ and $U(1)_Y$, respectively. The corresponding field strength tensors are:

$$W_{\mu\nu}^i = \partial_\mu W_\nu^i - \partial_\nu W_\mu^i + g\epsilon_{ijk}W_\mu^j W_\nu^k \quad (2.2.5)$$

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu. \quad (2.2.6)$$

The parameters λ and μ^2 are free parameters of the new field. The parameter (λ) needs to be positive to bound the potential from below and to ensure that a ground state exists. If $\mu^2 > 0$ the potential V only has a minimum at $\Phi = 0$, leading to a symmetric ground state under $SU(2)$, as shown by the green curve in figure [2.2](#). If, however, $\mu^2 < 0$, minimum occurs at

$$\Phi = e^{i\alpha} \sqrt{\mu^2/2\lambda} = v^2/2, \quad 0 \leq \alpha \leq 2\pi, \quad (2.2.7)$$

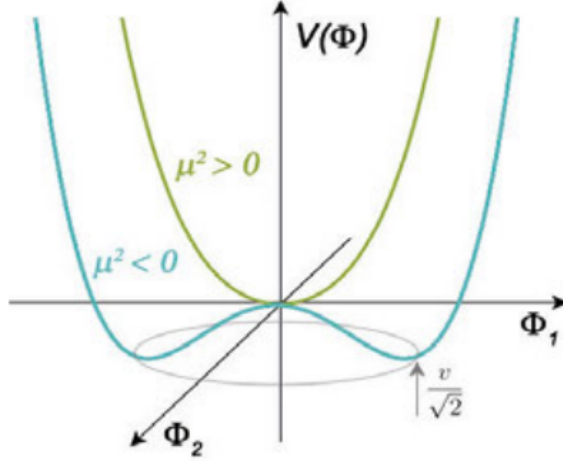


Figure 2.2: The Higgs potential $V(\Phi)$ for different signs of the parameter μ^2 .

where v is known as the vacuum expectation value (*vev*). In this latter case, the potential has a shape like a Mexican hat, as illustrated by the blue curve shown in Figure 2.2. From the figure, it is clear that there are an infinite degenerate states of minima lying on a ring in the complex plane. However, the choice of any minimum energy state breaks the $SU(2)_L$ electroweak gauge symmetry while the Lagrangian remains invariant under $SU(2)_L \times U(1)_Y$ transformations. This behaviour is called the spontaneous symmetry breaking (SSB). It is thus possible to arbitrarily choose $\alpha = 0$ and write the ground state of the field as:

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad (2.2.8)$$

which corresponds to $\phi_3 = v$, $\phi_1 = \phi_2 = \phi_4 = 0$. The three components of the complex doublet field that have zero vevs are called Goldstone bosons [30]. The excitation from the ground state are given by [31]:

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}, \quad (2.2.9)$$

where $H(x)$ is a physical neutral scalar field, which quantum excitation is called the Higgs boson. Using the definition in equation 2.2.4, the kinetic term of the scalar Lagrangian in equation 2.2.2 becomes:

$$\begin{aligned} (\mathcal{D}_\mu \Phi)^\dagger (\mathcal{D}^\mu \Phi) &= \frac{1}{2} \partial_\mu H \partial^\mu H + \frac{1}{2} \lambda v^2 H^2 - \lambda v H^3 - \frac{\lambda}{4} H^4 \\ &+ \frac{v^2 g^2}{8} ((W_\mu^1)^2 + (W_\mu^2)^2) + g^2 (g W_\mu^3 - g' B_\mu^2)^2 \\ &+ \text{mixed terms.} \end{aligned} \quad (2.2.10)$$

The massive scalar field H is called the Higgs field. The first line of the equation is composed of the kinematic term $\frac{1}{2}\partial_\mu H\partial^\mu H$, a mass term $\frac{1}{2}\lambda v^2 H^2$ and terms that describe self interactions of this field. The middle term describes the fields of the massive W_μ^i/B_μ bosons. The mixed terms, not explicitly formulated here, describe the interaction between the W_μ^i/B_μ gauge bosons and the Higgs field, giving mass to the gauge bosons. The charged fields $W_\mu^\pm$ are defined as a linear combination of the W^1 and W^2 and their complex conjugate as

$$W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp iW_\mu^2), \quad (2.2.11)$$

while the neutral physical fields (the photon and the Z boson fields) are defined as:

$$Z_\mu = (gW_\mu^3 - g'B_\mu)/\sqrt{g^2 + g'^2} \quad \text{and} \quad A_\mu = (g'W_\mu^3 + gB_\mu)/\sqrt{g^2 + g'^2}. \quad (2.2.12)$$

From this, the masses of the gauge bosons can be interpreted as

$$m_W = \frac{1}{2}gv, \quad m_Z = \frac{v}{2}\sqrt{g'^2 + g^2}, \quad \text{and} \quad m_\gamma = 0. \quad (2.2.13)$$

Finally, the mass of the Higgs boson depends on the unknown parameter λ :

$$m_H = \sqrt{2\lambda v^2}. \quad (2.2.14)$$

The ratio of the masses of the W and Z bosons can at leading order be expressed as $\cos\theta_W \approx m_W/m_Z$, where $\theta_W \in [0, \pi/2]$ and called the Weinberg angle or the weak mixing angle, whereas:

$$\sin\theta_W = g'/\sqrt{g^2 + g'^2}, \quad \cos\theta_W = g/\sqrt{g^2 + g'^2}. \quad (2.2.15)$$

The physical bosons A_μ and Z_μ can now be expressed as linear combinations of the W_μ^3 and B_μ fields with θ_W as :

$$A_\mu = \sin\theta_W W_\mu^3 + \cos\theta_W B_\mu^0 \quad \text{and} \quad Z_\mu = \cos\theta_W W_\mu^3 - \sin\theta_W B_\mu^0. \quad (2.2.16)$$

The vev is related to the gauge bosons and the Higgs masses, which in turn is related to Fermi coupling constant, G_F , by the relation [32]:

$$v = (\sqrt{2}G_F)^{-\frac{1}{2}}, \quad G_F = 1.1664 \times 10^{-5} \text{ GeV}^{-2}. \quad (2.2.17)$$

Moreover, the mechanism of SSB also allows for giving masses to the fermions by introducing Yukawa terms that describe the gauge invariant type of interaction between fermions and the complex scalar field Φ . Such terms can be written down in the following way [28, 29]:

$$-\mathcal{L}_{Yukawa} = \lambda_{ij}^d \bar{Q}_{Li} \Phi d_{Rj} + \lambda_{ij}^u \bar{Q}_{Li} \tilde{\Phi} u_{Rj} + \lambda_{ij}^\ell \bar{L}_{Li} \Phi \ell_{Rj} + \text{h.c.}, \quad (2.2.18)$$

with an implicit sum over the generation indices $i, j = 1, 2, 3$, where λ_{ij} are 3×3 complex matrices representing the Higgs–fermion Yukawa couplings. The $\overline{Q}_{L_i}$ and $\overline{L}_{L_i}$ denote the left-handed quark and lepton doublets, and fermion classes u_R, d_R , and e_R represent the right-handed up-type quarks, down-type quarks and lepton singlet, respectively. Note that the up-type quarks couple to the charged conjugate field $\tilde{\Phi} = -i\sigma_2\Phi^*$, with σ_2 the second Pauli matrix. Here, the h.c. denotes the Hermitian conjugate terms.

The Yukawa Lagrangian is, of course, applicable to all fermions, however mass terms for neutrinos are not possible due to the absence of right-handed neutrinos in the SM, hence, they remain massless and degenerate.

2.3 THEORETICAL CONSTRAINTS ON THE HIGGS BOSON MASS

The Higgs boson mass defined in equation 2.2.14 is not predicted by the SM. The v is known in terms of the experimentally well known W boson mass $m_W \propto v$, ($v \approx 246$ GeV), λ is a free parameter of the theory and therefore also m_H is a free parameter. However, constraints on its value were derived from theoretical argumentations. In particular, the requirements for the unitarity of scattering amplitudes and from the assumption on the energy scale up to which the SM is valid before perturbation theory breaks down, and then new physics emerge [33]. This imposes different upper and lower limits on the Higgs boson mass [34].

2.3.1 THE UNITARITY BOUNDS

The unitarity [35, 36] requirement constraints come from the SM calculation of the scattering amplitudes of the longitudinal components of the gauge bosons, for instance the process $W^+W^- \rightarrow W^-W^+$. This amplitude grows proportionally to the center-of-mass energy of the scattering and violates the unitarity at a certain energy scale if the Higgs boson is not sufficiently light ($m_H \ll \sqrt{s}$) [37]. Therefore, the unitarity condition of the theory is preserved if the Higgs boson mass is ≤ 780 GeV³ [38]. This is the unitarity bound on the Higgs boson mass (perturbative as it is leading order only). On the other hand, if the Higgs mass exceeds this bound, then new physics must appear at critical energy scale up to 1 or 2 TeV to restore unitarity in gauge bosons scattering.

² s is the squared center-of-mass energy

³If the scattering channels that involves W , Z and H are taken into account, the unitarity bound on the Higgs mass would become stronger and reads ≤ 710 GeV.

2.3.2 THE TRIVIALITY CONSTRAINT

The triviality constraint is derived from the evolution of the Higgs boson quartic self-coupling, λ in equation 2.2.14, with the energy of the interaction. To obtain this constraint, let's consider the one-loop radiative corrections to the Higgs boson quartic self-coupling, as shown in Figure 2.3. The variation of λ with energy scale q is given at one-loop by the Renormalization Group Equation (RGE) as follows,

$$\lambda(q^2)/dq^2 = 3\lambda(q^2)/(4\pi^2) + \mathcal{O}(\lambda^3) \quad (2.3.1)$$

If $q = v$ is chosen as reference point, the solution of this equation becomes logarithmically dependent of the squared energy scale

$$\lambda(q^2) = \lambda(v^2) [1 - (3\lambda(v^2)/4\pi^2) \log(q^2/v^2)]^{-1}. \quad (2.3.2)$$

In this equation, if $q^2 \ll v^2$, the λ becomes extremely small and eventually vanishes, and hence creates a non-interacting (trivial) theory. In the opposite limit, when $q^2 \gg v^2$, the λ gets larger and ultimately becomes infinite and hence the theory becomes non-perturbative. The energy at which $\lambda = \infty$ is called the Landau pole:

$$\Lambda_C = v \exp(4\pi^2/3\lambda) = v \exp(4\pi^2 v^2/m_m^2) \quad (2.3.3)$$

To ensure that the theory remains non-trivial and perturbative, the quartic self-coupling is required to remain finite, $0 < \lambda(q^2) < \infty$ for $q < \Lambda_C$. Therefore, one can view this argument differently: use the RGE for λ to establish the energy domain in which the SM is valid, the energy cut-off Λ_C below which λ remains finite. This sets an upper bound on the Higgs boson mass. In equation 2.3.3, we can see the inverse relation between the cut-off scale and the Higgs mass. For instance, if the cut-off energy is at the Plank scale around 10^{16} GeV, then the Higgs boson should be light and have mass up to 200 GeV (see Figure 2.4). In the case that Λ_C is small (equal to the electro-weak scale $\sim 10^3$ GeV), the Higgs boson mass must be lower than 1 TeV. However, when $\lambda \gg 1$ the perturbation theory breaks down and the constraint is lost; from simulations of gauge theories where non-perturbative effects are included, one obtains an upper limit for the Higgs mass of $m_H \leq 700$ GeV.

2.3.3 THE VACUUM STABILITY CONSTRAINT

This constraint implies a lower bound for the Higgs boson mass. If the Higgs boson self-coupling is considered for a low m_H , fermion and vector boson contributions must be included in the radiative correction to the self coupling. Since the Higgs boson couplings are proportional to the particle masses, thus the dominant corrections will arise from the heavy top quark and the massive gauge bosons. Some one-loop Feynman diagrams

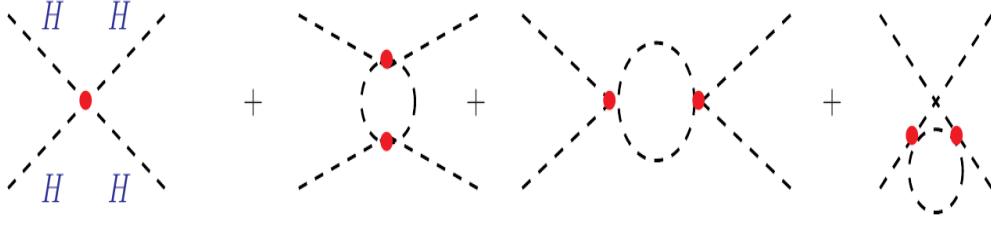


Figure 2.3: The Feynman diagrams for the tree-level and the one-loop corrections to the Higgs boson self-coupling [34].

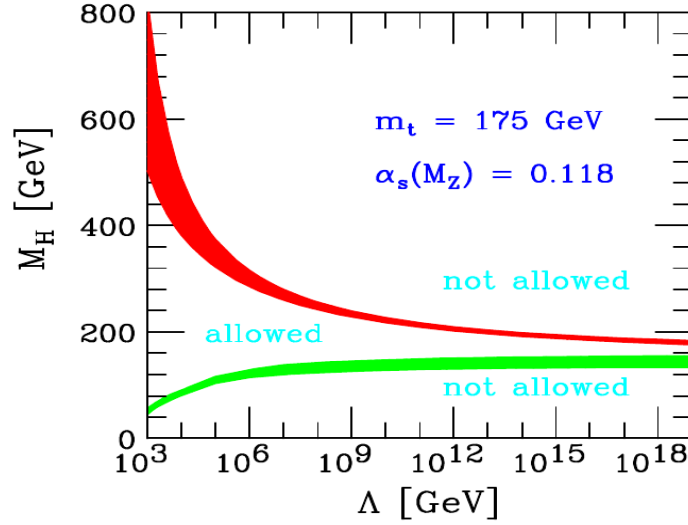


Figure 2.4: Theoretical constraints for the Higgs boson mass as a function of the energy cut-off scale Λ for the validity of the Standard Model. The upper red band corresponds to the triviality bound and its uncertainty, while the lower green band corresponds to the vacuum stability bound and its uncertainty; the allowed region lies between the two bands [34, 39].

for these additional contributions are given in Figure 2.5. Including the fermion and gauge boson contributions, the one-loop RGE for the quartic coupling is given by,

$$\frac{d\lambda}{d\log q^2} \simeq \frac{1}{16\pi^2} \left[12\lambda^2 + 6\lambda\lambda_t^2 - 3\lambda_t^4 - \frac{3}{2}\lambda(3g_2^2 + g_1^2) + \frac{3}{16}(2g_2^4 + (g_2^2 + g_1^2)^2) \right], \quad (2.3.4)$$

where $\lambda_t = \sqrt{s}m_t/v$ the top quark Yukawa coupling. if $q = v$ is taken again as a reference point and for $\lambda \ll g_1, g_2, \lambda_t$, the solution to one-loop RGE is,

$$\lambda(q^2) = \lambda(v^2) + \frac{1}{16\pi^2} \left[-12\frac{m_t^4}{v^4} + \frac{3}{16}(2g_2^4 + (g_2^2 + g_1^2)^2) \right] \log \frac{q^2}{v^2}. \quad (2.3.5)$$

Now, a strong constraint on the Higgs mass can be set due to the condition $V(v) < V(0)$, with the potential V is given in equation 2.2.3. This is equivalent to the requirement that says λ should remain positive at all scales up to Λ_C , otherwise the potential



Figure 2.5: Feynman diagrams for the one-loop fermion (F) and gauge boson (V) contributions to λ [34].

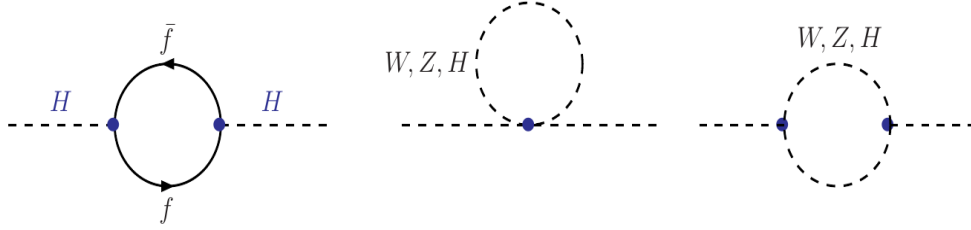


Figure 2.6: The most significant quadratically divergent contributions to the Higgs mass in the SM [34].

is unbounded from below and there is no ground state about which the Lagrangian can be expanded. Therefore, the Higgs boson mass is required to lie above a certain value depending on the cut-off Λ_C as shown in Figure 2.4. For a very high value of Λ_C , i.e. the Planck scale 10^{16} GeV, the Higgs mass should be ≥ 130 GeV, while for a relatively low cut-off value of (10^3 GeV), the Higgs mass should be ≥ 70 GeV. Even for these very different values of Λ_C , the constraints on the Higgs mass remain at the EW scale.

2.3.4 THE FINE-TUNING CONSTRAINT

This constraint arises from the radiative corrections to the bare Higgs bosons mass. In the SM, the calculation of m_H receives significant corrections in the form of heavy particle loops, involving top quarks, massive gauge bosons and the Higgs itself as shown in Figure 2.6. The Higgs mass is calculated as, $m_H^2 = m_{H,\text{bare}}^2 + \Delta m_H^2$, where $m_{H,\text{bare}}^2$ is the mass parameter in the Lagrangian and Δm_H^2 is the mass correction term. Considering the corrections to the Higgs mass from one-loop contribution of fermion with Yukawa coupling $\lambda_f = \sqrt{2}m_f/v$ and with number of fermion families N_f , we obtain [34, 40]:

$$\Delta m_H^2 = N_f \frac{\lambda_f^2}{8\pi^2} \left[-\Lambda_C^2 + 6m_f^2 \log \frac{\Lambda}{m_f} - 2m_f^2 \right] + \mathcal{O}(1/\Lambda_C^2). \quad (2.3.6)$$

This shows that m_H^2 diverges quadratically with the cut-off energy scale Λ_C . As a result, if the cut-off energy Λ_C is very large, i.e. the Plank scale or the grand unification scale, the corrections are huge. Therefore, a fine arrangement of the SM parameters is needed

in order to cancel out the divergences such as the one of equation 2.3.6 and obtain a physical Higgs boson mass in the range allowed by the theoretical constraints, namely $100 \text{ GeV} \leq m_H \leq 1 \text{ TeV}$.

2.4 PHYSICS BEYOND THE SM

The SM presented in Section 2.1 is a remarkably successful theory that offers a precise description of all observed phenomena in collider physics, covering a wide range of energies. This theory became complete after the discovery of the Higgs bosons, with properties matching those predicted by the SM. The SM is one of the most robustly tested and validated theories of nature, with no confirmed experimental evidence against it. However, there are several critical points that are unexplained by the SM, or conflict with its implications or predictions. These points arise both from theoretical consideration and experimental signatures. Section 2.4.1 briefly outlines some of the SM limitations, which motivate the formulation of the BSM theories.

A large variety of BSM theories have been formulated so far [41]. These models are an extension for the SM, where particles heavier than the SM Higgs boson appear. Some of the most basic extensions to the SM is Two-Higgs-doublet models (2HDMs), where an additional Higgs-doublet appears in the model. A brief overview of the 2HDMs is given in Section 2.4.2. The analysis presented in this thesis introduce a scalar singlet S to the 2HDM and the new model is referred to as 2HDM+S, as will be discussed in details in Chapter 4.

2.4.1 LIMITATIONS OF THE SM

2.4.1.1 ABSENCE OF GRAVITY

The SM does not include gravity, while unifying the other three fundamental forces. This action would require the gravity to be quantised. At all experimentally accessible energy scales, gravity is very weak. however, at length around the Planck scale, 10^{19} GeV , it cannot be neglected any more. At this scale the quantum effects of gravity have to be included, but at this scale the Einstein theory of gravity generally breaks down as being a non-renormalizable theory. This is a good reason to believe that the SM is only an effective theory, since it's just valid up to some energy scale. At this point, since there isn't any consistent quantization of gravity that can be incorporated with the SM [42, 43], therefore, a new more complete theory is needed to replace our low-energy description.

2.4.1.2 THE HIERARCHY PROBLEM

The Hierarchy problem [44, 45] is the most critical outstanding theoretical issue in the SM. The heart of this problem is that, the experimentally measured mass of the Higgs boson is vastly different with respect to its fundamental value provided by the theory. Even though, it receives significant radiative corrections in the form of heavy particle loops. This problem is related to the fine-tuning constraint, which is discussed in Section 2.3.4. Where the bare mass of the Higgs boson is tuned in a way that almost completely cancels the quantum corrections, in order to give a physical mass of about 125 GeV. Even if that is theoretically allowed, such level of tuning up to 17 digits seems to be unnatural and the corresponding is called the Hierarchy (naturalness) problem. Along the same lines, The SM offers no explanation regarding the large gap between the EW symmetry breaking scale, $\mathcal{O}(100 \text{ GeV})$, and the Planck scale, $\mathcal{O}(10^{19}) \text{ GeV}$.

2.4.1.3 ORIGIN OF NEUTRINO MASSES

In the formalism of the SM, neutrinos are assumed to be massless left-handed particles, with no right-handed component. However, the observation of neutrino flavour oscillation (transform from one type into another) [46, 47] implies that neutrinos have a small but non-zero mass. There are two possible mass terms for neutrinos, that can be written in the Lagrangian: a Dirac mass (as for the other fermions) and a Majorana mass⁴. If neutrinos are Dirac particles, the SM could be extended by adding right-handed neutrinos for every generation and build a four-dimensional Dirac field for neutrinos, using left and right-handed components (At least 7 more parameters)[48, 49]. However, it seems unsatisfactory to have a state included in the SM that would not interact at all with the other particles. On the other hand, if neutrinos are Majorana particles, their masses could arise as an effective realization of a higher-energy theory. The most popular approach to generate the neutrino masses is the so-called seesaw mechanism [50]. In this and similar models, the Hierarchy problem is potentially present.

2.4.1.4 DARK MATTER AND DARK ENERGY

Several cosmological and astrophysical observations [51, 52, 53, 54, 55, 56] have shown the presence of more matter in the Universe than what is predicted by the SM theory. Measurements of the cosmic microwave background [57] point out that ordinary matter (i.e. SM constituents) compose only $\sim 5\%$ of the total energy density of the universe, while the remaining contributions come from Dark Matter ($\sim 27\%$) and dark energy ($\sim 68\%$). Dark Matter refers to a kind of matter that is massive, stable and electrically

⁴For Dirac mass, a neutrino and an anti-neutrino exists while for a Majorana mass, neutrinos are their own anti-particles.

neutral. It is subject to gravity and if it interacts with ordinary matter, then it only does so weakly. The SM does not contain any particle that could exhibit all dark matter required properties. Some SM extensions (as Supersymmetry) provide good dark matter candidates, however, these have not yet been observed in experiments.

The Dark Energy was discovered due to the observation made by two teams of astronomers, the High-Z Supernova Search Team [58] and the Supernova Cosmology Project [59]. The observation indicates that the expansion of the Universe is accelerating by the presence of a dark energy filling the space homogeneously. However, the nature of dark energy is still unknown apart from the fact that it acts as the negative pressure on the Universe.

2.4.1.5 ASYMMETRY OF MATTER AND ANTIMATTER

It is evident that, in our visible universe today, there is a large predominance of matter over anti-matter, although, in the very early universe matter and antimatter, were produced and annihilated at the same rate in thermal equilibrium. This asymmetry is driven by some conditions: a Charge conjugation and Parity (CP) symmetry violation, a baryon number violating process and interactions outside thermal equilibrium [60]. There is no known process in the SM that violates baryon number, while the SM provides several sources of CP-violation in the weak sector, coming from the presence of a complex phase in the CKM matrix [61] that describe the mixing of different quark flavours. However, the amount of violation is not large enough to account for the apparent asymmetry [17, 62, 63]. Several extensions to the SM, such as the 2HDMs, address these in different ways.

2.4.2 TWO HIGGS DOUBLET MODELS

As introduced in Section 2.2, the SM Higgs boson is a complex scalar doublet. However, there are no constraints on the numbers of Higgs doublets, namely it is very easy to extend the number of Higgs doublets. In 1973, T.D. Lee proposed a simple model, the two-Higgs-doublet model (2HDM), which introduces a second $SU(2)_L$ scalar doublet in addition to the one from the SM, that postulates the existence of multiple Higgs bosons. The 2HDM is capable of solving some of the problems mentioned above while still preserving the good agreement between the SM and experiment results. In fact, there are many motivations for the 2HDM. Some broader BSM frameworks require at least two Higgs doublets. The most famous example is supersymmetry [64], in which an even number of Higgs doublets are needed to generate masses for all fermions. Another motivation behind 2HDM was to introduce additional sources of CP-violation, able to explain the observed matter-antimatter asymmetry.

The two Higgs doublets postulate the existence of five physical states: two neutral CP-even bosons (h and H , the latter being the more massive), a neutral CP-odd pseudoscalar boson (A), and two charged Higgs scalar bosons ($H^\pm$). Where the masses of these Higgs bosons are free parameters of the model. The Higgs boson that has been observed in LHC experiments would thus represent the Higgs boson of the lowest mass.

2.4.2.1 THE 2HDM LAGRANGIAN

Consider a 2HDM based on the two identical complex doublets of $SU(2)_L$ symmetry $\Phi_a(x), a = 1, 2$ with the same quantum numbers, such as:

$$\Phi_a = \begin{pmatrix} \phi_a^+ \\ \phi_a^0 \end{pmatrix}, \quad (2.4.1)$$

where ϕ_a^+ and ϕ_a^0 are complex fields. The corresponding charged conjugated fields $\tilde{\Phi}_a = i\sigma_2\Phi_a^*$, with σ_2 the second Pauli matrix, are also $SU(2)_L$ doublets. The most general renormalizable and gauge invariant $SU(2)_L \times U(1)_Y$ Lagrangian for the Higgs doublet model can be written as:

$$\mathcal{L} = \mathcal{L}_\Phi + \mathcal{L}_{\text{Yuk}} + \mathcal{L}_{\text{SM}}, \quad (2.4.2)$$

where the last term describes the SM interactions of the gauge bosons and fermions, $\mathcal{L}_\Phi$ describes the Higgs scalar Lagrangian and $\mathcal{L}_{\text{Yuk}}$ describes the interaction between the extended scalar sector of the 2HDM and the fermionic fields. In general, the fermions will couple to both doublets in the flavour basis,

$$\mathcal{L}_{\text{Yuk}} = - \sum_{a=1}^2 [\lambda_a^u \bar{Q}_{L,a} \tilde{\Phi}_a u_R + \lambda_a^d \bar{Q}_{L,a} \Phi_a d_R + \lambda_a^e \bar{L}_{L,a} \Phi_a e_R + \text{h.c.}], \quad (2.4.3)$$

where h.c. being the Hermitian conjugate of the three preceding terms. λ_a^f ($f = u, d, e$) are two 3×3 matrices of Yukawa couplings in the flavour space of each Higgs doublet ($a=1,2$), and fermion classes u_R, d_R , and e_R represent the right-handed up-type quarks, down-type quarks and lepton singlet, respectively. The $\bar{Q}_{L,a}$ and $\bar{L}_{L,a}$ denote the left-handed quark and lepton doublets.

The Higgs scalar Lagrangian $\mathcal{L}_\Phi$ is more complicated than in the SM, since it contains kinetic terms and a potential involving both doublets,

$$\mathcal{L}_\Phi = \sum_{a=1,2} (D_\mu \Phi_a)^\dagger (D^\mu \Phi_a) - V_{2\text{HDM}}(\Phi_1, \Phi_2) \quad (2.4.4)$$

with the covariant derivative as stated in (2.2.4). The 2HDM potential can involve all hermitian functions of the two doublets up to dimension four, such that the potential

is still renormalizable. If one imposes only gauge invariance, the most general scalar potential can be conventionally parameterized as

$$\begin{aligned}
V_{2HDM} = & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \text{h.c.}) + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 \\
& + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) + \frac{\lambda_5}{2} [(\Phi_1^\dagger \Phi_2)^2 + \text{h.c.}] \\
& + [\lambda_6 (\Phi_1^\dagger \Phi_1) (\Phi_1^\dagger \Phi_2) + \lambda_7 (\Phi_2^\dagger \Phi_2) (\Phi_1^\dagger \Phi_2) + \text{h.c.}], \tag{2.4.5}
\end{aligned}$$

with h.c. denotes the Hermitian conjugate term. The parameters m_{11}^2 , m_{22}^2 and λ_{1-4} are real, while the parameters m_{12}^2 and λ_{5-7} are in general complex, yielding a total number of 14 real degrees of freedom for the potential. This potential with real coefficients describes the theory without CP-violation in the Higgs sector while complex values of some coefficients here make CP-violation in Higgs sector possible (for more detailed discussion of many points see Ref. [65]). At the global minimum of the potential V_{2HDM} , the doublets acquire non-zero vacuum expectation values (*vevs*). It is possible to write the *vevs* as:

$$\langle \Phi_1 \rangle = \frac{v}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \quad \langle \Phi_2 \rangle = \frac{v}{\sqrt{2}} \begin{pmatrix} u \\ v_2 e^{i\xi} \end{pmatrix} \tag{2.4.6}$$

where v_1 and v_2 two positive real parameters represent the *vevs* of the two Higgs doublets which can be quadratically added $v^2 = v_1^2 + v_2^2$, with v corresponds to the SM *vev* of the Higgs field. The complex phases of the vacua introduce the possibility to break the CP-symmetry spontaneously. The arbitrary angle acquires values $0 \leq \xi < 2\pi$. In case of $u \neq 0$ vacuum is called charged. $U(1)_{EM}$ symmetry is spontaneously broken. Depending on the parameters of the Higgs scalar potential it describes minimum of the potential or saddle point. In case of $u = 0$, $U(1)_{EM}$ symmetry is preserved.

In the generic potential 2.4.5 coefficients m and λ are all $U(1)_Y$ group invariants but not under $SU(2)$ symmetry while v preserves invariance under $U(2)$. Also it is always possible to rephrase Φ in a such way that $\xi = 0$.

The two Higgs complex $SU(2)$ doublets correspond to eight fields, the charged complex field $\phi_a^\pm$, the neutral CP-even fields η_a and the neutral CP-odd fields ρ_a , with $a = 1, 2$, thus the doublets can be expanded around the potential minimum, taking the form:

$$\Phi_a = \begin{pmatrix} \phi_a^+ \\ (v_a + \rho_a + i\eta_a)/\sqrt{2} \end{pmatrix} \tag{2.4.7}$$

After EWSB, three out of these eight degrees of freedom are used to generate masses for the Goldstone boson, as in the SM case. While the remaining five give rise to the five Higgs bosons described above.

The mass eigenstates of the neutral, CP-even Higgs bosons h and H and the CP-odd A , and the charged Higgs bosons $H^\pm$, are given by diagonalizing the respective mass matrices with the rotation angles α and β , respectively. Moreover, the ratio of the *vevs* of the doublets is given by $\tan \beta = v_1/v_2$. The mixing angle α is defined such that h is the SM-like Higgs boson when $\sin(\beta - \alpha) = 1$. The two parameters α and β basically describe the interactions of the various physical scalar fields with the vector bosons and with the fermions; they are thus crucial in discussing the phenomenology of the 2HDMs.

2.4.2.2 FCNC IN 2HDM

We know that in case of the SM, diagonalizing the fermion mass matrices automatically diagonalizes the Yukawa interactions. As a consequence, there are no tree level flavour changing neutral currents (FCNC). This is not the case in the 2HDM, where the Yukawa Lagrangian 2.4.3 leads to FCNC couplings, because there are two different Yukawa matrices coupling to each fermion field. These can in general not be diagonalized simultaneously. Therefore, to avoid such Higgs boson associated FCNC interactions, each fermion should couple to only one of the Higgs doublets. Besides some other solution [66], this problem is elegantly solved by Glashow and Weinberg [67] through the introduction of a $\mathbb{Z}_2$ discrete symmetry. Applying such symmetry to 2HDM results in four different types of models with different Yukawa interactions. The models are:

- Type I: only one of the doublets, Φ_2 , couples to all fermions (quarks and leptons). The other one only couples to gauge bosons. This type is also referred to as fermiophobic.
- Type II: the doublet Φ_1 couples only to right-handed down-type quarks and leptons, whereas Φ_2 couples to right-handed up-type quarks and neutrinos. The Higgs sector in the minimal supersymmetric extension of the SM is a Type II 2HDM, in which the introduction of supersymmetry adds new particles and constrains the parameter space of the model. Therefore, this type is also called MSSM-like.
- Flipped model: the right-handed up-type quarks couple to Φ_2 , while the down-type quarks couple to Φ_1 as in type II, but now the right-handed leptons couple to Φ_2 .
- Lepton specific: the right-handed quarks all couple to Φ_2 and the right-handed leptons couple to Φ_1 .

Some of these models are known with different names in the literature, for example, X-type and Y-type were used for the flipped and lepton-specific models, respectively.

Besides the FCNC-free 2HDMs mentioned above, it is still possible to construct a viable 2HDM with FCNC being present at tree level [7, 68, 69, 70, 71]. Such a model just assumes that tree-level FCNCs are highly suppressed or can be cancelled by loop corrections down to empirical values.

2.5 THE SM HIGGS BOSON

The discovered Higgs boson has a mass approximately 125 GeV [5, 6]. For this mass and a large range of masses around it, calculations of the production cross-sections, partial decay widths and Branching Ratios (BRs) along with their theoretical uncertainties have been performed with great precision in order to determine the Higgs's properties. An extensive collection of these calculations is provided by the LHC Higgs Cross-Section Working Group in Refs. [72, 73, 74, 75].

2.5.1 THE HIGGS PRODUCTION MODES

At the LHC, the SM Higgs boson is produced from interactions of hadrons through processes all having partons (quarks or gluons) in the initial state. The four main production processes that contribute the most to the total Higgs boson production cross-section are namely: the ggF, Vector Boson Fusion (VBF), associated production with a $W^\pm$ or Z boson (VH) and associated production with a pair of top quarks ($t\bar{t}H$). Additional sub-dominant contributions exist from $b\bar{b}H$ and tHX with $X = q/W$ associated production. Figure 2.7 presents the tree level Feynman diagrams of these processes together with the fraction of the contribution to the total cross-section. These processes are described here, in decreasing order of production cross-sections:

- The ggF process is the leading Higgs production process at the LHC, since gluons have the largest contribution to the parton density function at high energies of the LHC. In this process, two gluons fuse and produce a Higgs boson via a loop of virtual heavy quarks, typically top quarks.
- The VBF process has the second-largest Higgs production cross-section at LHC. Its cross-section is about one order of magnitude lower than the ggF one for the large Higgs mass range. At tree level, this process occurs when two quarks or two anti-quarks, each radiate a Z or W boson, and the two bosons fuse producing a Higgs boson. This process produces two quark jets with large pseudorapidity and large di-jet mass.
- The VH process, also known as W/Z Bremsstrahlung process, has very small cross-sections, orders of magnitude lower than those of ggF and VBF. While WH and ZH have similar cross-section with WH being slightly higher. In this

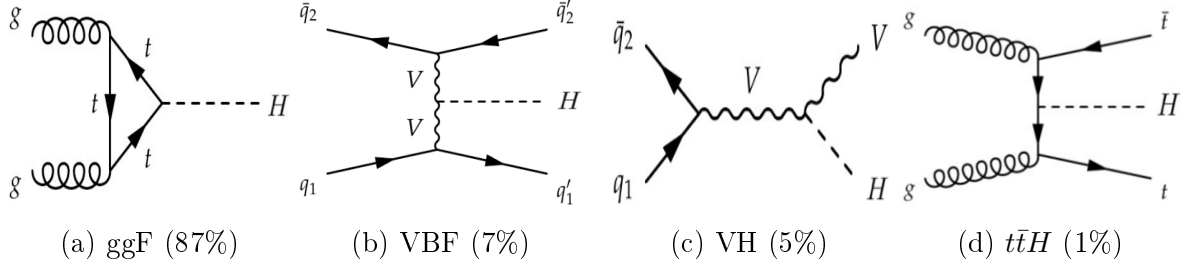


Figure 2.7: The leading order Feynman diagrams for the main SM Higgs boson production processes at the LHC with the fraction of the contribution to the total Higgs production cross-section.

process W and Z fields are created as a result of interaction between a quark and an anti-quark, this field in turns couples to Higgs particle and a W or Z particle.

- The $t\bar{t}H$ process in which is initiated by two gluons that produce two top quarks and the Higgs boson is emitted from the quark lines. Analogous to $t\bar{t}H$ production, the Higgs can be also produced in association with bottom quarks. This process has a cross-section higher than that of $t\bar{t}H$ at lower center-of-mass energies, as shown in table 2.1.

Table 2.1 shows the total cross-sections, σ^{tot} , and uncertainties for these production processes in pp collisions with $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV and $m_H = 125.09$ GeV. The table shows a significant difference in the σ^{tot} between the two different center-of-mass energies. Figure 2.8a also shows the σ^{tot} of the various production processes with $\sqrt{s} = 13$ TeV as a function of the Higgs mass.

In addition to the singular Higgs boson production, it is also possible to have the generation of two Higgs bosons in a process called pair production. The theoretical production cross-section is ≈ 10 fb which is very small to be detected with the currently acquired data.

2.5.2 THE HIGGS DECAY MODES

The Higgs boson is not a stable particle and has a predicted lifetime of 1.56×10^{-22} seconds, and is therefore only indirectly observed from its decay products. The Higgs boson can decay into almost any fermion-antifermion pairs, however, for low Higgs mass ($m_H < 2m_t$), the $t\bar{t}$ decay is not allowed. Additionally, the Higgs can also decay to pairs of W and Z bosons and to pairs of massless gauge bosons, the gg and $\gamma\gamma$, as well as $Z\gamma$ decay.

The probability for any given decay depends on the strength of the interaction, the mass of the decay products and the Higgs mass itself. Table 2.1 provides an overview of

the most dominant decay modes and their branching fractions as expected by the SM for $m_H = 125.09$ GeV, where BRs that are significantly negligible have been omitted. In Figure 2.8b, the Higgs decay BRs are presented as a function of m_H . Where one can see that below $m_H = 180$ GeV, the Higgs predominantly decays to $b\bar{b}$, while for higher Higgs mass, the BRs to weak vector bosons becomes dominate.

The diphoton channel has a considerably lower BRs than the other Higgs decay channels, however it played a crucial role in its discovery. This is due to the fact that the energy and momentum of the photons can be reconstructed very precisely, thus giving accurate measurement of the mass of the decaying product. The Higgs boson does not couple directly to the massless gauge bosons, therefore, $H \rightarrow \gamma\gamma$ and $H \rightarrow gg$ decay processes are only possible via loop diagrams containing massive charged particles i.g. top quark loops. The major physics analysis of this thesis is based on the search for new scalar resonances in this channel. This search is described in details in Chapter 5.

Mode	Order	Cross-section [pb]		Mode	Branching ratio [%]
		$\sqrt{s} = 8$ TeV	$\sqrt{s} = 13$ TeV		
ggF	N3LO	$21.39^{+5.45\%}_{-7.61\%}$	$48.51^{+5.61\%}_{-7.43\%}$	$H \rightarrow b\bar{b}$	$58.09^{+1.24\%}_{-1.26\%}$
VBF	NNLO	$1.600^{+2.15\%}_{-2.15\%}$	$3.779^{+2.20\%}_{-2.18\%}$	$H \rightarrow WW^*$	$21.52^{+1.53\%}_{-1.52\%}$
WH	NNLO	$0.701^{+2.11\%}_{-2.18\%}$	$1.370^{+2.00\%}_{-2.05\%}$	$H \rightarrow gg$	$8.180^{+5.15\%}_{-5.08\%}$
ZH	NNLO	$0.421^{+3.36\%}_{-2.94\%}$	$0.882^{+4.12\%}_{-3.40\%}$	$H \rightarrow \tau\bar{\tau}$	$6.256^{+1.65\%}_{-1.63\%}$
$t\bar{t}H$	NLO	$0.1326^{+5.84\%}_{-10.2\%}$	$0.5065^{+6.82\%}_{-9.88\%}$	$H \rightarrow c\bar{c}$	$2.884^{+5.55\%}_{-1.97\%}$
tH	NLO	$0.0190^{+8.64\%}_{-17.2\%}$	$0.0743^{+7.50\%}_{-15.2\%}$	$H \rightarrow ZZ^*$	$2.641^{+1.53\%}_{-1.52\%}$
$b\bar{b}H$	NLO	$0.2015^{+20.6\%}_{-22.3\%}$	$0.4863^{+20.1\%}_{-23.9\%}$	$H \rightarrow \gamma\gamma$	$0.227^{+2.09\%}_{-2.05\%}$
				$H \rightarrow Z\gamma$	$0.1541^{+5.81\%}_{-5.83\%}$
				$H \rightarrow \mu\bar{\mu}$	$0.0217^{+1.68\%}_{-1.70\%}$

Table 2.1: The SM Higgs boson production cross-sections and decay branching ratios, together with their total for $m_H = 125.09$ GeV. All values are taken from reference [75]. All cross-sections are calculated with NLO EW corrections, the “order” column refers only to the QCD corrections. LO refers to the leading order, NLO to the next-to-leading order, NNLO to the next-to-next-to-leading order and N3LO to the next-to-next-to-next-to-leading order calculations. The percentage uncertainties of the cross-sections are the quadrature sum of the uncertainties resulting from variations of QCD scales, PDF’s and the strong coupling α_s . Note that the star, i.g. W^* , refers to virtual or off-shell particles

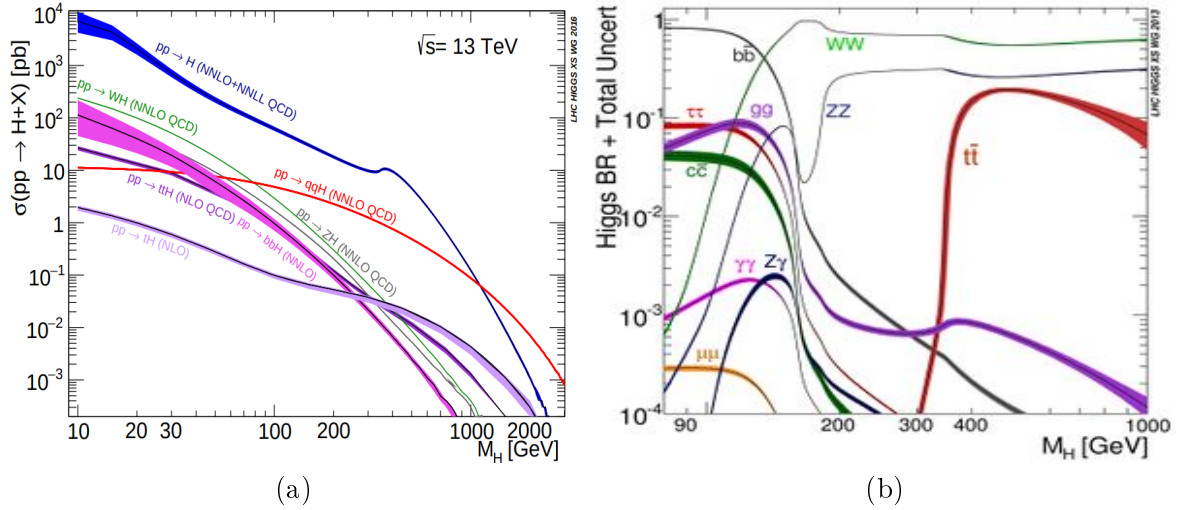


Figure 2.8: (a) SM Higgs boson cross-section for all Higgs production processes at LHC with $\sqrt{s} = 13$ TeV pp collisions as a function of the Higgs mass. (b) SM Higgs boson branching ratios for the different decay channels as a function of the Higgs boson mass $m_H \in [80, 1000]$ GeV. The coloured bands represent the total theoretical uncertainties on the cross-sections and BRs.

2.5.3 DISCOVERY OF THE SM HIGGS BOSON AT THE LHC

The searches for the last missing piece of the SM, the Higgs boson, was conducted at the CERN Large Electron Positron (LEP) collider [76, 77, 78, 79] which was operating from 1989 until 2000 and at the Tevatron at Fermilab from 1983 until 2001. Unfortunately, the Higgs boson was not observed during these eras, however other precision measurements of the SM were made possible by the LEP collider and its four detectors (ALEPH, DELPHI, L3 and OPAL). On the other hand, the main achievement of the Tevatron was the discovery of the heaviest of all observed elementary particles, the top quark in 1995. After that the search for the Higgs boson restarted again in 2008 at the LHC, where the Higgs boson was searched in all possible decay channels.

In 2012, an observation of a Higgs-like boson with a mass of approximately 125 GeV was reported by both the ATLAS and CMS collaborations [5, 6]. The discovery was made using datasets recorded by the two experiments, corresponding to an integrated luminosity of approximately 4.8 fb^{-1} collected at $\sqrt{s} = 7$ TeV in 2011 and 5.8 fb^{-1} at $\sqrt{s} = 8$ TeV in 2012. ATLAS and CMS presented the evidence of the SM Higgs boson in three bosonic decay channels: $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4\ell$ and $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$. The observed local p_0 value obtained from the combination of these channels are shown as a function of the Higgs mass in Figure 2.10 for ATLAS and CMS, respectively. Both experiments independently measured a local significance of $\geq 5\sigma$, implying that the probability of a statistical fluctuation from the background is less than one in a million.

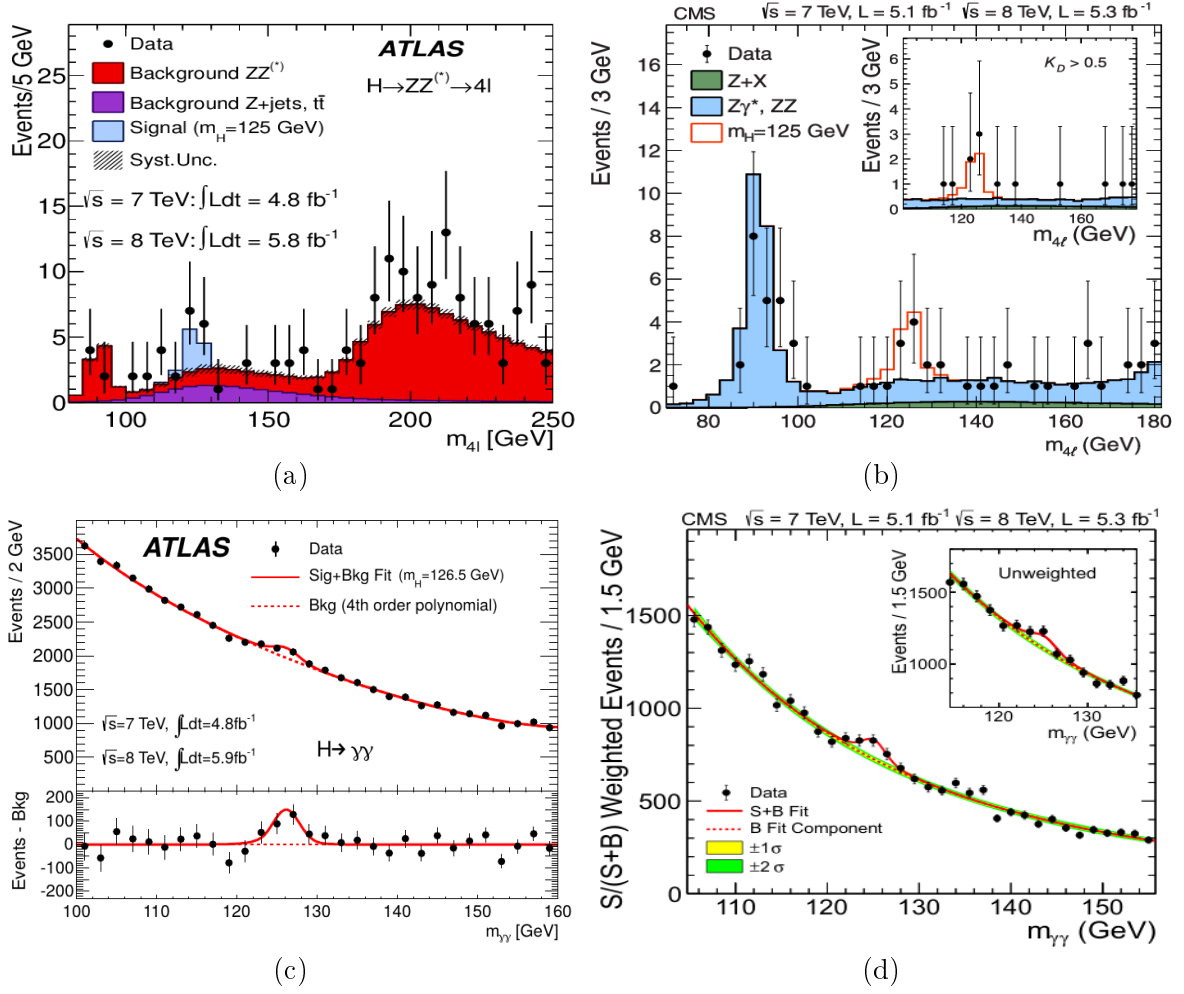


Figure 2.9: (a) and (b) are distributions of the four-lepton invariant mass from Higgs candidate events measured by the ATLAS [5] and CMS [6] experiments, respectively. (c) and (d) are weighted distributions of the diphoton invariant mass from Higgs candidate events measured by the ATLAS [5] and CMS [6] experiments, respectively.

The combination of the diphoton and the $ZZ \rightarrow 4\ell$ decay channels allow the most precise measurement of the Higgs boson mass, since the energy reconstruction of these final states can be done with a great precision. In these two channels, the Higgs boson was observed as a narrow mass peak over a non-resonant background. Figure 2.9 shows the invariant mass distributions of the diphoton and the four leptons channels obtained by ATLAS and CMS collaborations using Run-1 datasets. While Figure 2.11 presents a summary of Higgs boson mass measurements from the individual Run-1 and Run-2 analyses of ATLAS and CMS experiments.

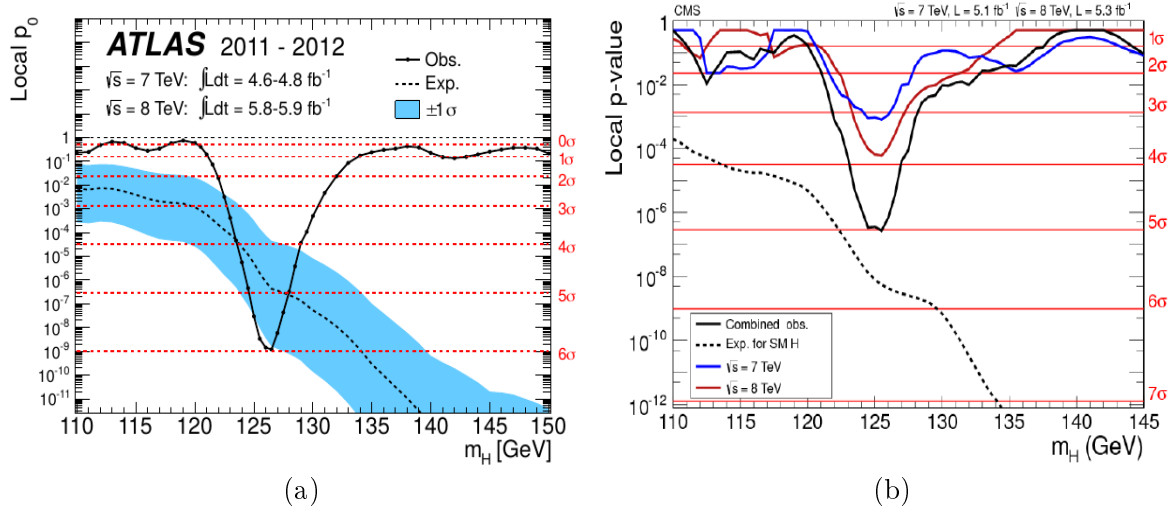


Figure 2.10: The observed (solid) local p-value as a function of m_H in the low mass range (a) ATLAS [5] and (b) CMS [6] for 7 TeV and 8 TeV data. The horizontal dashed lines indicate the p-values corresponding to significances.

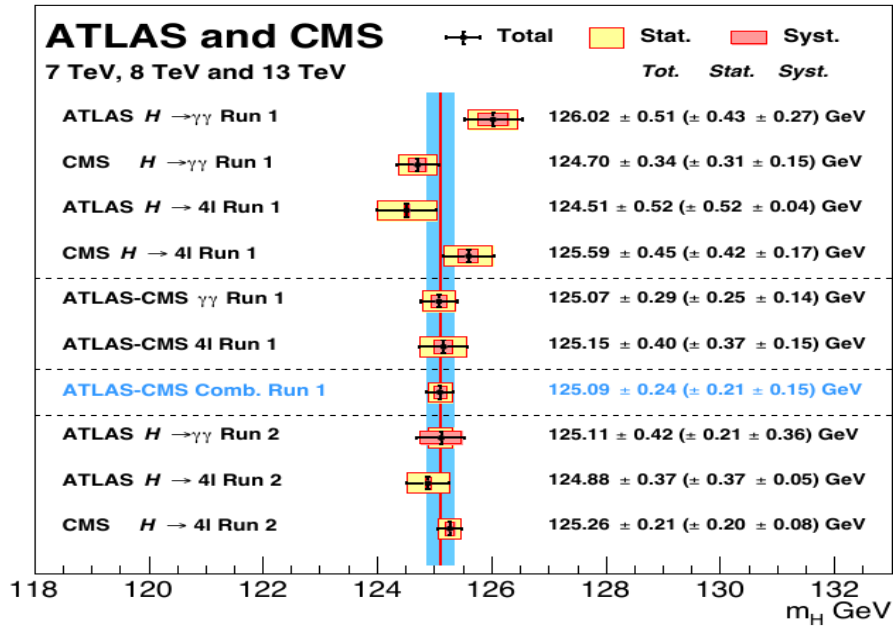


Figure 2.11: Combined Higgs mass measurements in the $\gamma\gamma$ and 4ℓ channels obtained by the ATLAS and CMS experiments in Run-1 and Run-2. The vertical red line and blue shaded column indicate the central value and the total uncertainty of the combined measurement, respectively [80].

EXPERIMENTAL APPARATUS

One of the largest and most important research institutions in the world, the European Organization for Nuclear Research (CERN¹), founded in September 1954, is located at the border between France and Switzerland, near Lake Geneva. CERN has by now 23 member states and over 600 universities and institutes around the world that use its facilities. CERN is the home of a wide range of the world’s most intricate scientific experiments and several particle accelerators and decelerators, needed for high-energy physics researches to probe the fundamental structure of matter. CERN has the largest and highest-energy particle accelerator in the world, the Large Hadron Collider (LHC), which was built between 1998 and 2008 in collaboration with engineers and scientists from all over the world. Such experiment is designed to probe the regimes of physics phenomena at very small time-scales and subatomic distances.

This chapter discusses the setup of the LHC and the CERN accelerator complex. An overview of the LHC performance and the key accelerator parameters during its operation periods is given in section 3.1.1, and the experiments at the LHC are introduced in section 3.1.3. The ATLAS detector which is within the scope of this thesis is afterwards discussed in detail in section 3.2.

3.1 THE LARGE HADRON COLLIDER

The LHC [81, 82, 83, 84] is a ring-shaped particle accelerator and collider with about 27 kilometres in circumference and between 45 and 170 meters below ground level, in a tunnel crossing the French-Swiss border four times. This tunnel was previously occupied by the LEP collider, which was operating from 1989 until 2000. The LHC is mainly designed to collide protons with number of collisions that exceeds 600 millions per second at very high center-of-mass energies and luminosities for new physics discoveries, measurement and verification of the SM parameters. Collisions of heavy ions such as proton-lead or lead-lead can also be performed. However, this thesis, will only focus on the pp collisions. The proton source is Hydrogen gas whose atoms are ionized by an applied electric field using pulsed ion source called “Duoplasmatron”. Protons are

¹The abbreviation comes from the French name **C**onseil **E**uropéen pour la **R**esearch **N**ucléaire

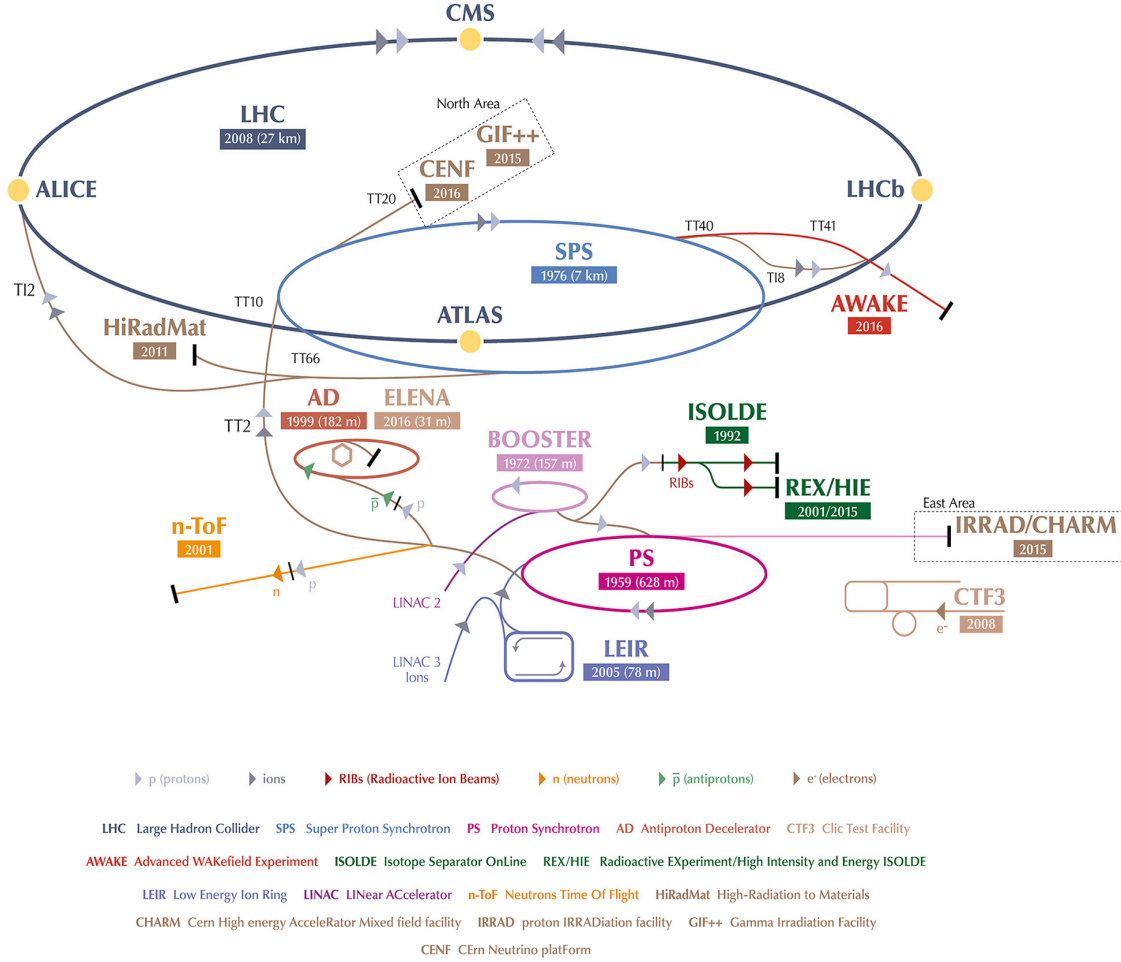


Figure 3.1: The CERN accelerator complex including all the pre-accelerators and the LHC with its four major experiments [85].

accelerated through a several successive pre-accelerators before being injected into the main LHC ring. This chain of accelerators known as the *CERN accelerator complex*, in which each accelerator boosts the energy of a proton beam as it passes through. Figure 3.1 shows a schema of the CERN accelerator complex including the LHC.

The linear accelerator (LINAC) accelerate the protons to 50 MeV and feed them into the Proton Synchrotron Booster (PSB) which can accelerate them up to 1.4 GeV. Protons are subsequently inserted into the Proton Synchrotron (PS), brought up to 26 GeV, here the protons reach the speed limit 99.9% of the speed of light, therefore, start getting heavier. Afterwards they are accelerated to 450 GeV by the Super Proton Synchrotron (SPS). Eventually, the proton bunches get injected into the LHC ring, in which they are brought to 7 TeV (LHC has not yet reached this energy).

The LHC ring consists of two parallel pipes which house the proton beams and allow them to circulate in opposite direction. These pipes are surrounded by accelerating structures and a large magnetic system. A series of 1232 superconducting dipole

magnets, each 15 meters long and 35 tons weight approximately, are niobium-titanium (NbTi) cables and placed at regular intervals along the ring. These magnets are used for both accelerate the proton beams and keep them at a fixed circular trajectory. They operate at a regulated temperature of 1.9 K using super fluid liquid helium, and thus can produce a magnetic field of around 8.3 Tesla. In addition to the dipole magnets, a set of 392 quadrupole magnets, 5 - 7 meters long, are used to focus the beams. Nominally, the LHC was designed to accelerate the protons beams up to 7 TeV, corresponding to centre-of-mass energy of 14 TeV. However, the maximum energy that the LHC has been run at is 13 TeV, more details are given in following subsection (3.1.1). Each beam of protons circulating within the LHC is designed to hold up to 2808 bunches² of typically an average of 115 billion protons, which are separated in time by 25 ns. After ensuring that the proton beams are in safe and stable conditions and can continue for about 24 hours, the beams are allowed to collide at the interaction points, around which big detectors are installed to collect physics data for the resulting shattered particles.

3.1.1 LHC PERFORMANCE

The LHC has been collecting data in two periods which are referred to as Run-1 and Run-2, with a short technical stop. Both runs are followed by two years of shutdown periods for essential repairs and upgrades, these periods called Long Shutdowns (LS). The first beam was circulated through the LHC in September 2008 and this was followed with a magnet quench incident that caused extensive damage to the machine components such as the vacuum pipe and the superconducting magnets. Due to this incident, the first LHC proton collection run, Run-1, officially began in March 2010 and ended by February 2013, in which the SM Higgs boson was observed. In the years 2010 and 2011, protons were collided at centre-of-mass energy of 7 TeV, which was increased to 8 TeV from April 2012 to the end of 2013. After this, the LS1 started, in which a major upgrade and maintenance programme has been launched for two years. During LS1 the power of the collider was improved, and so were its detection capabilities.

In April 2015, the second data taking period, Run-2 at the LHC started, which extended until late 2018, during this period the total energy of the collider beams reached 13 TeV and the luminosity increased almost twice of the first run. Run-2 produced some impressive results, and a ton of data still to be worked through. LS2 started December 2018 and finished successfully by early 2021, this second and latest upgrade equips the LHC with better protected magnets and more sensitive detectors, among other improvements. The work was in preparation for the Run-3 operation period, scheduled

²The highest number used so far was 2556 due to stability and safety requirements.

to last from 2022 to 2024. It is aimed to collide protons at $\sqrt{s} = 14$ TeV, and at twice the Run-2 instantaneous luminosity, collecting a predicted 1300 fb^{-1} of pp collision data. The first test beams were circulated in the LHC during October 2021. ATLAS successfully recorded 25-30 beam splashes from each beam. Between 2025 and 2027, further upgrades to the LHC will facilitate instantaneous luminosities seven times larger than the Run-2 luminosity, referred to as the High Luminosity LHC (HL-LHC) project. The HL-LHC physics programme is scheduled to last until 2037, collecting a total of $3000\text{--}4000 \text{ fb}^{-1}$ of pp collision data with 200 collisions expected in each bunch crossing.

3.1.2 LHC PARAMETERS OF INTEREST

The performance of particle colliders and accelerator is usually quantified by the instantaneous luminosity and beam energy. The luminosity is defined as the proportionality factor between the number of events “an event is a collision” per second of a certain process to its cross-section: $dN_{event}/dt = \mathcal{L} \cdot \sigma_{event}$. Considering that the two beams colliding are identical, the luminosity can be written in terms of the beam parameters as follows [84]:

$$\mathcal{L} = \frac{N_b^2 n_b f_{rev} \gamma_r}{4\pi \varepsilon_n \beta^*} F \text{ [cm}^{-2}\text{s}^{-1}\text{]}, \quad (3.1.1)$$

where n_b is the number of bunches per beam, N_b is the number of protons per bunch, f_{rev} is the revolution frequency and γ_r the relativistic Lorentz factor. In the denominator, the normalised transverse beam emittance ε_n and the beam cross-sectional size at injection β^{*3} are used to describe the area of overlap between the two colliding beams. The factor F describes the geometrical luminosity reduction due to the crossing angle θ_c of the two colliding beams at the interaction point. This factor can never be greater than one and is defined, in Gaussian approximation of the beam distribution, as $F = 1/\sqrt{1 + (\theta_c \sigma_z / 2\sigma_t)^2}$, where σ_z is the longitudinal bunch length and σ_t is the transverse size of the beam and represents the beams focusing at the interaction point. The instantaneous luminosity decreases over time as the beams are running, as there will be fewer and fewer protons in each bunch. The number of collisions produced by interesting processes over a certain time period is quantified by the integrated luminosity. It is defined to be the instantaneous luminosity integrated over time, $\mathcal{L}_{int} = \int_0^T \mathcal{L}(t) dt$. The unit of the $\mathcal{L}_{int}$ is therefore cm^{-2} (units of inverse cross-section).

Setting the luminosity higher by increasing the bunch population and decreasing the bunch spacing results in increasing the production rate of events. Meaning that, the higher the luminosity, the more data the experiments can gather to study rare processes. However, increasing luminosity increases the average number of interactions

³The beta function is defined as $\beta^* = \pi \sigma_t^2 / \varepsilon_n$.

Parameter	Symbol [Unit]	Nominal	Run-1			Run-2			
			2010	2011	2012	2015	2016	2017	2018
Beam energy	E [TeV]	7.0	3.5	3.5	4.0	6.5	6.5	6.5	6.5
Bunch spacing	[ns]	25	150	50	50	50-25	25	25	25
Max number of bunches	nb	2808	368	1380	1380	2244	2220	1868-2556	2556
Bunch intensity	N_p [$10^{11}p$]	1.15	1.0	1.3	1.5	1.2	1.25	1.25	1.1
Number of interactions	$\langle\mu\rangle$	20.7	< 5	9.1	20.7	13.3	25.1	37.8	36.1
Revolution frequency	f_{ref} [kHz]	11.2	11.25	11.25	11.25	11.25	11.25	11.25	11.25
Crossing Angle	θ_c [μ rad]	285	200	240	290	370	280/370	240-300	260-300
Beta function	β^* [m]	0.55	3.5	1.0-1.5	0.6	0.8	0.4	0.3-0.4	0.25-0.3
Normalized emittance	ε_n [μ m]	3.73	2.6	2.4	2.4	2.6-3.5	1.8-2.0	1.8-2.2	1.8-2.2
Peak luminosity	$\mathcal{L}$ [$10^{34}\text{cm}^{-2}\text{s}^{-1}$]	1.0	0.21	0.35	0.77	0.47	1.45	2.0	2.1
Integrated luminosity	$\mathcal{L}_{int}$ [cm^{-2}]	-	1.07×10^{-4}	5.46	22.8	4.2	38.5	50.2	63.3
Max stored energy	[MJ]	360	24	110	145	277	270	320	340

Table 3.1: Evolution of the LHC beam parameters for pp operation in Run-1(2010-2012) and Run-2 (2016-2018), shown together with the key design parameters [81, 86].

per proton bunch crossing (pile-up), denoted with $\langle\mu\rangle$. Pile-up is caused by overlapping pp interactions within the same (in-time pile-up) or neighbouring (out-of-time pile-up) bunch crossing at the interaction point. Pile-up can be defined in terms of the mean number of interactions per bunch crossing, which can also be related to the luminosity and to the beam parameters:

$$\mu = \frac{\mathcal{L}\sigma_{incl}}{n_b f_{rev}}, \quad (3.1.2)$$

where σ_{incl} is the cross-section for inelastic proton-proton scattering, taken to be 71.5 mb for 7 TeV collisions and 73.0 mb for 8 TeV collisions [87].

3.1.3 EXPERIMENTS AT THE LHC

There are four major experiments operating at the interaction points of the colliding beams circulating at the LHC. Two of them, ATLAS (A Toroidal LHC Apparatus) and CMS (Compact Muon Solenoid) are multi-purpose detectors designed to perform a wide range of measurements and searches available at the LHC. The LHCb (Large Hadron Collider beauty) focuses on flavour physics and studies of Charge Parity violation (CP-violation) by looking at the decays of b-hadrons [88] and ALICE (A Large Ion Collider Experiment) is specialized in measurements of heavy-ion collisions, which are used to study quark-gluon plasma and QCD processes [89]. A schematic view of the LHC and its experiments is shown in Figure 3.1. In addition to these four experiments, there are three other experiments operating at LHC. Whereas, LHCf (Large Hadron Collider forward) [90], TOTEM (Total Elastic and diffractive cross-section measurement) which are designed to study the elastic scattering, and the pp cross-section [91], and MoEDAL (Monopole and Exotics Detector at the LHC).

3.2 THE ATLAS DETECTOR

The ATLAS detector [92] is a multi-purpose particle detector that is designed to record the high energy pp and heavy-ion (Pb-Pb) collisions from the LHC to study a wide range of physics processes, search for physics in support of the SM and explore for evidence of the theories of particle physics Beyond the Standard Model (BSM).

The ATLAS detector is the largest detector at the LHC, it is a 44 m long, 25 m high and weighs around 7000 tons. ATLAS is composed of an individual concentric sub-systems. They are installed around the beam pipe and surrounding the collision point, each sensitive to different types of particles produced in the pp collisions. The detector components can generally be split into trackers (collectively known as the inner detector), calorimeters, and Muon spectrometer, and the magnetic system. These systems are made up of a barrel shaped section that is approximately uniform in the plane orthogonal to the beam line, and end-cap sections that are circular and located on the barrel's sides [93, 94]. Figure 3.2 shows a schematic overview of the full ATLAS detector.

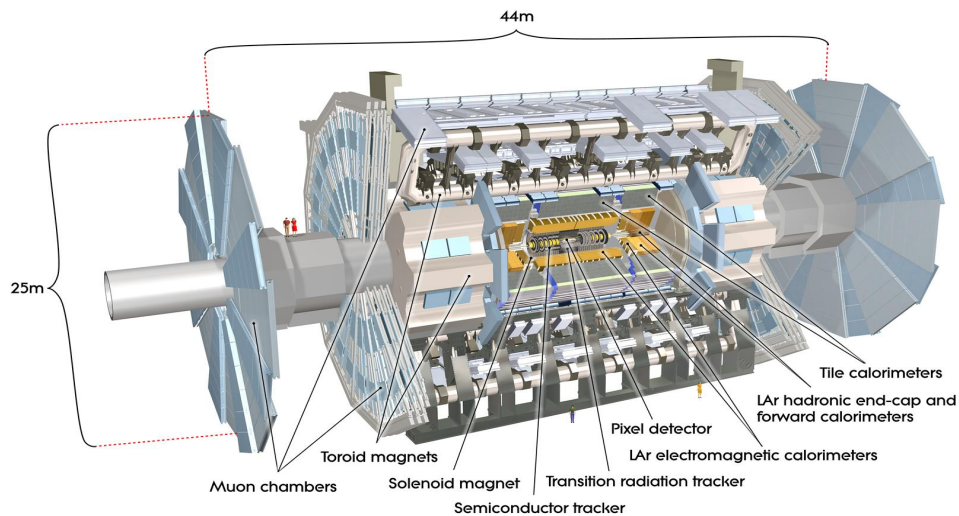


Figure 3.2: A cut-away view of the ATLAS detector showing dimensions and the main detector components [92]

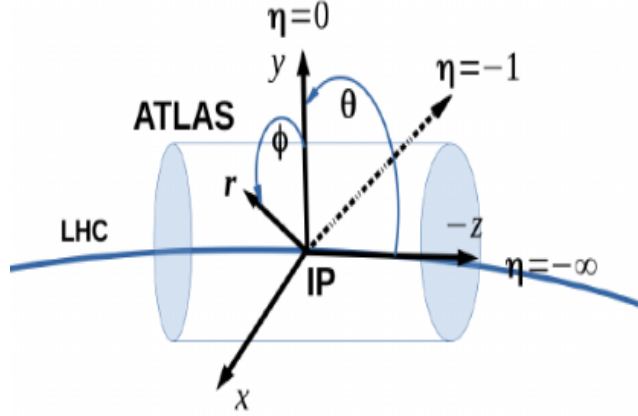


Figure 3.3: The ATLAS right-handed Cartesian and cylindrical coordinate systems. The $x - y$ plane is transverse to the beam line which runs parallel to the z axis.

The ATLAS reference frame is a right-handed Cartesian (x, y, z) coordinate system, with the origin fixed at the nominal Interaction Point (IP) in the centre of the detector. The z -axis lies along the proton beam direction. The origin of the coordinate system is fixed at the nominal IP in the centre of the detector. The $x - y$ plane defines the transverse plane to the beam axis as shown in Figure 3.3. The positive x -axis points from the IP to the centre of the LHC ring, while the positive y -axis points upwards towards the surface. Due to its cylindrical symmetry, ATLAS also uses the cylindrical coordinates (r, ϕ, z) ⁴, where r is the radial dimension measured from the origin and ϕ is the azimuthal angle around the beam line with $\phi = 0$ along the positive x -axis. The spherical polar angle, denoted with θ , is the angle measured with respect to the beam axis, with $\theta = 0$ parallel to the beam-pipe and $\theta = \pi/2$ in the transverse plane. The pseudorapidity η is used in place of θ to describe the angle of a particle relative to the beam axis due to its invariance under Lorentz boosts along the beam line, is then defined in terms of θ as $\eta = -\ln[\tan(\theta/2)]$. While pseudorapidity is used for massless or ultra-relativistic particles, massive particles use rapidity, defined as $y = \frac{1}{2} \ln(E + p_z / E - p_z)$ ⁵, where E is the particle's energy, and p_z is the particle's momentum in the z -direction. Furthermore, the angular separation between two particles is defined as $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ [92], where y is used instead of η when the massless approximation is not appropriate. The transverse momentum and the transverse energy are measured in the $x - y$ plane as $p_T = \sqrt{p_x^2 + p_y^2}$ and $E_T = \sqrt{p_T^2 + m^2}$, respectively. In addition to these two important kinematic variables, there is the missing transverse energy which

⁴ $r = \sqrt{x^2 + y^2}$, $\phi = \arctan(y/x)$ and $\theta = \arctan(r/z)$.

⁵For massless objects pseudorapidity and rapidity are equivalent.

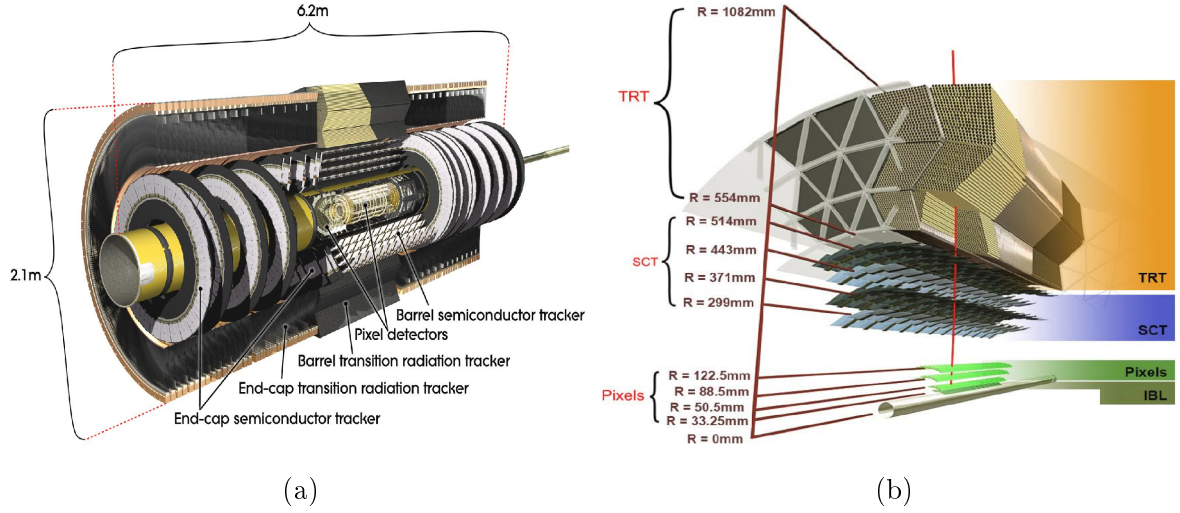


Figure 3.4: (a) An illustration of the ATLAS ID and its sub-systems. (b) A schematic cross-section of the central region barrel of the ATLAS ID depicting the layers of the subsystems and the distance at which they are located from the IP [105].

is defined as:

$$E_T^{\text{miss}} = |\vec{p}_T^{\text{miss}}| = \left| - \sum_i \vec{p}_{T,i}^{\text{rec}} \right|, \quad (3.2.1)$$

where $\vec{p}_T^{\text{miss}}$ is the missing transverse momentum which is given by the negative vectorial sum of all reconstructed momenta in the transverse plane.

In the following sections, I will present a general overview of the detector sub-systems that are important for the work in this thesis.

3.2.1 THE INNER DETECTOR

The Inner Detector (ID) [95, 96, 97] is used to measure the trajectories and the momenta of charged particles with transverse momentum above 0.5 GeV. Furthermore, the ID was designed to reconstruct both primary vertices and secondary vertices. Their measurement is important to distinguish the hard-scatter vertex from pile-up vertices. The ID is of cylindrical shape 6.2 m long having diameter of 2.1 m, immersed in 2 Tesla solenoid magnetic field. This field causes charged particle tracks to bend and by calculating the radius, the momentum and charge of the particles can be determined. It consists of several subsystems: Pixel Detector (PD) [96, 98] and Semi-Conductor Tracker (SCT) [99, 100, 101], conjuncted with the Transition Radiation Tracker (TRT) [102, 103, 104]. All of these subsystems have a similar structure, they are made up of a barrel section and two end-caps sections.

The PD is located very close to the beam pipe and covers a pseudorapidity range of

$|\eta| < 2.5$. It allows reconstructing the vertex position and measure the trajectories of the charged particles for $p_T > 500$ MeV. The barrel section of the PD consists of four cylindrical layers with different radii (3.33, 5.05, 8.85 and 12.25 cm), while each end-cap section consists of three disks at different z locations (49.5, 58.0 and 65.0 cm) from the detector's centre and along the beam line. The innermost cylindrical layer, known as the Insertable B-Layer (IBL)⁶ [106], has been installed at the beginning of Run-2 with a radius of 3.33 cm around the interaction region. The IBL uses radiation-hard technology to compensate for the radiation damage in the PD. There are 1744 sensor modules (1456 in the barrel and 288 in the end-caps), each module (6×2 cm active device) contains a silicon board with 47000 pixels. Individual pixels have a thickness of $250 \mu\text{m}$ and a surface area of $50 \times 400 \mu\text{m}$. All together, there are 92 million electronic channels, which are designed to provide spatial measurements with an intrinsic resolution of $10 \mu\text{m}$ in the $r - \phi$ plane orthogonal to the beam axis and $115 \mu\text{m}$ in the z -axis. When particles pass any of these layers, hits are recorded. These 3-dimensional space points are then used to reconstruct the trajectory of the particles, as well as identify the primary point of interaction.

The next part of the inner tracker is the SCT which completes the precision tracking of the PD. The barrel part of the SCT consists of four cylindrical double-layer silicon micro-strip modules located at $R = 299, 371, 443, 514$ mm and covering $|\eta| < 1.4$. These strips are 126 mm long and $80 \mu\text{m}$ wide. On the other hand, each end-cap consists of nine discs layers located at ± 854 to ± 2720 mm along the z -axis and covers $1.4 < |\eta| < 2.5$. Each disc is built of stereo strips and of aligned radial strips at an angle of $40 \mu\text{rad}$. These strips are $55\text{-}120 \mu\text{m}$ long and $57\text{-}90 \mu\text{m}$ wide. The SCT consists of 4088 modules covering an area of 62 m^2 with approximately 6.2 million readout channels. The SCT provides a resolution of $17 \mu\text{m}$ in the $R - \phi$ plane and $580 \mu\text{m}$ in z direction.

The last and outermost-layer of the ID sub-detectors is the TRT. It consists of straw tubes (52,500 in the barrel section and 123,000 in each end-cap section). These tubes cover the region $|\eta| < 2.0$ and have both the tracking and identification capabilities. Each tube is 4 mm in diameter, with gold-plated tungsten wire (of diameter $31 \mu\text{m}$) suspended in the centre of the tube and serves as an anode. The tubes are made from layers of polyimide, aluminium, polyurethane and graphite-polyimide. They are filled with a gas mixture of 70% xenon/argon, 27% carbon dioxide and 3% oxygen. When charged particles pass through the straw tubes, the gas inside is ionized and the ions move to the walls of the tube, where the total charge is recorded. Then, the path of the particle can be reconstructed by finding the line of the tubes that have signal in them. The reason for this design comes from the fact that, lighter charged particles

⁶It is also called B-Layer since it plays an important role in the reconstruction of jets produced by bottom quarks.

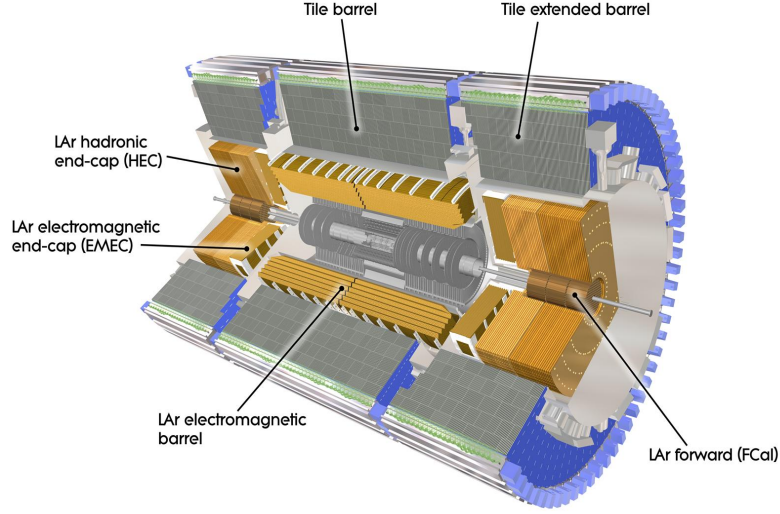


Figure 3.5: Cut-away view of the ATLAS calorimeter system [107].

emit more transition radiation than heavier ones. This allows the use of the TRT to help distinguish electrons from other particles.

3.2.2 THE CALORIMETERS SYSTEM

This system surrounds the solenoid, which produces the magnetic field inside the ID [110]. The role of the calorimeters is to measure the energy of highly energetic particles except for high-energy muons and neutrinos and also to contribute to particle identification. This system is composed of two major subsystems: the Electromagnetic Calorimeter (ECal) [111] and the Hadronic Calorimeter (HCal). The ECal is responsible for measurements related to electrons and photons through their electromagnetic interactions, while the HCal measures the energies of hadronic showers. All calorimeters at ATLAS use the sampling technique. They are made of layers of high-density absorbing material that stops incoming particles, interleaved with layers of an “active” medium that detect and measure their energy.

The ECal consists of lead or copper absorbers and Liquid-Argon (LAr) as active material. The absorber plates are folded into a distinctive accordion shape, as shown in Figure 3.6a. The ECal calorimeter has a very high precision for the measurements of the absorbed energy as well as the place of the deposition. The ECal is made up of barrel part (EMB), two end-cap components, and Forward Calorimeter covering the pseudorapidity range $|\eta| \leq 1.475$, $1.375 \leq |\eta| \leq 3.2$ and $3.1 \leq |\eta| \leq 4.9$ respectively. The EMB is made from two identical half-barrels separated by a 4 mm gap at $z = 0$,

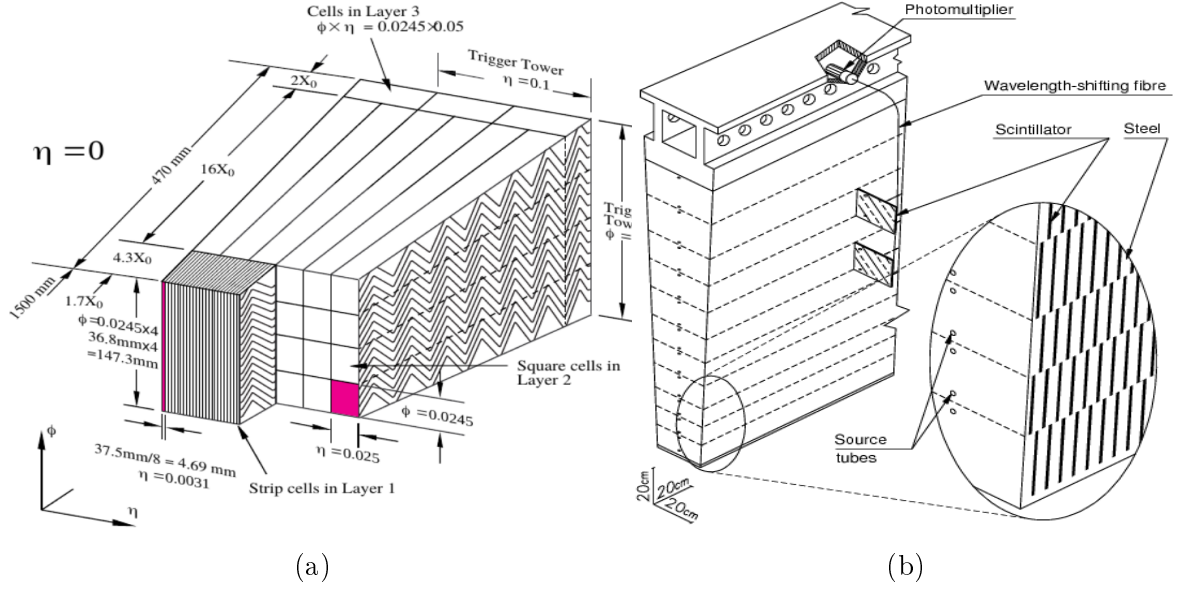


Figure 3.6: (a) A single module of the EMB, showing the accordion shape of the absorber plates [108]. (b) A single module of the TileCal, the interleaved steel absorbers and scintillating tiles are shown with the PMT readout [109].

and is segmented in depth into three layers for $|\eta| < 1.35$ and two layers in the remainder. Each end-cap consists of two wheels, the inner wheel is 2 layers in depth and the outer one is 3 layers in depth.

The HCal surrounds the ECal and composed of LAr Hadronic End-cap Calorimeter (HEC), LAr Forward Calorimeter (FCal) and Tile Calorimeters (TileCal). The HEC has a coverage of $1.5 < |\eta| < 3.2$ and uses copper as a passive absorber material and LAr as an active medium. The HEC consists of two wheels at each end-cap with an inner radius of 372-475 mm and outer radius of 2030 mm, and each wheel is divided into 32 modules. The FCal [112] covers up to $|\eta| = 4.9$ has three 45 cm deep modules, electromagnetic module with copper absorber and two hadronic modules tungsten absorbers. As used in the ECal and HEC the active sampling material in FCal is LAr.

The TileCal [113, 114] is a sampling calorimeter made of plastic scintillating tiles as active medium and steel plates as absorbers. It is divided into three longitudinal partitions, a fixed central barrel which covers $|\eta| < 1.0$ and two moveable extended barrels on either side of the central barrel covering $0.8 < |\eta| < 1.7$. The length of the barrel (extended barrel) is 5.8 m (2.6 m) and they all have inner radius of 2.28 m and an outer radius of 4.25 m, as shown in Figure 3.5. These barrels are composed of 64 modules along the azimuth ϕ and contain the scintillators, steel absorbers. As particles hit the layers of steel, they generate a shower of new particles. The plastic scintillators in turn

produce photons. The incident photons are transmitted by wavelength shifting fibres to Photo-Multiplier Tubes (PMTs). The PMTs convert these photons into an electric current whose intensity is proportional to the original particle’s energy.

All the LAr detectors are segmented transversally and divided into three or four layers in depth, and correspond to a total of 182 k readout cells.

The calorimeter response to an incident particle of a given energy follows an approximately normal distribution. The width of this distribution is referred to as the resolution, σ , and is usually parameterized by [115]:

$$\frac{\sigma_E}{E} = \frac{N}{E} \oplus \frac{S}{\sqrt{E}} \oplus C, \quad (3.2.2)$$

where E is the measured energy of the incident particle. The parameter N accounts for the electronic noise in the read-out systems, S is the stochastic uncertainty that accounts for the fluctuations of the number of particles in the shower evolution, and C is the constant term which reflects the non-uniformities in the detector. The symbol $\oplus$ refers to quadratic summation. In many analyses, excellent energy resolution is required. The design energy resolutions for the ATLAS constituent calorimeter sections, that were also validated using beam-test results, are summarised in Table 3.2.

Calorimeter Component	Energy Resolution $\sqrt{\sigma_E/E}$ [GeV]
ECal	$10\%/\sqrt{E} \oplus 0.7\%$
HEC	$71\%/\sqrt{E} \oplus 3\%$
FCal	$100\%/\sqrt{E} \oplus 10\%$
TileCal	$50\%/\sqrt{E} \oplus 10\%$

Table 3.2: Calorimetry energy resolution, as obtained from beam-test results [108]

3.2.3 MUON SPECTROMETER

The Muon Spectrometer (MS) [116, 117] is cylindrical, 22 m in diameter and 45 m in length and is the largest and outermost component of the ATLAS detector. An overview of the muon spectrometer is shown in Figure 3.7. The MS is designed to accurately measure the momenta of muons and any charged particles escaping from the end-cap Calorimeter, and then is limited at low p_T by multiple scattering and energy losses. The measurement is based on the magnetic deflection of tracks in three superconducting air-core toroidal magnets, instrumented with separate trigger and multiple layers of high-precision tracking chambers located at different radial distances from the beam axis. One toroid to cover the barrel region ($\eta < 1.2$) and two in the forward regions ($1.2 \leq \eta \leq 2.7$). Each toroid consists of eight flat coils that are

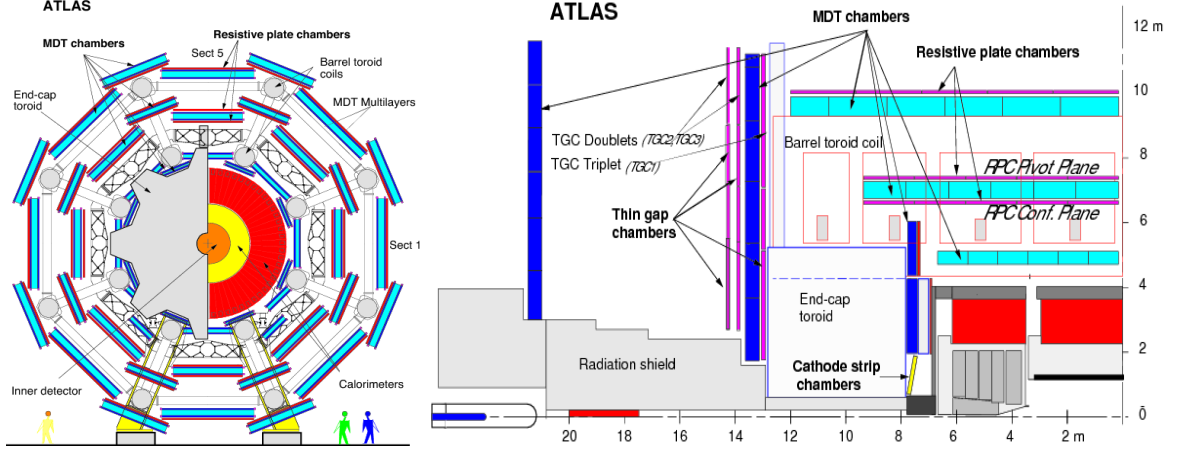


Figure 3.7: Transverse and longitudinal view of the ATLAS Muon Spectrometer [116].

assembled radially and uniformly around the beam line. These magnets generate an approximately toroidal field over a radial distance of the order of 5 m with an average field of 2.6 and 6 Tm⁷ in the barrel and end-caps respectively.

The MS has four types of chambers installed: Monitored Drift Tube chambers (MDT) [118] and Cathode Strip Chambers (CSC) [119], Resistive Plate Chambers (RPC) and Thin Gap Chambers (TGC). The MDTs and CSCs are referred to as “precision chambers” and are used for precision muon track measurements in the bending plane, while the TGCs and RPCs are used for triggering in the non-bending plane. Trigger chambers are characterized by a fast response compared to precision chambers. The CSCs cover $2.0 < |\eta| < 2.7$ in the end-caps; the remaining end-cap and barrel coverage in the range $|\eta| < 2.7$ is provided by the MDTs. Meanwhile, the RPCs cover the barrel ($|\eta| < 1.05$) and the TGCs cover the end-caps ($1.05 < |\eta| < 2.4$).

The MDTs consist of cylindrical aluminium drift tubes of diameter 29.97 mm, filled with a gaseous mixture of Ar (93%) and CO₂ (7%) at 3 bar absolute pressure. The MDT drift tubes also contain a central wire of tungsten-rhenium of diameter 50 μ m that acts as the anode which collects the gas electrons after being ionized by the passing muons. Over 380,000 aluminium tubes are stacked up in several layers in order to precisely trace the trajectory of each muon. The CSCs are composed of copper strips in orthogonal directions crossed by multi-wire proportional chambers with cathode planes and filled with a gas mixture of CO₂ (50%), Ar (30%) and CF₄ (20%) [120]. Each CSC is configured in two discs per end-cap, each segmented into eight chambers. Each chamber consists of four identical planes, which allow multiple measurements of η and ϕ for each of the muon tracks. Muons travelling through the gas are detected by

⁷Tm stands for Tesla-meter

both electron-collecting wires and ion-collecting strips.

The RPCs consist of pairs of parallel high-pressure phenolic laminate electrode plates at an electric potential difference 9.8 kV, separated by a 2 mm gas mixture of $\text{C}_2\text{H}_2\text{F}_4$. They are arranged in three concentric cylindrical layers around the beam axis at radii of approximately 5, 7.5 and 10 m, providing three trigger stations. Metallic orthogonal strips mounted on the outer faces of the plates read out the signal created by the traversing muons.

The TGCs are found at the ends of the ATLAS detector and consist of parallel $30\text{ }\mu\text{m}$ wires in a gas mixture CO_2 and $\text{n-C}_5\text{H}_{12}$. There are 560 RPC and 2588 TGC chambers with 359k/318k channels respectively. Both chambers have similar operating principle, and they detect muons when they ionise the gas mixture and generate a signal. They provide measurements of the η and ϕ coordinates for tracking, with a time resolution of 4 ns.

3.2.4 TRIGGER SYSTEM

At the ATLAS, the proton bunches collide at a rate of approximately 40 MHz [121]. Each bunch crossing allows around one billion pp collisions per second, most of which do not carry useful information for physics analyses. Additionally, it is not possible to consider all the information recorded by the trackers and calorimeters due to limitations in the data storage capacities. Hence, a two-level trigger system is designed to only select and record events of the interesting processes that are relevant for further physics analysis. The trigger system consists of a hardware Level-1 trigger (L1) [122] followed by a software-based High-Level Trigger (HLT) [123]. The HLT consists of the Level-2 trigger (L2) and the Event Filter (EF), and the Event Selection Software (ESS). With different selection criteria applied, each level uses the information from the previous one and then makes additional decisions.

The L1 trigger reduces the initial event rate to a maximum rate of approximately 75 kHz within a decision time of less than $2.5\text{ }\mu\text{s}$ per event. The L1 evaluates coarse granularity information from the muon and calorimeter systems. It identifies event features for high p_T objects such as (e, μ, γ, τ and jets). Once an object is identified by the L1 trigger, the region in the detector where it is located is defined as a Region of Interest (RoI). The L2 trigger uses the RoI information of the L1 trigger, which represents $\approx 2\%$ of the total event, and can make use of the full calorimeter granularity including information from the ID. The L2 trigger further reduces the event rate to $\approx 3.5\text{ kHz}$, with an event processing time of $\approx 40\text{ ms}$. At this point, before transferring them to the EF, events are passed to the Event Builder (EB), which collects event fragments and merges them into full-events. Event fragments are data produced from

different sub-detectors belonging to the same event. Now, the EF operates on fully-built events to further reduce acceptance event rate to 200 Hz with an average event processing time of 4 s. The EF is an off-line software, fully reconstructs the events using the ATLAS Athena reconstruction framework. From here, the datasets are transferred to the local storage space located at the experimental site and then exported to the CERN's Tier-0 computing infrastructure, where the full off-line event reconstruction runs.

CONSTRAINTS ON A 2HDM+S AND IMPLICATIONS IN THE SEARCH FOR HEAVY BOSONS AT THE LHC

4.1 INTRODUCTION

The Run-2 at the LHC delivered about 139 fb^{-1} of usable data at a proton-proton centre of mass energy of 13 TeV. Most of the studies released by the experiments at the LHC have been performed on about a half of this data set. Furthermore, some important studies have not yet been released with Run-2 data altogether.

In Refs. [10, 11, 12] the scalars H and S were introduced via an effective model to explain a number of features in the Run-1 data. These include distortions of the Higgs boson transverse momentum spectrum, accompanied with elevated associated jet activity, elevated rates of leptons in association with b -tagged jets used for the search of the associated production of the Higgs boson with top quarks, and results from the search for double Higgs boson and weak boson production. The potential impact on the measurements of some of the signal strengths of the newly discovered Higgs boson has been evaluated in Ref. [124]. The relevance and advantages of electron-proton collisions to search for additional scalar bosons have also been pointed out in Refs. [9, 125, 126].

The 2HDMs, introduced in Section 2.4.2, have been explored in the literature, where various facets related to the theory, phenomenology and constraints on these models using the experimental data from different collider environments have been explored [7, 8, 9]. However, as pointed out in Refs. [11, 12, 13, 14], a 2HDM alone is not able to accommodate the above-mentioned features of the data. As a result, a scalar singlet S is introduced in conjunction with a 2HDM in Ref. [12], referred to here as the 2HDM+S model. In addition, this type of model may also be able to explore scenarios with dark matter. In Ref. [12] it was discussed that a 2HDM+S model would result in the anomalous production of multiple leptons. This hypothesis has been compared to data [1], where large discrepancies between the data and MCs are observed that cannot be resolved with the current understanding of theoretical systematics. The features of the data examined in Ref. [1] have been studied with additional data in Ref. [15]. This

study indicates that these features have become more pronounced with more data.

Here we expand on the phenomenology described in Ref. [1, 12]. Firstly, we identify the parameter space of the 2HDM+S model that accommodates the features in the data studied in Ref. [1]. Secondly, we also evaluate the implications of this choice of parameter space for the heavy pseudo-scalar and the charged scalar. We are particularly interested in investigating the CP-odd scalar in the 2HDM+S model. In particular, we study the production of A through the ggF mode, and its decay into $A \rightarrow ZH$ channels, where the decay modes $H \rightarrow hh, Sh, SS$ are considered. This setup leads to a number of interesting final states with leptons and b -tagged jets.

The resulting kinematics of the decay of $A \rightarrow ZH$, where $m_A > m_Z + m_H$ and $H \rightarrow SS, Sh$, have been studied in Ref. [12]. Assuming that the width of A is much smaller than the experimental resolution obtained with the lbb decay, it was noted that a relatively narrow structure in the invariant mass spectrum of Zh is expected, such that $m_{Zh} < m_A$.

A structure in the Zh invariant mass spectrum has been reported by the ATLAS collaboration [127] with Run-2 data. The CMS collaboration has reported limits with Run-1 and Run-2 data that do not contradict the aforementioned results [128, 129]. The structure has been interpreted in terms of the decay $A \rightarrow Zh$ within a 2HDM, with a cross-section $\sigma(pp \rightarrow Zh) \approx 100 - 300$ fb in Ref. [130]. Here we interpret the structure in terms of the 2HDM+S model with the spectroscopy discussed in Refs. [10, 12] and Ref. [1], where $m_H \approx 270$ GeV and $m_S \approx 150$ GeV. The structure includes events with more than two b -tagged jets, which can be interpreted within a 2HDM as coming from a bottom-quark induced production of the CP-odd boson at intermediate values of $\tan \beta$. Here, the production of Zh with additional b -tagged jets from $A \rightarrow ZH \rightarrow ZSh, Zhh$ is discussed.

Note also that the CMS collaboration has reported discrepancies of 2.85σ in the production of three leptons, where one pair comes from the decay of a Z boson, in association with b -tagged jets but with reduced hadronic jet activity [131, 132]. These events are identified in the context of studying ttZ production, where the discrepancy emerges with low jet multiplicity. This excess can be explained by the production $A(600) \rightarrow ZH(270) \rightarrow ZS(145)h, Zhh$. In this setup we elaborate on the resulting characteristics corresponding to the production of three leptons, including a Z boson in association with b -tagged jets. The potential impact of the signal from a heavy CP-odd boson discussed in Ref. [130] is considered here on the measurement of the signal strength of Vh , ($V = ZW$) production.

This Chapter is organised into the following sections: In section 4.2 we describe the

model, in section 4.3 we describe the tools used and constraints imposed on the parameter scan, reporting on the allowed region of the parameter space where the implications on the branching ratios of the heavy pseudo-scalar and charged scalar are reported. In section 4.4 the findings from section 4.3 are compared to the data, and in section 4.5 we summarise and conclude.

4.2 THE MODEL

Following Ref. [12, 133, 134], a 2HDM with an additional real singlet Φ_S is the baseline for our formalism, where we use the notation used in Ref. [133], and call this model the 2HDM+S. As such, the potential is given by:

$$\begin{aligned} V(\Phi_1, \Phi_2, \Phi_S) = & m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 - m_{12}^2 \left(\Phi_1^\dagger \Phi_2 + \text{h.c.} \right) + \frac{\lambda_1}{2} \left(\Phi_1^\dagger \Phi_1 \right)^2 + \frac{\lambda_2}{2} \left(\Phi_2^\dagger \Phi_2 \right)^2 \\ & + \lambda_3 \left(\Phi_1^\dagger \Phi_1 \right) \left(\Phi_2^\dagger \Phi_2 \right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2 \right) \left(\Phi_2^\dagger \Phi_1 \right) + \frac{\lambda_5}{2} \left[\left(\Phi_1^\dagger \Phi_2 \right)^2 + \text{h.c.} \right] \\ & + \frac{1}{2} m_S^2 \Phi_S^2 + \frac{\lambda_6}{8} \Phi_S^4 + \frac{\lambda_7}{2} \left(\Phi_1^\dagger \Phi_1 \right) \Phi_S^2 + \frac{\lambda_8}{2} \left(\Phi_2^\dagger \Phi_2 \right) \Phi_S^2. \end{aligned} \quad (4.2.1)$$

Here the fields Φ_1 and Φ_2 are the $SU(2)_L$ Higgs doublets. The first two lines are the terms from real 2HDM potential, while the last line contains the contribution of the singlet field Φ_S . To prevent tree-level FCNCs, we must couple all quarks of a given charge to a single Higgs doublet. This can be accomplished by imposing a $\mathbb{Z}_2$ symmetry, which can be softly broken by the term m_{12}^2 . Also, the extension of the $\mathbb{Z}_2$ symmetry to the Yukawa sector guarantees the absence of FCNC at tree-level. A trivial generalisation of the usual 2HDM $\mathbb{Z}_2$ symmetry requires:

$$\Phi_1 \longrightarrow \Phi_1, \quad \Phi_2 \longrightarrow -\Phi_2, \quad \Phi_S \longrightarrow \Phi_S. \quad (4.2.2)$$

One can also consider another $\mathbb{Z}_2'$ symmetry:

$$\Phi_1 \longrightarrow \Phi_1, \quad \Phi_2 \longrightarrow \Phi_2, \quad \Phi_S \longrightarrow -\Phi_S, \quad (4.2.3)$$

which is not broken explicitly. For our study, we consider a scenario where the real singlet field Φ_S acquires a *vev* with $\mathbb{Z}_2$ symmetry.¹ Note that if Φ_S doesn't acquire a *vev*, the $\mathbb{Z}_2'$ symmetry then becomes a source of a viable dark matter candidate.

In this work we set the term $m_{12}^2 \neq 0$ in the 2HDM+S potential, which corresponds to a soft breaking of the $\mathbb{Z}_2$ symmetry, and consider the λ_i to be real, which corresponds

¹In principle Φ_S could be a complex singlet, and, in this case, the discrete $\mathbb{Z}_2$ symmetry would be promoted to a global $U(1)$ symmetry, where the spontaneous breaking would lead to a massless pseudo-scalar. This might be important and acceptable for phenomenology if it does not couple to the SM particles [135].

to a model without explicit CP violation. More discussions can be found in Refs. [133, 135, 136].

Assuming the *vevs* for the fields $\Phi_1 \rightarrow v_1/\sqrt{2}$, $\Phi_2 \rightarrow v_2/\sqrt{2}$ and $\Phi_S \rightarrow v_S$ are real after EWSB, the minimisation of the potential of the three Higgs fields leads to the three minimisation conditions:

$$\frac{\partial V}{\partial v_1} = \frac{\partial V}{\partial v_2} = \frac{\partial V}{\partial v_S} = 0. \quad (4.2.4)$$

The first derivative conditions for Φ_i ($i = 1, 2, S$) are:

$$\frac{\partial V}{\partial \Phi_1} = 0 \rightarrow m_{11}^2 = -\frac{1}{2}(v_1^2 \lambda_1 + v_2^2 \lambda_{345} + v_S^2 \lambda_7) + \frac{v_2}{v_1} m_{12}^2, \quad (4.2.5)$$

$$\frac{\partial V}{\partial \Phi_2} = 0 \rightarrow m_{22}^2 = -\frac{1}{2}(v_2^2 \lambda_2 + v_1^2 \lambda_{345} + v_S^2 \lambda_8) + \frac{v_2}{v_1} m_{12}^2, \quad (4.2.6)$$

$$\frac{\partial V}{\partial \Phi_S} = 0 \rightarrow m_S^2 = -\frac{1}{2}(v_1^2 \lambda_7 + v_2^2 \lambda_8 + v_S^2 \lambda_6), \quad (4.2.7)$$

where $\lambda_{345} \equiv \lambda_3 + \lambda_4 + \lambda_5$. Further, the doublet fields Φ_1 , Φ_2 and singlet field Φ_S can be parameterised as:

$$\Phi_1 = \begin{pmatrix} \phi_1^\pm \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^\pm \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix}, \quad \Phi_S = v_S + \rho_S, \quad (4.2.8)$$

where $\phi_j^\pm$ ($j = 1, 2$) are the charged complex fields, ρ_i are real neutral CP-even fields and η_i are the real CP-odd fields. By substituting the parametrisation (4.2.8) into the Higgs potential (4.2.1), the mass matrices in the gauge basis can be easily obtained from the second derivatives of the fields. Accordingly, the mass-matrix for the charged ($M_{H^\pm}^2$) and CP-odd (M_A^2) scalar sector will remain as it is in the 2HDM. Using a 2×2 rotation matrix, given as:

$$\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} \cos \beta & \sin \beta \\ -\sin \beta & \cos \beta \end{pmatrix} \begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix}, \quad (4.2.9)$$

where $G^\pm$ are a pair of charged Goldstone bosons and $H^\pm$ are the physical charged scalars; the mass squared charged scalar matrix is the same as in a 2HDM. It can be represented as:

$$M_{H^\pm}^2 = \begin{pmatrix} -(2m_{12}^2 + (\lambda_4 + \lambda_5) v_1 v_2) \frac{v_2}{2v_1} & m_{12}^2 + \frac{1}{2}(\lambda_4 + \lambda_5) v_1 v_2 \\ m_{12}^2 + \frac{1}{2}(\lambda_4 + \lambda_5) v_1 v_2 & -(2m_{12}^2 + (\lambda_4 + \lambda_5) v_1 v_2) \frac{v_2}{2v_1} \end{pmatrix}. \quad (4.2.10)$$

Similarly, the CP-odd scalar sector can be diagonalised using the same 2×2 rotation matrix:

$$\begin{pmatrix} G^0 \\ A \end{pmatrix} = \begin{pmatrix} \cos \beta & \sin \beta \\ -\sin \beta & \cos \beta \end{pmatrix} \begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix}, \quad (4.2.11)$$

where G^0 is a neutral Goldstone boson, A is the physical pseudo-scalar, and $\eta_{1,2}$ are real CP-odd fields. The mass squared CP-odd scalar matrix is exactly the same as in the 2HDM. It can be formulated as:

$$M_A^2 = \begin{pmatrix} -(m_{12}^2 + \lambda_5 v_1 v_2) \frac{v_2}{v_1} & m_{12}^2 + \lambda_5 v_1 v_2 \\ m_{12}^2 + \lambda_5 v_1 v_2 & -(m_{12}^2 + \lambda_5 v_1 v_2) \frac{v_2}{v_1} \end{pmatrix}, \quad (4.2.12)$$

where diagonalising the CP-odd mass squared matrix will result in the pseudo-scalars physical mass eigenstates A .

Since the 2HDM+S CP-even Higgs sector consists of additional Higgs bosons with respect to the 2HDM, due to the addition of the real scalar singlet, the CP-even neutral Higgs mass matrix is enlarged to a 3×3 matrix. In the interaction basis, (ρ_1, ρ_2, ρ_3) , it can be written as (using eqs. (4.2.5)-(4.2.7)):

$$M_{\text{CP-even}}^2 = \begin{pmatrix} \lambda_1 c_\beta^2 v^2 + t_\beta m_{12}^2 & -m_{12}^2 + \lambda_{345} c_\beta s_\beta v^2 & \lambda_7 c_\beta v v_S \\ -m_{12}^2 + \lambda_{345} c_\beta s_\beta v^2 & \lambda_2 s_\beta^2 v^2 + m_{12}^2 / t_\beta & \lambda_8 s_\beta v v_S \\ \lambda_7 c_\beta v v_S & \lambda_8 s_\beta v v_S & \lambda_6 v_S^2 \end{pmatrix}, \quad (4.2.13)$$

and it can be diagonalised by an orthogonal 3×3 matrix $\mathcal{R}$, in terms of mixing angles α_k ($k = 1, 2, 3$), and given as:²

$$\mathcal{R} = \begin{pmatrix} c_{\alpha_1} c_{\alpha_2} & s_{\alpha_1} c_{\alpha_2} & s_{\alpha_2} \\ -(c_{\alpha_1} s_{\alpha_2} s_{\alpha_3} + s_{\alpha_1} c_{\alpha_3}) & c_{\alpha_1} c_{\alpha_3} - s_{\alpha_1} s_{\alpha_2} s_{\alpha_3} & c_{\alpha_2} s_{\alpha_3} \\ -c_{\alpha_1} s_{\alpha_2} c_{\alpha_3} + s_{\alpha_1} s_{\alpha_3} & -(c_{\alpha_1} s_{\alpha_3} + s_{\alpha_1} s_{\alpha_2} c_{\alpha_3}) & c_{\alpha_2} c_{\alpha_3} \end{pmatrix}. \quad (4.2.14)$$

The three physical mass eigenstates h, S and H in terms of the interaction basis (ρ_1, ρ_2, ρ_3) , are given as:

$$\begin{pmatrix} h \\ S \\ H \end{pmatrix} = \mathcal{R} \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_S \end{pmatrix}. \quad (4.2.15)$$

Here the mixing angles $\alpha_{1,2,3}$ for the CP-even Higgs states can be constrained within $-\pi/2 < \alpha_{1,2,3} < \pi/2$, without loss of generality. And thus the CP-even mass squared matrix $M_{\text{CP-even}}^2$ can be diagonalised using the orthogonal matrix $\mathcal{R}$ as:

$$\mathcal{R} M_{\text{CP-even}}^2 \mathcal{R}^T = \text{diag}(m_h^2, m_S^2, m_H^2). \quad (4.2.16)$$

It is important to note that this model can connect the anomalies and features seen and discussed in section 4.1, including the few analyses performed in Refs. [10, 12, 13,

²The abbreviations used here are $s_{\alpha_k} \equiv \sin \alpha_k$, $c_{\alpha_k} \equiv \cos \alpha_k$ and $t_\beta \equiv \tan \beta$, where t_β is defined as $t_\beta = v_2/v_1$ and $v^2 = v_1^2 + v_2^2$. By letting $\alpha_{2,3} \rightarrow 0$ and $\alpha_1 \rightarrow \alpha + \pi/2$ the 2HDM+S approaches the limit of a 2HDM with an added decoupled singlet, where α diagonalises the 2×2 mass matrix of the CP-even sector.

	u -type	d -type	leptons
type I	$\mathcal{R}_{i2}/s_\beta$	$\mathcal{R}_{i2}/s_\beta$	$\mathcal{R}_{i2}/s_\beta$
type II	$\mathcal{R}_{i2}/s_\beta$	$\mathcal{R}_{i1}/c_\beta$	$\mathcal{R}_{i1}/c_\beta$
lepton-specific	$\mathcal{R}_{i2}/s_\beta$	$\mathcal{R}_{i2}/s_\beta$	$\mathcal{R}_{i1}/c_\beta$
flipped	$\mathcal{R}_{i2}/s_\beta$	$\mathcal{R}_{i1}/c_\beta$	$\mathcal{R}_{i2}/s_\beta$

Table 4.1: The coupling coefficient $c(H_i f f)$ as defined in eq. (4.2.19).

[14, 124], by considering the couplings of additional bosons among themselves, as well as with gauge bosons and fermions. For example, consider the coupling of $H_i = (h, S, H)$ with a pseudo-scalar A and the Z boson, where the Feynman rule is given by:

$$\lambda_\mu(H_i Z A) = \frac{\sqrt{g^2 + g'^2}}{2} (p_{H_i} - p_A)_\mu \tilde{c}(H_i Z A), \quad (4.2.17)$$

where g' is the $U(1)_Y$ gauge coupling with $\tilde{c}(hZA) = -c_{\alpha_2} s_{\beta-\alpha_1}$, $\tilde{c}(SZA) = s_{\beta-\alpha_1} s_{\alpha_2} s_{\alpha_3} + c_{\alpha_3} c_{\beta-\alpha_1}$, and $\tilde{c}(HZA) = c_{\alpha_3} s_{\beta-\alpha_1} s_{\alpha_2} - s_{\alpha_3} c_{\beta-\alpha_1}$. The four-momenta p_{H_i} and p_A of H and A respectively, are taken as inputs. Note that the tilde over the coupling factor ($\tilde{c}$) denotes that it is not an effective coupling, since due to no SM counterpart it is not normalised to a corresponding SM coupling. Similarly, the trilinear Higgs coupling hSH is given by:

$$\begin{aligned} \lambda_{hSH} = \frac{1}{v} \bigg(& \mu^2 \left[(2\mathcal{R}_{12}\mathcal{R}_{13} + \mathcal{R}_{32}\mathcal{R}_{33})c_\beta + (\mathcal{R}_{31}\mathcal{R}_{33} - 3\mathcal{R}_{12}\mathcal{R}_{23}\mathcal{R}_{33} - \mathcal{R}_{21}\mathcal{R}_{23})s_\beta \right. \\ & \left. + 3\mathcal{R}_{12}\mathcal{R}_{22} \left(\frac{\mathcal{R}_{31}}{c_\beta} - \frac{\mathcal{R}_{32}}{s_\beta} \right) + 3\mathcal{R}_{13}\mathcal{R}_{23}\mathcal{R}_{31} \frac{s_\beta^2}{c_\beta} \right] \\ & \left. + \frac{\sum_{i=1}^3 m_{H_i}^2}{v_S} \left[\mathcal{R}_{13}\mathcal{R}_{23}\mathcal{R}_{33}v + \mathcal{R}_{12}\mathcal{R}_{22}\mathcal{R}_{32} \frac{v_S}{s_\beta} - \mathcal{R}_{11}(\mathcal{R}_{22}\mathcal{R}_{32} + \mathcal{R}_{23}\mathcal{R}_{33}) \frac{v_S}{c_\beta} \right] \right), \end{aligned} \quad (4.2.18)$$

where $\mu^2 = m_{12}^2/(s_\beta c_\beta)$ and $\mathcal{R}_{ij}$ are the elements of the orthogonal matrix $\mathcal{R}$. In this model the Yukawa Lagrangian is given as:

$$\mathcal{L}_Y = - \sum_{i=1}^3 \frac{m_f}{v} c(H_i f f) \bar{\psi}_f \psi_f H_i, \quad (4.2.19)$$

where the coupling coefficient $c(H_i f f)$ are shown in Table 4.1 in terms of mixing matrix elements $\mathcal{R}_{ij}$ and mixing angle β and the couplings of A and $H^\pm$ are same as in the 2HDMs. For further details we refer the reader to Ref. [133].

It is also important to note that the parameter space described in Ref. [133] and the one chosen for this work (see next section 4.3) are checked with respect to: (a) theoretical constraints, like tree-level perturbative unitarity, the vacuum stability from

global minimum conditions of the 2HDM+S potential and conditions which bound the potential from below; (b) the experimental constraints from R_b [137, 138] and $B \rightarrow X_s \gamma$ [138, 139, 140, 141]; and (c) the compatibility with the oblique parameters S, T and U .

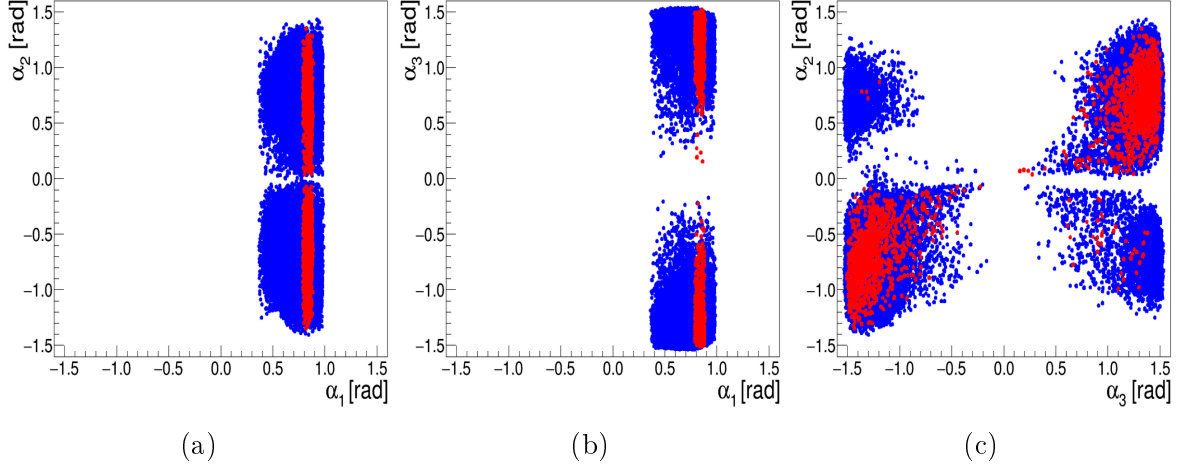


Figure 4.1: Allowed values of α_1, α_2 and α_3 for the benchmark considered here, where the values in *red* (*blue*) are by considering the BRs of the lightest CP-even scalar consistent within 10% (20%) of the prediction for the SM Higgs boson.

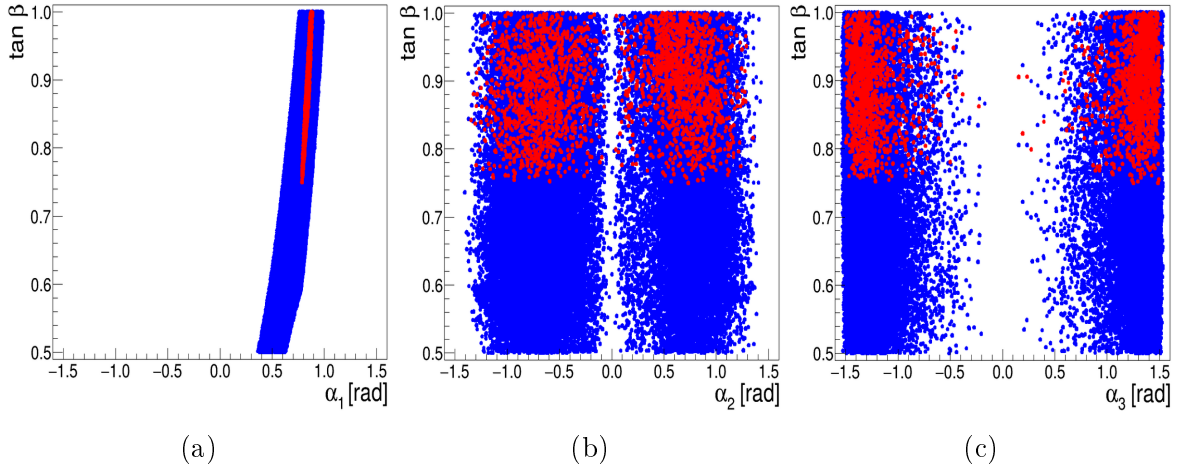


Figure 4.2: Allowed values of α_1, α_2 and α_3 against $\tan \beta$ for the benchmark considered here, where the values in *red* (*blue*) are by considering the BRs of the lightest CP-even scalar consistent within 10% (20%) of the prediction for the SM Higgs boson.

4.3 TOOLS AND PHENOMENOLOGY

In the 2HDM+S model described in section 4.2, the input parameters are following:

$$\alpha_1, \alpha_2, \alpha_3, \tan \beta, v, v_S, m_{H_{1,2,3}}, m_A, m_{H^\pm}, m_{12}^2. \quad (4.3.1)$$

For our phenomenological analysis we use type-II 2HDM+S throughout and fix the masses of CP-even and CP-odd scalars in the theory as a benchmark point. From here we denote the lightest CP-even scalar as around the SM Higgs boson with mass $m_h = 125$ GeV, the second one as S with mass $m_S = 140$ GeV, and the heaviest one as H with mass $m_H = 270$ GeV. The CP-odd neutral scalar mass $m_A = 600$ GeV and the charged scalar is taken with $m_{H^\pm} = 600$ GeV. These mass values of the scalars are based on the previous studies considered by the authors of Ref. [12]. Other parameters are varied in different ranges $-\pi/2 \leq \alpha_{1,2,3} \leq \pi/2$, $0.5 \leq \tan \beta \leq 1.0$. Further, we also vary the masses of scalars, v_S , m_{12}^2 for relevant studies and mentioned at appropriate sections. For numerical calculations we use the publicly available code **N2HDECAY** [133]. The **N2HDECAY** code calculates all 2HDM+S scalar boson decay widths and branching ratios (BRs), which include higher order QCD corrections and off-shell decays, however, in this code electroweak corrections are neglected. Furthermore, theoretical constraints on this model for the above-defined benchmark points, like perturbative unitarity and vacuum stability, are also checked with the package **ScannerS** [142].³ In addition to these, the following constraints are applied to get the allowed parameter space:

- BRs of the lightest boson should be consistent with the SM within 20% and 10%. This is in order to comply with the wealth of constraints coming from the SM Higgs boson measurements.
- The sum of the BRs of the heavy scalar to lighter scalars should be 80%-90% [1].
- The size of the coupling of h to particles in the SM must be in the range 0.8 ± 0.12 of the prediction of the SM.
- Based on the estimate of the Yukawa coupling of the heavy scalar to top quarks, $\beta_g^2 = 1.38 \pm 0.22$ [1], where β_g is a scaling factor with respect to the SM. From here it follows $\tan^2 \beta = 0.72 \pm 0.12$.

In Figure 4.1 we show the allowed values of α_1, α_2 and α_3 for the benchmark considered here. One can appreciate that the mixing angle α_1 seems more constrained than the other mixing angles. The constraints on α_2 and α_3 are better appreciated in Figure 4.1c, where one can see that certain areas in the plane are excluded. Results are shown by

³This package is used to perform the checks described in section 4.2 and Ref. [133] in addition with bounds from the collider searches at Tevatron, LEP and LHC.

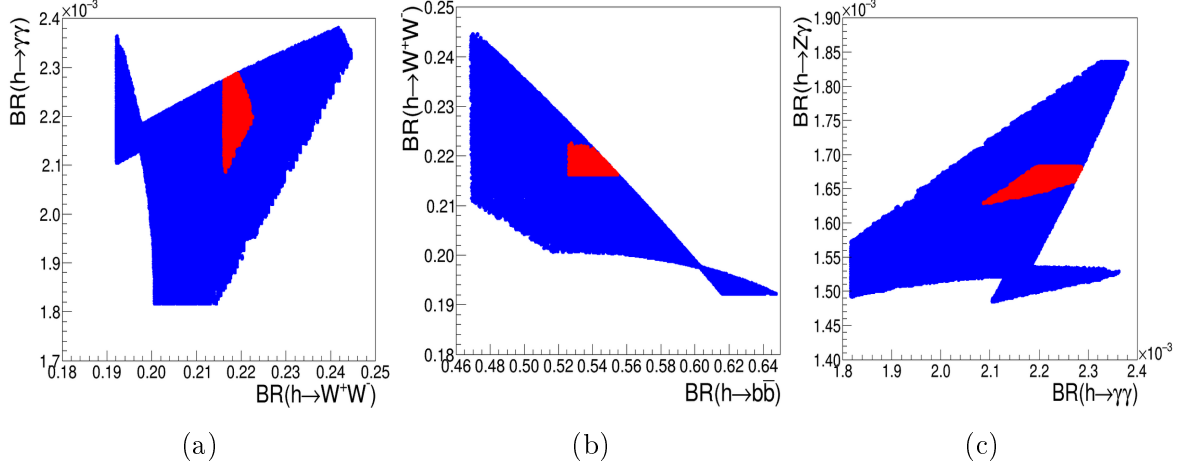


Figure 4.3: Correlation plots between the BRs of (a) $h \rightarrow WW$ vs $h \rightarrow \gamma\gamma$, (b) $h \rightarrow b\bar{b}$ vs $h \rightarrow WW$ and (c) $h \rightarrow \gamma\gamma$ vs $h \rightarrow Z\gamma$ where the values in red (blue) are by considering the BRs of the lightest h boson consistent within 10% (20%).

imposing the condition that the BRs of the lightest scalar be consistent between 20% and 10%. Going from 20% to 10% has a strong impact on how the mixing angles are constrained. Figure 4.2 displays the correlation between mixing angles and $\tan\beta$, where the results are also shown for the two different constraints on the BRs of the light scalar. The allowed values of $\tan\beta$ become more constrained while going from 20% to 10%. The correlation between $\tan\beta$ and α_1 is noticeable, while the correlation with α_2 and α_3 appears small. Additional parameter correlations can be found in Appendix A.

Currently, the sensitivity to the Higgs boson BRs at the LHC is not significantly better than 20%. This leaves a significant window of opportunity for new physics. Here we investigate the correlations among the relevant BRs that emerge within this 20% constraint, where ratios of BRs can vary considerably. In Figure 4.3 we show these correlations for a 20% as well as for 10%. One can appreciate that the allowed parameter space corresponding to a maximum 10% deviation is considerably more constrained than for 20%. This has to do with the fact that the central values for some of the BRs deviate from the SM, thus strongly restricting the range of deviations from the SM. As the values of the BR departure form the central values of the SM, the blue bands become narrower. While the decay $h \rightarrow Z\gamma$ is not yet observed at the LHC, the correlation between the $h \rightarrow WW$, $h \rightarrow \gamma\gamma$ and $h \rightarrow b\bar{b}$ rates can now be measured by the experiments. The ratio of the BR of $h \rightarrow WW$ to that of $h \rightarrow \gamma\gamma$ will be measured with an accuracy better than 3%, and an integrated luminosity that is expected to be accumulated by the High Luminosity LHC. This can be achieved with the application of a full jet veto, where theoretical uncertainties corresponding to the signal production will cancel.

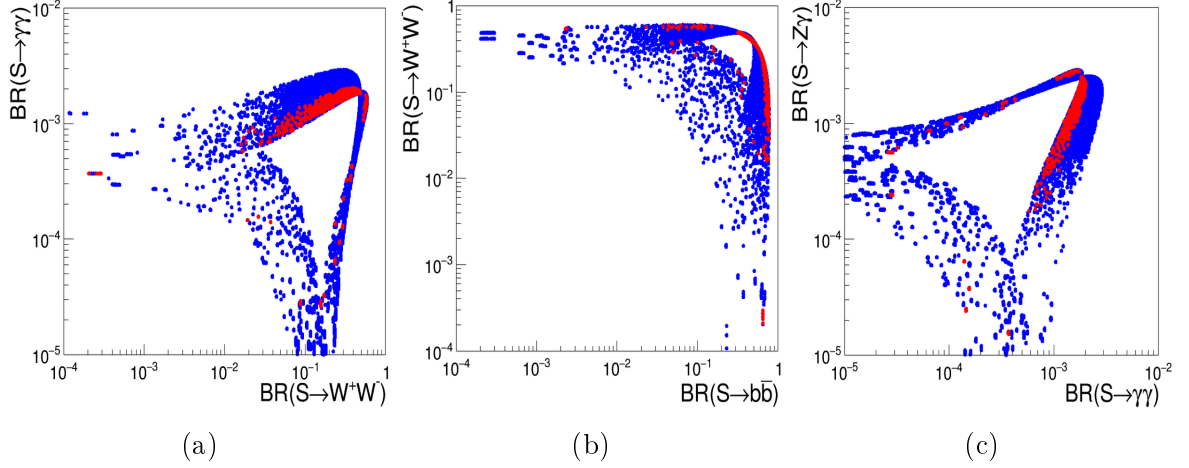


Figure 4.4: Correlation plots between the BRs of (a) $S \rightarrow WW$ vs $S \rightarrow \gamma\gamma$, (b) $S \rightarrow b\bar{b}$ vs $S \rightarrow WW$ and (c) $S \rightarrow \gamma\gamma$ vs $S \rightarrow Z\gamma$ where the values in red (blue) are by considering the BRs of the lightest h boson consistent within 10% (20%). Here $m_S = 140$ GeV and $m_H = 270$ GeV.

Figure 4.4 displays the correlations between the BRs of S to SM particles. As opposed to the SM Higgs boson, S is significantly less constrained. Three distinct regimes can be appreciated in Figure 4.4b. The first regime corresponds to the dominance of the $S \rightarrow b\bar{b}$ decay, where the second corresponds to the dominance of the $S \rightarrow WW$ decay for $m_S = 140$ GeV. The latter regime would be the preferred one in light of the multi-lepton excesses reported in Ref. [1]. This behaviour is closer to that displayed by a SM Higgs-like boson. In section 4.4 S will be assumed to have the same decays as the SM Higgs boson after taking m_S into account.

The two regimes identified here generate certain correlations in the $\text{BR}(S \rightarrow \gamma\gamma)$ vs $\text{BR}(S \rightarrow WW)$ plane, shown in Figure 4.4a, and the $\text{BR}(S \rightarrow Z\gamma)$ vs $\text{BR}(S \rightarrow \gamma\gamma)$ plane, shown in Figure 4.4c. The first regime corresponds to the ridges in Figure 4.4a and 4.4c where the $\text{BR}(S \rightarrow \gamma\gamma)$ is largest. The second and preferred regime corresponds to a situation where $\text{BR}(S \rightarrow Z\gamma) > \text{BR}(S \rightarrow \gamma\gamma)$, with $\text{BR}(S \rightarrow Z\gamma) \approx 10^{-3}$. The latter can be accessible at the HL-LHC [143].

There is a third regime where both BRs in Figure 4.4b display moderate values. In this regime $\text{BR}(S \rightarrow Z\gamma)$ and $\text{BR}(S \rightarrow \gamma\gamma)$ are small and of order of 10^{-4} .

Furthermore, we investigate the BRs of S, H, A and $H^\pm$ to understand the implications of the constraints detailed above on the decays, and how these can lead to final states that have not been explored before in the context of searches for new bosons. For this purpose a set of allowed parameter values is selected: $\alpha_1 = +0.885$, $\alpha_2 = -0.167$, $\alpha_3 = -1.28$, $m_{12}^2 = 3.5 \text{ (TeV)}^2$ and $v_S = 1.5 \text{ TeV}$. Figure 4.5 shows the BRs of S, H, A

and $H^\pm$ in the mass ranges (130 - 200), (200 - 300), (400 - 800) and (400 - 800) GeV, respectively. This benchmark ensures that the experimental constraints detailed above are described by the model.

Figure 4.5a displays the BRs of the S boson to SM particles, where the mass of S is varied within (130 - 200) GeV [12]. One can appreciate that the selected set of parameters sit within the regime where the decay to $b\bar{b}$ is dominant for $m_S = 140$ GeV (see the earlier discussions regarding Figure 4.4). For the case when S is treated as a SM Higgs-like boson, the BRs to W^+W^- and $b\bar{b}$ cross just above $m_S = 130$ GeV, where here it happens just over 150 GeV. On the other hand, the BRs of $Z\gamma$ and $\gamma\gamma$ in the SM Higgs-like boson case crosses at 130 GeV, but here this happens at 145 GeV. In the case of $\tau^+\tau^-$ and ZZ^* the corresponding masses are 130 GeV and just over 150 GeV, respectively. In this setup the decay to $b\bar{b}$ is dominant up to $m_S = 155$ GeV above which the decay to W^+W^- becomes dominant.

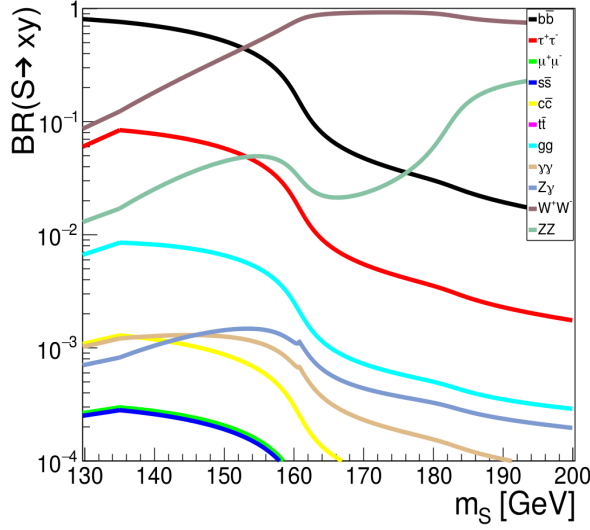
Figure 4.5b displays the BRs of the H boson. It is shown that the CP-even heavy scalar H decays predominantly to hh for $250 < m_H < 265$ GeV while above $m_H = 265$ GeV the $H \rightarrow Sh$ BR is dominant. These limits on the masses depend on the masses of the other scalars and it is due to the fact that the N2HDECAY program does not include Higgs-to-Higgs off-shell decays in computing the BRs. In this setup, and ignoring off-shell decays involving S and h bosons, the dominant decay up to $m_H \approx 200$ GeV is $b\bar{b}$, where the decay to W^+W^- overtakes it at $m_H \approx 210$ GeV. The BRs for rare decays, such as $\gamma\gamma$, $Z\gamma$ and $\mu^+\mu^-$ for $m_H < 2m_h$ are of the order of 10^{-4} . It should be noted that the results from Figures 4.5a and 4.5b respect the sum rule, which states that the coupling squared of the CP-even scalars to VV ($V = W^\pm, Z$) have to add up to 1 in terms of the squared SM Higgs coupling to VV .

The constraints from the data implemented here apply to the masses and production rates of the neutral scalar bosons. It is therefore very interesting to evaluate the impact on the BRs of the pseudo-scalar and the charged scalar with the assumption that $m_A, m_{H^\pm} > m_H$. Figure 4.5c displays the BRs of the pseudo-scalar. With the parameter choice used here the dominant decay mode in the range $2m_t < m_A < 600$ GeV is $A \rightarrow t\bar{t}$. For $m_A > 600$ GeV the dominant decay is $A \rightarrow ZH$. The latter leads to interesting final states, as discussed in Ref. [12]. In section 4.4 we further investigate this decay and, most notably, we scrutinise the rate of production of ZH in association with b -tagged jets. In addition, the production of Z in association with a lepton and b -tagged jets coming from this decay is compared to the data reported by CMS. The production of this final state with a large enough rate to be produced at the LHC is a feature of the $A \rightarrow ZH$ decay. The third most important decay is $A \rightarrow ZS$, which also leads to interesting final states [12]. The decay $A \rightarrow Zh$ is suppressed and

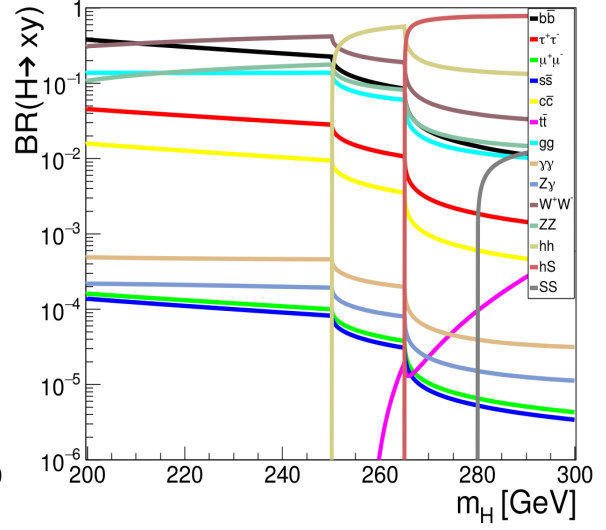
sits at the level of 1%. The production of Zh in association with S and h would come from the decay chain $A \rightarrow ZH \rightarrow ZSh, Zh h$ (see Figure 4.5b and section 4.4). As the pseudo-scalar gets heavier, the decay $A \rightarrow W^\pm H^\mp$ opens up. A distinctive feature of this model is that the decay $A \rightarrow \tau^+ \tau^-$ would be suppressed, sitting at the level of $10^{-4} - 10^{-5}$, depending on the mass and same follows for the decay $A \rightarrow b\bar{b}$ with a factor of ~ 10 larger.

Figure 4.5d shows the BRs of the charged scalar. The decay $H^+ \rightarrow t\bar{b}$ is dominant up to $m_{H^+} \approx 600$ GeV, where the $H^+ \rightarrow HW^+$ decay becomes dominant. The latter leads to a tri-boson final state following $H \rightarrow hS, hh, W^+W^-, ZZ$ at tree-level. The production of charged Higgs bosons can occur via different modes, $gg, q\bar{q}$ fusion in association with t - and b -quark at the LHC. Also $H^\pm$ can be produced in association with t -quark through the mechanism $gb \rightarrow tH^-$. Henceforth, multiple leptons in association with b -tagged jets are expected in these production and decay modes of charged Higgs bosons [12]. The third dominant decay is $H^+ \rightarrow SW^+$, where as in the case of the $A \rightarrow \tau^+ \tau^-$, the $H^+ \rightarrow \tau^+ \nu$ decay is suppressed. The decay $H^+ \rightarrow hW^+$ is suppressed relative to the $H^+ \rightarrow HW^+, SW^+$ decays and it stands at about 1%.

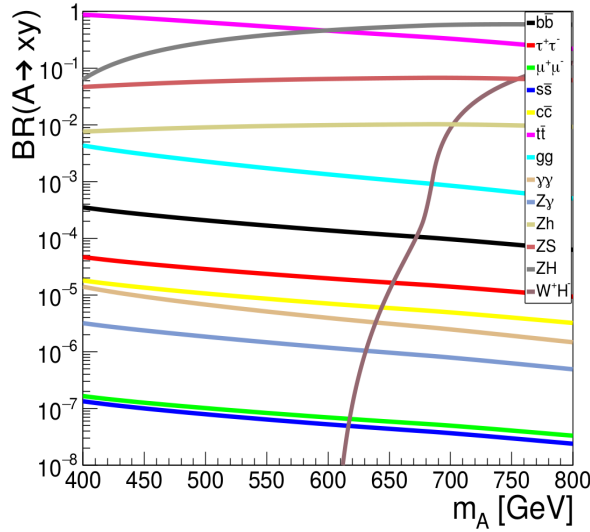
Production cross-sections of different bosons have been checked with the set of parameters used here. The production cross-section of the scalar S is about ten times smaller than that of the SM Higgs boson. The cross-section for the production of H is compatible with that obtained in Ref. [1]. Therefore, the main production mechanism for S would be that of the decay of H .



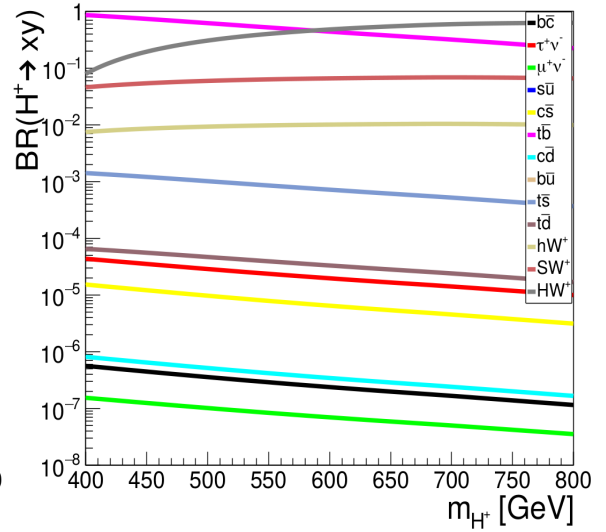
(a)



(b)



(c)



(d)

Figure 4.5: (a) Plot of $\text{BR}(S \rightarrow xy)$ against m_S , (b) $\text{BR}(H \rightarrow xy)$ against m_H . (c) $\text{BR}(A \rightarrow xy)$ against m_A and (d) $\text{BR}(H^\pm \rightarrow xy)$ against $m_{H^\pm}$ on the right. In the left, it is shown that the CP-odd scalar A decays predominantly to ZH if its mass is above 600 GeV. On the right, the charged scalar $H^\pm$ decays predominantly to $HW^\pm$ if its mass is greater than 600 GeV.

4.4 THE MC STUDIES

The primary aim of this section is to confront the data with the benchmark points in the parameter space described in section 4.3. One of the relevant implications with regard to heavy pseudo-scalars considered here is the dominance of $A \rightarrow t\bar{t}, ZH$ decays, where the decay $A \rightarrow Zh$ appears suppressed. As seen in Figure 4.5, the branching ratio of the $A \rightarrow ZH$ decay becomes dominant for $m_A > 600$ GeV. The decay $A \rightarrow ZH$ leads to interesting final states, as pointed out in Ref. [12]. For the sake of simplicity, here we consider the case where S decays exclusively to SM particles and the decays $H \rightarrow hh, Sh$ are dominant.

It is important to reiterate that the scan performed in this section pertains to a significant number of measurements that do not include the $A \rightarrow Zh$ resonance search, which is interpreted here as emerging from $A \rightarrow ZH \rightarrow hh, Sh$. Therefore, the parameters are greatly constrained by data different from the Zh spectrum. The latter constrains the mass of the pseudo-scalar, whereas the branching ratios are constrained with other data sets.

A distinctive set of final states that emerge from the $A \rightarrow ZH$ decay is the production of relatively high transverse momentum Z bosons in association with a lepton and two b -tagged jets. This final state would not appear in $A \rightarrow Zh$ decay in that no additional leptons would be expected in addition to the Z boson and b -tagged jets. The $bbA(\rightarrow Zh)$ production mechanism could produce this final state. However, the yield would be too small, as discussed below. The CMS experiment has recently reported a discrepancy in the production of Z bosons with an additional lepton, b -tagged jets and low additional jet multiplicity [131, 132]. The discrepancy, corresponding to a local significance of 2.85σ , appears in the study of the production of ttZ with $Z \rightarrow \ell\ell, \ell = e, \mu$. Here we interpret this discrepancy with the production of $A \rightarrow ZH$, where the parameters of the model are fixed elsewhere, as discussed above.

MC simulated samples are used to model the background and signal processes for this search. Signal samples are simulated using PYTHIA8 [144] and then passed through DELPHES [145] to estimate the detector response. Events were generated for an A boson mass at fixed working points: 500, 550 and 600 GeV. For the interpretation of the $H \rightarrow Sh$, where h is the Higgs boson with $m_h=125$ GeV, the masses of the H and S are assumed to be equal to 270 GeV and 145 GeV, respectively. For simplicity, S BRs are taken from that of the SM Higgs boson at the corresponding mass. Jets were clustered using FAST-JET [146] with the anti- k_T algorithm [147] using the distance parameter, $R = 0.4$.

Section 4.4.1 covers the interpretation of the $A \rightarrow Zh$ search, whereas section 4.4.2

interprets the discrepancy observed in the $Z(\rightarrow \ell\ell) + \ell + 2b$ -tagged jet final state.

4.4.1 $A \rightarrow Zh$ SEARCH

The ATLAS and CMS collaborations perform searches for a CP-odd heavy scalar within a 2HDM using various decay channels, where the decay $\ell\ell b\bar{b}$ plays an important role. A structure in the Zh invariant mass spectrum has been recently reported by the ATLAS collaboration [127] with Run-2 data. The CMS collaboration has reported limits with Run-1 data that do not contradict these results [128].

The authors of Ref. [130] have interpreted the structure in terms of a 2HDM where $A \rightarrow Zh$. Here we attempt a different interpretation in light of the spectroscopy discussed in Refs. [10, 12] and Ref. [1] in the context of an extension of the 2HDM, as discussed in section 4.2. In Ref. [12] it was demonstrated that the decay chain $A \rightarrow ZH$, where $H \rightarrow Sh$ generates a structure in the invariant mass spectrum of the Zh system that resembles that of a resonance with moderate width and a mass in the neighbourhood of $m_A - m_S$. The structure reported in Ref. [127] peaks around 450 GeV. Assuming $m_S = 145$ GeV, the mass of the pseudo-scalar considered here is 600 GeV. The corresponding cross-section of the structure lies in the range between 100 fb and 300 fb.

An important feature of the Zh structure is that it also appears in events with additional b -tagged jets. Within the context of a 2HDM the structure has been interpreted in terms of the ggF and bbA production mechanisms. In the scenario considered here, the decay entails a three boson final state that also produces a structure in the Zh invariant mass spectrum in association with additional b -tagged jets.

Figure 4.6 displays the multiplicity of all jets and b -tagged jets for the decay $A \rightarrow ZH \rightarrow ZSh$ produced via ggF. Hadronic jets have $p_T > 25$ GeV and $|\eta| < 2.5$. One can appreciate that the average jet multiplicity overshoots that expected from the direct production of $A \rightarrow Zh$. Because of the significant branching ratio of $S \rightarrow b\bar{b}$, the yield of events with more than two b -tagged jets becomes significant so as to mimic the production of bbA in a 2HDM.

In order to evaluate the ability of the 2HDM and the 2HDM+S approaches to describe the data the event selection described in Ref. [127] is adopted here as a baseline. This includes the following requirements:

- At least two b -tagged jets are required such that $p_T > 20$ GeV and $|\eta| < 2.5$. The invariant mass of the two leading b -tagged jet has to lie in the range 100 – 145 GeV. The transverse momentum of the leading b -tagged jet has to be greater than 45 GeV.

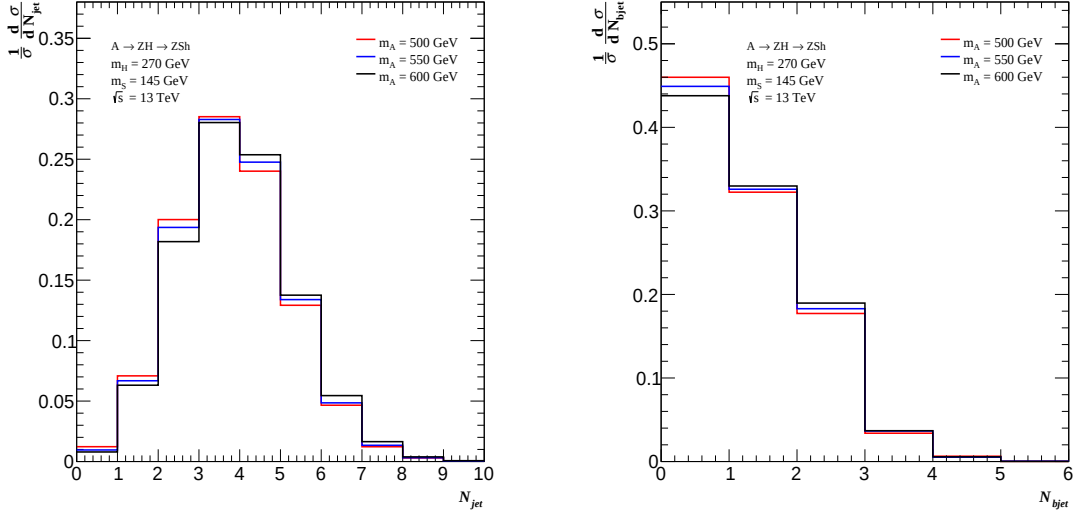


Figure 4.6: The jet multiplicity for the decay $A \rightarrow ZH \rightarrow ZSh$ produced via ggF (see text). The plot on the left corresponds to all jets, whereas the plot on the right shows the multiplicity of b -tagged jets.

- It is required to have at least two leptons, the transverse momentum of the leading and sub-leading leptons should be greater than 27 GeV and 7 GeV, respectively.
- The missing transverse momentum is required to be below a threshold (in GeV):

$$E_T^{\text{miss}}/\sqrt{H_T} < 1.15 + 8 \times 10^{-3} \cdot m_{Zh}, \quad (4.4.1)$$

where H_T is defined as the scalar sum of the transverse momenta of all leptons and hadronic jets.

- The transverse momentum of the dilepton system should conform to the following expression (in GeV):

$$p_T^{\ell\ell} > 20 + 9 \cdot \sqrt{m_{Zh} - 320}, \quad (4.4.2)$$

this requirement is applied for $m_{Zh} > 320$ GeV.

- The invariant mass of the dilepton system should obey the following expression (in GeV):

$$\max[40, 87 - 0.030 \cdot m_{Zh}] < m_{\ell\ell} < 97 + 0.013 \cdot m_{Zh} \quad (4.4.3)$$

It is probably relevant to note that this event selection is the result of optimizing for the sensitivity of the search for $A \rightarrow Zh$ in a 2HDM. Here the efficiencies for different production mechanism relative to the ggF production of $A \rightarrow Zh$, in a 2HDM are compared. After the application of the requirements described above the relative rate of additional production of b -tagged jets is evaluated.

Process	$A(450) \rightarrow Zh$	$bbA(450) \rightarrow bbZh$	$A(600) \rightarrow Zhh$	$A(600) \rightarrow ZSh$
$f(N_b = 2)$	0.95	0.83	0.73	0.77
$f(N_b > 2)$	0.05	0.17	0.27	0.23

Table 4.2: The fraction of events with exactly two or more than two b -tagged jets after the application of the event selection described in the text with respect to the ggF production of $A \rightarrow Zh$ in a 2HDM. Here $m_H = 270$ GeV and $m_S = 145$ GeV are used, where S is treated as an SM Higgs-like scalar.

Table 4.2 shows the fraction of events with at least one additional b -tagged jet varies for different mechanisms for the production of Zh with respect to the ggF production of $A \rightarrow Zh$ in a 2HDM. The fraction is small for $A(450) \rightarrow Zh$, whereas for $bbA(450) \rightarrow bbZh$ the fraction increases to 17%. The fraction of events with additional b -tagged jets increases to 27% and 23% for $A(600) \rightarrow ZH \rightarrow Zhh$ and $A(600) \rightarrow ZH \rightarrow ZSh$, respectively. The fraction of events in the Zh mass region between 400 GeV and 500 GeV with an additional b -tagged jet is about 25% of the total amount of events in the structure, but the statistical error on this fraction is too large at this moment.

Tables 4.3 and 4.4 display the BSM signal efficiency as a function of the pseudo-scalar mass after successive event selection requirements for the $A \rightarrow ZH \rightarrow Zhh$ and $A \rightarrow ZH \rightarrow ZSh$ decays, respectively, where $m_H = 270$ GeV and $m_S = 145$ GeV. Results are shown for final states with at least and exactly two b -tagged jets, as detailed in section 4.4.1. The signal efficiency increases strongly with the pseudo-scalar mass. This is driven to a large extent by the requirement in expression (4.4.2), which was implemented as a result of an optimization for the 2HDM signal discussed in section 4.4.1. As a result, the signal efficiency for $m_A = 600$ GeV is about 80% larger than that for $m_A = 500$ GeV. The signal efficiency for the $A \rightarrow ZH \rightarrow Zhh$ decay is superior to that of $A \rightarrow ZH \rightarrow ZSh$ for the choice of masses used here. The final signal efficiency ranges between 0.1% and 0.35%, depending on the pseudo-scalar mass and the decay chain. For illustration purposes, for a signal $A(600) \rightarrow ZH \rightarrow ZS(145)h$ and assuming a cross-section of 300 fb and 36 fb⁻¹ of integrated luminosity, the signal yield would correspond to about 25 events compared to a background of about 100 events.

Figure 4.7 displays the distribution of the invariant mass of the Zh system from the $A \rightarrow ZH \rightarrow Zhh$ and $A \rightarrow ZH \rightarrow ZSh$ decays after the application of the event selection detailed in section 4.4.1. The distributions display a cut-off at 320 GeV described in section 4.4.1. As the m_A becomes larger so that the phase-space available enhancing the invariant mass of the Zh system and its apparent width.

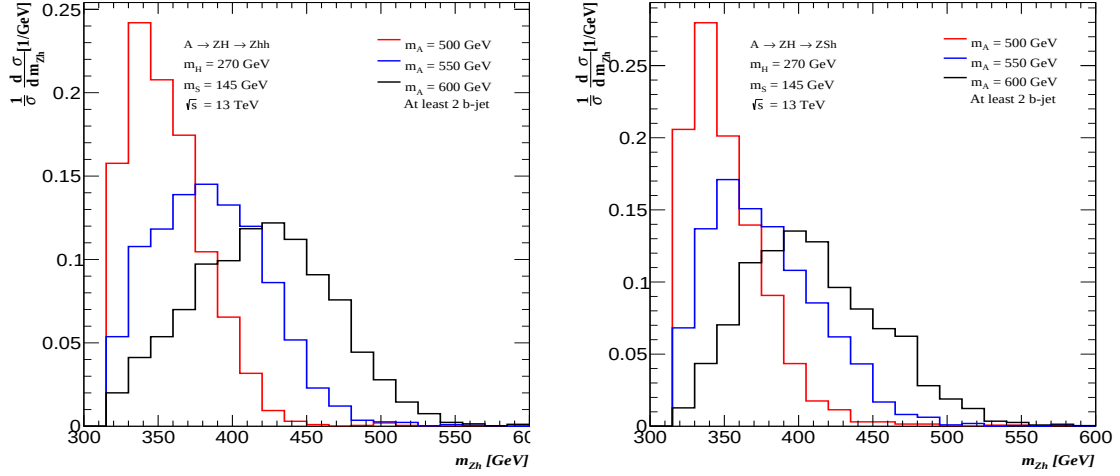


Figure 4.7: Distribution of the invariant mass of the Zh system from the $A \rightarrow ZH \rightarrow Zhh$ (left) and $A \rightarrow ZH \rightarrow ZSh$ (right) decays, where $m_H = 270$ GeV and $m_S = 145$ GeV. Results are shown for different pseudo-scalar masses after the event selection described in section 4.4.1.

4.4.2 THREE LEPTONS IN ASSOCIATION WITH TWO b -TAGGED JETS

The CMS collaboration has reported a discrepancy in a particular corner of the phase space [131]. This includes the presence of two opposite sign and same flavor charged leptons (electrons or muons) with the invariant mass close to that of the Z boson, an additional charged lepton and at least two b -tagged jets. The discrepancy appears in events with exactly two and three hadronic jets. This region of the phase space is weakly populated by the $t\bar{t}Z$ process, where a large number of hadronic jets is expected. The number of events in the data in excess of the SM prediction corresponds to 28.1 ± 9.5 events with an integrated luminosity of 35.9 fb^{-1} at 13 TeV center of mass energy.

Following Ref. [131], the event selection includes the following kinematic requirements:

- Leptons are required to have $p_T > 10$ GeV and $|\eta| < 2.5$ (2.4) for electrons (muons).
- The events are required to have exactly three leptons ($\mu\mu\mu$, $\mu\mu e$, μee or eee), where the leading, subleading, and trailing lepton are required to have p_T thresholds above 40, 20, and 10 GeV, respectively.
- It is required to have a pair of leptons with an opposite charge and same flavor (OSSF) which satisfies $|m_{\ell\ell} - m_z| < 10$ GeV.
- Events containing more than one jet are selected, and then are further split into three categories according to the hadronic jet multiplicity, $N_j = 2, 3$, and > 3 .

Cuts \ Categories	(I) At least 2 b -jets			(II) Exactly 2 b -jets		
	$m_A = 500$ GeV	$m_A = 550$ GeV	$m_A = 600$ GeV	$m_A = 500$ GeV	$m_A = 550$ GeV	$m_A = 600$ GeV
$N_{bjet} = (I) \text{ or } (II)$	0.4454	0.4504	0.4525	0.2871	0.2893	0.2904
Two leptons	0.0127	0.0143	0.0151	0.0097	0.0108	0.0115
$100 < m_{bb}[\text{GeV}] < 145$	0.0052	0.0055	0.0056	0.0041	0.0043	0.0044
$P_T^{led-bj} > 45$ GeV	0.0049	0.0053	0.0054	0.0038	0.0041	0.0042
$P_T^{\ell\ell} > 20 + 9 \cdot \sqrt{m_{Zh} - 320}$ GeV	0.0023	0.0036	0.0041	0.0017	0.0026	0.0030
m_{Zh} cut	0.0021	0.0035	0.0036	0.0015	0.0023	0.0027
$E_T^{miss}/\sqrt{H_T} < 1.15 + 08 \cdot m_{Vh}$ [GeV]	0.0020	0.0031	0.0035	0.0014	0.0022	0.0025
$A \rightarrow ZH \rightarrow Zh h$						

Table 4.3: The fraction of events after the application of the event selections described in section 4.4.1 with respect to at least and exactly two b -tagged jets final states for the signal sample $A \rightarrow ZH \rightarrow Zh h$, with $m_H = 270$ GeV.

Cuts \ Categories	(I) At least 2 b -jets			(II) Exactly 2 b -jets		
	$m_A = 500$ GeV	$m_A = 550$ GeV	$m_A = 600$ GeV	$m_A = 500$ GeV	$m_A = 550$ GeV	$m_A = 600$ GeV
$N_{bjet} = (I) \text{ or } (II)$	0.3524	0.3587	0.3600	0.2467	0.2493	0.2504
Two leptons	0.0113	0.0122	0.0130	0.0092	0.0100	0.0106
$100 < m_{bb}[\text{GeV}] < 145$	0.0045	0.0046	0.0047	0.0037	0.0038	0.0039
$P_T^{led-bjet} > 45$ GeV	0.0042	0.0043	0.0044	0.0034	0.0036	0.0037
$P_T^{\ell\ell} > 20 + 9 \cdot \sqrt{m_{Zh} - 320}$ GeV	0.0016	0.0026	0.0029	0.0012	0.0020	0.0024
m_{Zh} cut ⁴	0.0014	0.0022	0.0025	0.0010	0.0017	0.0020
$E_T^{miss}/\sqrt{H_T} < 1.15 + 08 \cdot m_{Vh}$ [GeV]	0.0013	0.0021	0.0023	0.0010	0.0016	0.0018
$A \rightarrow ZH \rightarrow ZSh$						

Table 4.4: The fraction of events after the application of the event selections described in section 4.4.1 with respect to at least and exactly two b -tagged jets final states for the signal sample $A \rightarrow ZH \rightarrow ZSh$. Here $m_H = 270$ GeV and $m_S = 145$ GeV are used.

Hadronic jets, including b -tagged jets, have $p_T > 30$ GeV and $|\eta| < 2.5$. After the application of the event selections described above over the samples we tabulated, the fraction of events for the $A \rightarrow Zh h$ and $A \rightarrow ZSh$ decay channels are as detailed in Table 4.5. The quantitative analysis reported here indicates that about 60% to 65% of the signal displays low hadronic jet multiplicity with $N_j < 3$.

The efficiency of the event selection with DELPHES is checked against that reported for the production of ttZ in events with at least two b -tagged jets and at more than three jets. Taking into account the results from section 4.4.1, the expected yield of the signal $A(600) \rightarrow ZH(270) \rightarrow ZS(145)h$ with $N_j < 3$ is about 3 events. This is to be compared to a background of about 50 events. This estimate appears low despite the relatively large uncertainties that characterise the discrepancy discussed here. That being said, it is very important to note that the simplified ansatz that S behaves as a

Process	N_j	$A = 500 \text{ GeV}$	$m_A = 550 \text{ GeV}$	$m_A = 600 \text{ GeV}$
$A \rightarrow ZH \rightarrow Zh h$	$=2$	0.26	0.27	0.25
	$=3$	0.39	0.38	0.36
	>3	0.35	0.35	0.39
$A \rightarrow ZH \rightarrow ZSh$	$=2$	0.32	0.27	0.23
	$=3$	0.33	0.36	0.30
	>3	0.35	0.37	0.46

Table 4.5: The fraction of events after the application of the event selections described in the text with respect to three lepton final states for both $A \rightarrow ZH \rightarrow Zh h$ and $A \rightarrow ZH \rightarrow ZSh$ signals. Here $m_H = 270 \text{ GeV}$ and $m_S = 145 \text{ GeV}$ are used.

SM Higgs-like boson plays a very important role in the prediction of the cross-section in the corner of the phase-space described here. The assumption made here impacts directly the branching ratio of S decaying into leptons and the jet multiplicity in the final state. The contribution from the $bbA(450)$ signal in this corner of the phase-space is too little to be considered.

4.4.3 MEASUREMENT OF Vh PRODUCTION SIGNAL STRENGTH

The ATLAS [148, 149] and CMS [150, 151] collaborations have independently reported observation of the decay of the decay $h \rightarrow b\bar{b}$. The evidence reported is based on excesses in the data in the search for the SM Higgs boson in association with a Z or a W boson. In doing so the experiments also report the corresponding signal strength of the Vh production mechanism in the SM.

Different event selections are developed depending on the presence of high transverse momentum charged leptons. Here, the impact of the different production mechanisms normalised to the size of the structure observed by ATLAS in the Zh spectrum on the measurement of the Vh signal strength in the different final states is discussed here. The potential contamination from the different BSM signal production mechanisms in the phase-space of the measurement of Vh production is evaluated.

Events with two jets tagged as containing b -tagged jets and with either zero, one or two charged leptons (electrons or muons) are selected. The lepton candidates are required to have $p_T > 7 \text{ GeV}$ and $|\eta| < 2.47$ (2.7) for electrons (muons). All events are required to have at least two jets with $p_T > 20 \text{ GeV}$ and $|\eta| < 2.5$, and exactly two with $100 \text{ GeV} \leq m_{bb} \leq 145 \text{ GeV}$ must pass the b -tagging requirement. The p_T of the leading b -tagged jet is required to be above 45 GeV . Events are assigned to zero-, one- and two-lepton channels depending on the number of charged leptons. In the following, the

physics objects and the event selection criteria for each channel are described:

- The zero-lepton events are required to have $E_T^{\text{miss}} > 150 \text{ GeV}$. The scalar sum of the transverse momenta of the jets in the event, H_T , is required to be less than 150 GeV. This is to remove a marginal region of phase space in which the trigger efficiency exhibits a small dependence on the jet multiplicity. Also, the following angular selection is applied:

$$\begin{aligned}
& - \Delta\phi(b_1, b_2) < 140^\circ, \\
& - \Delta\phi(\mathbb{E}_T^{\text{miss}}, bb) > 120^\circ, \\
& - \min [\Delta\phi(\mathbb{E}_T^{\text{miss}}, jets)] > 30^\circ,
\end{aligned}$$

where b_1 and b_2 are the two b -tagged jets forming the Higgs boson candidates dijet system bb , and $\mathbb{E}_T^{\text{miss}} > 150 \text{ GeV}$ is the missing transverse momentum which is defined as the negative vector sum of the transverse momenta of electrons, muons and jets.

- In the one-lepton channel, events are required to contain exactly one electron with $p_T > 27 \text{ GeV}$ or one muon with $p_T > 25 \text{ GeV}$. With the electron an additional of $E_T^{\text{miss}} > 30 \text{ GeV}$ is applied.
- In the two-lepton channel events are required to have exactly two leptons of the same flavour with leading lepton $p_T > 27 \text{ GeV}$. In dimuon events, the two muons are considered to have opposite-sign charges. The invariant mass of the dilepton system must be consistent with the Z boson mass, such that $81 \text{ GeV} < m_{\ell\ell} < 101 \text{ GeV}$.

Events are then categorised into two categories according to jet multiplicity. In the zero- and one-lepton channels, events are considered with three or fewer jets. In the two-lepton channel events are considered with higher jet multiplicities which is three or more jets. Furthermore, selections for the reconstructed vector boson's transverse momentum, p_T^V , are applied. This observable corresponds to E_T^{miss} in the zero-lepton channel, to the vectorial sum of $\mathbb{E}_T^{\text{miss}}$ and the charged lepton's transverse momentum in the one- and two-lepton channels. In the zero- and one-lepton channels, a single region is defined, with $p_T^V > 150 \text{ GeV}$. In the 2-lepton channel, two regions are considered, $75 \text{ GeV} < p_T^V < 150 \text{ GeV}$ and $p_T^V > 150 \text{ GeV}$. Here, yields of the different signals are integrated for $p_T^V > 75 \text{ GeV}$.

Table 4.6 displays the potential contamination of the BSM signals. Results are shown in terms of the BSM signal yield normalized to the yield of the SM Vh production in the phase-space described here. A cross-section of 200 fb [127] is assumed for all BSM signals reported in Table 4.6. It is very important to note that a number of more

Process	$A(450) \rightarrow Zh$	$bbA(450) \rightarrow bbZh$	$A(600) \rightarrow Zhh$	$A(600) \rightarrow ZSh$
$N_\ell=0$	1.12	1.42	0.68	0.42
$N_\ell=1$	0.05	0.06	0.08	0.07
$N_\ell=2$	0.71	0.70	0.67	0.48

Table 4.6: The potential contamination from the BSM production mechanisms discussed here in the measurement of the signal strength of the Vh , $Z = Z, W$ in the SM. Results are presented in terms of the signal yield with respect to the Vh production in the SM for zero, one and two charged lepton final states (see text). Here $m_H = 270$ GeV and $m_S = 145$ GeV are used.

sophisticated techniques have been used by the experiments to extract the SM signal. As a result, the potential contamination reported in Table 4.6 is an upper bound of the potential contamination. Making a more accurate estimate of the contamination goes beyond the scope of this paper. The results shown in Table 4.6 are better suited for a comparative analysis.

One can appreciate that the contamination on the one-lepton final state is quite small, whereas the contamination on the zero-lepton final state is significant, followed by that of the one-lepton final state. The contamination is maximum for the 2HDM signals, where for the bbA production mechanism the contamination would be largest and comparable to the Vh signal in the SM. By contrast, the 2HDM+S signals have a moderate impact on the SM Vh production where the most important decay, $A \rightarrow ZH \rightarrow ZSh$ would have the smallest effect.

4.5 SUMMARY

In Refs. [10, 12] scalars H and S were introduced via an effective model to explain a number of features in the Run-1 data. These scalars were embedded into a 2HDM+S model in Ref. [12], where it was pointed out that the anomalous production of multiple leptons would be a prominent feature of the model. This hypothesis has been compared to data [1, 152] where large discrepancies between the data and SM MCs are observed that cannot be resolved with available tools. These discrepancies are interpreted using a simplified model where $m_H = 270$ GeV and $m_S = 145$ GeV.

In this study we attempt to identify the corners of the parameter space in a 2HDM+S model that satisfy the conclusions arrived at in Ref. [1]. The implications on the decays of the heavy pseudo-scalar and charged scalar are discussed. With the parameter choice used here the dominant decay mode in the range $2m_t < m_A < 600$ GeV is $A \rightarrow t\bar{t}$. For $m_A > 600$ GeV the dominant decay is $A \rightarrow ZH$. The third most important

decay is $A \rightarrow ZS$, which also leads to interesting final states. The decay $A \rightarrow Zh$ is suppressed and sits at the level of 1%. The production of Zh would come from the decay chain $A \rightarrow ZH \rightarrow ZSh, Zh h$. As the pseudo-scalar gets heavier, the decay $A \rightarrow W^\pm H^\mp$ opens up. A distinctive feature of this model is that the decay $A \rightarrow \tau^+ \tau^-$ would be suppressed, sitting at the level of $10^{-4} - 10^{-5}$ depending on the mass. The decay $H^+ \rightarrow t\bar{b}$ is dominant up to $m_{H^+} \approx 600$ GeV where the $H^+ \rightarrow HW^+$ decay becomes dominant. The third dominant decay is $H^+ \rightarrow SW^+$, the $H^+ \rightarrow \tau^+ \nu$ decay is suppressed. The decay $H^+ \rightarrow hW^+$ is suppressed relative to the $H^+ \rightarrow HW^+, SW^+$ decays. The conclusions from these studies further reinforce the relevance of multi-lepton final states in the search for new bosons.

A structure in the Zh invariant mass spectrum has been reported by the ATLAS collaboration [127] with Run-2 data, which appears in association with b -tagged jets, in addition to those assigned to the decay of h . Here we interpret the structure in terms of the 2HDM+S model. The production of Zh with additional b -tagged jets from $A(600) \rightarrow Z(270)H \rightarrow ZS(145)h, Zh h$ is discussed. The fiducial efficiency of this production mechanism is similar to other production mechanisms, like $A(450) \rightarrow Zh$ and $bbA(450) \rightarrow bbZh$. However, one of the features of the 2HDM+S signal considered here is the production of $Z(\rightarrow \ell\ell)$ in association with a lepton and two b -tagged jets. The jet activity would be significantly different from that displayed by the production of ttZ . An excess is seen by CMS in this final state in events with low additional jet multiplicity, a regime where the production of ttZ is suppressed. By contrast, the 2HDM signals considered here do not contribute significantly to this final state. The potential existence of a heavy pseudo-scalar would contribute to the production of Zh and contaminate the phase-space where the signal strength of the Vh production is measured by the experiments. The 2HDM signals considered here would bring considerable contamination, where the largest contamination would come from $bbA(450) \rightarrow bbZh$, the preferred option in a 2HDM to explain the structure in the Zh invariant mass spectrum. The preferred signal in a 2HDM+S would yield a moderate impact on the measurement of the Vh signal strength. On the other hand, the mass spectrum of this model is computed at tree-level only, though the decays are computed with higher-order corrections. So a non-negligible contribution from one-loop corrections to scalars mass may impact the analyses carried here, for example the observables for $A \rightarrow ZH$ might get affected. Hence, a future study may be followed considering these corrections.

As this search was being reviewed [153], CMS and ATLAS have reported excesses in $t\bar{t}$ and $Zb\bar{b}$ final states [154, 155, 156] that can be interpreted with $m_A \approx 600$ GeV and in the range of $\tan\beta$ considered here. In conclusion, the 2HDM+S model with the parameters obtained here is able to accommodate the excesses at the LHC reported in Ref. [1]. Without varying these parameters additional excesses in the Zh spectrum

and the production of 3 leptons plus two b -tagged jets can be explained assuming $m_A \approx 600$ GeV.

SEARCH FOR A RESONANCE DECAYING INTO TWO PHOTONS IN ASSOCIATION WITH B-JETS

5.1 INTRODUCTION

This analysis proposes a search for a heavy resonance decaying into two photons and produced in association with at least a b -quark. This final state is sensitive to the models that a CP-even or CP-odd heavy resonance couples with top quark through Yukawa couplings [157, 158, 159] or a Vector-like quark couples with a heavy resonance [160, 161]. An Axion-like particle (ALP) model can also be examined in this final state [162, 163]. Similar analyses have been performed by ATLAS [164] and CMS [165] in the $\mu^+\mu^-$ and $b\bar{b}$ final states as well.

Three production modes are tested in this search, the $t\bar{t}X$, $b\bar{b}X$ and the ZX where Z boson decays into two b -quarks. The X is a Higgs like heavy resonance. The Feynman diagrams for these models are shown in Figure 5.1. The search examines the diphoton invariant mass spectrum from 130 GeV to 1.6 TeV with one b -tagged jet, two b -tagged jets and one b -tagged jet plus one lepton final states. Limits on the production cross-section times branching ratio to diphoton final state are set on the resonance range from 180 GeV to 1.6 TeV. Only the narrow width assumption is tested. This analysis uses pp -collision data collected by the ATLAS experiment during Run-2 at a centre-of-mass energy of 13 TeV at 139 fb^{-1} , and simulated samples, all described in Section 5.2. The selection of the events and the objects are described in Section 5.3. Section 5.4 and 5.5 describes the event optimization and the event selection respectively. Sections 5.6 and 5.8 details the signal and background parameterization. Finally, the results and the statistical analysis are shown in section 5.9.

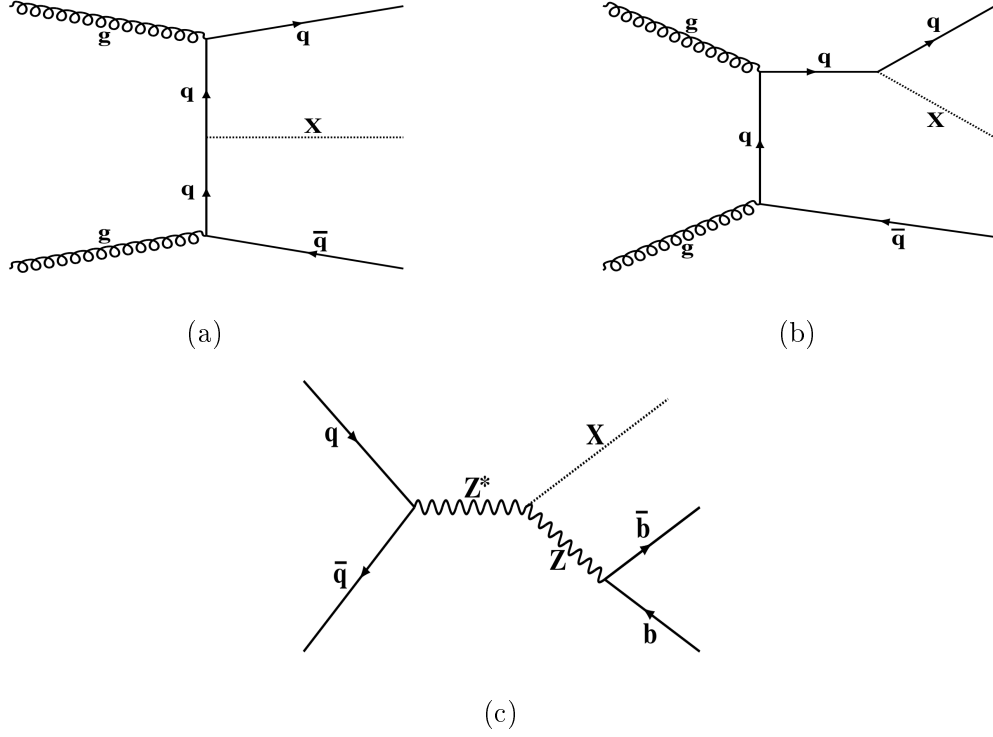


Figure 5.1: (a) and (b) are two of the possible Feynman diagrams correspond to the production of the Higgs like boson in association with a pair of top/bottom quarks processes, where q stands for both top and bottom quarks. (c) a Feynman diagram corresponds to the production of the Higgs like boson in association to the Z boson.

5.2 DATA AND SIMULATED SAMPLES

5.2.1 DATA

The pp collision data with a bunch crossing interval of 25 ns, collected between 2015–2018 at $\sqrt{s} = 13$ TeV is used in this analysis. All events recorded with stable beam conditions, fully operational tracking system and calorimeters are used in this analysis. The data-quality requirements and event cleaning are applied to each event. Events are required to pass the Run 2 diphoton triggers, where two reconstructed photon candidates with transverse energies (E_T) of at least 35 and 25 GeV for the leading and sub-leading photons. In 2015-2016 data taking, the “loose” photon identification is applied at the HLT primary diphoton triggers. In 2017-2018 data taking, the “medium” photon identification is applied. The recorded data sample has an integrated luminosity of 139 fb^{-1} .

5.2.2 SIGNAL

The signal and background samples are generated and simulated using MC event generator. The $t\bar{t}X$ signals are generated using the Madgraph [166] generator at NLO in QCD using the NNPDF30NLO [167] Parton Distribution Function (PDF) set. Parton showering and hadronisation are simulated using the Pythia8 [168] generator with the A14 tune [169], also using the NNPDF2.3LO PDF set. The $b\bar{b}X$ and ZX signals are generated and showered using Pythia8 at LO. The A14 tune [169] and NNPDF2.3LO PDF set are used. The detector effect of the $t\bar{t}X$ and $b\bar{b}X$ events are simulated using AltFast II [170], a fast simulation of the ATLAS detector response. The detector effect of the ZX events is simulated using the full simulation [171] based on Geant4 [172]. The cross section times branching ratio to diphoton final state of each model is set to $1fb$. The signal samples are listed as in Table 5.1.

5.2.3 BACKGROUNDS

The dominant backgrounds of this analysis are the non-resonant $\gamma\gamma$, γj , $V\gamma\gamma$, $V\gamma$, $t\bar{t}\gamma$, $t\bar{t}\gamma\gamma$ and $b\bar{b}\gamma\gamma$ production, where V stands for W or Z boson. The γj background is estimated from the data by reversing one of the photon identification (ID) criteria. All other background samples are generated using MC and listed as in Table 5.2.

The MC samples are only used to setup the categories in the optimisation, to produce data/MC comparison plots and to choose the background fit functions. The normalisation of $\gamma\gamma$ backgrounds as well as the γj shape are directly obtained from data, as described in Section 5.7. In the statistical fit, the shape and normalisation are directly obtained from the $m_{\gamma\gamma}$ spectrum in the data.

Detector effects are modelled by processing all background MC samples through either a full simulation [171] based on Geant4 [172] or a fast simulation [170] of the ATLAS detector. Corrections obtained from measurements in data are applied to the simulated events to account for small differences between data and MC. The simulations include a realistic modelling of the multiple proton-proton collisions per bunch crossing observed in the data by overlaying additional interactions generated by Pythia8 using the A14 tune with four different PDF sets [169]. The simulated distribution of the average number of interactions per bunch crossing is reweighted to accurately reproduce the observed distribution.

Process	Mass	N_{events}
$b\bar{b}X$	180	120000
$b\bar{b}X$	250	120000
$b\bar{b}X$	500	120000
$b\bar{b}X$	800	120000
$b\bar{b}X$	1500	120000
$t\bar{t}X$	180	120000
$t\bar{t}X$	250	120000
$t\bar{t}X$	500	120000
$t\bar{t}X$	800	120000
$t\bar{t}X$	1500	120000
ZX	160	140000
ZX	200	30000
ZX	300	30000
ZX	400	30000
ZX	500	30000
ZX	600	30000
ZX	800	30000
ZX	1000	30000
ZX	1500	30000
ZX	2000	30000

Table 5.1: The $t\bar{t}X$, $b\bar{b}X$, ZX signal samples used in this analysis.

Process	Generator	Simulation Type	N_{events}
$\gamma\gamma, m_{\gamma\gamma} \in [105, 170] \text{ GeV}$	Sherpa	AFII	507M
$\gamma\gamma, m_{\gamma\gamma} \in [175, 2000] \text{ GeV}$	Sherpa		35M
$t\bar{t}\gamma$	Madgraph	AFII	39M
$b\bar{b}\gamma\gamma$	Madgraph	AFII	0.4M
$t\bar{t}\gamma y$	Madgraph	AFII	0.12M
$ee\gamma\gamma; m_{\gamma\gamma} > 80 \text{ GeV}$	Sherpa	Full Sim	3.7M
$\mu\mu\gamma\gamma; m_{\gamma\gamma} > 80 \text{ GeV}$	Sherpa	Full Sim	3.7M
$\tau\tau\gamma\gamma; m_{\gamma\gamma} > 80 \text{ GeV}$	Sherpa	Full Sim	3.6M
$\tau\tau\gamma\gamma; m_{\gamma\gamma} > 80 \text{ GeV}$	Sherpa	Full Sim	0.37M
$e\nu\gamma\gamma; m_{\gamma\gamma} > 80 \text{ GeV}$	Sherpa	Full Sim	3.7M
$\mu\nu\gamma\gamma; m_{\gamma\gamma} > 80 \text{ GeV}$	Sherpa	Full Sim	3.7M
$\tau\nu\gamma\gamma; m_{\gamma\gamma} > 80 \text{ GeV}$	Sherpa	Full Sim	3.7M
$V(\text{leptonic decay})\gamma$	Sherpa	13.6M	

Table 5.2: Non-resonant background processes relevant in this analysis.

5.3 OBJECT SELECTION

Photons, leptons (electrons and muons) and jets are used in the selection of this analysis. Their reconstruction techniques and identification criteria are summarised as below.

5.3.1 PHOTONS

Photons are reconstructed from clusters of energy deposits in the electromagnetic calorimeter that are collected in topological clusters [173]. The photons are categorised into converted or unconverted photons. The converted photon is matched to a pair of tracks that pass a TRT-hits requirement and form a vertex in the ID which is consistent with originating from a massless particle or a single track passing a TRT-hits requirement and having a first hit after the innermost layer of the pixel detector. Otherwise, the photon is unconverted. The photon energy is corrected by applying the energy scale factors derived from a data-driven method using $Z \rightarrow e^+e^-$ events [174].

Photon identification criteria are applied to distinguish from π^0 or other neutral hadrons decaying to two photons. The “tight” and “loose” criteria exploit the feature of the photon energy deposition in different layers of the electromagnetic calorimeter [175]. Two candidate photons are required to have $p_T > 25$ GeV, within $|\eta| < 2.37$, excluding the EM calorimeter transition region $1.37 < |\eta| < 1.52$ and to satisfy the “loose” identification. These pre-selected photons are used for the electron-photon ambiguity separation, overlap removal and vertex decision. Afterward the photons used in the event selection must satisfy the “tight” identification criteria.

To further increase the background rejection, the calorimeter and track isolation variables (E_T^{iso} and p_T^{iso}) are applied. The calorimeter isolation variable is the sum of the transverse energies of positive-energy topological clusters [176] deposited in the calorimeter within a cone of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.2$ around each photon. The track isolation variable is similar by summing up the transverse momentum (p_T) of the nearby tracks with $p_T > 1$ GeV. Isolated photons are required to have $E_T^{\text{iso}} < 0.065E_T$ and $p_T^{\text{iso}} < 0.05E_T$.

5.3.2 LEPTONS

Electrons are reconstructed from energy deposits measured in the EM calorimeter which are associated to ID tracks [174]. The electrons are required to have $p_T > 10$ GeV and located within the central region defined by region $|\eta| < 2.47$ excluding electrons in the EM calorimeter transition region $1.37 < |\eta| < 1.52$. The electrons are required to pass

“Medium” identification criteria “FCLoose” isolation criteria. The significance of the transverse impact parameter, defined as the transverse impact parameter d_0 divided by its estimated uncertainty, σ_{d_0} , of tracks with respect to the primary vertex is required to satisfy $|d_0|/\sigma_{d_0} < 5.0$. The longitudinal impact parameter z_0 must satisfy $|z_0| \sin \theta < 0.5$ mm.

Muons are reconstructed from high-quality MS segments alone or combined with ID tracks when available [177]. The muons candidates are required to have $p_T > 10$ GeV within a region defined by $|\eta| < 2.7$ as well as significance $|d_0|/\sigma_{d_0} < 3.0$ with respect to the primary vertex and $|z_0| \sin \theta < 0.5$ mm. The identification and isolation criteria for the muons are “medium” and “PflowLoose_FixedRad”.

5.3.3 JETS

Jets are reconstructed using the anti- k_t algorithm [147] with the radius parameter $R = 0.4$. Charged-particle tracks, calorimeter energy deposits, or algorithmic combinations of the two combined measurements from the tracker and the calorimeter are processed in the *particle-flow* (PFlow) algorithm [178]. The resulting PFlow jets exhibit improved energy and angular resolution, reconstruction efficiency, and pile-up stability compared to the topocluster jets. All the jets are reconstructed with respect to the selected diphoton vertex, as below, instead of the default hardest vertex with highest $\sum p_T^2$ of tracks. All jet-related quantities are recalculated with respect to the selected vertex. Quality criteria are applied in order to reject jets affected by noisy cells in the calorimeter or other bad performance detector effects. Events with jets consistent with noise in the calorimeter or non-collision background are vetoed. Jets are required to have $|\eta| < 4.4$ and $p_T > 25$ GeV. In this analysis, the jets in the central region in the calorimeter is used, which requires the $|\eta| < 2.5$.

A Jet Vertex Tagger (JVT) [179] variable is used to reject jets originated from the pile up vertices. The JVT exploits the fraction of the p_T^2 of tracks originated from the selected vertex and the total p_T^2 . It also uses the fraction of track p_T and the calorimeter p_T of the jet [180, 181]. The JVT only applies on the jet within $p_T < 60$ GeV, $|\eta| < 2.4$. The cut on the JVT is 0.50.

5.3.4 B-TAGGING JETS

To identify the jet originated from a b -quark, a DL1r b -tagging discriminator, combining deep-neural-network and recurrent-neural-network algorithm and exploiting the correlation between the tracks impact parameters, is applied [182]. Optimization shows 70% efficiency has the best sensitivity to these searches.

5.3.5 PRIMARY VERTEX

Unlike the default primary vertex, which uses the one with the highest $\sum p_T^2$ of associated tracks, in this analysis the diphoton vertex is selected. All the objects are corrected with respect to this selected vertex. The diphoton vertex is based on a neural network algorithm using the combined z -position of the intersection of the extrapolated photon trajectories with the beam axis, the $\sum p_T^2$, $\sum p_T$ of the associated tracks, the difference in azimuthal angle $\Delta\phi$ between the direction defined by the vector sum of the track momenta associated to a vertex and the diphoton system direction. In this analysis, for a $b\bar{b}X$ model, 72% of events has a same selected vertex as the default primary vertex. For $t\bar{t}X$ and ZX models, this fraction is 99% and 91%.

5.3.6 OVERLAP REMOVAL

Overlap removal between different objects is applied to remove the duplicated reconstructed objects in an event and it is performed in the following order.

- Remove electrons within $\Delta R = 0.4$ of any photon.
- Remove muons within $\Delta R = 0.4$ of any photon.
- Remove jets within $\Delta R = 0.4$ of any photon.
- Remove jets within $\Delta R = 0.2$ of any electron.
- Remove electrons within $0.4 \Delta R$ of any jet.
- Remove muons within $\Delta R = 0.4$ of any jet.

Here the pre-selected photons and all other objects are used after applying their selections criteria as described above.

5.4 EVENT OPTIMIZATION

The optimization is performed based on the preselection, two identified and isolated photons with p_T larger than 40 and 30 GeV and at least one b -tagged jet. The samples $t\bar{t}X$ with $m_X = 180$ GeV, $b\bar{b}X$ $m_X = 180$ GeV and ZX $m_X = 200$ GeV are used for this event optimization. This is because for the low mass region, where the background is relatively large, a finer categorization was needed to improve the sensitivity. All background samples are merged and normalized to 139 fb^{-1} for the optimization. Multiple variables such as the diphoton transverse momentum missing transverse momentum, are tried to improve the significance. However, it is finally decided to use the variables N_{cjet} and $\Delta\phi(\gamma, \gamma)$ for categorization due to the best performance.

		$S/\sqrt{S+B}$			$S/\sqrt{B}$		
		N_{cjet}	$\Delta\phi(\gamma, \gamma)$	Significance	N_{cjet}	$\Delta\phi(\gamma, \gamma)$	Significance
$t\bar{t}X180$	$1l1b$	3	2.0	2.18	3	1.2	2.75
	$0l1b$	6	2.4	1.16	6	2.4	1.26
	$0l2b$	6	2.0	1.52	6	2.0	1.80
$t\bar{t}X250$	$1l1b$	3	2.4	3.00	6	1.2	5.94
	$0l1b$	5	2.0	1.74	6	2.0	2.00
	$0l2b$	5	2.0	2.34	6	2.4	3.18

Table 5.3: The optimization results for the $t\bar{t}X$ and $b\bar{b}X$ models. The significance corresponding to the optimal $\Delta\phi(\gamma, \gamma)$ and N_{cjet} cuts for each region.

		$S/\sqrt{S+B}$			$S/\sqrt{B}$		
$\Delta\phi(\gamma, \gamma)$		$m_{bb}(H)$	$m_{bb}(L)$	Significance	$m_{bb}(H)$	$m_{bb}(L)$	Significance
ZX200	1.6	105	65	0.277	105	65	0.284
	2.0	105	65	0.282	105	65	0.289
	2.4	105	65	0.286	105	65	0.294
	2.8	105	65	0.275	105	70	0.281
	3.2	105	65	0.257	105	65	0.262

Table 5.4: The optimization result for the ZX model in the two b -tagged jets region. The significance corresponding to the optimal cuts on the high and low values of m_{bb} with different $\Delta\phi(\gamma, \gamma)$.

The $t\bar{t}X$ model is split into leptonic, 2 b -tagged jet, 1 b -tagged jet regions. In each region, events are further split into four bins by making a 2D scan on $\Delta\phi(\gamma, \gamma)$ and N_{cjet} for the $t\bar{t}X$ model. The ZX model is split into two b -tagged jets and one b -tagged jet regions. In the two b -tagged jets region the variables m_{bb} and $\Delta\phi(\gamma, \gamma)$ are used for the ZX optimization. The m_{bb} is defined with the invariant mass of the two leading bjets. The $b\bar{b}X$ optimization only used the number of central jets.

The default significance is calculated using the formula $S/\sqrt{B}$ to avoid the arbitrariness of the signal cross section, where S and B are the signal and background events, respectively. The formula $S/\sqrt{S+B}$ is also used just for the sake of comparison. Here, the signal is normalized to 50 events in the inclusive case, while the background is calculated in a small range of the diphoton invariant mass spectrum ($m_{\gamma\gamma} \pm 10$ GeV). Then the quadrature sum of significance for all four bins in each region is obtained.

Figure 5.2 shows the optimization result for $t\bar{t}X$ with $m_X = 180$ GeV in each region. Appendix B.1 shows the results corresponding to the $t\bar{t}X$ and ZX . The optimization using higher mass models is shown as well. Tables 5.3 and 5.4, show a summary of the optimized results for $t\bar{t}X$ and ZX models, respectively. For the $b\bar{b}X$ models, the events are split by requiring the number of central jet larger equal than 2.

Here at least 100 expected data yields for the $m_{\gamma\gamma}$ spectrum are required, to avoid getting too low background fit in one of the categories. Thus, the four categories in the leptonic channel for $t\bar{t}X$ model are merged together. The $N_{cjet} \geq 4$ is used as the separation of the two small categories. The low jet multiplicity categories in the 1 b -tagged jet region and 2 b -tagged jets region are also merged for the $t\bar{t}X$ model. For the same reason, the $N_{cjet} \geq 5$ is used instead of 6 in the 2 b -tagged jets region for the $t\bar{t}X$ model.

Usually increasing the relative p_T cut of the photons can improve the significance, as shown in Tables 5.5 - 5.7. Figure 5.3 shows the distribution of all background with the relative photon p_T in different categories. Here, the relative p_T is defined as the p_T of the photons dividing the invariant mass. The result only performs in the most sensitive category. However, his optimization is not used because it increases a few percentage significance but significantly reduces the $m_{\gamma\gamma}$ spectrum tail.

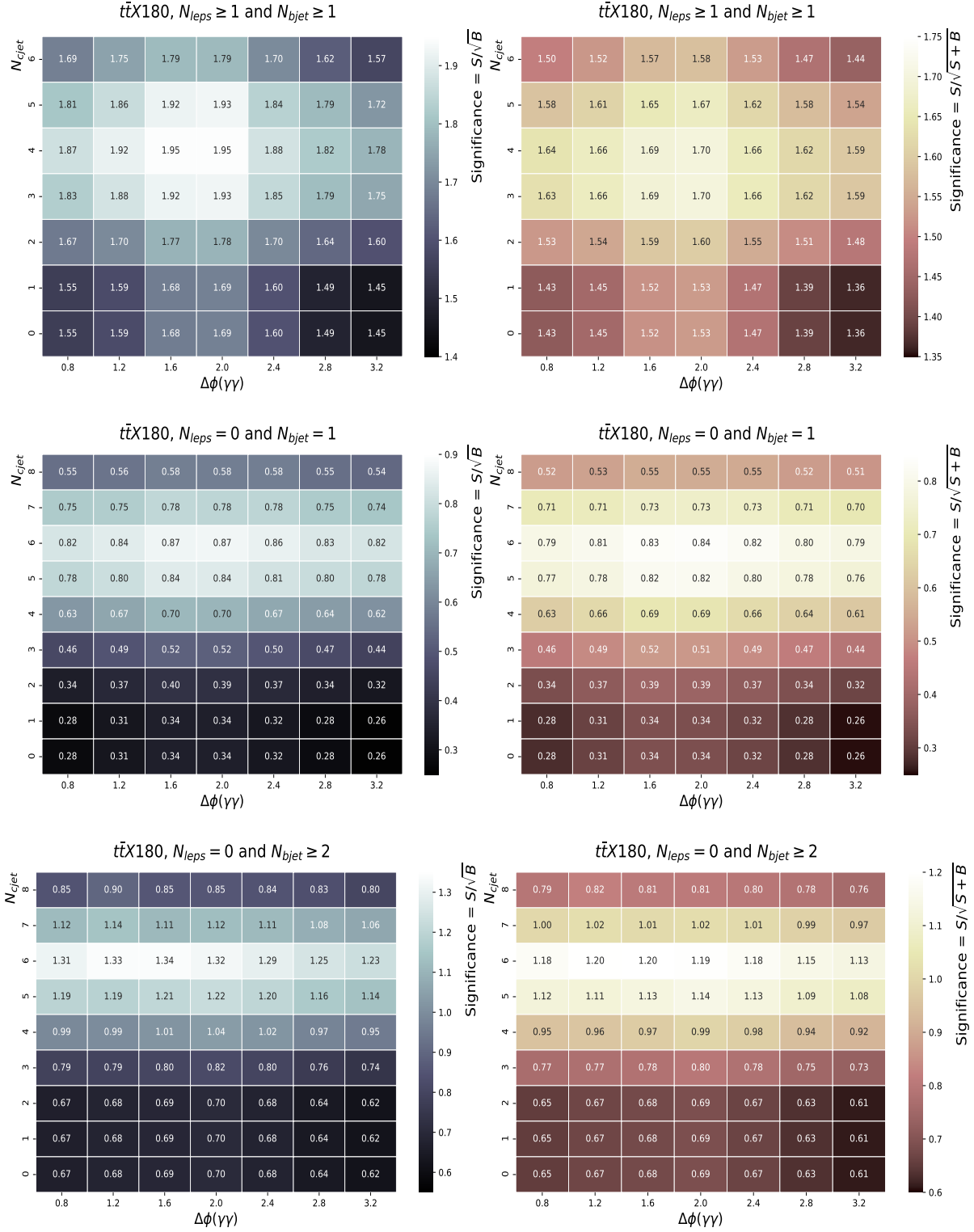


Figure 5.2: The optimization result for the $t\bar{t}X$ $m_X = 180$ GeV. The first row is one lepton region, the second row is one bjet region, the last row is two bjet region. The right is using the $S/\sqrt{S+B}$. The left is using the $S/\sqrt{B}$.

Sample	$S/\sqrt{S+B}$					$S/\sqrt{B}$				
	$p_T^{\gamma^1}/m_{\gamma\gamma}$	$p_T^{\gamma^2}/m_{\gamma\gamma}$	Signal	Background	Significance	$p_T^{\gamma^1}/m_{\gamma\gamma}$	$p_T^{\gamma^2}/m_{\gamma\gamma}$	Signal	Background	Significance
$t\bar{t}X180$	0.20	0.10	9.77	17.26	1.878	0.20	0.10	9.77	17.26	2.351
	0.25	0.15	9.75	17.02	1.885	0.25	0.15	9.75	17.02	2.364
	0.30	0.20	9.27	15.20	1.875	0.30	0.20	9.27	15.20	2.378
	0.35	0.25	8.23	10.97	1.878	0.35	0.25	8.23	10.97	2.484
	0.40	0.30	7.09	7.57	1.852	0.40	0.30	7.09	7.57	2.577
$t\bar{t}X250$	0.20	0.10	11.07	7.94	2.539	0.20	0.10	11.07	7.94	3.929
	0.25	0.15	10.79	7.41	2.529	0.25	0.15	10.79	7.41	3.963
	0.30	0.20	10.00	5.91	2.507	0.30	0.20	10.00	5.91	4.113
	0.35	0.25	8.93	3.77	2.506	0.35	0.25	8.93	3.77	4.597
	0.40	0.30	7.41	2.49	2.355	0.40	0.30	7.41	2.49	4.696
$t\bar{t}X500$	0.20	0.10	13.08	0.38	3.565	0.20	0.10	13.08	0.38	21.137
	0.25	0.15	12.62	0.30	3.511	0.25	0.15	12.62	0.30	23.122
	0.30	0.20	11.88	0.25	3.411	0.30	0.20	11.88	0.25	23.763
	0.35	0.25	10.58	0.20	3.222	0.35	0.25	10.58	0.20	23.519
	0.40	0.30	8.73	0.19	2.924	0.40	0.30	8.73	0.19	20.292

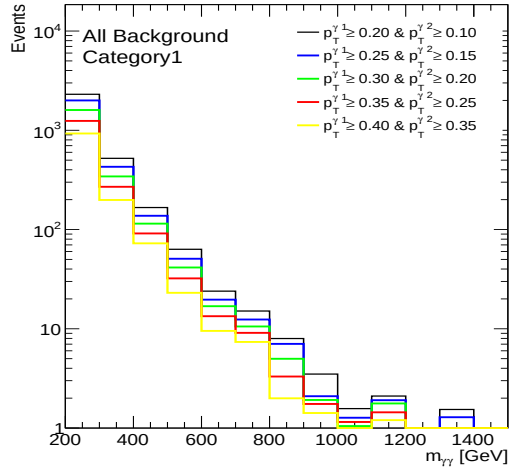
Table 5.5: Relative p_T cut on the $t\bar{t}X$ samples with $m_X = 180, 250$ and 500 GeV for category $N_{bjet} \geq 1 \& N_{leps} \& N_{cjet} \geq 4$.

Sample	$S/\sqrt{S+B}$					$S/\sqrt{B}$				
	$p_T^{\gamma^1}/m_{\gamma\gamma}$	$p_T^{\gamma^2}/m_{\gamma\gamma}$	Signal	Background	Significance	$p_T^{\gamma^1}/m_{\gamma\gamma}$	$p_T^{\gamma^2}/m_{\gamma\gamma}$	Signal	Background	Significance
$b\bar{b}X180$	0.20	0.10	8.41	1328.36	0.230	0.20	0.10	8.41	1328.36	0.231
	0.25	0.15	8.39	1296.71	0.232	0.25	0.15	8.39	1296.71	0.233
	0.30	0.20	8.10	1111.96	0.242	0.30	0.20	8.10	1111.96	0.243
	0.35	0.25	7.48	872.50	0.252	0.35	0.25	7.48	872.50	0.253
	0.40	0.30	6.48	642.92	0.254	0.40	0.30	6.48	642.92	0.256
$b\bar{b}X250$	0.20	0.10	8.41	407.85	0.412	0.20	0.10	8.41	407.85	0.417
	0.25	0.15	8.39	350.56	0.443	0.25	0.15	8.39	350.56	0.448
	0.30	0.20	8.10	283.69	0.474	0.30	0.20	8.10	283.69	0.481
	0.35	0.25	7.48	215.46	0.501	0.35	0.25	7.48	215.46	0.509
	0.40	0.30	6.48	161.60	0.500	0.40	0.30	6.48	161.60	0.510
$b\bar{b}X500$	0.20	0.10	13.58	21.51	2.293	0.20	0.10	13.58	21.51	2.929
	0.25	0.15	13.25	17.91	2.373	0.25	0.15	13.25	17.91	3.130
	0.30	0.20	12.63	14.11	2.443	0.30	0.20	12.63	14.11	3.363
	0.35	0.25	11.71	12.43	2.384	0.35	0.25	11.71	12.43	3.322
	0.40	0.30	10.28	9.55	2.309	0.40	0.30	10.28	9.55	3.327

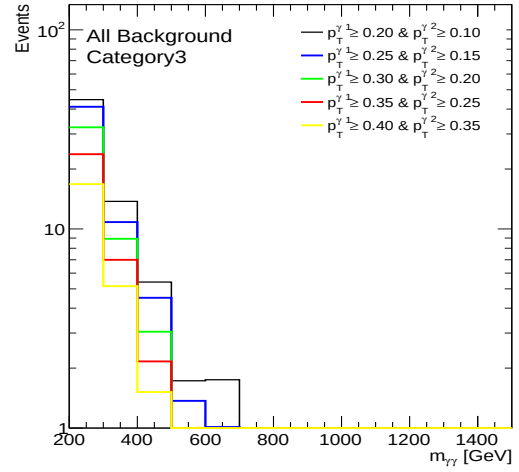
Table 5.6: Relative p_T cut on the $t\bar{t}X$ samples with $m_X = 180, 250$ and 500 GeV for category $N_{bjet} \geq 1 \& N_{leps} \& N_{cjet} \geq 4$.

Sample	$S/\sqrt{S+B}$					$S/\sqrt{B}$				
	$p_T^{\gamma^1}/m_{\gamma\gamma}$	$p_T^{\gamma^2}/m_{\gamma\gamma}$	Signal	Background	Significance	$p_T^{\gamma^1}/m_{\gamma\gamma}$	$p_T^{\gamma^2}/m_{\gamma\gamma}$	Signal	Background	Significance
$ZX200$	0.20	0.10	1.25	19.58	0.274	0.20	0.10	1.25	19.58	0.283
	0.25	0.15	1.25	19.07	0.286	0.25	0.15	1.25	19.07	0.277
	0.30	0.20	1.20	13.62	0.325	0.30	0.20	1.20	13.62	0.312
	0.35	0.25	1.08	10.42	0.334	0.35	0.25	1.08	10.42	0.318
	0.40	0.30	0.92	8.60	0.314	0.40	0.30	0.92	8.60	0.299
$ZX400$	0.20	0.10	1.66	1.43	0.942	0.20	0.10	1.66	1.43	1.384
	0.25	0.15	1.59	1.22	0.949	0.25	0.15	1.59	1.22	1.440
	0.30	0.20	1.49	1.00	0.943	0.30	0.20	1.49	1.00	1.488
	0.35	0.25	1.35	0.80	0.918	0.35	0.25	1.35	0.80	1.501
	0.40	0.30	1.16	0.61	0.872	0.40	0.30	1.16	0.61	1.482

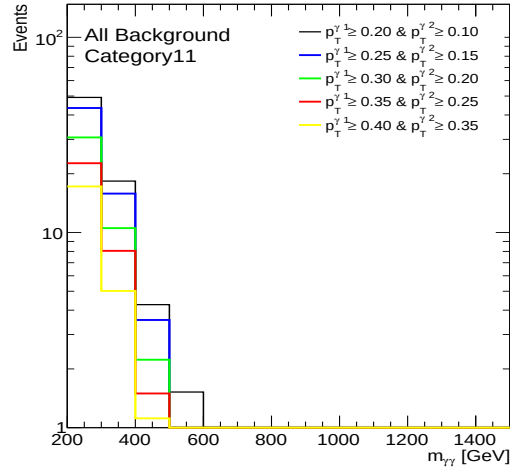
Table 5.7: Relative p_T cut on the ZX samples with $m_X = 200$ and 400 GeV for category 11.



(a)



(b)



(c)

Figure 5.3: All background distribution with relative photon p_T cuts for (a) category-1, (b) category-3 and (c) category-11.

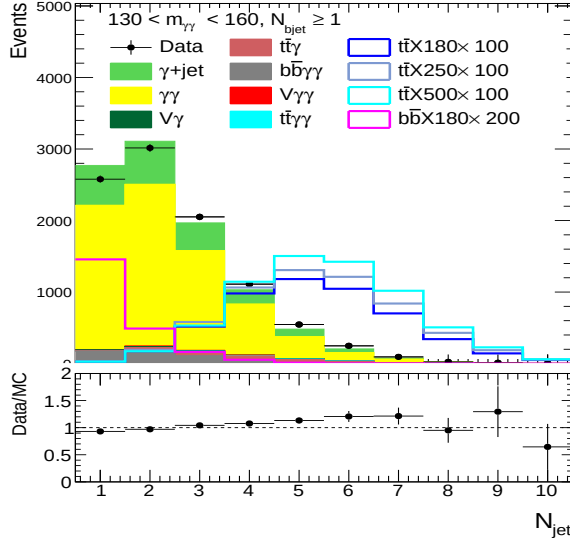
5.5 EVENT SELECTIONS

As shown in the previous section, events are categorized as in Table 5.8 after the preselection. The preselection requires that the transverse momentums of the leading and sub-leading photons to be greater than 40 GeV, and 30 GeV respectively, the $m_{\gamma\gamma}$ should be greater than 130 GeV and the event should have at least one b -tagged jet. Because in the high mass region, the expected data in this region is not enough to support a fit, the models with mass above 600 GeV use the merged categories as shown in Table 5.8.

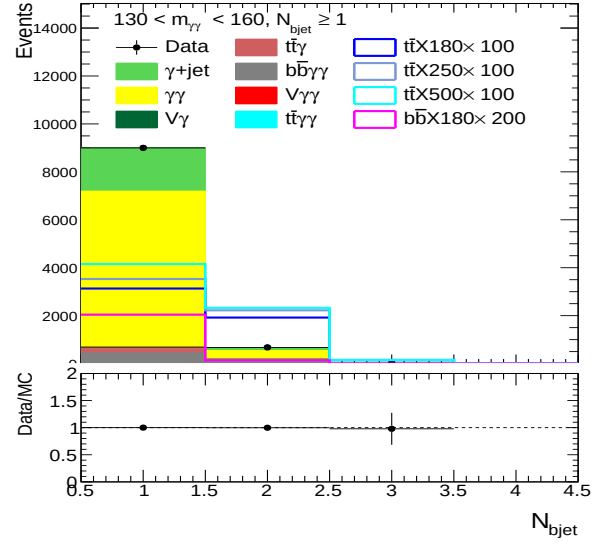
The expected background yields and data in each category are shown in Table 5.9, where the $m_{\gamma\gamma}$ range is constrained with in 130-160 GeV (control region). This is to show the compatibility between the data and MC. The expected background yields in the full mass range are shown in Table 5.10, where the data is blinded above 160 GeV. The signal yields are shown in Table 5.11. The signal samples are normalized to 1 fb before any selection. Thus, the number in this table divided by 139 would be the acceptance times efficiency. Figure 5.4 display the kinematic distributions corresponding to different variables after the event preselection in the control region ($m_{\gamma\gamma}$ in 130-160 GeV). Figures 5.5 and 5.6 display the kinematic distributions corresponding to the $\Delta\phi(\gamma, \gamma)$ and m_{bb} respectively. Additional distributions are shown in Appendix B.2. As one can see that the agreement between data and total background is reasonable in both the cores and tails.

	Category index	Cuts
Preselection		Photon $m_{\gamma\gamma} > 130$ GeV & $p_T > 40, 30$ GeV & $N_{bjet} \geq 1$
$m_{\gamma\gamma}$ in 160-1600 GeV		
$b\bar{b}X$ Categories	1	$N_{cjet} = 1$
	2	$N_{cjet} \geq 2$
$m_{\gamma\gamma}$ in 160-600 GeV		
$t\bar{t}X$ Categories	3	$N_{bjet} \geq 1$ & $N_{leps} \geq 1$ & $N_{cjet} \geq 4$
	4	$N_{bjet} \geq 1$ & $N_{leps} \geq 1$ & $N_{cjet} < 4$
	5	$N_{bjet} \geq 2$ & $N_{leps} = 0$ & $N_{cjet} \geq 5$ & $\Delta\phi(\gamma, \gamma) < 2$
	6	$N_{bjet} \geq 2$ & $N_{leps} = 0$ & $N_{cjet} \geq 5$ & $\Delta\phi(\gamma, \gamma) > 2$
	7	$N_{bjet} \geq 2$ & $N_{leps} = 0$ & $N_{cjet} < 5$
	8	$N_{bjet} = 1$ & $N_{leps} = 0$ & $N_{cjet} \geq 6$ & $\Delta\phi(\gamma, \gamma) < 2.4$
	9	$N_{bjet} = 1$ & $N_{leps} = 0$ & $N_{cjet} \geq 6$ & $\Delta\phi(\gamma, \gamma) > 2.4$
	10	$N_{bjet} = 1$ & $N_{leps} = 0$ & $N_{cjet} < 6$
ZX Categories	11	$N_{bjet} \geq 2$ & $(65 < m_{bb} [\text{GeV}] < 105)$ & $\Delta\phi(\gamma, \gamma) < 2.4$
	12	$N_{bjet} \geq 2$ & $(65 < m_{bb} [\text{GeV}] < 105)$ & $\Delta\phi(\gamma, \gamma) > 2.4$
	13	$N_{bjet} \geq 2$ & $(m_{bb} \text{ GeV} < 65 \text{ or } m_{bb} \text{ GeV} > 105)$
$t\bar{t}X, ZX$ for $m_{\gamma\gamma}$ in 600-900 GeV		
	14	$N_{bjet} = 1$
	15	$N_{bjet} \geq 2$
$t\bar{t}X, ZX$ for $m_{\gamma\gamma}$ in 900-1600 GeV		
	0	$N_{bjet} \geq 1$

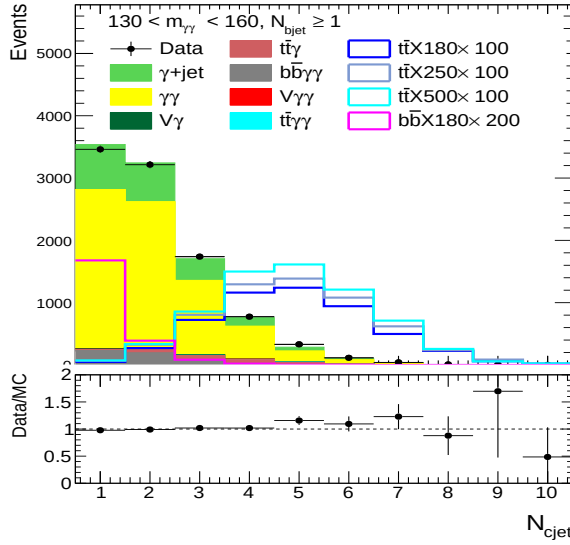
Table 5.8: The definition of each category, for different models and mass range.



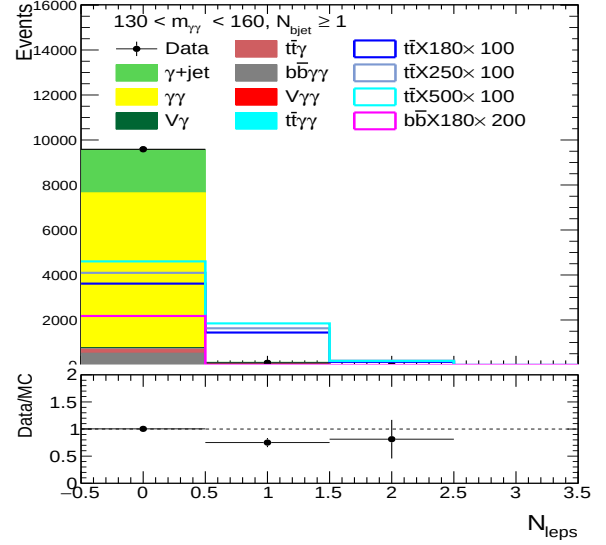
(a)



(b)



(c)



(d)

Figure 5.4: Distributions of (a) number of jets, (b) b-jet multiplicity, (c) central jet multiplicity and (d) the number of leptons after the event preselection in the control region ($m_{\gamma\gamma}$ in 130-160 GeV).

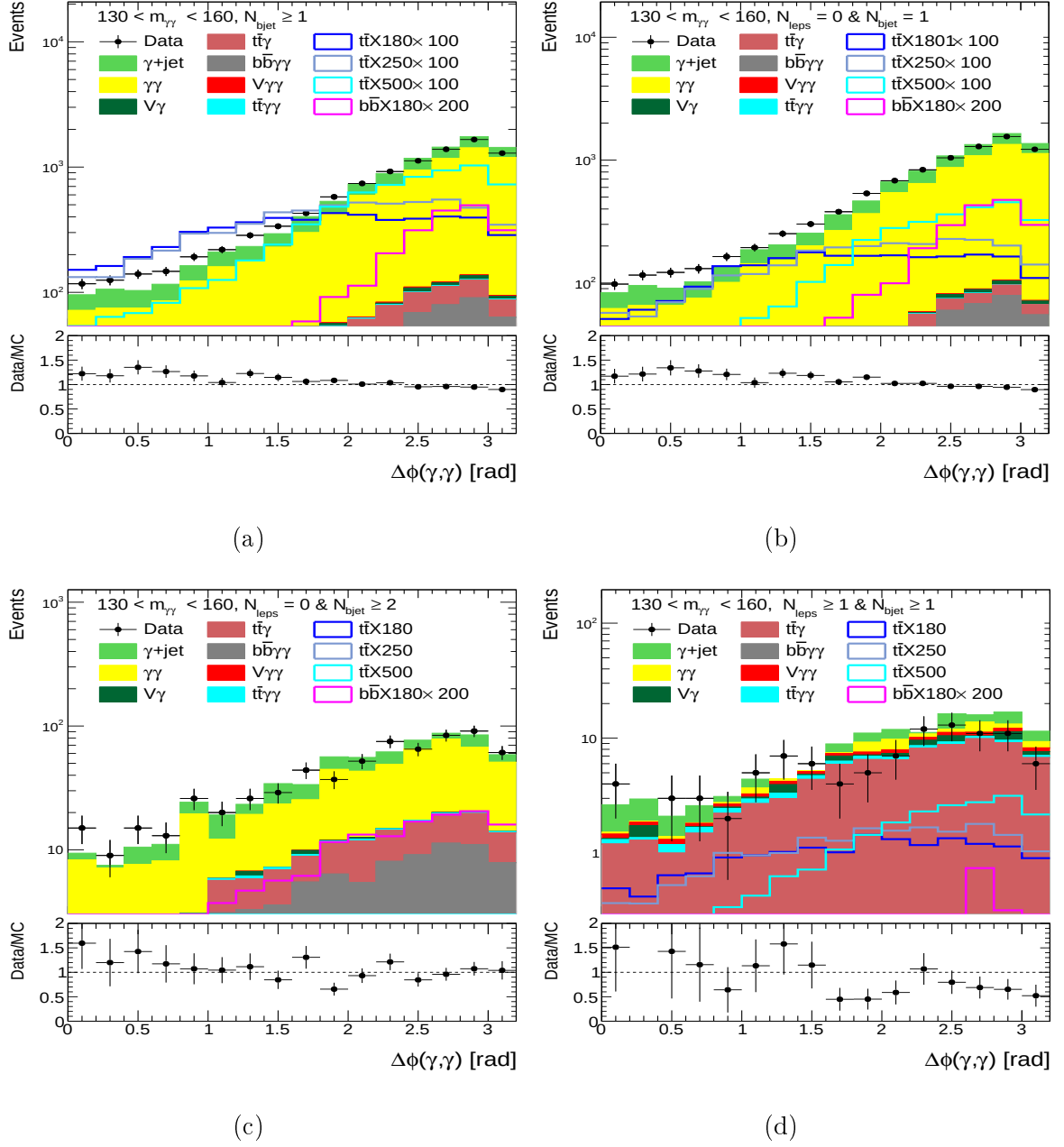
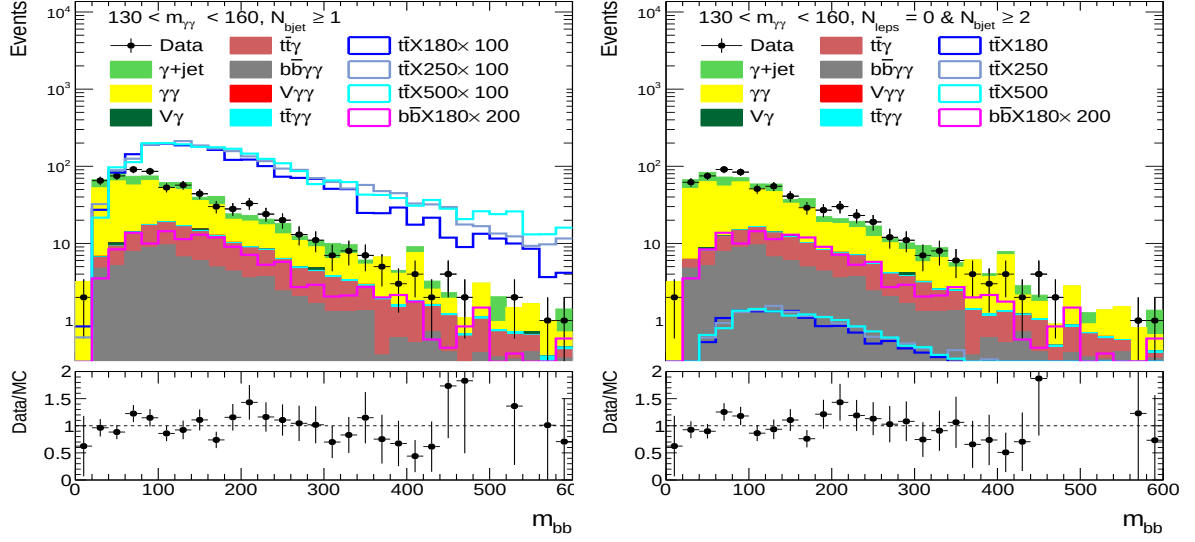
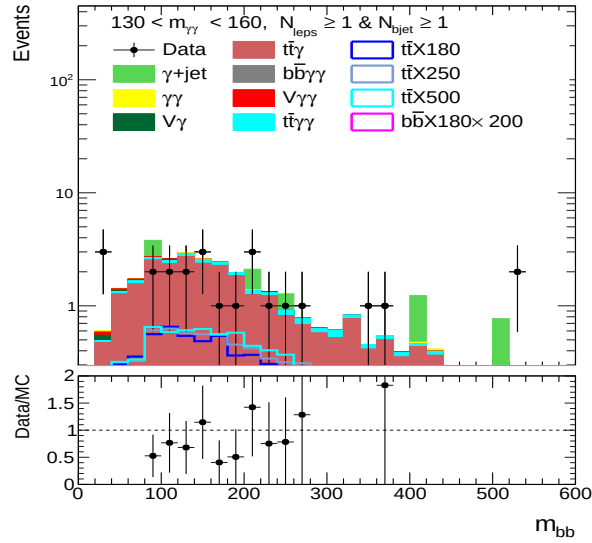


Figure 5.5: Distributions of $\Delta\phi_{\gamma\gamma}$ after (a) the preselection, (b) selecting events with $N_{leps} = 0$ & $N_{bjet} = 1$, (c) selecting events with $N_{leps} = 0$ & $N_{bjet} \geq 2$, and (d) selecting events with $N_{leps} \geq 1$ & $N_{bjet} \geq 1$.



(a)

(b)



(c)

Figure 5.6: Distributions of m_{bb} after (a) the preselection, (b) after selecting events with $N_{leps} = 0 \text{ \& } N_{bjet} \geq 2$, and (c) selecting events with $N_{leps} \geq 1 \text{ \& } N_{bjet} \geq 1$.

Cutflow	Category	Data	γ_{jet}	$V\gamma\gamma$	$V\gamma$	$t\bar{t}\gamma\gamma$	$t\bar{t}\gamma$	$\gamma\gamma$	$b\bar{b}\gamma\gamma$	All background
$N_{b_{\text{jet}}} \geq 1$	0	9684.00±98.41	1936.81±35.17	16.46±0.20	48.71±7.92	16.24±0.24	266.96±3.39	6880.14±70.65	519.15±7.20	9684.47±124.76
$b\bar{b}X$ Categories										
$N_{c_{\text{jet}}} = 1$	1	3776.00±61.45	800.47±22.56	83.17±0.39	142.65±18.76	0.41±0.04	22.10±0.99	2590.77±43.88	228.21±4.78	3867.77±91.39
$N_{c_{\text{jet}}} \geq 2$	2	6455.00±80.34	1262.89±28.50	82.94±0.39	141.22±13.95	17.09±0.25	268.29±3.39	4347.62±55.67	292.05±5.39	6412.10±107.54
$t\bar{t}X$ Categories										
$N_{b_{\text{jet}}} \geq 1 \& N_{\text{eps}} \geq 1 \& N_{c_{\text{jet}}} \geq 4$	3	26.00±5.10	5.17±1.88	1.10±0.05	0.70±0.28	2.59±0.10	25.75±1.03	0.81±0.38	0.00±0.00	36.12±3.73
$N_{b_{\text{jet}}} \geq 1 \& N_{\text{eps}} \geq 1 \& N_{c_{\text{jet}}} < 4$	4	73.00±8.54	17.82±3.35	5.14±0.10	6.62±1.76	2.38±0.09	52.01±1.49	10.06±2.43	1.20±0.35	95.23±9.58
$N_{b_{\text{jet}}} \geq 2 \& N_{\text{eps}} = 0 \& N_{c_{\text{jet}}} \geq 5 \& \Delta\phi(\gamma, \gamma) < 2$	5	51.00±7.14	11.75±2.75	0.07±0.01	0.00±0.00	1.59±0.08	8.78±0.61	18.17±2.87	0.83±0.31	41.19±6.63
$N_{b_{\text{jet}}} \geq 2 \& N_{\text{eps}} = 0 \& N_{c_{\text{jet}}} \geq 5 \& \Delta\phi(\gamma, \gamma) > 2$	6	65.00±8.06	11.41±2.68	0.07±0.01	0.34±0.34	1.59±0.08	12.68±0.73	34.36±7.53	1.42±0.36	61.88±11.75
$N_{b_{\text{jet}}} \geq 2 \& N_{\text{eps}} = 0 \& N_{c_{\text{jet}}} < 5$	7	546.00±23.37	102.44±8.06	0.46±0.04	1.40±0.89	1.34±0.07	44.34±1.39	323.36±15.24	78.89±2.80	552.23±28.48
$N_{b_{\text{jet}}} = 1 \& N_{\text{eps}} = 0 \& N_{c_{\text{jet}}} \geq 6 \& \Delta\phi(\gamma, \gamma) < 2.4$	8	83.00±9.11	17.45±3.41	0.20±0.02	0.64±0.54	1.44±0.07	5.97±0.51	43.27±4.20	0.59±0.26	69.56±9.01
$N_{b_{\text{jet}}} = 1 \& N_{\text{eps}} = 0 \& N_{c_{\text{jet}}} \geq 6 \& \Delta\phi(\gamma, \gamma) > 2.4$	9	43.00±6.56	8.43±2.35	0.08±0.01	0.98±0.69	0.68±0.05	3.06±0.36	21.23±2.34	0.12±0.12	34.59±5.93
$N_{b_{\text{jet}}} = 1 \& N_{\text{eps}} = 0 \& N_{c_{\text{jet}}} < 6$	10	8797.00±93.79	1762.34±33.55	9.34±0.16	38.03±7.60	4.61±0.13	114.37±2.23	6428.89±68.30	436.10±6.60	8793.68±118.56
ZX Categories										
$N_{b_{\text{jet}}} \geq 2 \& (65 < m_{t\bar{t}} [\text{GeV}] < 105) \& \Delta\phi(\gamma, \gamma) < 2.4$	11	82.00±9.06	13.87±2.83	0.12±0.02	0.08±0.07	0.45±0.04	7.38±0.56	36.78±3.57	8.41±0.92	67.09±8.01
$N_{b_{\text{jet}}} \geq 2 \& (65 < m_{t\bar{t}} [\text{GeV}] < 105) \& \Delta\phi(\gamma, \gamma) > 2.4$	12	88.00±9.38	10.99±2.64	0.07±0.01	0.00±0.00	0.32±0.04	7.52±0.57	46.51±5.87	7.88±0.89	73.30±10.02
$N_{b_{\text{jet}}} \geq 2 \& (m_{t\bar{t}} \text{GeV} < 65 \text{ or } m_{t\bar{t}} \text{GeV} > 105)$	13	516.00±22.72	104.36±8.18	0.76±0.04	1.96±0.96	5.74±0.14	77.70±1.83	292.79±15.81	64.85±2.54	548.16±29.50
$N_{b_{\text{jet}}} = 1$	14	8998.00±94.86	1807.58±33.99	15.51±0.19	46.67±7.86	9.73±0.19	174.37±2.74	6504.07±68.51	438.00±6.61	8995.93±120.09
$N_{b_{\text{jet}}} \geq 2$	15	686.00±26.19	129.23±9.05	0.96±0.05	2.04±0.96	6.51±0.15	92.59±2.00	376.07±17.24	81.15±2.84	688.54±32.29

Table 5.9: The background cut flow table in the control region with $m_{\gamma\gamma} = 130\text{-}160$ GeV.

Cutflow	Category	γ_{jet}	$V\gamma\gamma$	$V\gamma$	$t\bar{t}\gamma\gamma$	$t\bar{t}\gamma$	$\gamma\gamma$	$b\bar{b}\gamma\gamma$	All background
$N_{b\text{jet}} \geq 1$	0	5866.97 $\pm$ 61.26	55.55 $\pm$ 0.36	198.14 $\pm$ 15.42	71.52 $\pm$ 0.52	856.68 $\pm$ 6.07	19098.79 $\pm$ 92.40	1539.84 $\pm$ 12.39	27687.49 $\pm$ 188.43
<i>bbX</i> Categories									
$N_{cjet} = 1$	1	2135.72 $\pm$ 36.93	25.48 $\pm$ 0.68	551.19 $\pm$ 43.29	1.66 $\pm$ 0.08	64.98 $\pm$ 1.69	6237.65 $\pm$ 54.98	608.41 $\pm$ 7.81	9854.46 $\pm$ 145.46
$N_{cjet} \geq 2$	2	4114.88 $\pm$ 51.42	293.41 $\pm$ 0.75	505.10 $\pm$ 32.20	75.24 $\pm$ 0.53	867.75 $\pm$ 6.10	13044.17 $\pm$ 74.66	935.67 $\pm$ 9.64	19836.21 $\pm$ 175.29
<i>ttX</i> Categories									
$N_{bjet} \geq 1 \& N_{leps} \geq 1 \& N_{cjet} \geq 4$	3	19.67 $\pm$ 3.57	4.43 $\pm$ 0.09	4.77 $\pm$ 1.02	11.86 $\pm$ 0.21	96.92 $\pm$ 2.01	3.98 $\pm$ 0.98	0.09 $\pm$ 0.09	141.71 $\pm$ 7.97
$N_{bjet} \geq 1 \& N_{leps} \geq 1 \& N_{cjet} < 4$	4	53.74 $\pm$ 5.93	16.95 $\pm$ 0.18	36.90 $\pm$ 8.87	9.97 $\pm$ 0.19	154.03 $\pm$ 2.56	22.99 $\pm$ 2.88	3.67 $\pm$ 0.60	298.25 $\pm$ 21.22
$N_{bjet} \geq 2 \& N_{leps} = 0 \& N_{cjet} \geq 5 \& \Delta\phi(\gamma, \gamma) < 2$	5	30.08 $\pm$ 4.31	0.24 $\pm$ 0.03	0.11 $\pm$ 0.06	6.05 $\pm$ 0.15	28.65 $\pm$ 1.10	73.24 $\pm$ 5.09	3.69 $\pm$ 0.62	142.07 $\pm$ 11.37
$N_{bjet} \geq 2 \& N_{leps} = 0 \& N_{cjet} \geq 5 \& \Delta\phi(\gamma, \gamma) > 2$	6	46.12 $\pm$ 5.36	0.30 $\pm$ 0.03	1.40 $\pm$ 0.62	8.45 $\pm$ 0.18	45.99 $\pm$ 1.39	128.13 $\pm$ 9.06	7.63 $\pm$ 0.85	238.03 $\pm$ 17.49
$N_{bjet} \geq 2 \& N_{leps} = 0 \& N_{cjet} < 5$	7	351.02 $\pm$ 14.97	1.61 $\pm$ 0.07	6.14 $\pm$ 2.01	5.82 $\pm$ 0.15	135.16 $\pm$ 2.43	950.15 $\pm$ 19.06	252.67 $\pm$ 5.00	1702.57 $\pm$ 43.68
$N_{bjet} = 1 \& N_{leps} = 0 \& N_{cjet} \geq 6 \& \Delta\phi(\gamma, \gamma) < 2.4$	8	61.21 $\pm$ 6.34	0.70 $\pm$ 0.04	4.33 $\pm$ 1.84	5.76 $\pm$ 0.14	18.83 $\pm$ 0.90	161.13 $\pm$ 6.65	1.84 $\pm$ 0.43	253.81 $\pm$ 16.34
$N_{bjet} = 1 \& N_{leps} = 0 \& N_{cjet} \geq 6 \& \Delta\phi(\gamma, \gamma) > 2.4$	9	39.22 $\pm$ 4.96	0.38 $\pm$ 0.03	1.92 $\pm$ 0.86	3.66 $\pm$ 0.12	15.19 $\pm$ 0.80	121.52 $\pm$ 5.18	1.53 $\pm$ 0.38	183.43 $\pm$ 12.32
$N_{bjet} = 1 \& N_{leps} = 0 \& N_{cjet} < 6$	10	5265.89 $\pm$ 58.04	30.94 $\pm$ 0.29	142.57 $\pm$ 12.23	19.95 $\pm$ 0.27	361.92 $\pm$ 3.97	17637.64 $\pm$ 89.37	1268.71 $\pm$ 11.26	24727.63 $\pm$ 175.43
<i>ZX</i> Categories									
$N_{bjet} \geq 2 \& (65 < m_{b\bar{b}} [\text{GeV}] < 105) \& \Delta\phi(\gamma, \gamma) < 2.4$	11	48.97 $\pm$ 5.62	0.41 $\pm$ 0.03	0.80 $\pm$ 0.48	1.98 $\pm$ 0.08	21.39 $\pm$ 0.95	113.09 $\pm$ 6.03	23.84 $\pm$ 1.54	210.47 $\pm$ 14.73
$N_{bjet} \geq 2 \& (65 < m_{b\bar{b}} [\text{GeV}] < 105) \& \Delta\phi(\gamma, \gamma) > 2.4$	12	49.12 $\pm$ 5.59	0.29 $\pm$ 0.02	0.62 $\pm$ 0.39	1.44 $\pm$ 0.07	23.14 $\pm$ 0.99	150.79 $\pm$ 7.36	29.51 $\pm$ 1.70	254.91 $\pm$ 16.14
$N_{bjet} \geq 2 \& (m_{b\bar{b}} \text{ GeV} < 65 \text{ or } m_{b\bar{b}} \text{ GeV} > 105)$	13	342.84 $\pm$ 14.71	2.89 $\pm$ 0.09	7.59 $\pm$ 2.12	25.27 $\pm$ 0.31	252.42 $\pm$ 3.29	888.19 $\pm$ 19.52	210.72 $\pm$ 4.56	1729.93 $\pm$ 44.60
$N_{bjet} = 1$	14	5426.04 $\pm$ 58.93	51.95 $\pm$ 0.35	189.13 $\pm$ 15.26	42.83 $\pm$ 0.40	559.74 $\pm$ 4.91	17946.73 $\pm$ 89.82	1275.76 $\pm$ 11.29	25492.18 $\pm$ 180.97
$N_{bjet} \geq 2$	15	440.93 $\pm$ 16.71	3.60 $\pm$ 0.10	9.01 $\pm$ 2.21	28.69 $\pm$ 0.33	296.94 $\pm$ 3.57	1152.07 $\pm$ 21.71	264.08 $\pm$ 5.11	2195.31 $\pm$ 49.73

Table 5.10: The background cut flow table in all region.

$t\bar{t}X$ samples								
Cutflow	Category	$t\bar{t}X180$	$t\bar{t}X250$	$t\bar{t}X500$	$t\bar{t}X750$	$t\bar{t}X1500$		
$N_{bjet} \geq 1$	0	51.97±0.60	59.17±0.65	66.33±0.81	68.15±0.86	67.25±0.92		
$N_{bjet} \geq 1 \& N_{leps} \geq 1 \& N_{cjet} \geq 4$	3	9.77±0.27	11.08±0.30	13.23±0.38	13.36±0.41	13.82±0.44		
$N_{bjet} \geq 1 \& N_{leps} \geq 1 \& N_{cjet} < 4$	4	6.05±0.18	7.14±0.20	7.06±0.23	7.03±0.23	6.00±0.23		
$N_{bjet} \geq 2 \& N_{leps} = 0 \& N_{cjet} \geq 5 \& \Delta\phi(\gamma, \gamma) < 2.4$	5	8.25±0.24	8.90±0.26	6.48±0.27	5.00±0.25	2.22±0.19		
$N_{bjet} \geq 2 \& N_{leps} = 0 \& N_{cjet} \geq 5 \& \Delta\phi(\gamma, \gamma) > 2.4$	6	2.83±0.14	3.90±0.16	6.65±0.27	9.54±0.33	12.03±0.41		
$N_{bjet} \geq 2 \& N_{leps} = 0 \& N_{cjet} < 5$	7	3.45±0.14	3.80±0.15	3.93±0.17	4.00±0.17	3.34±0.17		
$N_{bjet} = 1 \& N_{leps} = 0 \& N_{cjet} \geq 6 \& \Delta\phi(\gamma, \gamma) < 2.4$	8	6.01±0.22	6.52±0.24	5.59±0.27	4.37±0.25	2.01±0.19		
$N_{bjet} = 1 \& N_{leps} = 0 \& N_{cjet} \geq 6 \& \Delta\phi(\gamma, \gamma) > 2.4$	9	2.02±0.13	2.72±0.15	5.28±0.26	7.23±0.32	10.71±0.41		
$N_{bjet} = 1 \& N_{leps} = 0 \& N_{cjet} < 6$	10	13.59±0.30	15.11±0.31	18.11±0.38	17.63±0.40	17.12±0.41		
$N_{bjet} = 1$	14	31.32±0.47	35.29±0.51	41.53±0.64	41.74±0.68	42.07±0.72		
$N_{bjet} \geq 2$	15	20.65±0.37	23.88±0.41	24.80±0.50	26.41±0.53	25.18±0.57		
$b\bar{b}X$ samples								
Cutflow	Category	$b\bar{b}X180$	$b\bar{b}X250$	$b\bar{b}X500$	$b\bar{b}X750$	$b\bar{b}X1500$		
$N_{bjet} \geq 1$	0	10.90±0.12	14.20±0.14	20.11±0.17	22.49±0.18	22.21±0.18		
$N_{cjet} = 1$	1	8.41±0.11	10.55±0.12	13.72±0.14	14.58±0.14	13.51±0.14		
$N_{cjet} \geq 1$	2	10.92±0.12	14.23±0.14	20.14±0.17	22.52±0.18	22.24±0.18		
ZX samples								
Cutflow	Category	$ZX200$	$ZX300$	$ZX400$	$ZX600$	$ZX800$	$ZX1000$	$ZX1500$
$N_{bjet} \geq 1$	0	8.32±0.10	10.42±0.11	11.80±0.12	13.10±0.13	13.88±0.13	14.21±0.13	14.46±0.13
$N_{bjet} \geq 2 \& m_{bb} > 65 \& m_{bb} < 105 \& \Delta\phi(\gamma, \gamma) < 2$	11	1.25±0.04	1.48±0.04	1.67±0.05	1.43±0.04	1.08±0.04	0.69±0.03	0.25±0.02
$N_{bjet} \geq 2 \& m_{bb} > 65 \& m_{bb} < 105 \& \Delta\phi(\gamma, \gamma) > 2$	12	0.54±0.03	0.88±0.03	1.15±0.04	1.57±0.04	1.72±0.05	1.81±0.05	1.60±0.04
$N_{bjet} \geq 2 \& (m_{bb} < 65 \& m_{bb} > 105)$	13	0.56±0.03	0.76±0.03	0.85±0.03	1.00±0.03	0.93±0.03	0.95±0.03	0.90±0.03
$N_{bjet} = 1$	14	5.98±0.09	7.30±0.09	8.13±0.10	9.10±0.11	10.15±0.11	10.76±0.12	11.72±0.12
$N_{bjet} \geq 2$	15	2.35±0.05	3.12±0.06	3.67±0.07	4.00±0.07	3.73±0.07	3.45±0.07	2.74±0.06

Table 5.11: The cutflow for the $t\bar{t}X$, $b\bar{b}X$ and ZX signal samples normalized to 1fb with $m_{\gamma\gamma} > 130$ GeV.

Sample	Category	S	B	$S/\sqrt{S+B}$	$S/\sqrt{B}$
$t\bar{t}X180$	0	50.58	3637.56	0.833	0.839
	3	9.65	17.26	1.861	2.324
	4	5.91	42.79	0.847	0.903
	5	6.53	21.30	1.238	1.415
	6	4.24	27.05	0.757	0.815
	7	3.33	210.96	0.228	0.230
	8	5.85	25.94	1.038	1.149
	9	3.66	22.68	0.712	0.768
	10	20.16	3516.18	0.339	0.340
	14	30.48	3364.48	0.523	0.525
	15	20.11	273.08	1.174	1.217
$t\bar{t}X250$	0	57.21	1303.99	1.551	1.584
	3	10.70	7.99	2.474	3.784
	4	6.84	20.06	1.320	1.528
	5	6.41	6.07	1.815	2.603
	6	6.03	12.83	1.389	1.685
	7	3.67	81.97	0.397	0.406
	8	6.35	12.98	1.444	1.762
	9	5.24	13.77	1.202	1.413
	10	22.22	1244.91	0.624	0.630
	14	34.09	1196.00	0.972	0.986
$t\bar{t}X500$	15	23.13	107.99	2.020	2.225
	0	60.43	94.38	4.857	6.220
	3	12.03	0.39	3.414	19.348
	4	6.39	1.66	2.251	4.950
	5	3.61	0.83	1.713	3.962
	6	8.56	1.69	2.675	6.594
	7	3.52	6.36	1.120	1.397
	8	5.06	0.88	2.076	5.384
	9	8.69	1.92	2.668	6.267
	10	24.19	89.15	2.273	2.562
$t\bar{t}X750$	14	37.68	85.13	3.400	4.084
	15	22.75	9.25	4.022	7.481
	0	64.81	31.81	6.593	11.491
$t\bar{t}X1500$	14	39.73	28.09	4.825	7.497
	15	25.07	3.71	4.673	13.009
$t\bar{t}X1500$	0	55.45	1.43	7.352	46.402

Table 5.12: Significance in each category for $t\bar{t}X$ in each mass points with some selected categories

Sample	Category	S	B	$S/\sqrt{S+B}$	$S/\sqrt{B}$
ZX200	0	8.26	2619.15	0.161	0.161
	11	1.25	19.58	0.273	0.282
	12	0.53	24.13	0.108	0.109
	13	1.78	43.72	0.264	0.269
	14	5.92	2415.89	0.120	0.121
	15	2.34	203.24	0.163	0.164
ZX300	0	10.24	706.43	0.382	0.385
	11	1.46	5.12	0.569	0.645
	12	0.87	6.77	0.313	0.333
	13	2.33	11.89	0.617	0.674
	14	7.16	640.56	0.281	0.283
	15	3.08	65.87	0.371	0.379
ZX400	0	11.43	236.41	0.726	0.743
	11	1.62	1.92	0.863	1.172
	12	1.12	4.01	0.493	0.558
	13	2.74	5.93	0.931	1.126
	14	7.86	212.52	0.530	0.539
	15	3.57	23.89	0.681	0.730
ZX600	0	12.02	42.64	1.626	1.841
	11	1.30	0.16	1.077	3.269
	12	1.45	0.31	1.095	2.618
	13	2.76	0.47	1.535	4.032
	14	8.36	36.71	1.245	1.380
	15	3.66	5.92	1.182	1.503
ZX800	0	13.58	22.49	2.261	2.864
	14	9.93	20.86	1.789	2.173
	15	3.66	1.64	1.590	2.859
ZX1000	0	13.64	5.09	3.152	6.047
ZX1500	0	12.91	1.43	3.409	10.802

Table 5.13: Significance in each category for ZX in each mass points with some selected categories.

Sample	Category	S	B	$S/\sqrt{S+B}$	$S/\sqrt{B}$
$b\bar{b}X180$	0	10.72	3637.56	0.177	0.178
	1	8.28	1328.36	0.226	0.227
	2	2.46	2581.45	0.048	0.048
$b\bar{b}X250$	0	13.80	1303.99	0.380	0.382
	1	10.26	420.14	0.494	0.500
	2	3.56	981.46	0.113	0.114
$b\bar{b}X500$	0	18.36	94.38	1.729	1.889
	1	12.54	25.25	2.040	2.495
	2	5.84	78.56	0.636	0.659
$b\bar{b}X750$	0	21.58	31.81	2.954	3.827
	1	13.99	9.59	2.881	4.517
	2	7.63	24.89	1.338	1.529
$b\bar{b}X1500$	0	18.61	1.43	4.157	15.570
	1	11.33	0.16	3.342	27.999
	2	7.31	1.35	2.484	6.295

Table 5.14: Significance in each category for $b\bar{b}X$ in categories 0-3 in each mass points

5.6 SIGNAL PARAMETERIZATION

A functional form that is the Double-sided Crystal Ball function (DSCB) is used to model the heavy scalar signal shape. The function consist of a Gaussian central part extended by asymmetric power-law tails on both sides. The DSCB function modelling method is described in more detail in [183]. Figure 5.7 shows a graphical representation of the function shape and its parameters, while the mathematical expression of it is given in the following equation:

$$N \cdot \begin{cases} e^{-0.5t^2} & \text{if } -\alpha_{\text{low}} \geq t \geq \alpha_{\text{high}} \\ e^{-0.5\alpha_{\text{low}}^2} \left[\frac{\alpha_{\text{low}}}{n_{\text{low}}} \left(\frac{n_{\text{low}}}{\alpha_{\text{low}}} - \alpha_{\text{low}} - t \right) \right]^{-n_{\text{low}}} & \text{if } t < -\alpha_{\text{low}} \\ e^{-0.5\alpha_{\text{high}}^2} \left[\frac{\alpha_{\text{high}}}{n_{\text{high}}} \left(\frac{n_{\text{high}}}{\alpha_{\text{high}}} - \alpha_{\text{high}} + t \right) \right]^{-n_{\text{high}}} & \text{if } t > \alpha_{\text{high}}, \end{cases} \quad (5.6.1)$$

where $t = (m_{\gamma\gamma} - \mu_{CB})/\sigma_{CB}$ with μ_{CB} and σ_{CB} representing the peak and the width of the Gaussian part of the distribution. N is a normalization parameter, α_{low} (α_{high}) is the point where the distribution of the invariant mass becomes a power-law function on the low (high)-mass side, and n_{low} (n_{high}) the exponent of this power-law function. Four of these six parameters are found to be mass dependent. n_{low} and n_{high} are not mass dependent and so will be modelled with constants.

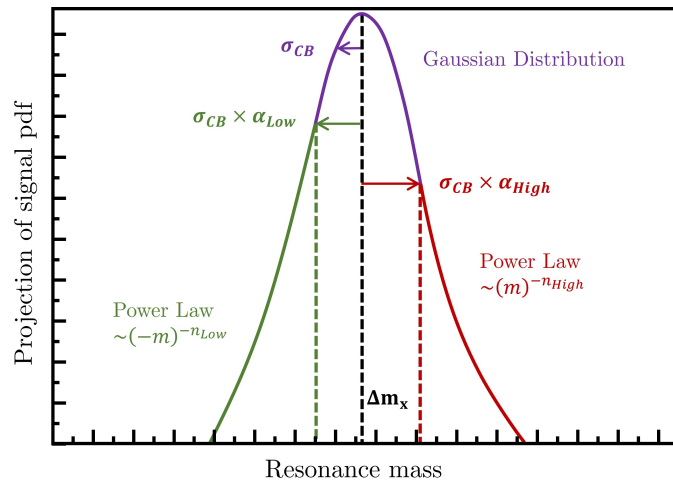


Figure 5.7: Description of the double-sided Crystal Ball function shape and parameters, The different parameters are described in the text.

The MC signal samples that are shown in Table 5.1 are used for this signal parametrization. These samples correspond to the processes $t\bar{t}X$, $b\bar{b}X$ and ZX and are categorized into 15 categories as described in section 5.5. The DSCB shape is fitted to signal distributions of the di-photon invariant mass spectrum for each mass point m_X , yielding a set of DSCB parameters for each category. Figures 5.8a shows the result of a single fit of the DSCB function for a $t\bar{t}X$ signal sample with mass point $m_X = 180$ GeV for category 3 case and those corresponding to the other categories are shown in Appendix C.1. The DSCB parameter σ_{CB} , the width of the Gaussian core and α are then parametrised as a function of the generated mass m_X for each process and all categories using linear functions. Figures 5.8b shows the fit result for the mass dependant width σ_{CB} in category 3 case and those corresponding to the other categories are shown in Appendix C.1. Additionally, figures for the DSCB parameters α_{high} and α_{low} can be found in each category for all signal processes. For simplicity, the n_s for each models are set to a fixed value.

Diffident analytical functions (linear, exponential functions of different-order or polynomials) are used to parameterize the acceptance times efficiencies in order to estimate the signal yield. The parametrization is determined in three steps. In the initial step, a fit for the categories 0-2, 14 and 15 for each model using a functional type $(p_1 + p_2 \exp(p_3x) \times \exp(p_4x))$ is directly performed. Hence, the parametrization for the $b\bar{b}X$ samples is simply done. The second step is needed now to enable us to fit the rest of the categories for $t\bar{t}X$ (3-10), and the ZX (11-13). In this step we, define three more categories dedicated for signal parameterization, namely 16, 17, and 18 as shown in Table 5.15. For category 16, it is the merged category of 3 and 4 (leptonic category). Category 17 is merging the categories 5, 6 and 7 (two b -tagged jet and non lepton category), while category 18 is the merged category of 8, 9 and 10 (one b -tagged jet and non lepton category). In addition, the category 15 is already merging the categories 11-13 (two b -tagged jet category). Now these categories are parameterized using the above mentioned functional forms to obtain the acceptance times efficiency in these merged categories. Then the fraction of events in category 3-13 over the upper level merged categories is obtained. For example, to get the efficiency in category 3 or 4, the events in category 3 or 4 to are used to divide the number of events in 16. Then a fit is preformed for this fraction with a simple second order polynomial as a function of the resonance mass. In the last step, for example, the fraction of category 3 over category 16 is multiplied with the acceptance times efficiency of category 16, to obtain the acceptance times efficiency of category 3. Figures 5.9a and 5.9c show the fraction of events the results of the final acceptance times efficiency fit for the $t\bar{t}X$ category 3. While figure 5.9b shows the acceptance times efficiency for the $t\bar{t}X$ category 16, which is the intermediate step in the fit process. Additional figures that supplement

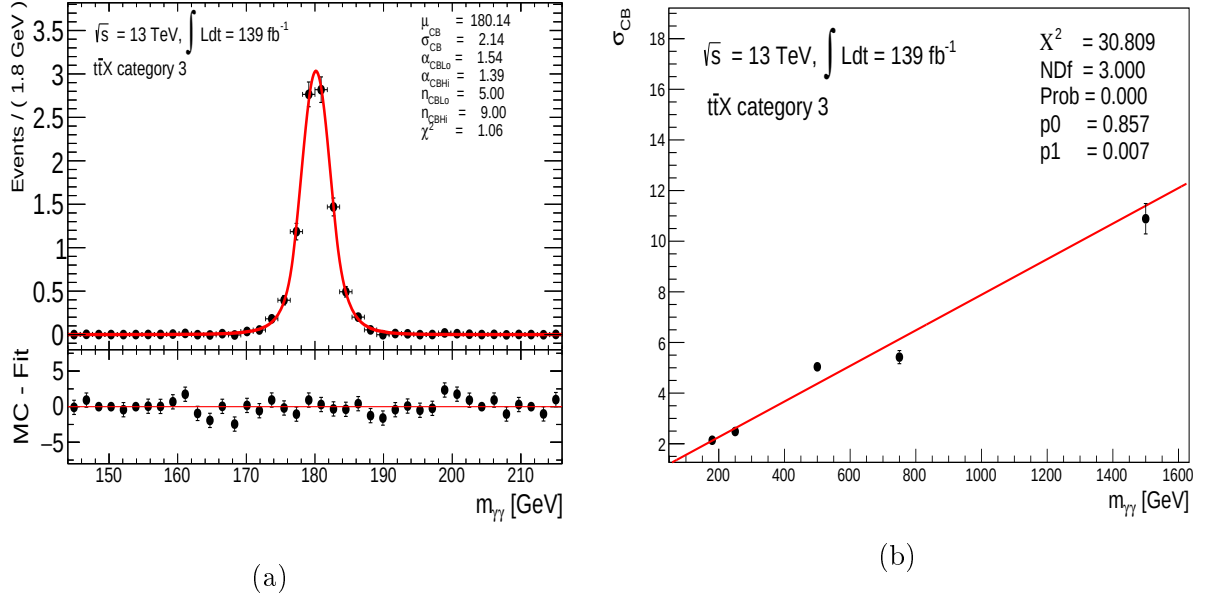


Figure 5.8: (a) The results of a single fit of a DSCB function (lines) for $t\bar{t}X$ signal sample with $m_H = 180$ GeV in the category 3. (b) The width of the resonance peak (σ_{CB}) as a function of the resonance mass for the simulated signal sample $t\bar{t}X$ in category 3.

this study are shown in Appendix C.1.

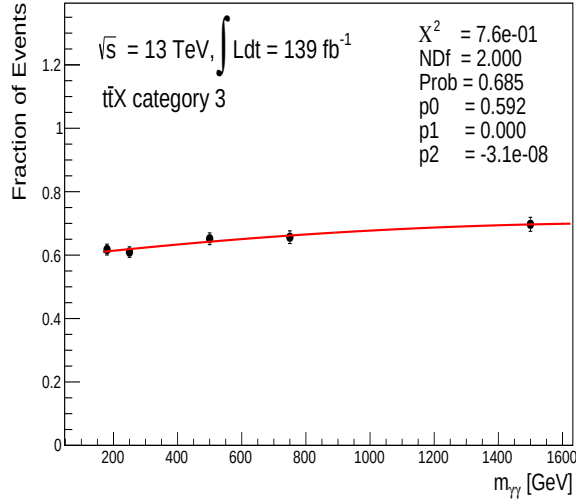
The maximum difference between the predicted acceptance times efficiency and the MC points is treated as the systematic uncertainty. The maximum difference is used within the mass range where the category is considered. For example, the maximum difference below $m_X = 700$ GeV is used for category 3-13 with the energy range 160-600 GeV. The statistical uncertainty of the MC samples is also taken into account. Table 5.16 shows the statistical and systematic uncertainties in the estimation of the signal efficiencies for each category.

	Category index	Cuts	
$t\bar{t}X$ and ZX categories	16	$N_{bjet} \geq 1 \& N_{leps} \geq 1$	Merged of cate 3 and 4
	17	$N_{bjet} \geq 2 \& N_{leps} = 0$	Merged of cate 5,6 and 7
	18	$N_{bjet} = 1 \& N_{leps} = 0$	Merged of cate 8,9 and 10

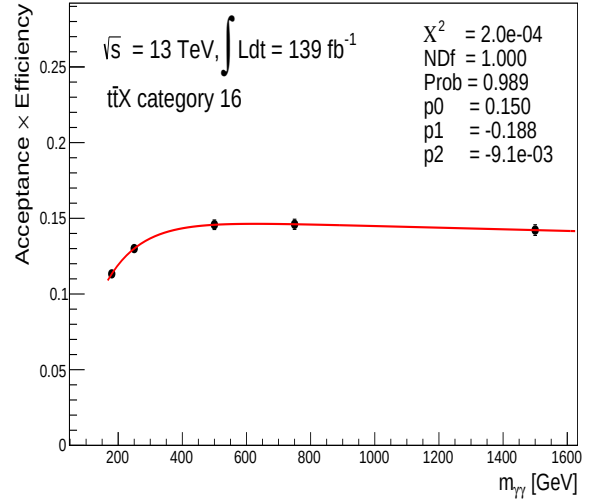
Table 5.15: The temporarily defined category dedicated for the signal efficiency parameterisation.

Model	Category	Total systematic (%)
$t\bar{t}X$ categories	0	0.608
	3	1.547
	4	2.702
	5	9.234
	6	5.498
	7	3.145
	8	1.809
	9	1.604
	10	2.348
	14	1.064
	15	3.329
ZX categories	0	1.008
	11	5.039
	12	1.420
	13	4.013
	14	2.210
	15	2.152
$b\bar{b}$ categories	0	0.826
	1	0.783
	2	1.833

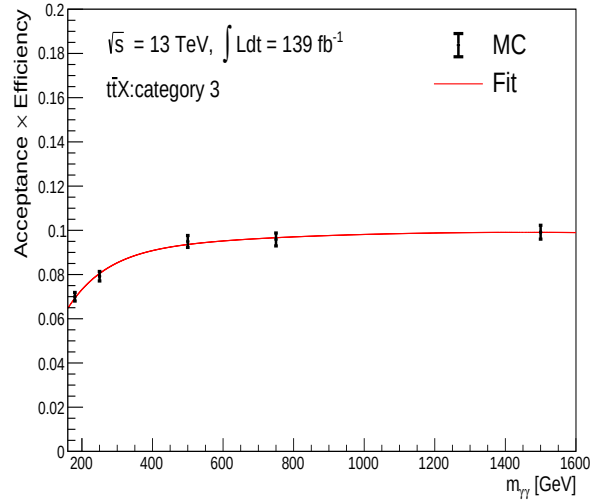
Table 5.16: The statistical and systematic uncertainties in the estimation of the signal efficiencies.



(a)



(b)



(c)

Figure 5.9: An example of the acceptance times efficiency fit process for $t\bar{t}X$, where (a) is the fraction of events for category 3 as first step in the fit process, (b) the acceptance times efficiency for the $t\bar{t}X$ category 16 and (c) the results of the final acceptance times efficiency fit for category 3.

5.7 DIPHOTON PURITY MEASUREMENT

To estimate the background functional shape, a background template is necessary. The background template involves the contribution from all the seven processes: $\gamma\gamma$, γj , $V\gamma$, $V\gamma\gamma$, $t\bar{t}\gamma$, $t\bar{t}\gamma\gamma$, $b\bar{b}\gamma\gamma$. The $\gamma\gamma$ and γj contributions are estimated by the diphoton purity in each category, while the other processes are derived from the MC samples. The γj sample is obtained from data by requiring that one of the photon fails the photon tight ID. In the control region that $130 \text{ GeV} < m_{\gamma\gamma} < 160 \text{ GeV}$, the γj sample is normalised to $1 - \text{purity}$ times the yields of data. The diphoton purity is defined as the number of diphoton events over the total data yields. The dijet events are treated as negligible. The Sherpa $\gamma\gamma$ sample is normalised to the purity times the yields of data then subtracted by the other five backgrounds which are normalised to their cross-sections. If the $\gamma\gamma$ normalisation is negative, it is set to zero. To simplify the problem, the photon misidentified from an electron (especially in the $V\gamma$ and $t\bar{t}\gamma$ samples) is regarded as a photon rather than a jet.

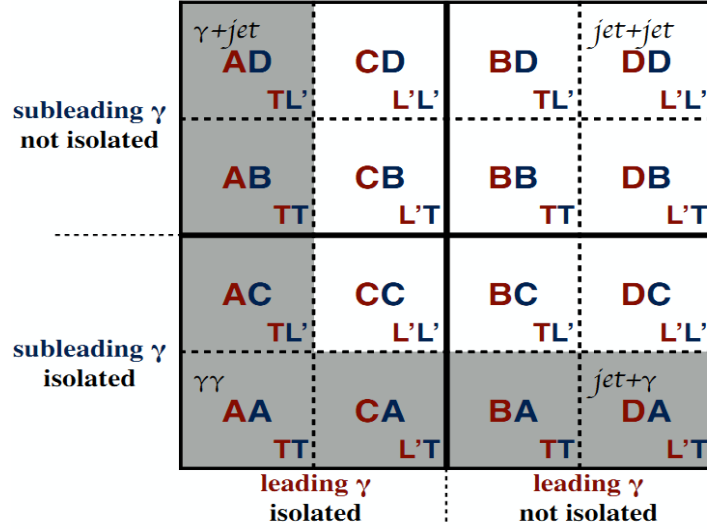


Figure 5.10: 1 signal and 15 control regions in 2x2D sideband method, this data-driven method is based on photon tight ID and photon isolation.

In each category, the diphoton purity is estimated by the 2x2D sideband method. The method exploits the information of the photon ID and isolation variables. The events are chosen by requiring both the photons passing a *Loose'* definition. The photon after this selection may pass the tight ID or isolation. Thus, each photon enters one of the four categories with passing or failing the tight ID and isolation criteria. Each event with the two photons is put into one of the 16 categories. By fitting the fraction of the diphoton, γj , $j\gamma$, jet-jet contribution in these 16 categories, the purity of the diphoton

sample in the tight ID and isolation category is obtained. The definition of one signal and 15 control regions are defined in Figure 5.10.

Purity corresponding to 139 fb^{-1} for the full Run-2 data is estimated. Sherpa $\gamma\gamma$ sample is used as the irreducible diphoton background template. The measured purity is shown in Table 5.17. The purity is performed in the region with at least one b -tagged jet and mass range greater than 130 GeV. Two alternative mass range 180 to 700 GeV and greater than 700 GeV are also provided for comparison. The jet-jet contribution is absorbed in the γj contribution. The actual γj contribution is defined as $1 - \text{purity}_{\gamma\gamma}$ to make the sum of the purity as 100%.

The result will be used to build up the background templates for the spurious study in Section 5.8.

	γ -jet, jet- γ fraction	jet-jet fraction	$\gamma\gamma$ purity
$m_{\gamma\gamma} > 130 \text{ GeV}$	0.18 ± 0.01	0.02 ± 0.00	0.80 ± 0.01
$180 \text{ GeV} < m_{\gamma\gamma} < 700 \text{ GeV}$	0.20 ± 0.01	0.02 ± 0.00	0.78 ± 0.01
$m_{\gamma\gamma} > 700 \text{ GeV}$	0.15 ± 0.06	0.02 ± 0.02	0.83 ± 0.07

Table 5.17: Purities with 2x2D sideband method with at least one b -jet selection.

5.8 BACKGROUND PARAMETERIZATION

The background template for each category is made by merging the seven background processes as described in the previous section. The usage of each process is shown in Table 5.18. Due to the lack of MC statistics, the $V\gamma$ sample is absorbed in the $V\gamma\gamma$ events. The γj and $\gamma\gamma$ sample are estimated using the control region where the b -jet is not tagged, while all the jet and $\Delta\phi(\gamma, \gamma)$ selections are kept. The other MC samples are directly used after all the selections. Here, an assumption is made that the $m_{\gamma\gamma}$ shapes of the $\gamma\gamma$ sample in the control or the signal regions can be described by a simple continuous function. Due to large statistical uncertainty of the γj sample in the signal region, it is directly trusted that the shape of γj between the signal and control region is same.

5.8.1 THE RATIO METHOD

The the γj and $\gamma\gamma$ samples do not have enough statistics to provide a smooth template when using them after the b -tagging. Therefore, to evaluate that in the signal region, the shapes of these distributions is used in the control region before the b -tagging .

Samples	Shape	Normalisation
$\gamma\gamma$	Ratio method	Normalised to about 80% of data side band at preselection
γj	Ratio method	Normalised to about 20% of data side band at preselection
$V\gamma\gamma$	MC prediction	$V\gamma+V\gamma\gamma$ expected yields
$V\gamma$	Absorbed in $V\gamma\gamma$	Absorbed in $V\gamma\gamma$
$b\bar{b}\gamma\gamma$	MC prediction	Expected yields
$t\bar{t}\gamma\gamma$	MC prediction	Expected yields
$t\bar{t}\gamma$	MC prediction	Expected yields

Table 5.18: The treatment of each MC background template for their shape and normalisations.

It is assumed that they have the similar kinematics and can be described by a simple function, as shown in Table 5.19.

In category 3 and 4, firstly the ratio of the $\gamma\gamma$ or γj sample over the $t\bar{t}\gamma$ sample in the control region is calculated. Then this ratio is parameterized with a smooth function. Then, such functional form is multiplied with the shape of the $t\bar{t}\gamma$ sample in the control region to obtain the smoothed $m_{\gamma\gamma}$ shape for $\gamma\gamma$ or γj in the control region. Finally, one can normalize these samples to the signal region and treat them as the sample in the signal region. This assumption will not cause significant bias in the background modelling, because the fraction of $\gamma\gamma$ and γj samples over the total background in the signal region is low.

For the other $\gamma\gamma$ categories, the ratio of the shape of the $\gamma\gamma$ sample in the signal region over the shape of $\gamma\gamma$ sample is calculated in the control region. Then this ratio is parameterized with a smooth function. Then the functional form is multiplied with the shape of the $\gamma\gamma$ sample in the control region. For the γj samples, one can use the ratio of the γj shapes in the control region divided by the $\gamma\gamma$ shapes in the control region. Then multiply the parameterized ratio with the shape of $\gamma\gamma$ in the control region. Here, it is assumed that the γj shape is same in the signal and control region. In the above method, all the ratios are parameterized by different functional forms within the pre-defined fit range are shown in Table 5.19. The obtained background templates are normalised to their predicted yields in each category.

The ratios of the simulated background samples γj and $\gamma\gamma$ in category 3 are shown in Figure 5.11. The smoothed and raw shape of γj and $\gamma\gamma$ in category 3 are also compared with the merged template, which is used for the spurious signal fit, as displayed in Figure 5.12. Additional figures that supplement this study are shown in Appendix C.2.

Category of $\gamma\gamma$	Control region	Ratio	Expected shape	Fit function
0	≥ 1 cjet	$\frac{\gamma\gamma_{SR}}{\gamma\gamma_{CR}}$	Ratio $\times \gamma\gamma_{CR}$	Exp
1	Exact 1 cjet	$\frac{\gamma\gamma_{SR}}{\gamma\gamma_{CR}}$	Ratio $\times \gamma\gamma_{CR}$	Exp
2	≥ 2 cjet	$\frac{\gamma\gamma_{SR}}{\gamma\gamma_{CR}}$	Ratio $\times \gamma\gamma_{CR}$	Pol1
3	≥ 4 cjet	$\frac{\gamma\gamma_{CR}}{t\bar{t}\gamma_{CR}}$	Ratio $\times t\bar{t}\gamma_{CR}$	Pol2
4	< 4 cjet	$\frac{\gamma\gamma_{CR}}{t\bar{t}\gamma_{CR}}$	Ratio $\times t\bar{t}\gamma_{CR}$	Pol2
5	≥ 5 cjet and $(\Delta\phi(\gamma, \gamma) < 2)$	$\frac{\gamma\gamma_{SR}}{\gamma\gamma_{CR}}$	Ratio $\times \gamma\gamma_{CR}$	Pol2
6	≥ 5 cjet and $(\Delta\phi(\gamma, \gamma) > 2)$	$\frac{\gamma\gamma_{SR}}{\gamma\gamma_{CR}}$	Ratio $\times \gamma\gamma_{CR}$	Pol2
7	≤ 4 cjet	$\frac{\gamma\gamma_{SR}}{\gamma\gamma_{CR}}$	Ratio $\times \gamma\gamma_{CR}$	Pol2
8	≥ 6 cjet and $(\Delta\phi(\gamma, \gamma) < 2.4)$	$\frac{\gamma\gamma_{SR}}{\gamma\gamma_{CR}}$	Ratio $\times \gamma\gamma_{CR}$	Pol2
9	≥ 6 cjet and $(\Delta\phi(\gamma, \gamma) > 2.4)$	$\frac{\gamma\gamma_{SR}}{\gamma\gamma_{CR}}$	Ratio $\times \gamma\gamma_{CR}$	Pol2
10	≤ 5 cjet	$\frac{\gamma\gamma_{SR}}{\gamma\gamma_{CR}}$	Ratio $\times \gamma\gamma_{CR}$	Pol2
11	≥ 2 cjet and $65 < m_{bb} [\text{GeV}] < 105$ and $\Delta\phi(\gamma, \gamma) < 2.4$	$\frac{\gamma\gamma_{SR}}{\gamma\gamma_{CR}}$	Ratio $\times \gamma\gamma_{CR}$	Pol2
12	≥ 2 cjet and $65 < m_{bb} [\text{GeV}] < 105$ and $\Delta\phi(\gamma, \gamma) > 2.4$	$\frac{\gamma\gamma_{SR}}{\gamma\gamma_{CR}}$	Ratio $\times \gamma\gamma_{CR}$	Pol2
13	≥ 2 cjet and $m_{bb} > 105 \text{ GeV}$ or $m_{bb} < 65 \text{ GeV}$	$\frac{\gamma\gamma_{SR}}{\gamma\gamma_{CR}}$	Ratio $\times \gamma\gamma_{CR}$	Pol2
14	Exact 1 cjet	$\frac{\gamma\gamma_{SR}}{\gamma\gamma_{CR}}$	Ratio $\times \gamma\gamma_{CR}$	Exp
15	≥ 2 cjet	$\frac{\gamma\gamma_{SR}}{\gamma\gamma_{CR}}$	Ratio $\times \gamma\gamma_{CR}$	Exp
Category of γj	Control region	Ratio	Expected shape	Fit function
0	≥ 1 cjet	$\frac{j\gamma_{CR}}{\gamma\gamma_{CR}}$	Ratio $\times \gamma\gamma_{CR}$	ExpA+ExpB
1	Exact 1 cjet	$\frac{j\gamma_{CR}}{\gamma\gamma_{CR}}$	Ratio $\times \gamma\gamma_{CR}$	ExpA+ExpB
2	≥ 2 cjet	$\frac{j\gamma_{CR}}{\gamma\gamma_{CR}}$	Ratio $\times \gamma\gamma_{CR}$	Exp2
3	≥ 4 cjet	$\frac{j\gamma_{CR}}{t\bar{t}\gamma_{CR}}$	Ratio $\times t\bar{t}\gamma_{CR}$	Pol2
4	< 4 cjet	$\frac{j\gamma_{CR}}{t\bar{t}\gamma_{CR}}$	Ratio $\times t\bar{t}\gamma_{CR}$	Pol2
5	≥ 5 cjet and $(\Delta\phi(\gamma, \gamma) < 2)$	$\frac{j\gamma_{CR}}{\gamma\gamma_{CR}}$	Ratio $\times \gamma\gamma_{CR}$	Pol2
6	≥ 5 cjet and $(\Delta\phi(\gamma, \gamma) > 2)$	$\frac{j\gamma_{CR}}{\gamma\gamma_{CR}}$	Ratio $\times \gamma\gamma_{CR}$	Pol2
7	≤ 4 cjet	$\frac{j\gamma_{CR}}{\gamma\gamma_{CR}}$	Ratio $\times \gamma\gamma_{CR}$	Pol2
8	≥ 6 cjet and $(\Delta\phi(\gamma, \gamma) < 2.4)$	$\frac{j\gamma_{CR}}{\gamma\gamma_{CR}}$	Ratio $\times \gamma\gamma_{CR}$	Pol2
9	≥ 6 cjet and $(\Delta\phi(\gamma, \gamma) > 2.4)$	$\frac{j\gamma_{CR}}{\gamma\gamma_{CR}}$	Ratio $\times \gamma\gamma_{CR}$	Pol2
10	≤ 5 cjet	$\frac{j\gamma_{CR}}{\gamma\gamma_{CR}}$	Ratio $\times \gamma\gamma_{CR}$	Pol2
11	≥ 2 cjet and $65 < m_{bb} [\text{GeV}] < 105$ and $\Delta\phi(\gamma, \gamma) < 2.4$	$\frac{j\gamma_{CR}}{\gamma\gamma_{CR}}$	Ratio $\times \gamma\gamma_{CR}$	Pol2
12	≥ 2 cjet and $65 < m_{bb} [\text{GeV}] < 105$ and $\Delta\phi(\gamma, \gamma) > 2.4$	$\frac{j\gamma_{CR}}{\gamma\gamma_{CR}}$	Ratio $\times \gamma\gamma_{CR}$	Pol2
13	≥ 2 cjet and $m_{bb} > 105 \text{ GeV}$ or $m_{bb} < 65 \text{ GeV}$	$\frac{j\gamma_{CR}}{\gamma\gamma_{CR}}$	Ratio $\times \gamma\gamma_{CR}$	Pol2
14	Exact 1 cjet	$\frac{j\gamma_{CR}}{\gamma\gamma_{CR}}$	Ratio $\times \gamma\gamma_{CR}$	Pol2 up to 730 GeV
15	≥ 2 cjet	$\frac{j\gamma_{CR}}{\gamma\gamma_{CR}}$	Ratio $\times \gamma\gamma_{CR}$	Exp2

Table 5.19: The definition of the control regions and the ratio method of the $\gamma\gamma$ and γj samples.

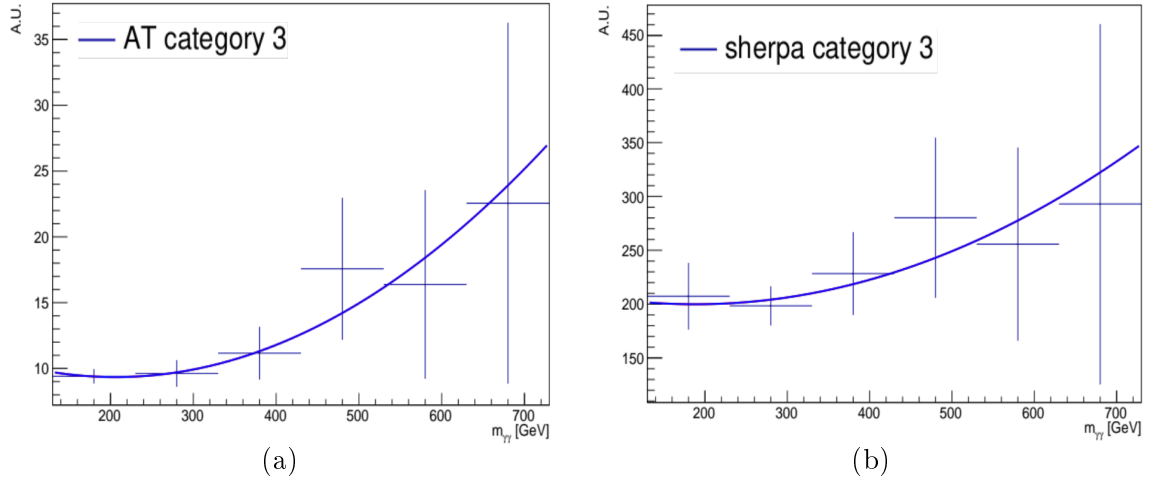


Figure 5.11: (a) the ratio of γj sample in signal and control region for category 3 and (b) the ratio of $\gamma\gamma$ sample in signal and control region for category 3. The fit is also shown.

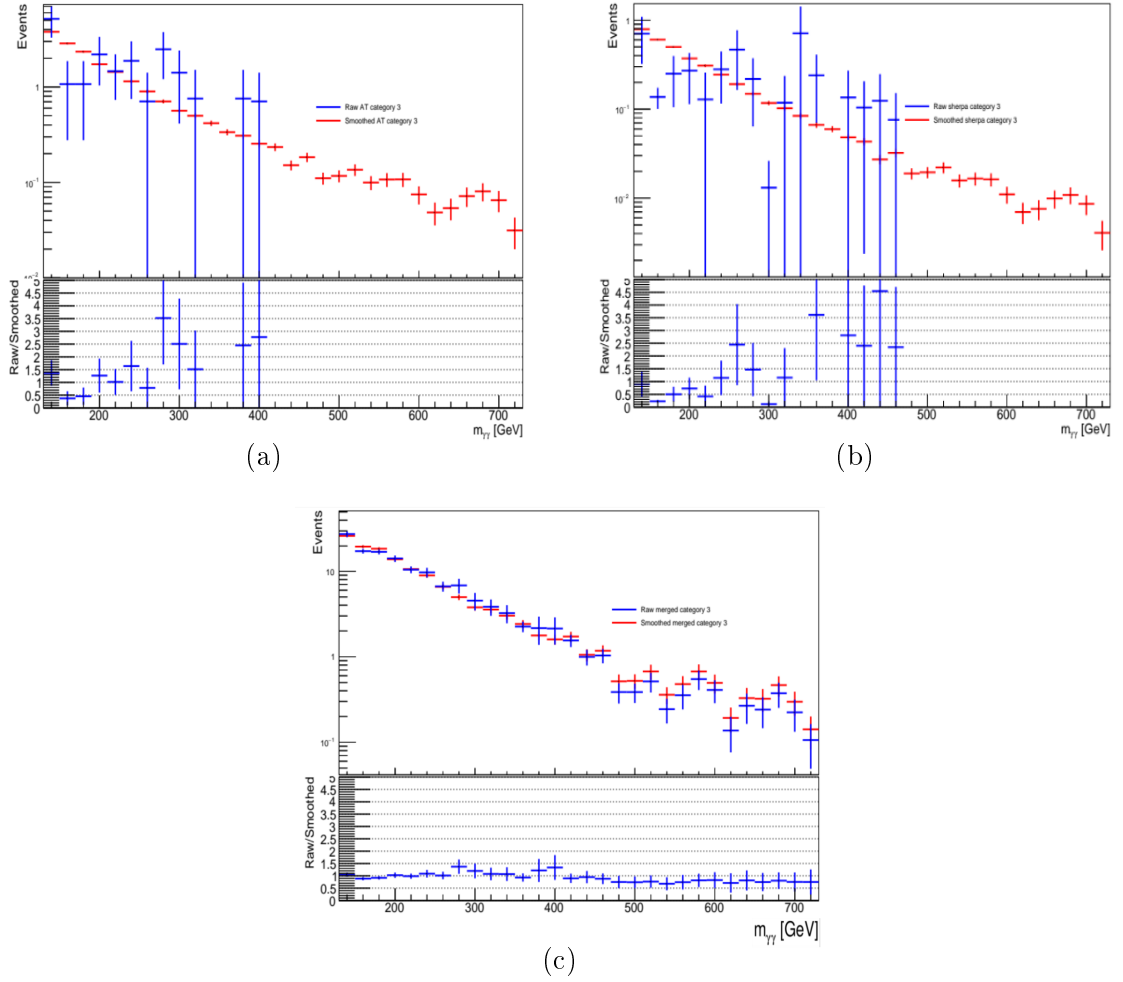


Figure 5.12: The smoothed shape and the raw shape of (a) γj sample and (b) $\gamma\gamma$ sample in category 3. (c) the smoothed merged shape and the raw merged shape of all the background samples in category 3.

5.8.2 THE SPURIOUS SIGNALS

The uncertainty of the choice of different functions describing the background shape is estimated in this section. This uncertainty is about fitting a pure background template using a given signal plus background functional form with a non-zero N_{sig} result, known as the spurious signal. The background template form is a combination of all the six background MC samples and the reverse ID data sample (γj) in each category. The diphoton and γj backgrounds are normalised using the purity obtained from Section 5.7. Several functional forms are listed here as the candidates. They are the different order of the so called “Dijet” functions [184]:

$$f_k(x; b, \{a_k\}) = (1 - x)^b x^{\sum_{j=0}^k a_j \log(x)^j}, \quad (5.8.1)$$

where $k = 0, 1, 2$, noted as FK0, FK1 and FK2.

The template sample is saved in the histogram with 1 GeV per bin from 130 GeV to 2500 GeV. A scan of the existence of signal with 5 GeV steps is performed from 160 GeV to 2000 GeV with the signal shape varying as a function of mass. The smoothed template fitted with the functional form rebinned to 10 GeV for the $t\bar{t}$ category 3 is shown in Figure 5.13. The spurious signal over the uncertainty fitted with the unsmoothed template is shown in Figure 5.14a while the smoothed version is in Figure 5.14b. After obtaining the result, the outliers and failed fit are removed from the graph. The envelopes of the absolute spurious signals are obtained in each category. The envelopes are parametrised between 160 GeV to 1500 GeV with a second polynomial exponential function with a constant term. Figure 5.14c shows the result for the $t\bar{t}X$ category 3 case. Additional figures that supplement this study are shown in Appendix C.3.

The functional forms are shown in Table 5.20 and Table 5.21. To decide which functional form to be used is that the number of spurious signal (N_{spur}) has to be as small as possible ideally. In other words, among the different analytic functions, the parameterization with the smallest N_{spur} or that with the least number of free parameters when the same N_{spur} values are obtained, is chosen as the nominal background parameterization to describe the background shape. In addition to this, a “F-test” test is performed in order to make certain that the selected fit is compatible with data in each category. Figure 5.15 shows the results for category 3. A higher order of functional forms will be used if its “F-test” shows a p-value smaller than 5%. Table 5.22 shows the selected analytic functions corresponding to each category.

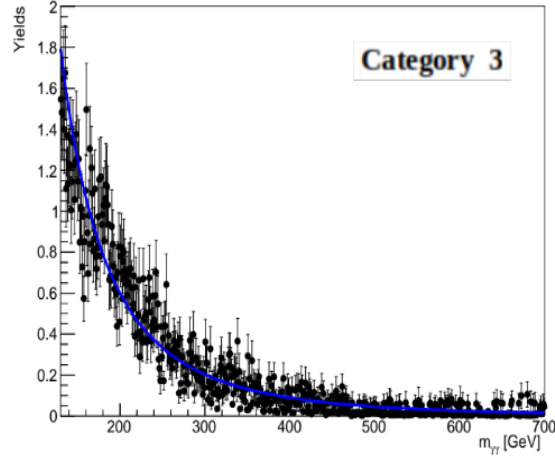
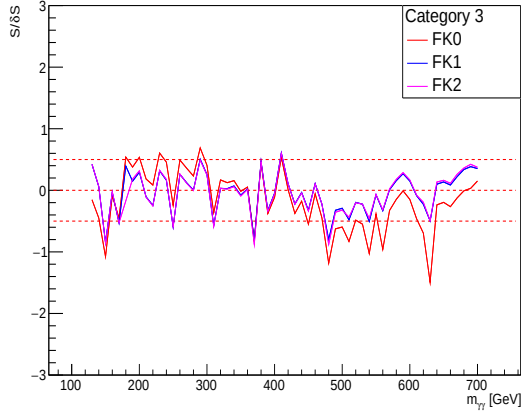
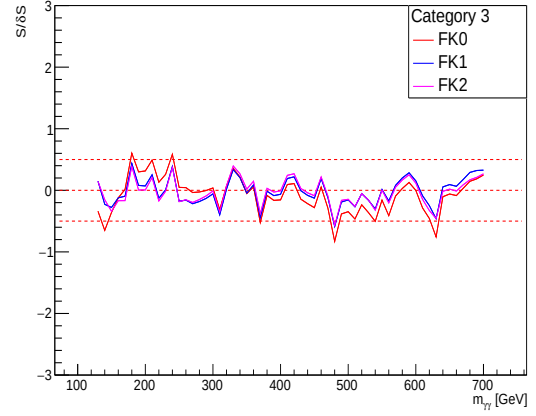


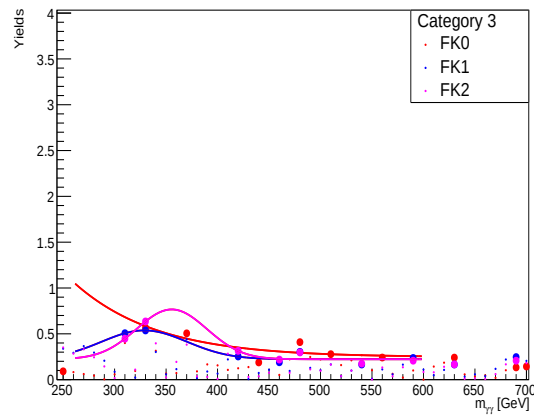
Figure 5.13: Example of fitting on the background MC template for category 3, using a signal plus background function.



(a)



(b)



(c)

Figure 5.14: The $N_{spur}/\delta N_{spur}$ as a function of mass for each functional form in category 3 using (a) raw background and (b) smoothed background. (c) The N_{spur} envelop for each functional form in categories 3.

Functional form	Parameterized Spurious signal	Spurious signal at 200 GeV
Category 0		
FK0	$\exp(6.55 - 0.012 m_{\gamma\gamma} + 0.000004 m_{\gamma\gamma}^2) + 3.94$	84.18
FK1	$\exp(1.75 + 0.010 m_{\gamma\gamma} - 0.000021 m_{\gamma\gamma}^2) + 1.67$	19.81
FK2	$\exp(3.67 - 0.003 m_{\gamma\gamma} - 0.000000 m_{\gamma\gamma}^2) + 0.51$	22.39
Category 1		
FK0	$\exp(10.98 - 0.039 m_{\gamma\gamma} + 0.000018 m_{\gamma\gamma}^2) + 1.37$	51.72
FK1	$\exp(4.35 - 0.012 m_{\gamma\gamma} + 0.000005 m_{\gamma\gamma}^2) + 0.17$	8.45
FK2	$\exp(4.63 - 0.004 m_{\gamma\gamma} + 0.000001 m_{\gamma\gamma}^2) - 5.37$	47.25
Category 2		
FK0	$\exp(1.86 + 0.024 m_{\gamma\gamma} - 0.000068 m_{\gamma\gamma}^2) + 3.72$	51.22
FK1	$\exp(1.25 + 0.010 m_{\gamma\gamma} - 0.000027 m_{\gamma\gamma}^2) + 0.75$	9.89
FK2	$\exp(-2.38 + 0.037 m_{\gamma\gamma} - 0.000071 m_{\gamma\gamma}^2) + 1.37$	11.04
Category 3		
FK0	$\exp(2.83 - 0.011 m_{\gamma\gamma} - 0.000003 m_{\gamma\gamma}^2) + 0.25$	1.95
FK1	$\exp(-32.66 + 0.192 m_{\gamma\gamma} - 0.000291 m_{\gamma\gamma}^2) + 0.22$	0.23
FK2	$\exp(-54.68 + 0.304 m_{\gamma\gamma} - 0.000428 m_{\gamma\gamma}^2) + 0.22$	0.22
Category 4		
FK0	$\exp(5.42 - 0.029 m_{\gamma\gamma} + 0.000026 m_{\gamma\gamma}^2) + 0.20$	2.06
FK1	$\exp(-2.36 + 0.014 m_{\gamma\gamma} - 0.000030 m_{\gamma\gamma}^2) + 0.16$	0.60
FK2	$\exp(0.93 - 0.008 m_{\gamma\gamma} + 0.000004 m_{\gamma\gamma}^2) + 0.05$	0.71
Category 5		
FK0	$\exp(-0.31 + 0.003 m_{\gamma\gamma} - 0.000004 m_{\gamma\gamma}^2) - 0.82$	0.27
FK1	$\exp(-0.20 + 0.003 m_{\gamma\gamma} - 0.000004 m_{\gamma\gamma}^2) - 0.97$	0.26
FK2	$\exp(-0.04 + 0.003 m_{\gamma\gamma} - 0.000004 m_{\gamma\gamma}^2) - 1.29$	0.20
Category 6		
FK0	$\exp(-83.19 + 0.778 m_{\gamma\gamma} - 0.001788 m_{\gamma\gamma}^2) + 0.39$	2.74
FK1	$\exp(2.94 - 0.018 m_{\gamma\gamma} + 0.000013 m_{\gamma\gamma}^2) + 0.24$	1.10
FK2	$\exp(2.76 - 0.017 m_{\gamma\gamma} + 0.000012 m_{\gamma\gamma}^2) + 0.24$	1.11
Category 7		
FK0	$\exp(2.89 - 0.001 m_{\gamma\gamma} - 0.000028 m_{\gamma\gamma}^2) + 1.41$	6.25
FK1	$\exp(-6.17 + 0.056 m_{\gamma\gamma} - 0.000116 m_{\gamma\gamma}^2) + 0.58$	2.18
FK2	$\exp(-7.00 + 0.060 m_{\gamma\gamma} - 0.000119 m_{\gamma\gamma}^2) + 0.55$	1.91

Table 5.20: Parameterized functions form to describe the Spurious signal for categories 0-7. The yields of the spurious signal correspond to 2015-2018 139 fb^{-1} luminosity.

Functional form	Parameterized Spurious signal	Spurious signal at 200 GeV
Category 8		
FK0	$\exp(5.93 - 0.035 m_{\gamma\gamma} + 0.000029 m_{\gamma\gamma}^2) + 0.61$	1.71
FK1	$\exp(-5.50 - 0.005 m_{\gamma\gamma} - 0.000007 m_{\gamma\gamma}^2) - 0.00$	0.00
FK2	$\exp(2.09 - 0.009 m_{\gamma\gamma} + 0.000004 m_{\gamma\gamma}^2) + 0.17$	1.62
Category 9		
FK0	$\exp(0.94 - 0.001 m_{\gamma\gamma} - 0.000008 m_{\gamma\gamma}^2) + 0.57$	2.23
FK1	$\exp(3.40 - 0.017 m_{\gamma\gamma} + 0.000012 m_{\gamma\gamma}^2) + 0.49$	1.97
FK2	$\exp(3.56 - 0.018 m_{\gamma\gamma} + 0.000013 m_{\gamma\gamma}^2) + 0.50$	1.98
Category 10		
FK0	$\exp(-130.74 + 1.134 m_{\gamma\gamma} - 0.002375 m_{\gamma\gamma}^2) + 11.83$	14.73
FK1	$\exp(3.28 - 0.003 m_{\gamma\gamma} + 0.000001 m_{\gamma\gamma}^2) - 4.60$	10.79
FK2	$\exp(4.14 - 0.000 m_{\gamma\gamma} - 0.000000 m_{\gamma\gamma}^2) - 49.35$	10.39
Category 11		
FK0	$\exp(3.01 - 0.019 m_{\gamma\gamma} + 0.000013 m_{\gamma\gamma}^2) + 0.19$	1.02
FK1	$\exp(-2.16 + 0.012 m_{\gamma\gamma} - 0.000025 m_{\gamma\gamma}^2) + 0.08$	0.50
FK2	$\exp(-2.00 + 0.011 m_{\gamma\gamma} - 0.000024 m_{\gamma\gamma}^2) + 0.07$	0.50
Category 12		
FK0	$\exp(6.51 - 0.039 m_{\gamma\gamma} + 0.000037 m_{\gamma\gamma}^2) + 0.34$	1.65
FK1	$\exp(-7.54 + 0.052 m_{\gamma\gamma} - 0.000109 m_{\gamma\gamma}^2) + 0.30$	0.52
FK2	$\exp(-4.98 + 0.033 m_{\gamma\gamma} - 0.000074 m_{\gamma\gamma}^2) + 0.30$	0.55
Category 13		
FK0	$\exp(-7.80 + 0.084 m_{\gamma\gamma} - 0.000189 m_{\gamma\gamma}^2) + 1.29$	5.83
FK1	$\exp(-28.93 + 0.220 m_{\gamma\gamma} - 0.000411 m_{\gamma\gamma}^2) + 0.66$	0.91
FK2	$\exp(-12.64 + 0.105 m_{\gamma\gamma} - 0.000213 m_{\gamma\gamma}^2) + 0.68$	1.56
Category 14		
FK0	$\exp(-159.74 + 1.269 m_{\gamma\gamma} - 0.002448 m_{\gamma\gamma}^2) + 8.59$	8.61
FK1	$\exp(5.88 - 0.015 m_{\gamma\gamma} + 0.000008 m_{\gamma\gamma}^2) + 1.42$	26.35
FK2	$\exp(9.52 - 0.032 m_{\gamma\gamma} + 0.000022 m_{\gamma\gamma}^2) + 5.77$	56.09
Category 15		
FK0	$\exp(-3.70 + 0.052 m_{\gamma\gamma} - 0.000120 m_{\gamma\gamma}^2) + 0.95$	7.45
FK1	$\exp(1.69 - 0.004 m_{\gamma\gamma} - 0.000001 m_{\gamma\gamma}^2) + 0.18$	2.36
FK2	$\exp(4.44 - 0.017 m_{\gamma\gamma} + 0.000009 m_{\gamma\gamma}^2) + 0.42$	4.89

Table 5.21: Parameterized functions form to describe the Spurious signal for categories 8-15. The yields of the spurious signal corresponds to 2015-2018 139 fb^{-1} luminosity.

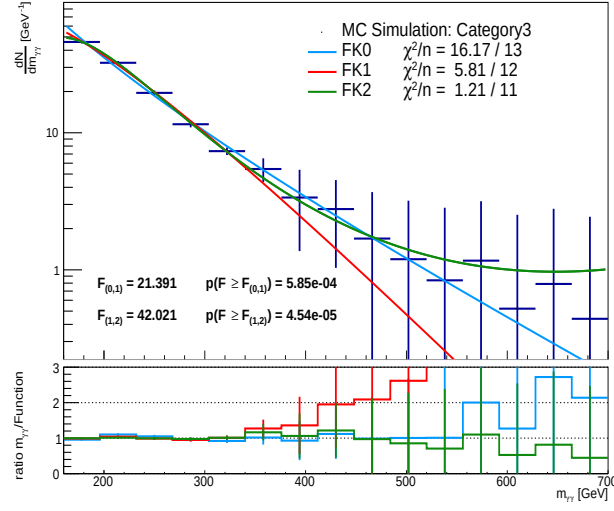


Figure 5.15: Fitting on the background MC template for categories 3, using background functions.

Category	Chosen function
0	FK2
1	FK2
2	FK2
3	FK0
4	FK0
5	FK2
6	FK1
7	FK2
8	FK2
9	FK1
10	FK2
11	FK1
12	FK2
13	FK2
14	FK2
15	FK2

Table 5.22: The selected functional forms for each category.

5.9 STATISTICAL INTERPRETATION OF RESULTS

5.9.1 SYSTEMATIC UNCERTAINTIES

The systematic uncertainties from both experimental and theoretical sources are used in obtaining the result of this analysis. As the background shapes are described by fitting in the data, the uncertainties except the spurious signal, which is discussed in section 5.8.2, are estimated on the signal samples only. The systematic uncertainties are implemented via nuisance parameters in the profiled likelihood fit. The major sources of uncertainties are briefly discussed in this section. A summary of the experimental and theoretical uncertainties is given in Table 5.23 in terms of the relative impact on the number of events from the signal for the most sensitive category.

5.9.1.1 EXPERIMENTAL UNCERTAINTIES

The following experimental uncertainties are considered:

Luminosity: The uncertainty in the combined 2015-2018 integrated luminosity is 1.7%. It is derived from the calibration of the luminosity scale using x - y beam-separation scans, following a methodology similar to that detailed in Ref. [185], and using the LUCID-2 detector for the baseline luminosity measurements [186].

Trigger efficiency: The efficiency of the diphoton trigger used to select events is evaluated in MC using a trigger matching technique and in data using a bootstrap method [187]. The trigger efficiency for events after the diphoton mass cut of 130 GeV is greater than 99.2% with an uncertainty 1.0%.

Vertex selection efficiency: The uncertainty in the vertex selection efficiency is assessed by comparing the efficiency of finding photon-pointing vertices in $Z \rightarrow e^+e^-$ events in data and MC [188]. The uncertainty is $< \pm 0.01\%$.

Photon identification and isolation efficiency: The systematic uncertainties due to the photon identification and isolation efficiencies are estimated [174]. They are evaluated as switching up and down the uncertainty variations of the correction factors of photon selection efficiencies in the MC. The resulting uncertainty in the photon identification efficiency is 0.6–1.5% for different signals. The photon isolation efficiency uncertainty is 0.6–2.6% for different signals in each category. An additional uncertainty of 2% is added to compensate the difference between the fast simulation and full simulation in the photon identification [189], which is only applied in $t\bar{t}X$ and $b\bar{b}X$ samples.

Pile-up reweighting: The weights used to reweight the distribution of the average number of interactions per bunch crossing in simulation to the observed distribution are measured with an uncertainty. This uncertainty is propagated through the event selection, and results in a maximum 7.4% uncertainties in the event yield of the signals, while in most categories it is about 2%.

$e\gamma$ energy scale and resolution: The uncertainties in photon scale and resolution are obtained from Ref. [174]. The uncertainty in the energy scale has an effect of 0.3% in the normalization of the signals in each category. The uncertainty in the energy resolution has an effect below 0.6% in the normalization of the signals. The uncertainties affecting the signal mass distributions due to the photon energy scale and resolution are also evaluated and parameterized in the fit to the MC, which has a maximum 30% uncertainty in the signal resolution and 1% in the mass position. The uncertainty due to the AFII simulation is included as well.

Lepton efficiency: The electron and muon identification and isolation efficiencies are estimated by varying up and down the variations of the correction factors of the selection efficiencies, which is about 0.8% for electrons and 0.3% for muons in category 3 and 4 for $t\bar{t}X$ signal.

b -tagging: The uncertainty in the event yields due to the mismatching between data and MC in selecting the heavy flavour tagged jets is evaluated by varying the b -tagging efficiency with its uncertainty. This results in a maximum 4% uncertainty.

Signal efficiency: The signal efficiency is estimated in Section 5.6. The uncertainty due to interpolating the signal efficiency between the available MC samples is estimated by comparing the maximum difference between the value from interpolation and the MC samples. The maximum value is 1.3% to 9% for each category. The MC statistical uncertainty is absorbed in this term as well.

The systematic uncertainties in the signal yields for the $t\bar{t}X$ category 3 are shown in Figure 5.16. In each figure, the systematic terms are shown by combining all the nuisance parameters from similar sources, without considering the correlation. In the actual fit, each individual nuisance parameter is taken into account. The figure shows each systematic uncertainty as a function of the resonance mass. The systematic uncertainty in the signal shape is shown in Figure 5.17, for the $t\bar{t}X$ category 3. Additional figures that supplement this study are shown in Appendix D.1.

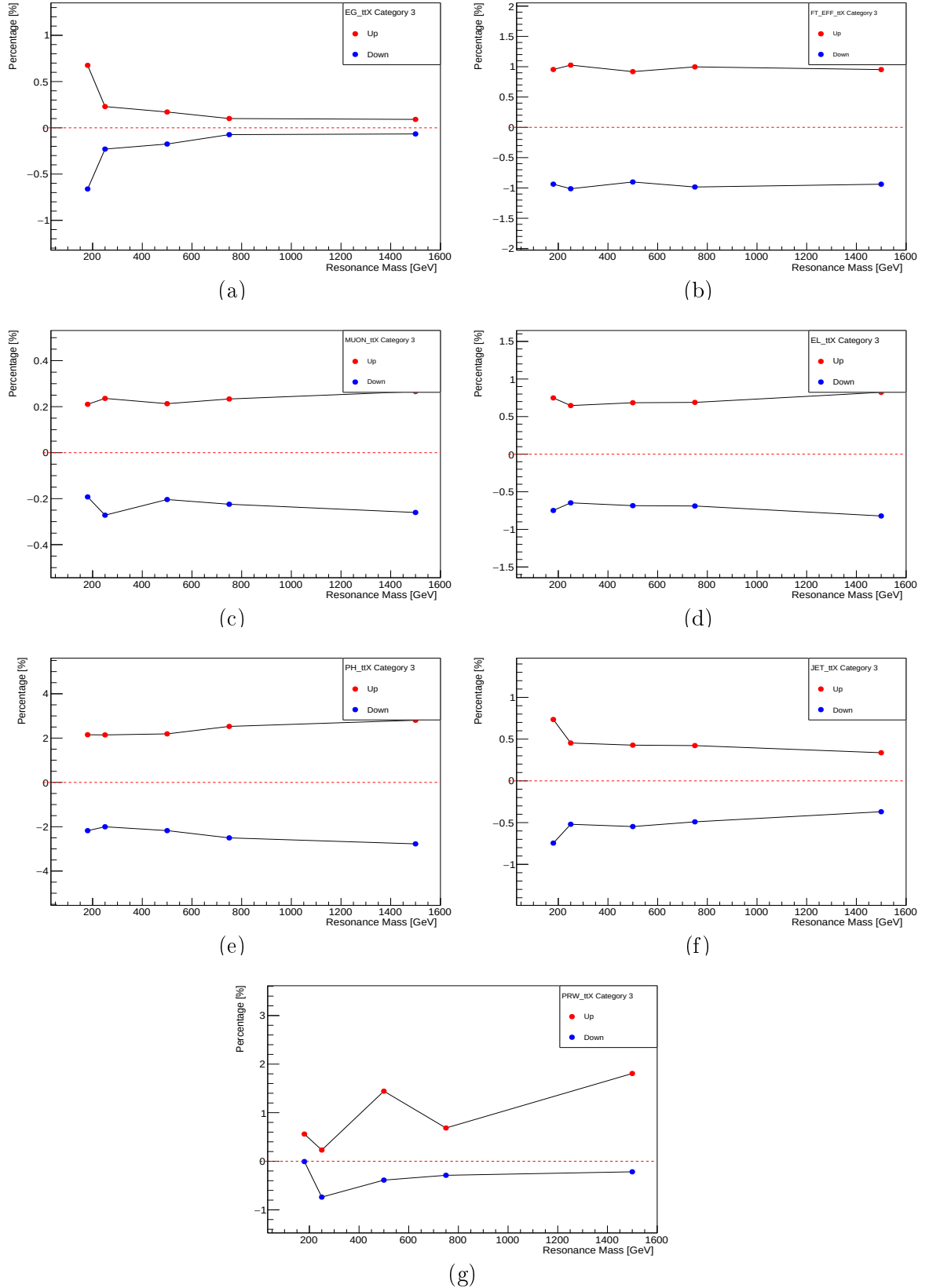
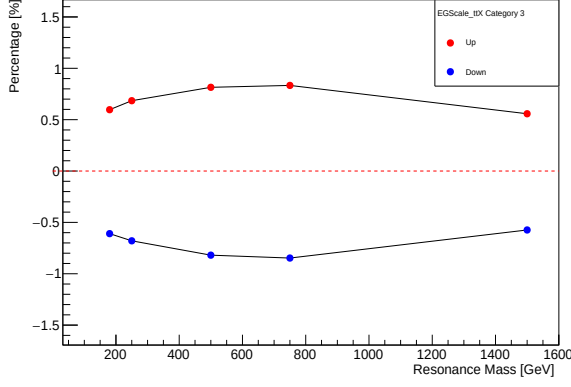
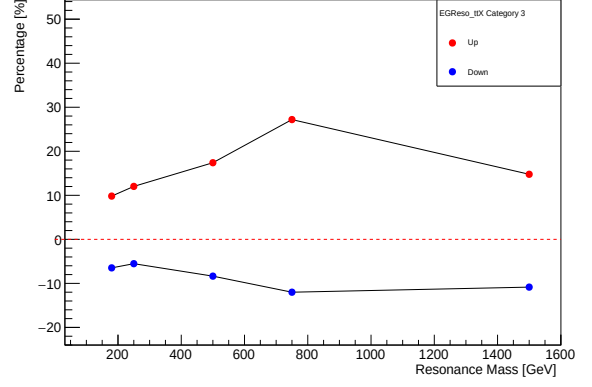


Figure 5.16: The systematic uncertainty in the signal yields corresponding different objects for category 0 given as a function of the resonance mass: (a) due to $e - \gamma$ scale and resolution affecting the signal yields, (b) due to the b -tagging, (c) due to muon selection efficiency, (d) due to electron selection efficiency, (e) due to photon selection efficiency, (f) due to jet energy resolution, energy scale and selection efficiency and (g) due to pile-up reweighting.

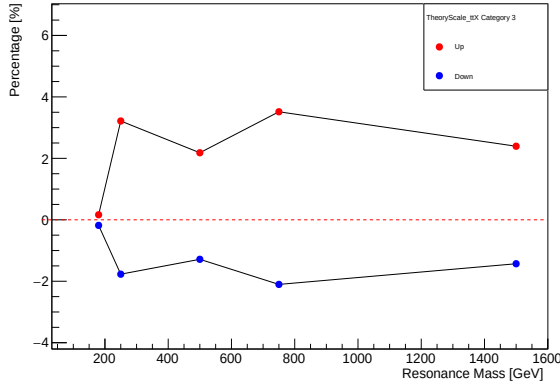


(a)

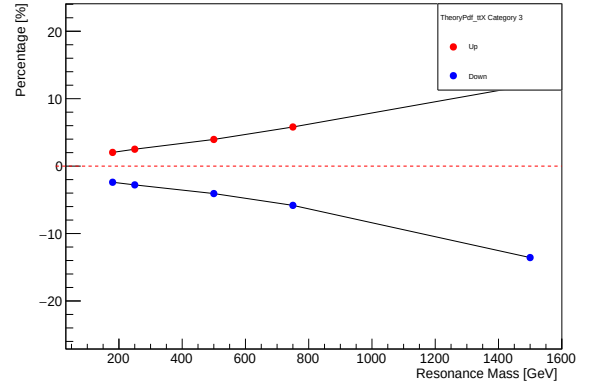


(b)

Figure 5.17: (a) The systematic uncertainty of $e - \gamma$ scale in the signal shape as a function of the resonance mass in category 3 and (b) The systematic uncertainty of $e - \gamma$ resolution in the signal shape as a function of the resonance mass in category 3.



(a)



(b)

Figure 5.18: (a) The scale uncertainty in the migration of the signal yields as a function of the resonance mass in category 3 and (b) The PDF+ α_S uncertainty in the migration of the signal yields as a function of the resonance mass in category 3.

5.9.1.2 THEORETICAL UNCERTAINTIES

The signal scale uncertainty: These scale uncertainties are estimated by varying the factorization and renormalization scales (μ_F and μ_R) up and down from their nominal values by a factor of two, recalculating the cross-section in each case, and taking the largest deviation from the nominal cross-section as the uncertainty. Figure 5.18a shows the scale uncertainty in the migration of the signal yields as a function of the resonance mass in the $t\bar{t}X$ category 3 and those corresponding to the other categories are shown in Appendix D.1, Figure D.10. The theoretical systematics in the normalization of the cross-sections of the signal samples are not used due to the signal cross-section is set to be 1 fb^{-1} . The uncertainties vary from 1% to 7% in different categories.

PDF uncertainty: For the signal process, PDF+ α_S uncertainties in the migration of each category are estimated by varying the parameters of the NNPDF3.0LO PDF set. The combined variation is taken as the uncertainty. The uncertainties vary from 1% to 5% in different categories. Figure 5.18b shows the PDF+ α_S uncertainty in the migration of the signal yields as a function of the resonance mass in $t\bar{t}X$ category 3. Additional figures corresponding to the other categories are shown in Appendix D.1, Figure D.11.

ISR/FSR, MPI, parton shower and hadronization uncertainty: The effects of Initial State Radiation (ISR), Final State Radiation (FSR), Multi-Parton Interactions (MPI), Parton Shower (PS) and hadronization are evaluated by varying the eigen-variables in the Pythia8 or comparing the Herwig or Pythia samples. The result shows a 3% uncertainty in most of the categories. In some less important category the maximum value is up to 10%.

5.9.2 STATISTICAL MODELS

The extended likelihood provided by the following formula is used to describe the data $m_{\gamma\gamma}$ invariant mass shape.

$$\mathcal{L}_c = \text{Pois}(n_c | N_c(\theta)) \cdot \prod_{i=1}^{n_c} f_c(m_{\gamma\gamma}^i, \theta) \cdot G(\theta), \quad (5.9.1)$$

where the θ_s are the nuisance parameters representing the systematic uncertainties. The $G(\theta)$ represents the Gaussian constrain terms which constrain the systematics. The f is the $m_{\gamma\gamma}$ shape and c represents different cateogry. The $m_{\gamma\gamma}$ shape consists of the BSM signal shape, the background shape and the spurious signal shape. The signal strength, known as μ , is the parameter of interest in this model. As all the signal

models are set with the cross-section equal to 1 fb^{-1} . The signal strength represents the fitted cross-section in the unit of fb. The spurious signal uses the shape same as the BSM signal with float normalization centred at zero. This normalization is constrained by a Gaussian term, with a standard deviation equal to one. The spurious signal is noted as $N_{\text{spur},c}$. The total yields in one category is listed as follows:

$$N_c = \mu \cdot N_{\text{BSM},c}(\theta_c^{\text{yield}}, \theta_c^{\text{migr}}) + N_{\text{spur},c} \cdot \theta_{\text{spur},c} + N_{\text{bkg},c}. \quad (5.9.2)$$

Signal model is fixed to a DSCB function as described in Section 5.6. The non-resonant background shapes are using the FK0, FK1 or FK2 functions decided in the background modelling study in Section 5.8.2. The parameters are set to be free. The simultaneous fits are performed over different categories for each model, the shape in each category is described as below:

$$\begin{aligned} f_c(m_{\gamma\gamma}^i) = & \left[(\mu \cdot N_{\text{BSM},c}) \cdot f_{\text{BSM},c}(m_{\gamma\gamma}^i, \theta_{\text{BSM},c}^{\text{shape}}) \right. \\ & + N_{\text{spur},c} \cdot \theta_{\text{spur},c} \cdot f_{\text{spur},c}(m_{\gamma\gamma}^i, \theta_{\text{spur},c}^{\text{shape}}) \\ & \left. + N_{\text{bkg},c} \cdot f_{\text{bkg},c}(m_{\gamma\gamma}^i, \theta_{\text{bkg},c}^{\text{shape}}) \right] / N_c, \end{aligned} \quad (5.9.3)$$

The likelihood ratio is built as follows:

$$\lambda(\mu) = -2 \ln \frac{\mathcal{L}(\mu, \hat{\theta}_\mu)}{\mathcal{L}(\hat{\mu}, \hat{\theta})}. \quad (5.9.4)$$

Source	Uncertainty (%)
Experimental	
Luminosity	1.7
Trigger efficiency	1.0
Vertex selection (inclusive cat.)	< 0.01
Photon identification efficiency	0.6–1.5
Photon identification efficiency due to fast simulation	2.0
Photon isolation efficiency	0.6–1.5
Photon energy scale	0.3
Photon energy resolution	0.6
Pile-up reweighting	2.0–7.4
Signal efficiency interpolation	1.3–9
Theoretical	
Factorization and renormalization scale in migration	1–7
PDF+ α_S in migration	1–5
PS, hadronization	3.0
ISR, FSR, Multi-parton interactions	3.0–10.0

Table 5.23: Breakdown of the dominant systematic uncertainties. Representative values for the impact on the most sensitive category are shown, unless given source has very different impacts on different categories, in which cases the largest and the smallest impacts are shown separately.

5.9.3 RESULTS

As highlighted in Section 5.9.2, the findings of this analysis are derived from a likelihood fit of the invariant mass of the two photons $m_{\gamma\gamma}$ distribution in the 16 categories for the different three models. The fit range starts from 130 GeV and ends at 1700 GeV. The scan range of the signals range from 160 to 1600 GeV. The scan step is 1 GeV below 400 GeV, 2 GeV up to 900 GeV, 3 GeV up to 1200 GeV and 5 GeV for the rest.

Figure 5.19 shows the $m_{\gamma\gamma}$ distribution as well as the analytical fits to the Asimov data obtained from the MC background templates, with the signal mass at 180 GeV for the $t\bar{t}X$ categories 0 and 3. The templates for the other categories together with other signal processes are available in Appendix D.2. In each distribution, the ratio figures show the significance for each of the mass point. The correlation of systematic uncertainties and the ranking of them are shown in Figure 5.20 and Figures 5.21-5.23 respectively.

The CLs approach in the asymptotic approximation [190, 191] is used to calculate upper limits at 95% Confidence Level (CL). The fits are performed on each mass points for each model. The CL_s limits on the production cross-section times the branching fraction $X \rightarrow \gamma\gamma$ are set to each of the model as a function of the resonance mass m_X , as shown in Figure 5.24. The steps in the $t\bar{t}X$ and ZX curve are due to the merging of the categories in the high mass region. The limits for the $t\bar{t}X$ model range from 0.6 fb for $m_X = 160$ GeV to about 0.06 fb for $m_X = 1600$ GeV. The limits for the $b\bar{b}X$ model range from about 1.8 fb for $m_X = 160$ GeV to 0.15 fb for $m_X = 1600$ GeV. Finally, for the ZX model, the limits range from 7 fb $m_X = 160$ GeV and 0.3 fb $m_X = 1600$ GeV.

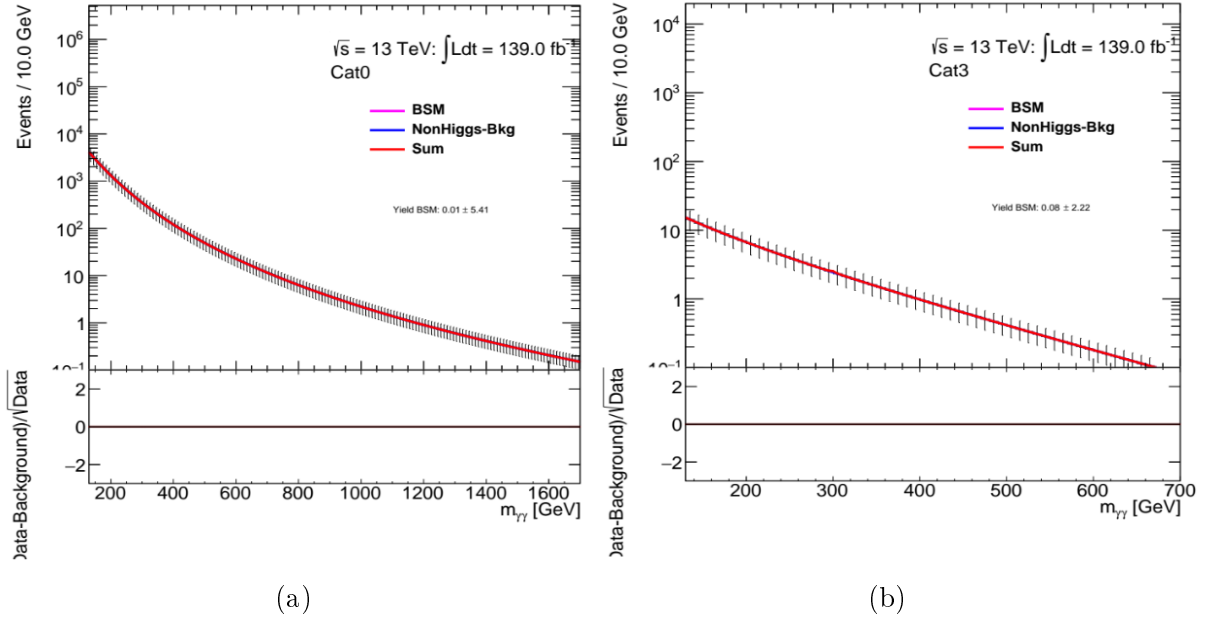


Figure 5.19: The fit on the background only Asimov data based on the MC background template in the $t\bar{t}X$ channel (a) with 800 GeV signal and (b) with 1200 GeV signal.

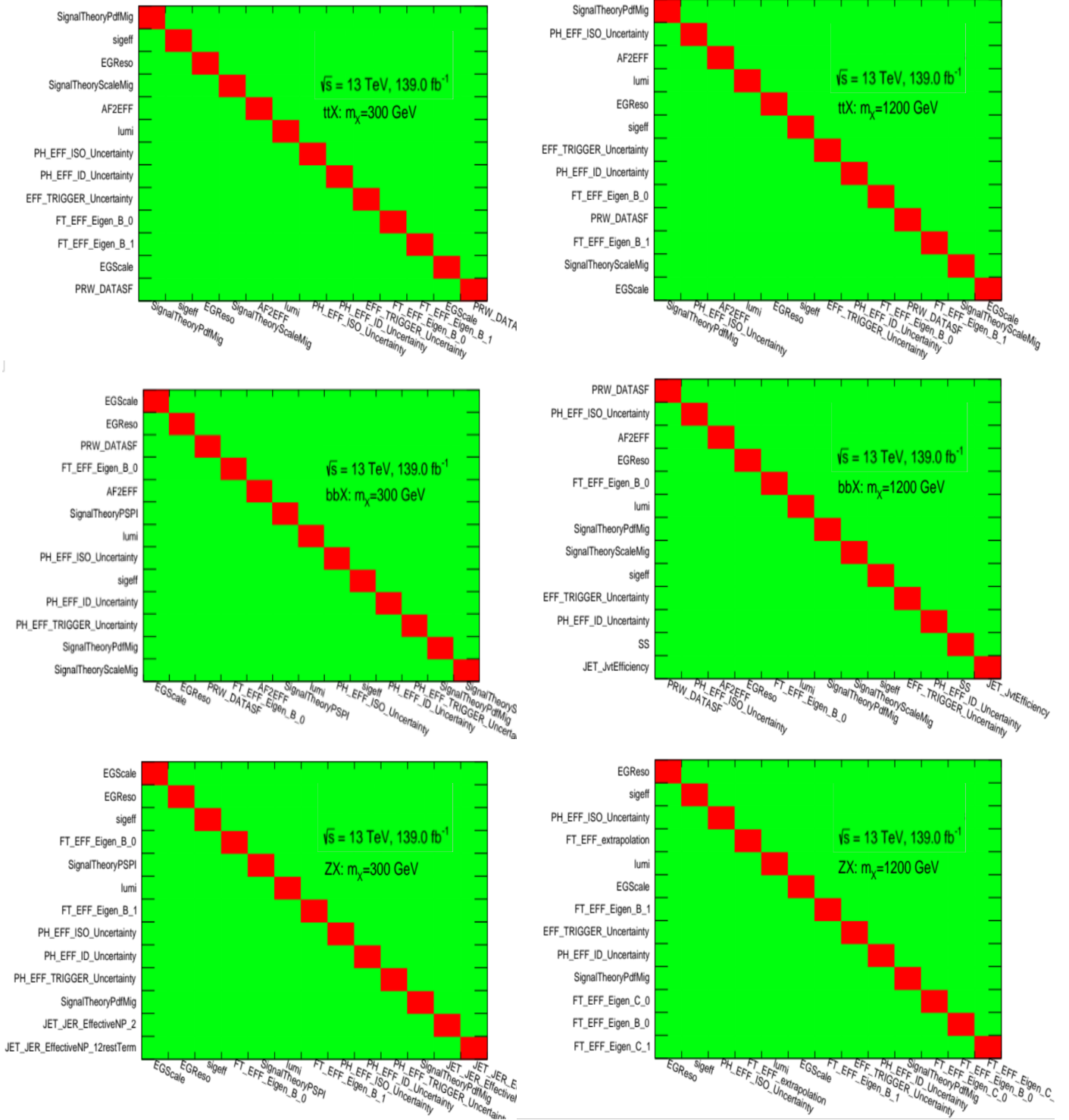


Figure 5.20: The correlation matrix for all the systematics for $t\bar{t}X$ (first row), $b\bar{b}X$ (second row), ZX (last row) samples for 300 GeV mass (left) and 1200 GeV mass (right).

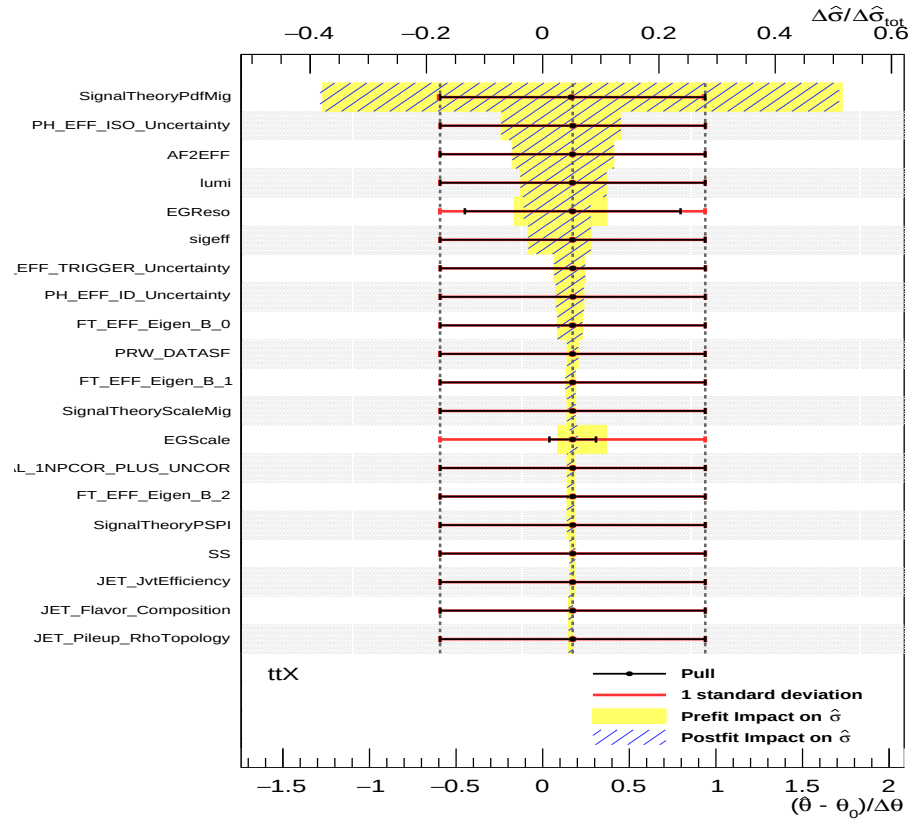
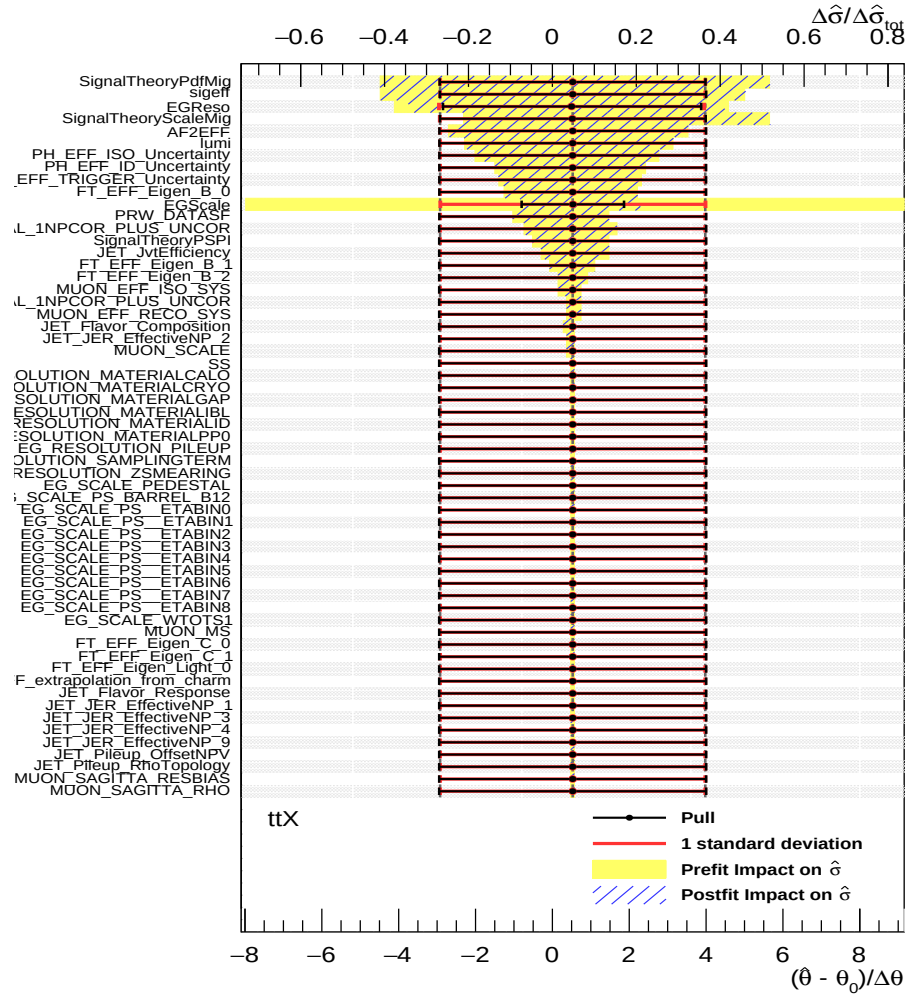


Figure 5.21: The ranking for all the systematics for ttX , samples for 300 GeV mass (top) and 1200 GeV mass (bottom). 112

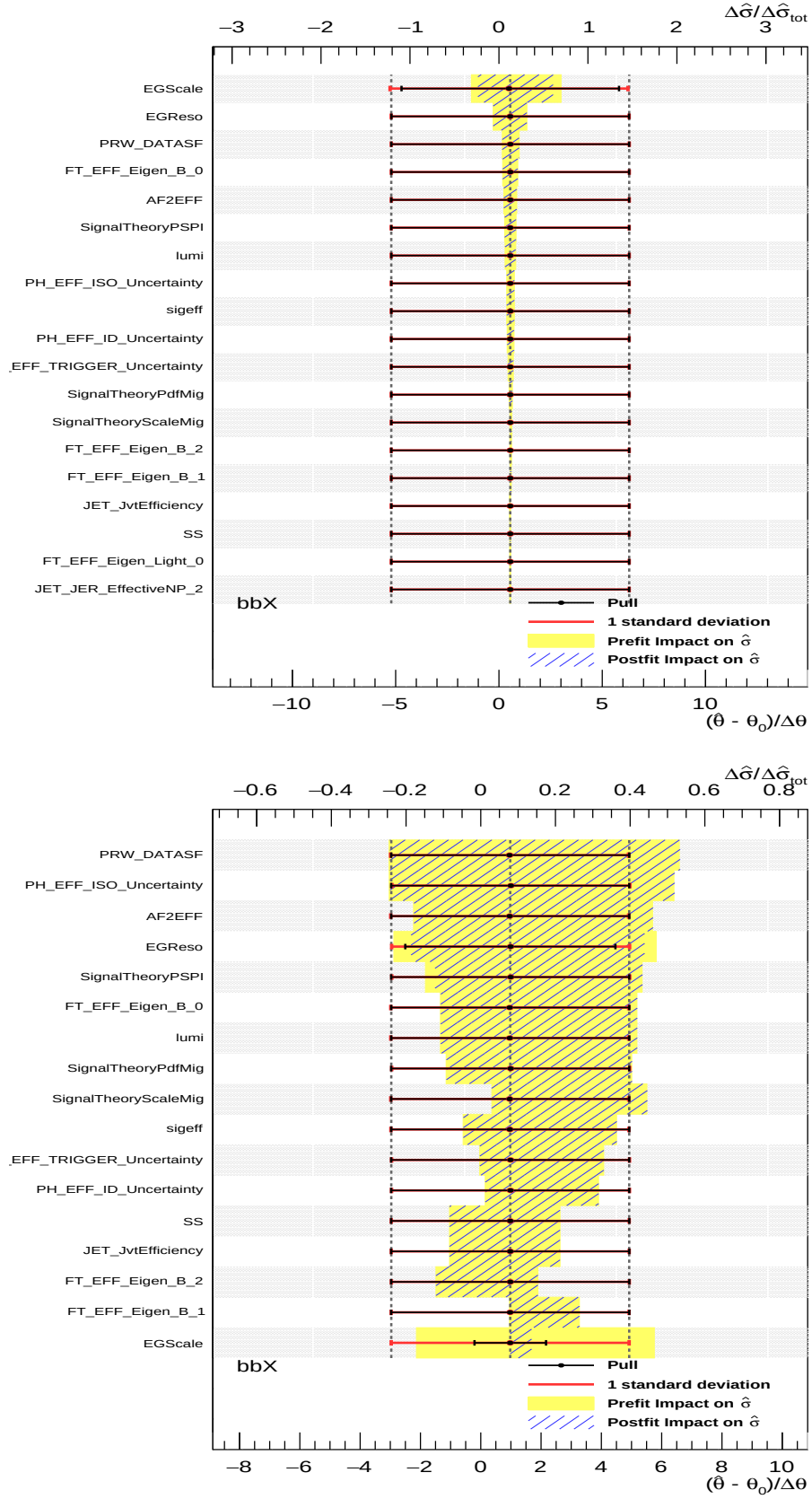


Figure 5.22: The ranking for all the systematics for bbX , samples for 300 GeV mass (top) and 1200 GeV mass (bottom)

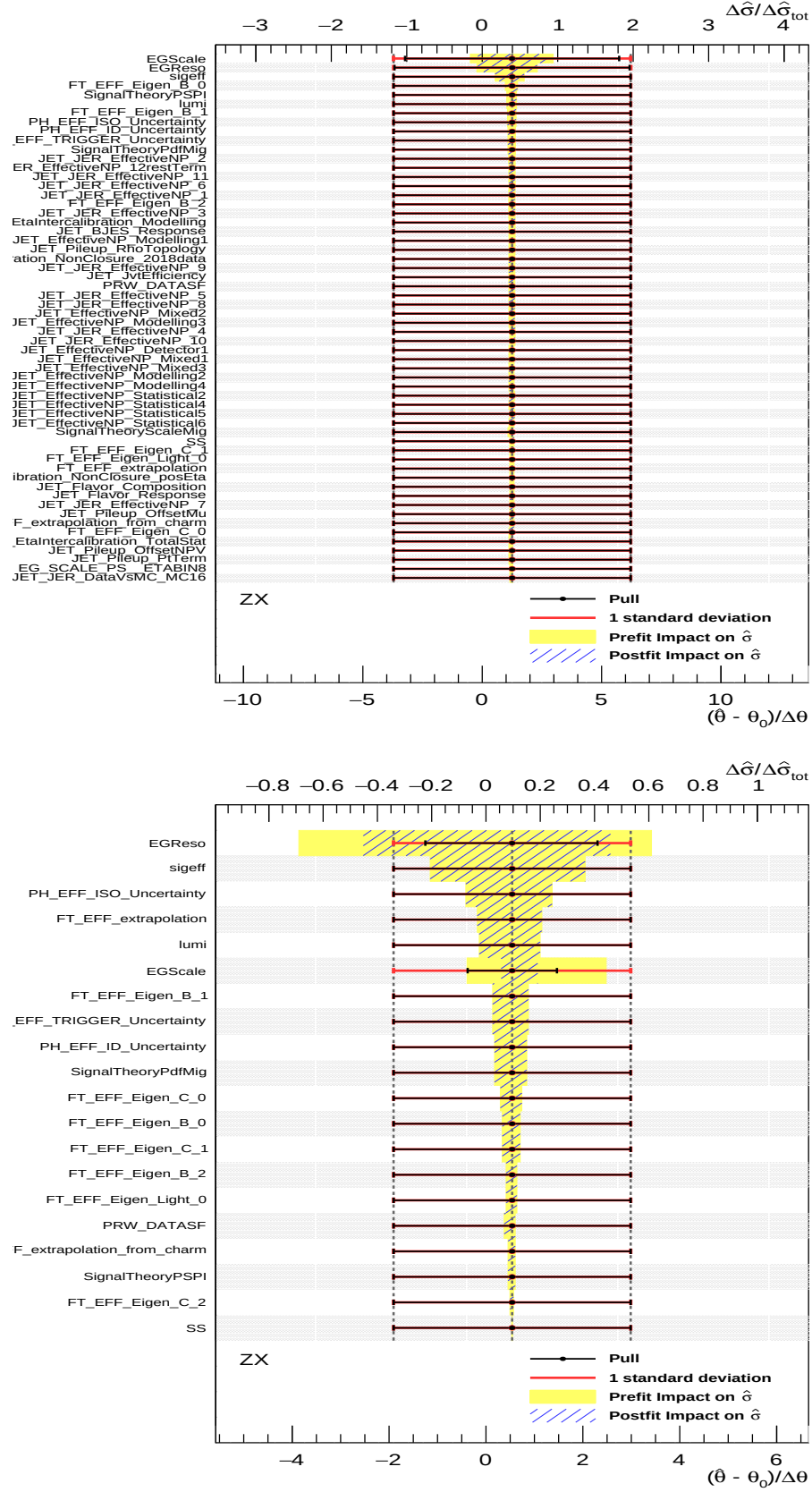


Figure 5.23: The ranking for all the systematics for ZX, samples for 300 GeV mass (top) and 1200 GeV mass (bottom)

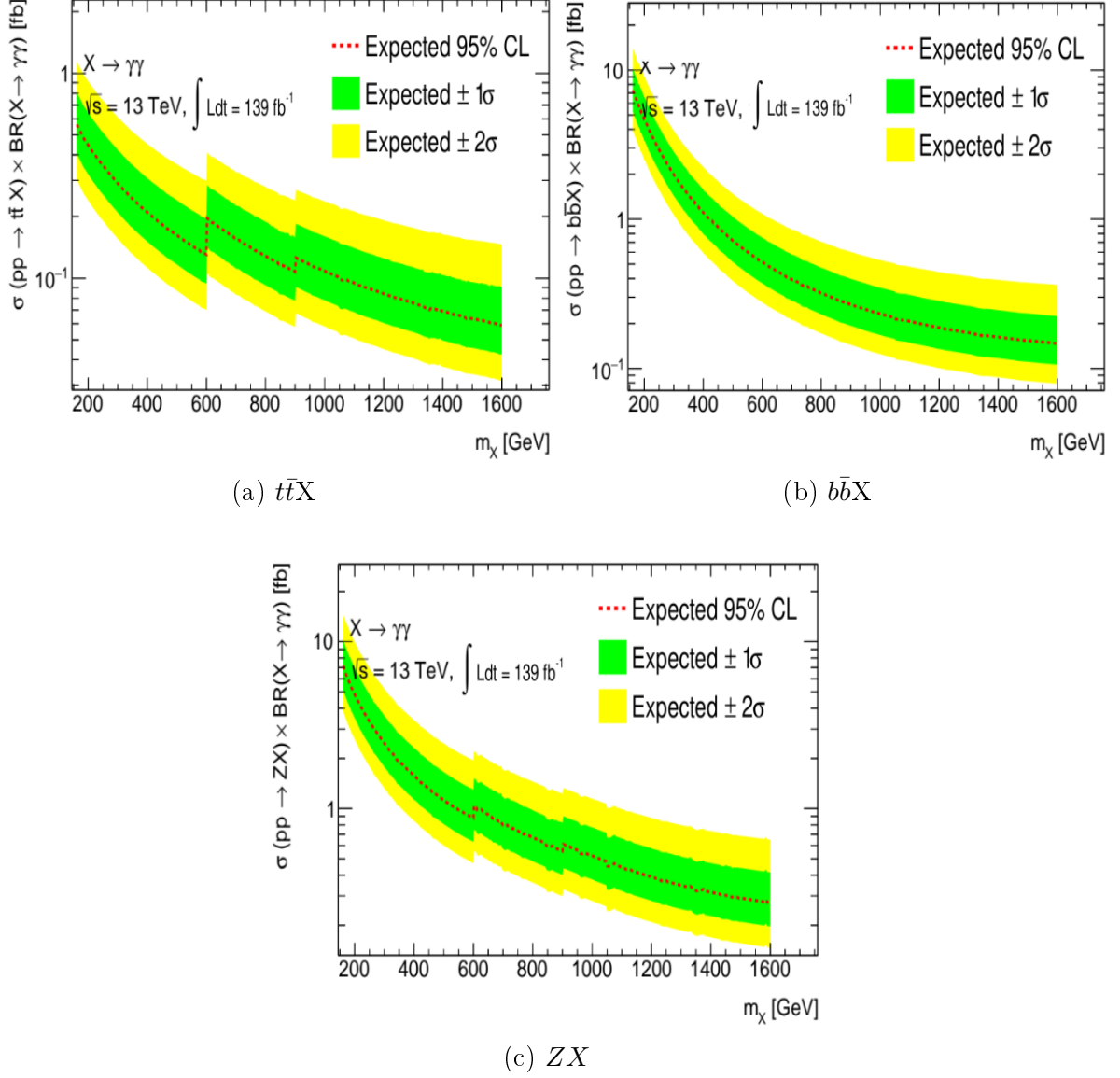


Figure 5.24: The expected CLs limits on the production cross-section of the resonance X times its branching fraction to $\gamma\gamma$ as a function of the resonance mass m_X for each model. The green and yellow errors bands indicate 1σ and 2σ ranges, based on the uncertainties of the MC prediction, both from theoretical and experimental sources. The steps in the $t\bar{t}X$ and ZX curve are due to the merging of the categories in the high mass region.

CONCLUSIONS

The standard model is still incomplete as an ultimate theory and experimentalists are vigorously searching for signs of new physics beyond the SM. The journey is still far from the end. All the exciting discoveries and reliable measurements own to the precise reconstruction and calibration of the physics objects at ATLAS and other LHC experiments. The successful restart of the LHC in 2015 with an increased centre-of-mass energy of $\sqrt{s}=13$ TeV, marked the beginning of a new chapter in the history of high-energy physics. The increased energy has opened up new phase space for searches of unexplored phenomena falling under the umbrella of the BSM physics. The ATLAS detector has been operated with an outstanding performance and high quality data have been recorded. ATLAS collaboration at the LHC is taking a leading role in the ongoing BSM searches. At the time of finishing the write-up of this thesis, the particle physics community is eagerly awaiting the results of the LHC third experimental run and optimistic about something exciting to eventually shows up: a particle for dark matter, additional dimensions of space, or maybe a new type of symmetry.

This thesis focused on the physics beyond the SM, where two studies have been performed. The first study was a phenomenology work in which a two-Higgs doublet model was extended with an additional singlet scalar (2HDM+S), a brief introduction to the model and its parameters was provided. Constraints are applied to the parameter space of this model in order to accommodate a number of discrepancies in the data that have been interpreted in Ref. [1]. Implications of this choice of parameter space for the heavy pseudo-scalar (A) and charged scalar (H^+) are also discussed. In particular, the production of A through the gluon-gluon-fusion mode, and its decay into ZH channels, with the decay modes $H \rightarrow hh, Sh, SS$, is considered. This setup leads to a number of interesting final states with multi-leptons and b -tagged jets. The decay $A \rightarrow ZH \rightarrow ZSh$ results in the production of a high transverse momentum Z produced in association with a lepton and two b -quarks with little additional jet activity. These predictions are compared to the data with the model's benchmark points. The findings of these studies further reinforce the relevance of multi-lepton final states in the search for new bosons. In conclusion, the 2HDM+S model with the parameters obtained here, the model is able to accommodate the features at the LHC reported in

Ref. [1]. Without varying these parameters additional excesses in the $Zb\bar{b}$ and $t\bar{t}$ invariant mass spectra, and the production of three leptons plus two b -tagged jets can be explained assuming $m_A \approx 600$ GeV.

In parallel, a search for heavy resonances decaying into a pair of photons in association with b -tagged jets has been performed. This study is based on pp -collisions data corresponding to an integrated luminosity of 139 fb^{-1} recorded by the ATLAS experiment at the LHC at a center-of-mass energy of 13 TeV, during Run-2 campaigns. Three different models are tested in this search. A Higgs boson like heavy scalar X produced with top quarks, b quarks or Z boson decaying into $b\bar{b}$ are examined. The mass range for the hypothetical resonance spans between 160 GeV and 1600 GeV. For this search, expected 95% CL upper limits were set on the production cross-section the resonances X times the branching fraction to two photons, as a function of the resonance mass. The limits for the $t\bar{t}X$ model range from 0.6 fb for $m_X = 160$ GeV to about 0.06 fb for $m_X = 1600$ GeV. The limits for the $b\bar{b}X$ model range from about 1.8 fb for $m_X = 160$ GeV to 0.15 fb for $m_X = 1600$ GeV. Finally, for the ZX model, the limits range from 7 fb $m_X = 160$ GeV and 0.3 fb $m_X = 1600$ GeV.

In 2026, the LHC machine is expected to undergo a significant upgrade that allows it to produce high luminosity in the so-called HL-LHC [192]. This program will deliver a large dataset at $\sqrt{s} = 14\text{ TeV}$ with an integrated luminosity of 3000 fb^{-1} . The ATLAS and CMS detectors will also undergo major upgrade to be able to cope with the HL-LHC environment. The BSM searches will be the main component of the extensive physics program at the HL-LHC. Refs. [193, 194] highlight the expected physics reach for a wide range of measurements and searches at the HL-LHC for the ATLAS and CMS experiments including Higgs boson measurements, di-Higgs boson production sensitivity, electroweak boson measurements, Vector Boson Scattering prospects, and searches for supersymmetry. These studies have been performed either with a full simulation of the upgrade of the ATLAS and CMS detectors or with extrapolation from results obtained from the LHC Run-2 data. The projections for these studies indicate an improvement of the sensitivity of the scenarios mentioned. Even though most of these searches benefit from the increase in the integrated luminosity and the centre-of-mass energy, some suffer from large systematic uncertainties related to the theoretical modelling of the signal and background processes. However, these challenging scenarios serve as ideal benchmarks for further improvements in the detector performance, reconstruction techniques and analysis methods using HL-LHC data. Improvements that could be expected with the upgraded detector will provide additional sensitivity for the searches presented. Depending on these studies, I expect an improvement in the sensitivity of the search of a heavy resonance in the diphoton plus b -jets channel with the ATLAS detector.

Appendices

Appendix A

ADDITIONAL PARAMETER CORRELATIONS FOR SECTION 4.3

This appendix shows additional parameter correlations that are directly relevant to section 4.3. Results are shown for the requirement that the BRs of the lightest scalar be within 20% and 10% of the BRs predicted in the SM for the Higgs boson. Figure A.1 displays the correlation between m_{12}^2 and α_1 , α_2 and α_3 , the mixing angles. The correlation with α_1 is weak, where the correlation with the other two mixing angles is noticeable. Figure A.2 shows the correlations between v_s and α_1 , α_2 and α_3 , where overall the correlations are weak. Figure A.3 shows the correlations between $\tan\beta$ and m_{12}^2 , v_s and m_{12}^2 and finally, v_s and $\tan\beta$. Correlations are weak except for Figure A.3c where a certain range of values for v_s and m_{12}^2 are disallowed.

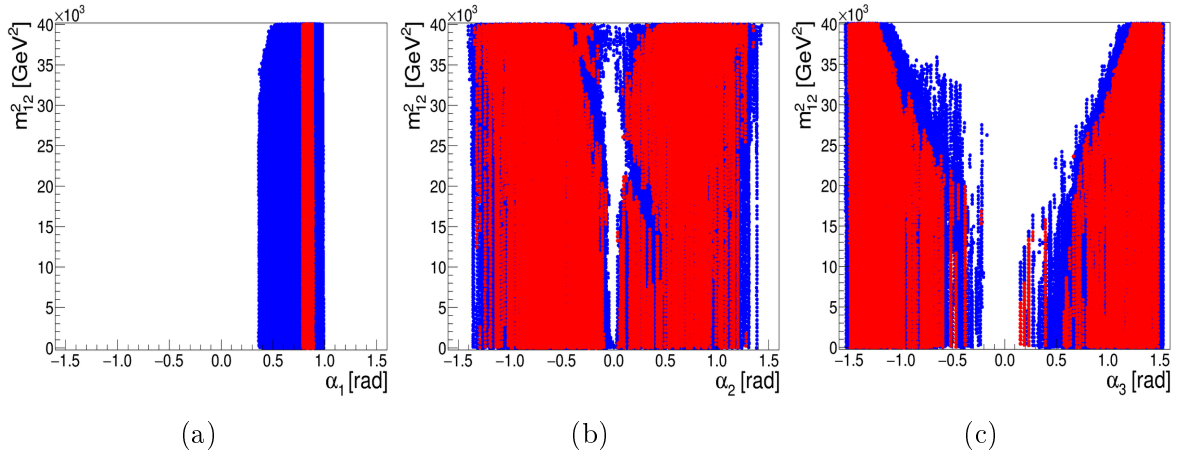


Figure A.1: Allowed values of α_1 , α_2 and α_3 against m_{12}^2 for the benchmark considered here, where the values in *red* (*blue*) are by considering the BRs of the lightest CP-even scalar consistent within 10% (20%) of the prediction for the SM Higgs boson.

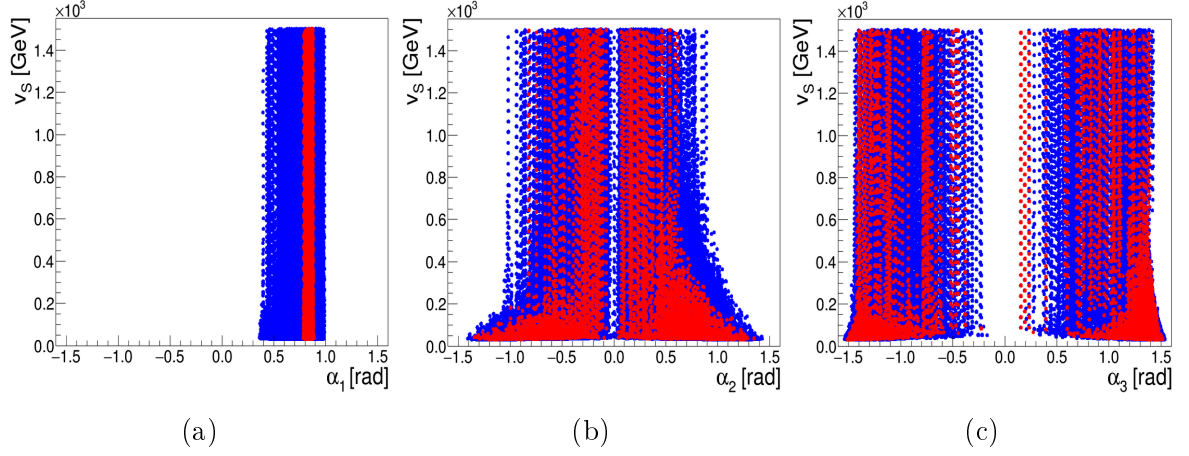


Figure A.2: Allowed values of α_1, α_2 and α_3 against v_S for the benchmark considered here, where the values in *red* (*blue*) are by considering the BRs of the lightest CP-even scalar consistent within 10% (20%) of the prediction for the SM Higgs boson.

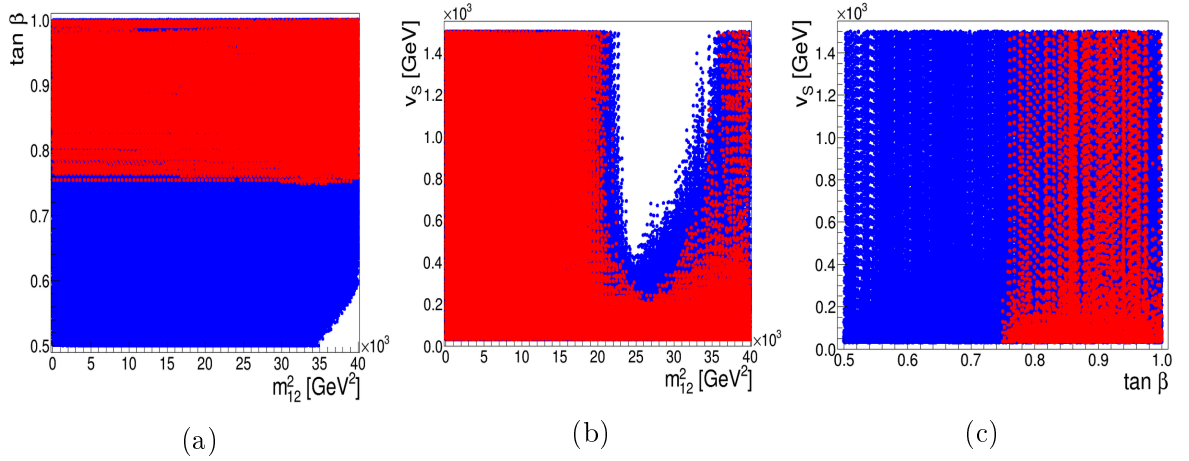


Figure A.3: Correlation of allowed values between (a) m_{12}^2 and $\tan \beta$, (b) m_{12}^2 and v_S , (c) $\tan \beta$ and v_S for the benchmark considered here, where the values in *red* (*blue*) are by considering the BRs of the lightest CP-even scalar consistent within 10% (20%) of the prediction for the SM Higgs boson.

Appendix B

ADDITIONAL PLOTS FOR SECTIONS 5.4 AND 5.5

B.1 EVENT OPTIMIZATION

This appendix shows additional figures in support of the optimization study in Section 5.4. Figure B.1 shows the optimization result for $t\bar{t}X$ with $m_X = 250$ GeV in each region. The optimization results correspond to the ZX and $b\bar{b}X$ are shown in Figures B.2-B.4.

B.2 EVENT SELECTION

This appendix shows additional kinematic distributions corresponding to different variables for different categories in the control region ($m_{\gamma\gamma}$ in 130-160 GeV). Figures B.5 and B.6 shows the jet and central jet multiplicity in each region. The transverse momentum of the leading and subleading photons are shown in Figures B.7 and B.8.

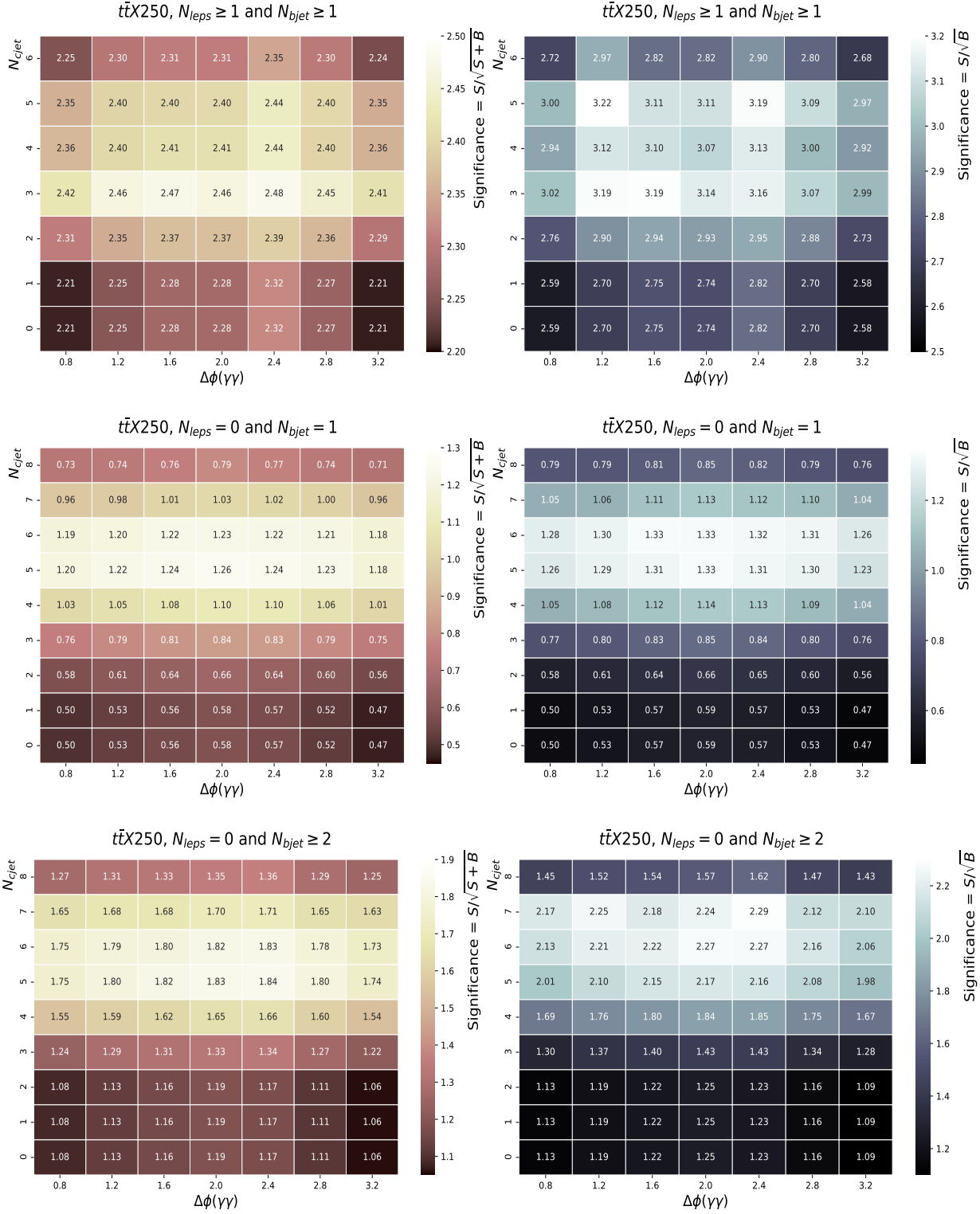


Figure B.1: The optimization result for the $t\bar{t}X$ $m_X = 250$ GeV. The first row is one lepton region, the second row is two b jets region, the last row is one b jet region. The left is using the $S/\sqrt{S+B}$. The right is using the $S/\sqrt{B}$.

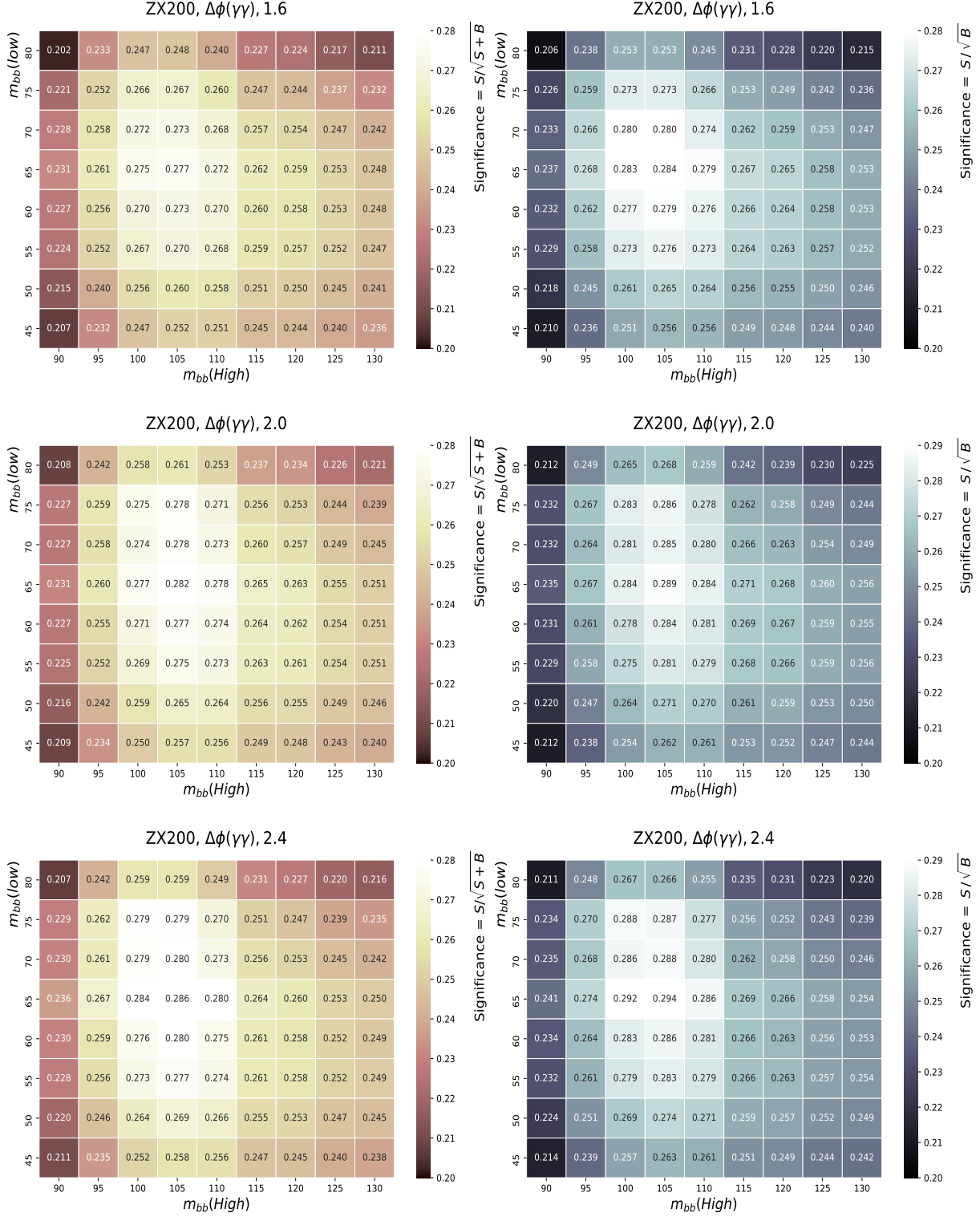


Figure B.2: The optimization result for the ZX $m_H = 200$ GeV with different $\Delta\phi_{\gamma\gamma}$ cuts. The left is using the $S/\sqrt{S+B}$. The right is using the $S/\sqrt{B}$.

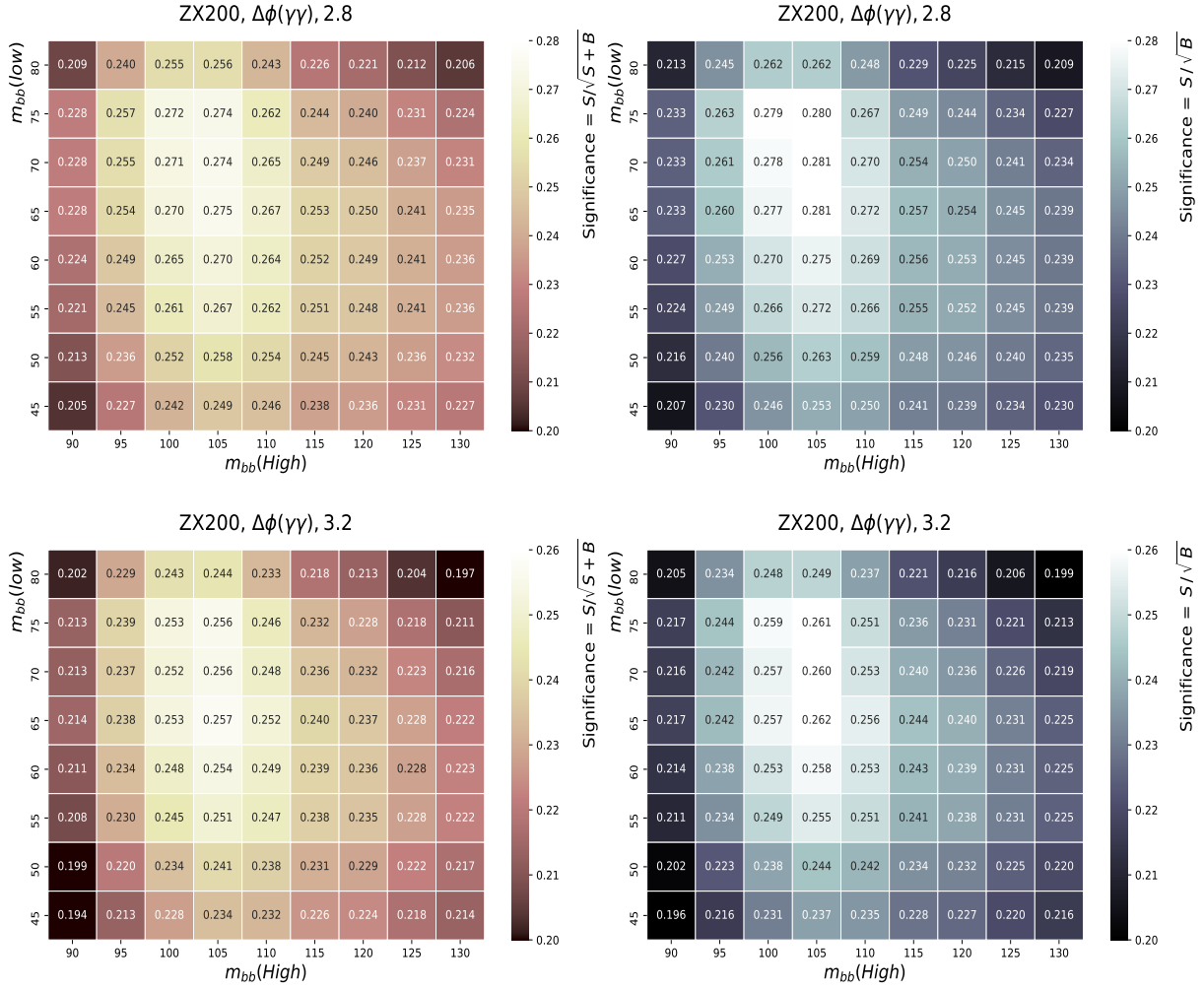


Figure B.3: The optimization scan for the ZX $m_H = 200$ GeV with different $\Delta\phi_{\gamma\gamma}$ cut. The left is using the $S/\sqrt{S+B}$. The right is using the $S/\sqrt{B}$.

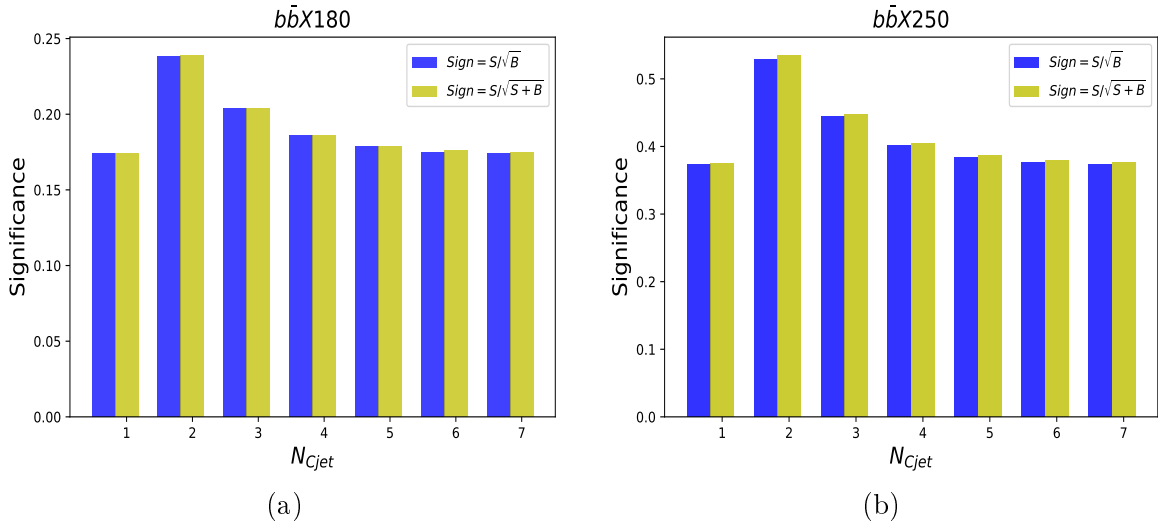
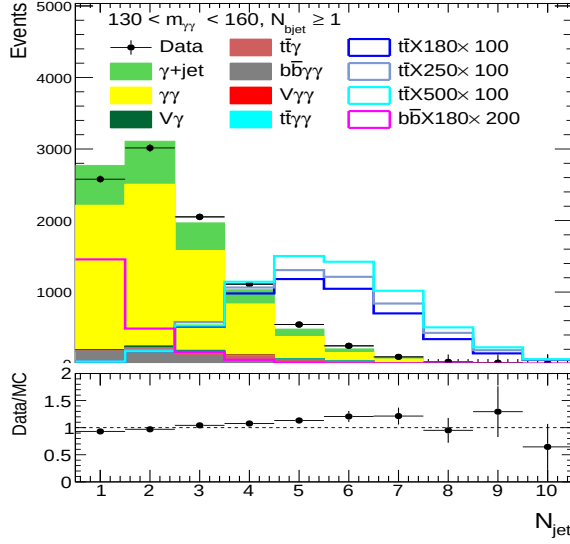
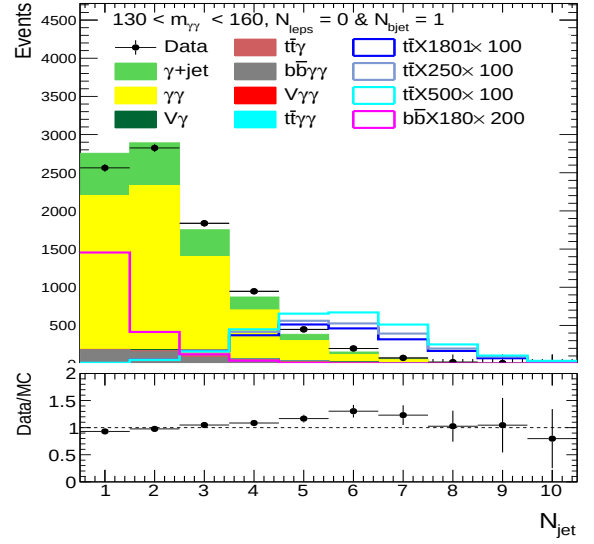


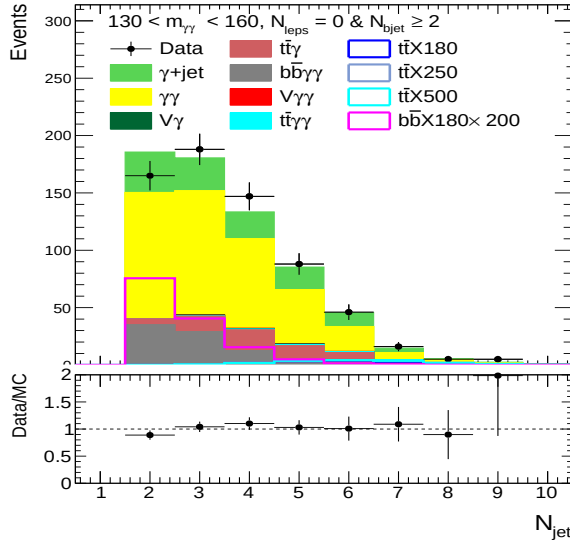
Figure B.4: The optimization result for the $b\bar{b}X$ with (a) $m_X = 180$ GeV and (b) $m_X = 250$ GeV.



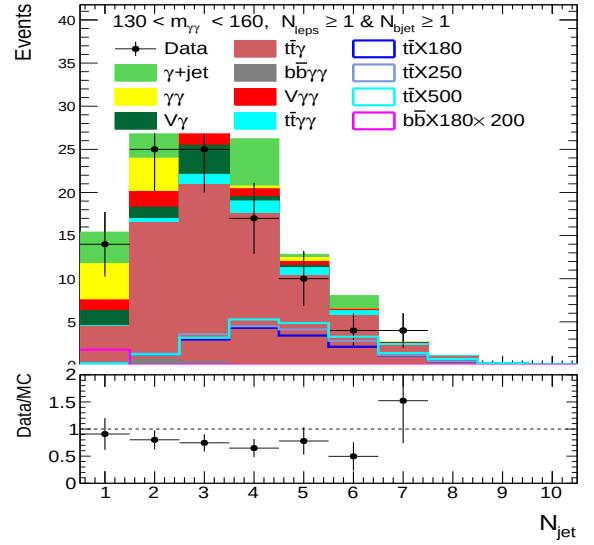
(a)



(b)



(c)



(d)

Figure B.5: Distributions of the jet multiplicity (B.5a) after the preselection, (B.5b) after selecting events with $N_{leps} = 0$ & $N_{bjet} = 1$, (B.5c) after selecting events with $N_{leps} = 0$ & $N_{bjet} \geq 2$, and (B.5d) after selecting events with $N_{leps} \geq 1$ & $N_{bjet} \geq 1$.

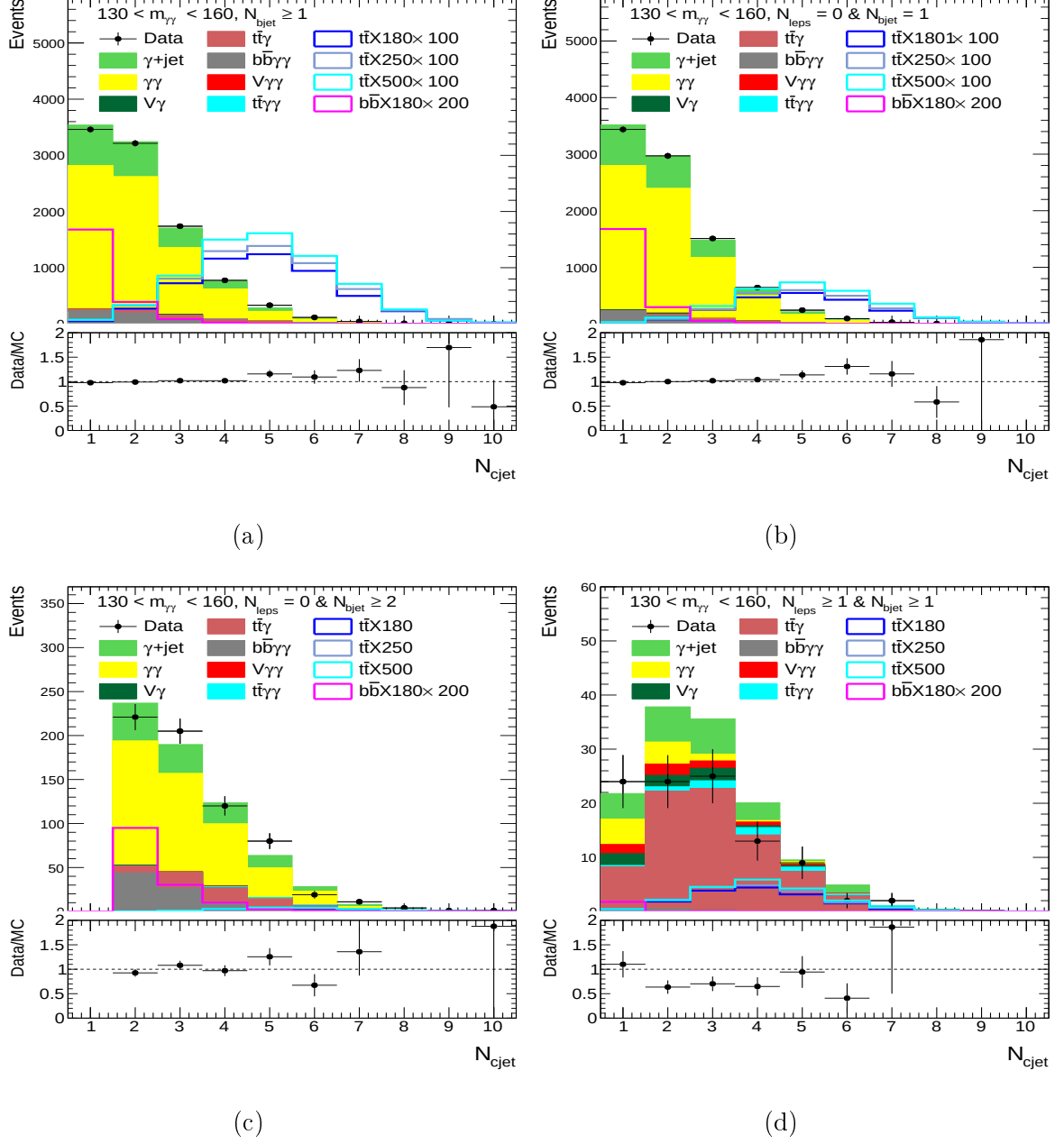
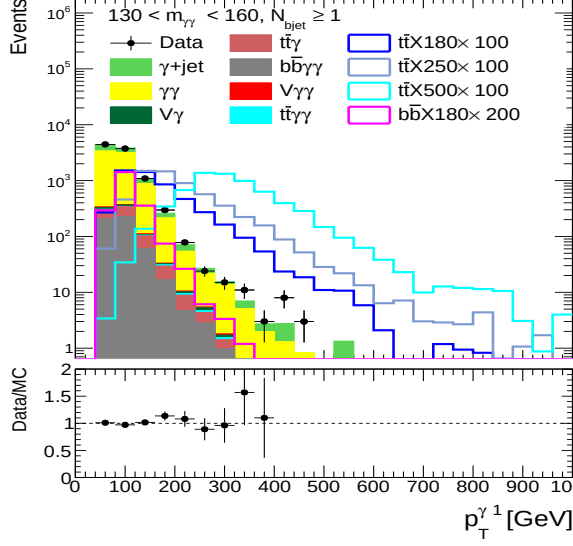
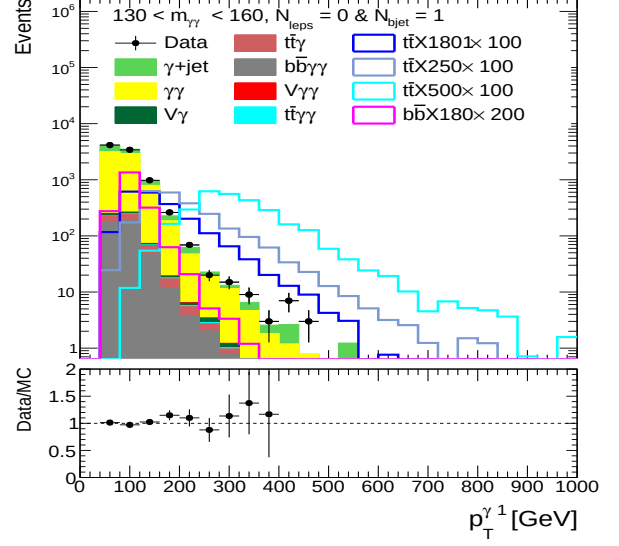


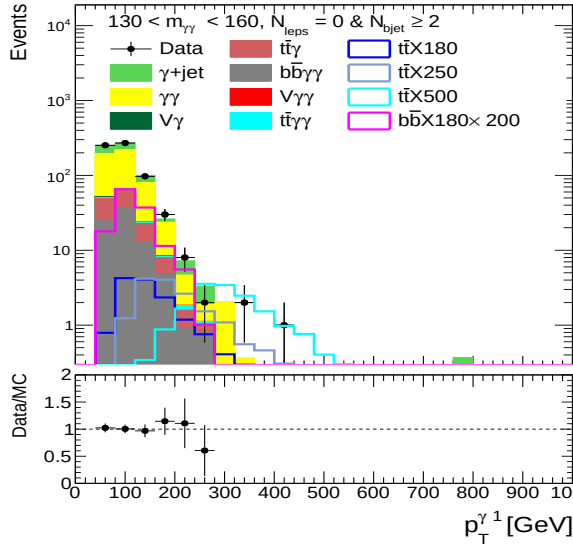
Figure B.6: Distributions of the central jet multiplicity (B.6a) after the preselection, (B.6b) after selecting events with $N_{\text{leps}} = 0$ & $N_{\text{bjet}} = 1$, (B.6c) after selecting events with $N_{\text{leps}} = 0$ & $N_{\text{bjet}} \geq 2$, and (B.6d) after selecting events with $N_{\text{leps}} \geq 1$ & $N_{\text{bjet}} \geq 1$.



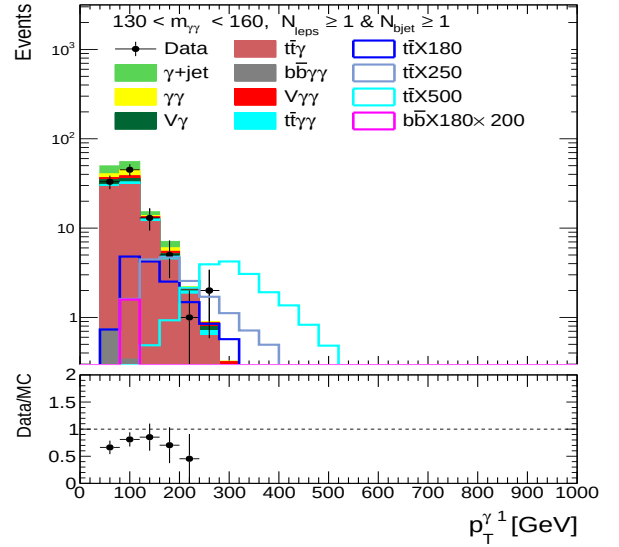
(a)



(b)



(c)



(d)

Figure B.7: Distributions of the transverse momentum of the leading photon (B.7a) after the preselection, (B.7b) after selecting events with $N_{leps} = 0$ & $N_{bjet} = 1$, (B.7c) after selecting events with $N_{leps} = 0$ & $N_{bjet} \geq 2$, and (B.7d) after selecting events with $N_{leps} \geq 1$ & $N_{bjet} \geq 1$.

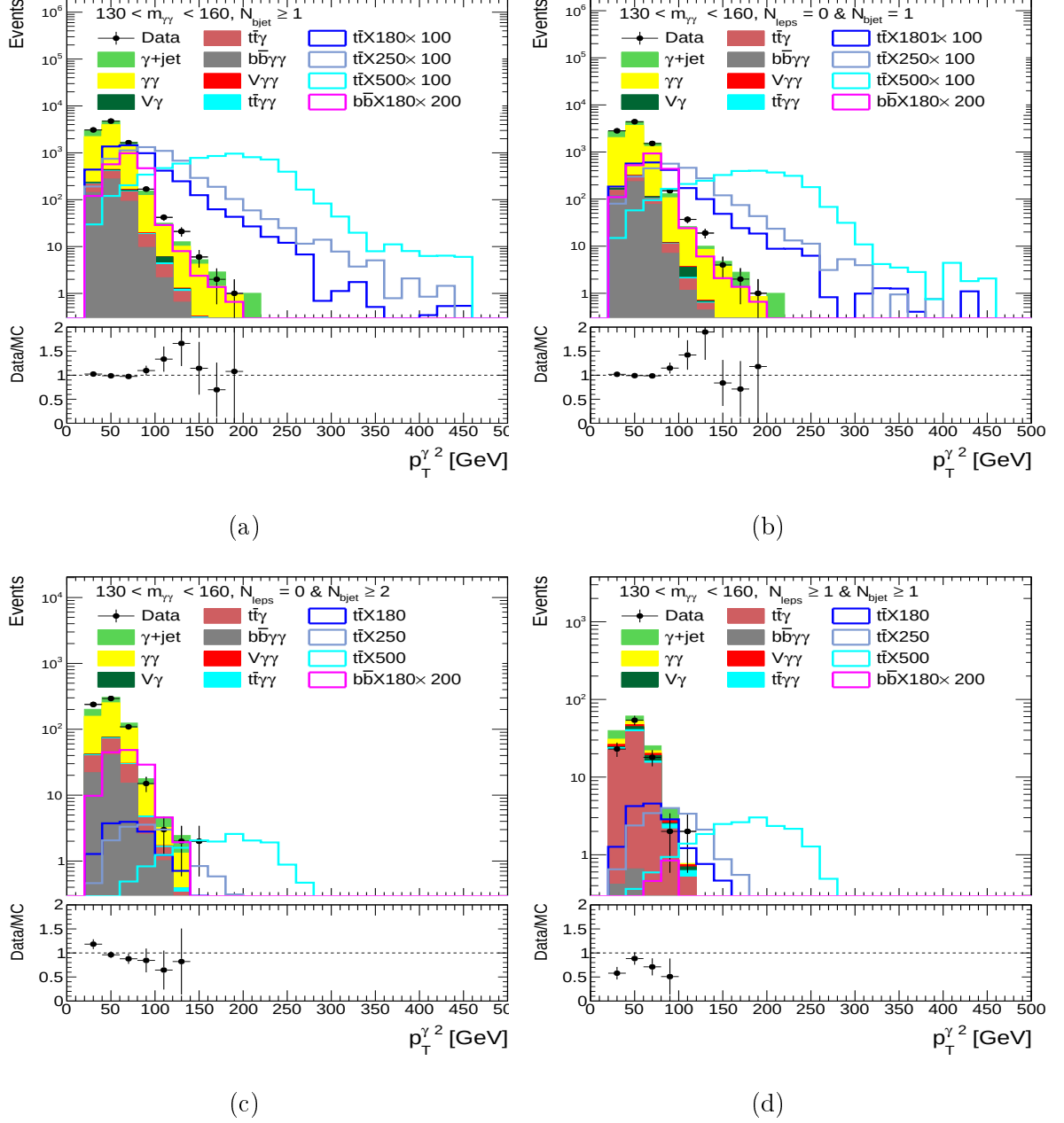


Figure B.8: Distributions of the transverse momentum of the subleading photon (B.8a) after the preselection, (B.8b) after selecting events with $N_{leps} = 0$ & $N_{bjet} = 1$, (B.8c) after selecting events with $N_{leps} = 0$ & $N_{bjet} \geq 2$, and (B.8d) after selecting events with $N_{leps} \geq 1$ & $N_{bjet} \geq 1$.

Appendix C

ADDITIONAL PLOTS FOR SECTION 5.6 TO 5.8

C.1 SIGNAL PARAMETRIZATION

This appendix shows additional figures in support of the signal parametrization study discussed in Section 5.6. Figure C.1 shows the results of a single fit of a DSCB function (lines) functions along with its parameters for a $t\bar{t}X$ signal with $m_X = 180$ GeV for all categories. Figures C.2, C.3 and C.4 show the results of the width of the DSCB resonance peak as a function of the resonance mass for the $t\bar{t}X$, $b\bar{b}X$ and ZX simulated signal samples in their corresponding categories respectively. While the DSCB parameters α_{low} and α_{high} are shown only for the $t\bar{t}X$ samples in Figures C.5 and Figures C.6.

For the acceptance times efficiency, the fit process is done in three steps as discussed in Section 5.6. In the first step, the parametrization for the categories 0-2, 14 and 15 for each model is directly performed and shown in Figure C.7-C.9. Figures C.10 and C.11 shows the results correspond to the second step, in which we parametrized the merged categories that are defined in Table 5.15. Figures C.12 and C.15 show the fraction of events for the $t\bar{t}X$ categories 3-10 and the ZX categories 11-13 over the upper level merged categories. Lastly, the results of the final fit for the $t\bar{t}X$ categories 3-10 and the ZX categories 11-13 are given in Figures C.12 and C.15 respectively.

C.2 THE RATIO METHOD

This appendix shows additional figures in support of the ratio method discussed in Section 5.8. The ratios of each sample in each region are shown in Figure C.16 and Figure C.17. The smoothed shape are compared with the raw shape in each category in Figure C.18 to Figure C.21. The merged template, which is used for the spurious signal fit, are shown in Figure C.22 and Figure C.23.

C.3 SPURIOUS SIGNAL

In support of the spurious signal studies in Section 5.8. Figure C.24 shows the different fits on the smoothed template using the functional form rebinned to 10 GeV. The spurious signal over the uncertainty fitted with the unsmoothed template is shown in Figure C.25 while the smoothed version is in Figure C.26. The envelopes of the absolute spurious signals are obtained in each category, shown in Figure 5.14c. The envelopes are parametrised between 160 GeV to 1500 GeV with a second polynomial exponential function with a constant term.

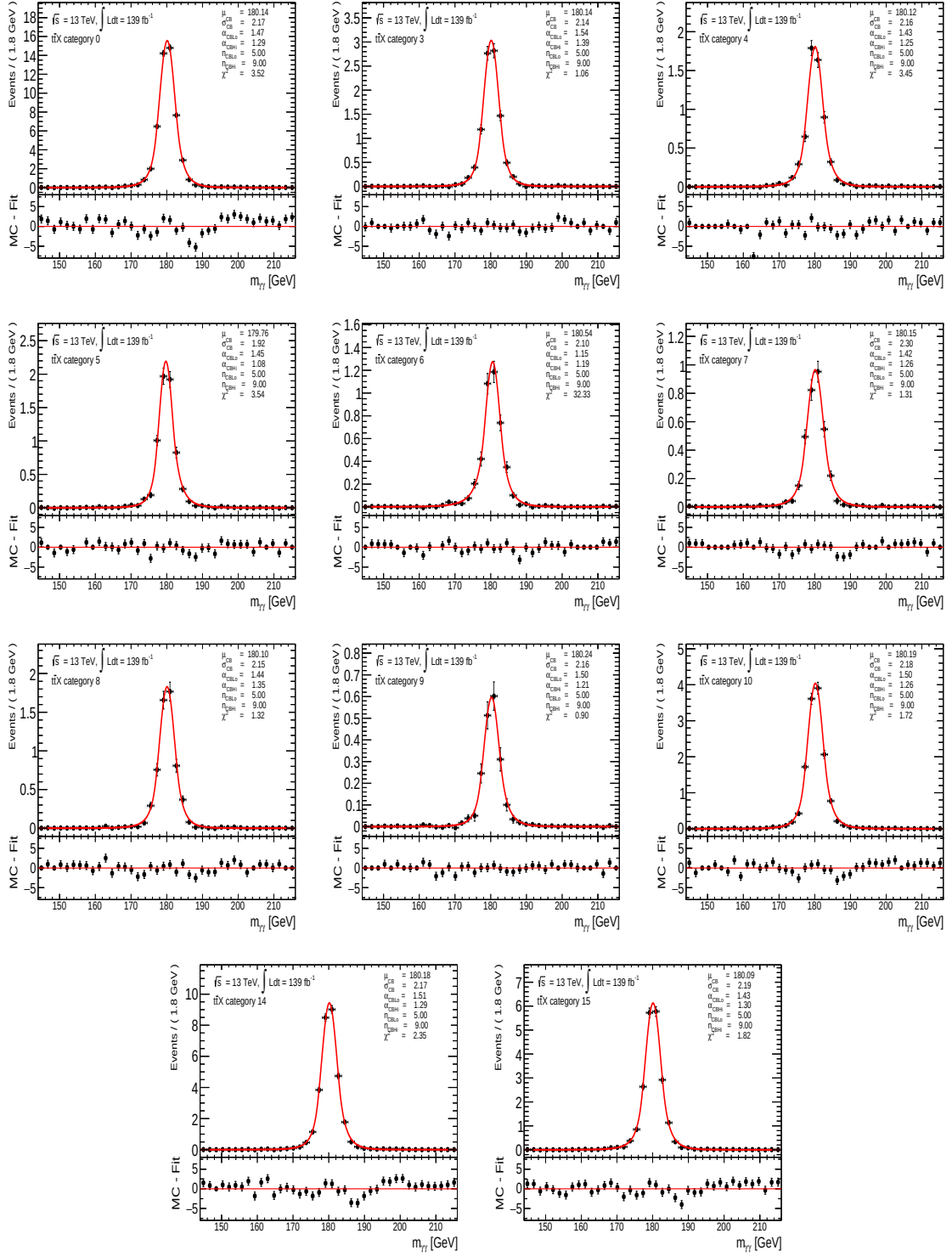


Figure C.1: The results of a single fit of a DSCB function (lines) for $t\bar{t}X$ signal sample with $m_H = 180$ GeV in the categories 0, 3-10, 14 and 15

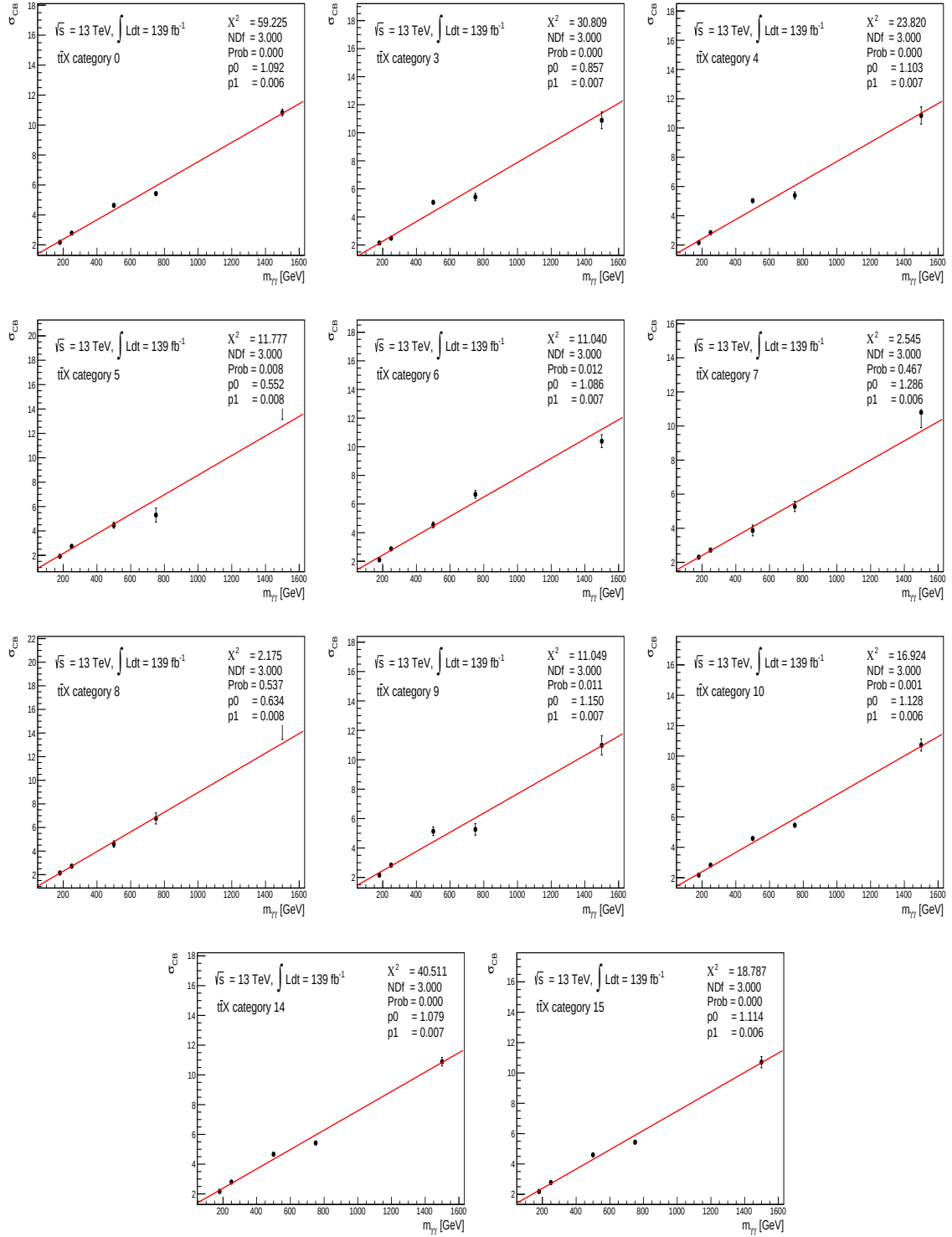


Figure C.2: Width of the resonance peak as a function of the resonance mass for $t\bar{t}X$ signal in the categories 0, 3-10, 14 and 15.

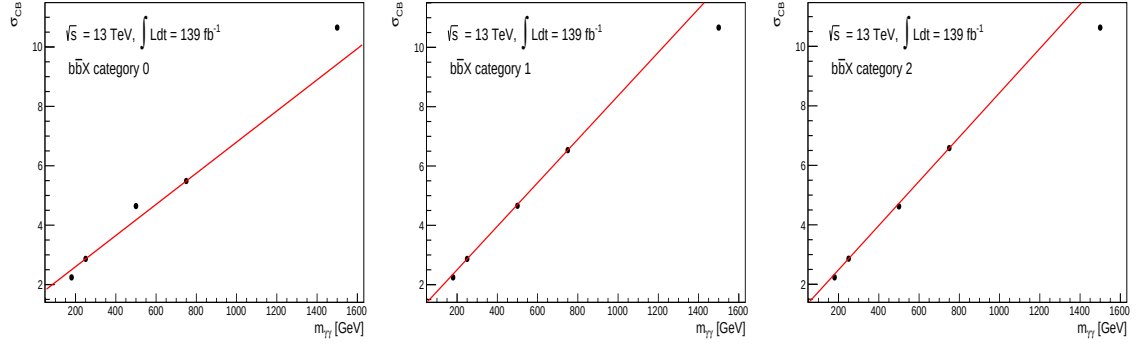


Figure C.3: Width of the resonance peak as a function of the resonance mass for $b\bar{b}X$ signal in each category.

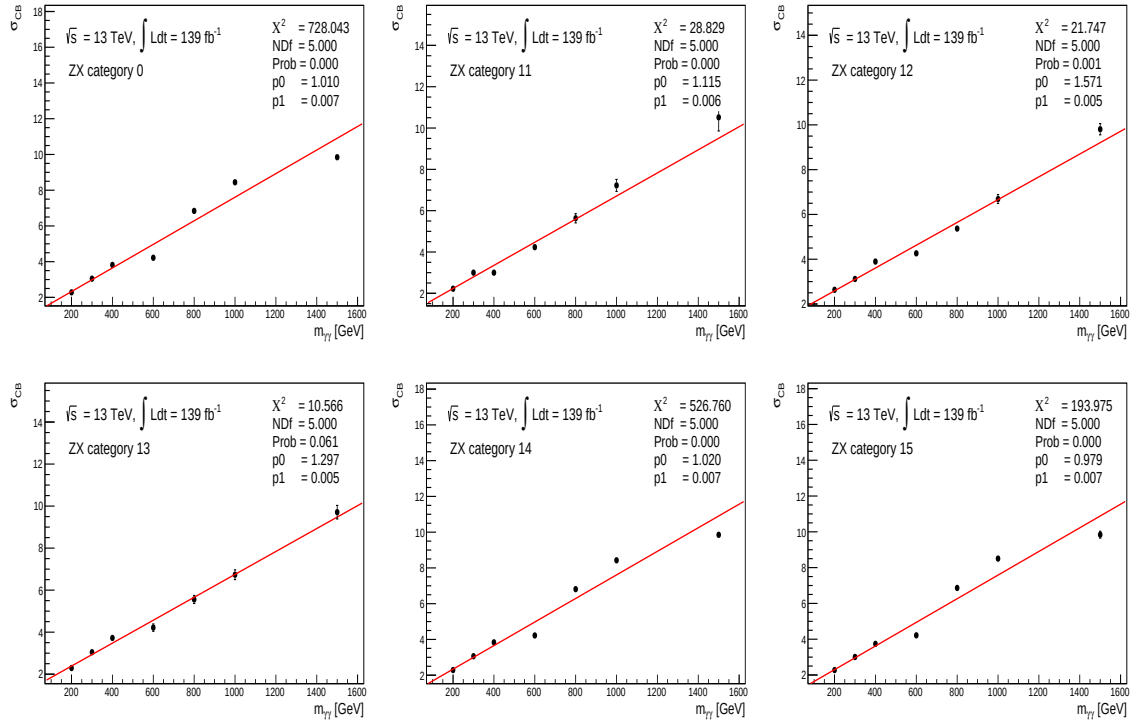


Figure C.4: Width of the resonance peak as a function of the resonance mass for the ZX signal in each category.

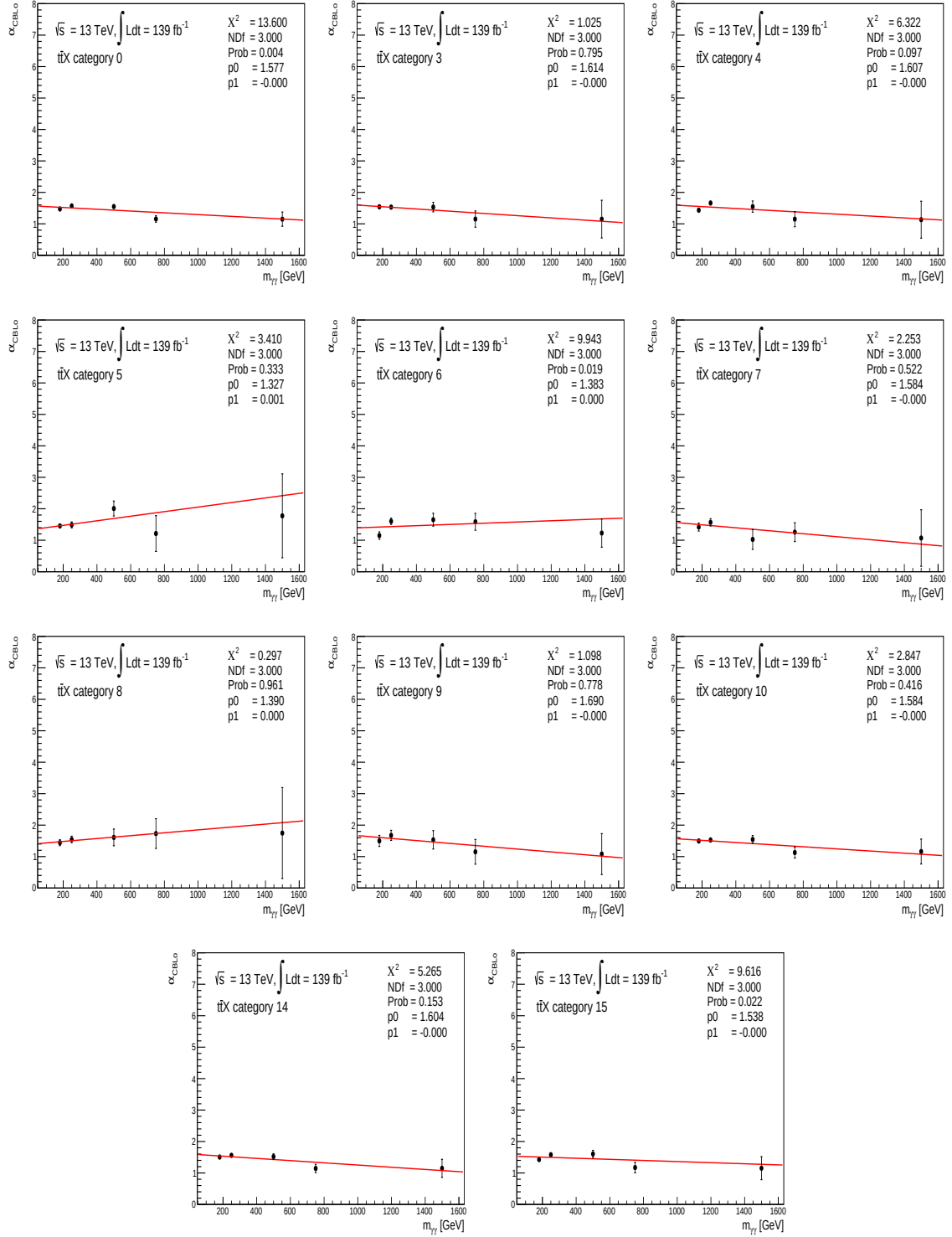


Figure C.5: The DSCB parameter α_{low} as a function of the resonance mass for $t\bar{t}X$ signal in the categories 0, 3-10, 14 and 15.

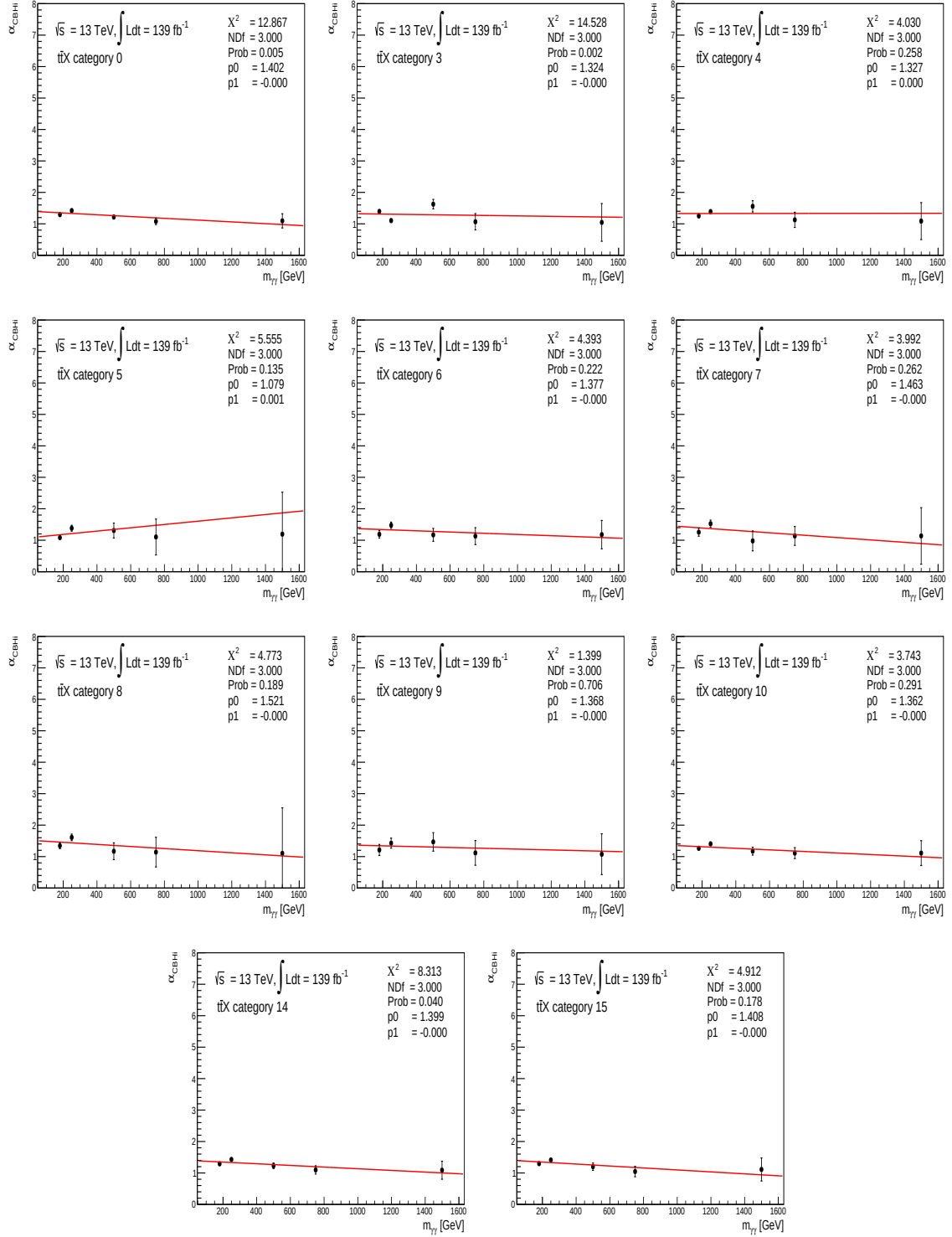


Figure C.6: The DSCB parameter α_{high} as a function of the resonance mass for ttX signal in the categories 0, 3-10, 14 and 15.

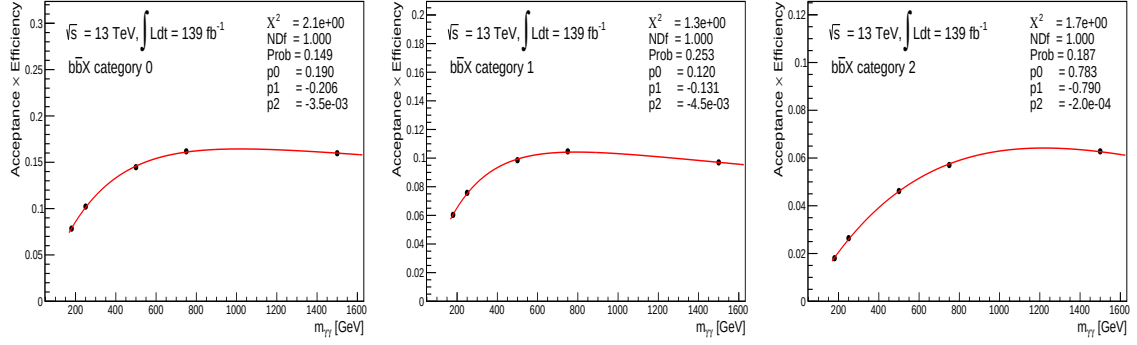


Figure C.7: Acceptance times efficiency at different mass points of the $b\bar{b}X$ signal in categories 0-2.

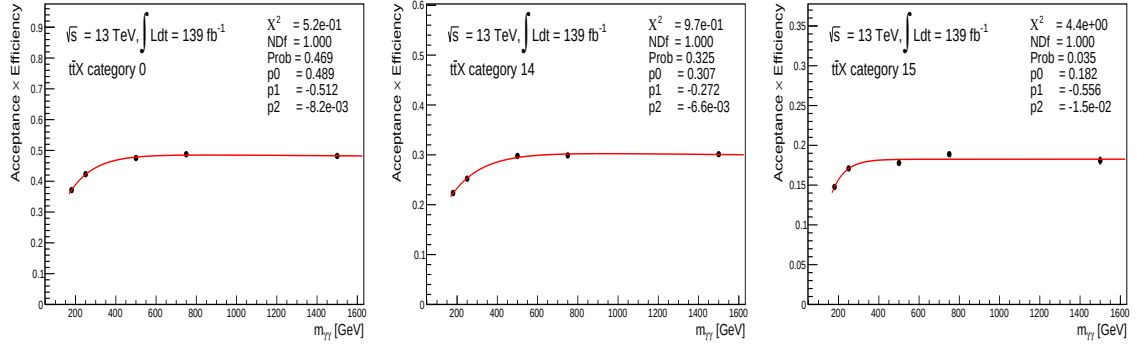


Figure C.8: Acceptance times efficiency at different mass points of the $t\bar{t}X$ signal in the categories 0, 14 and 15.

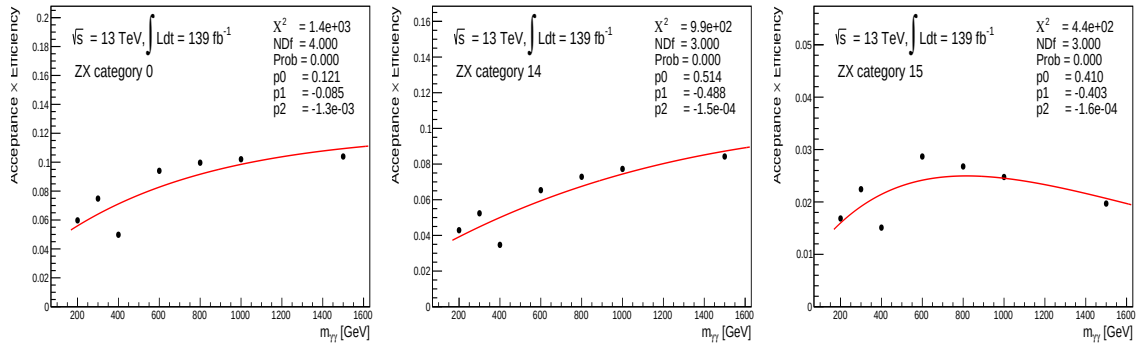


Figure C.9: Acceptance times efficiency at different mass points of the ZX signal in categories 0, 14 and 15.

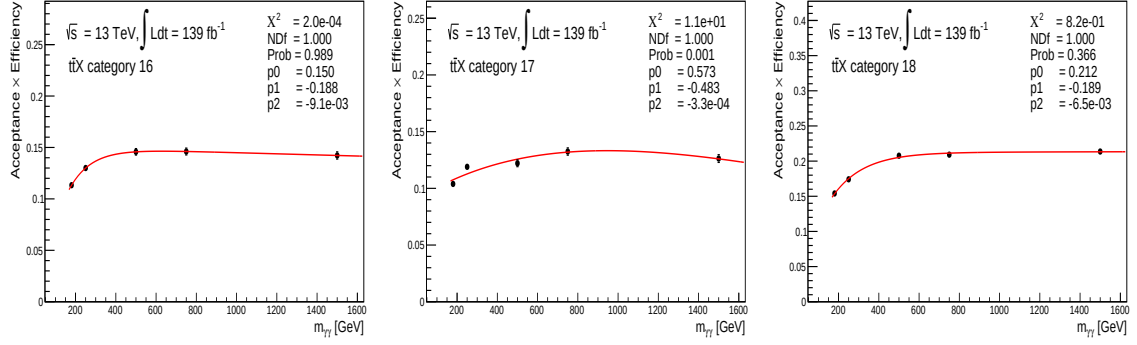


Figure C.10: Acceptance times efficiency at different mass points of the $t\bar{t}X$ signal in the categories 16-18.

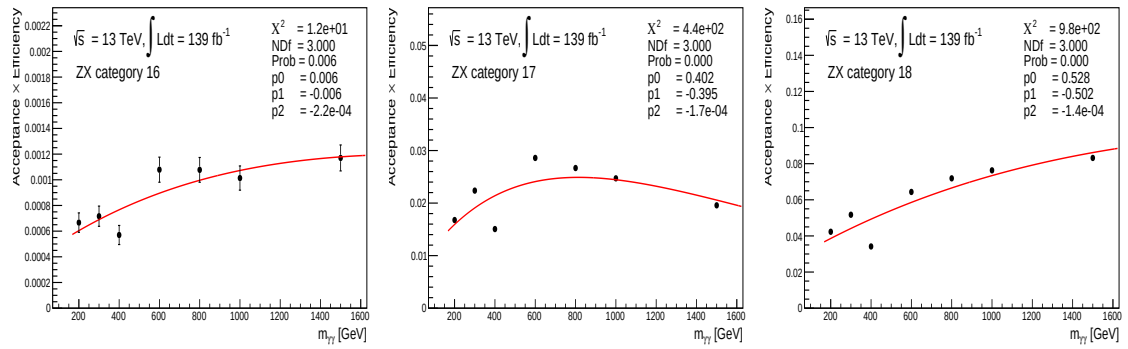


Figure C.11: Acceptance times efficiency at different mass points of the ZX signal in categories 16-18

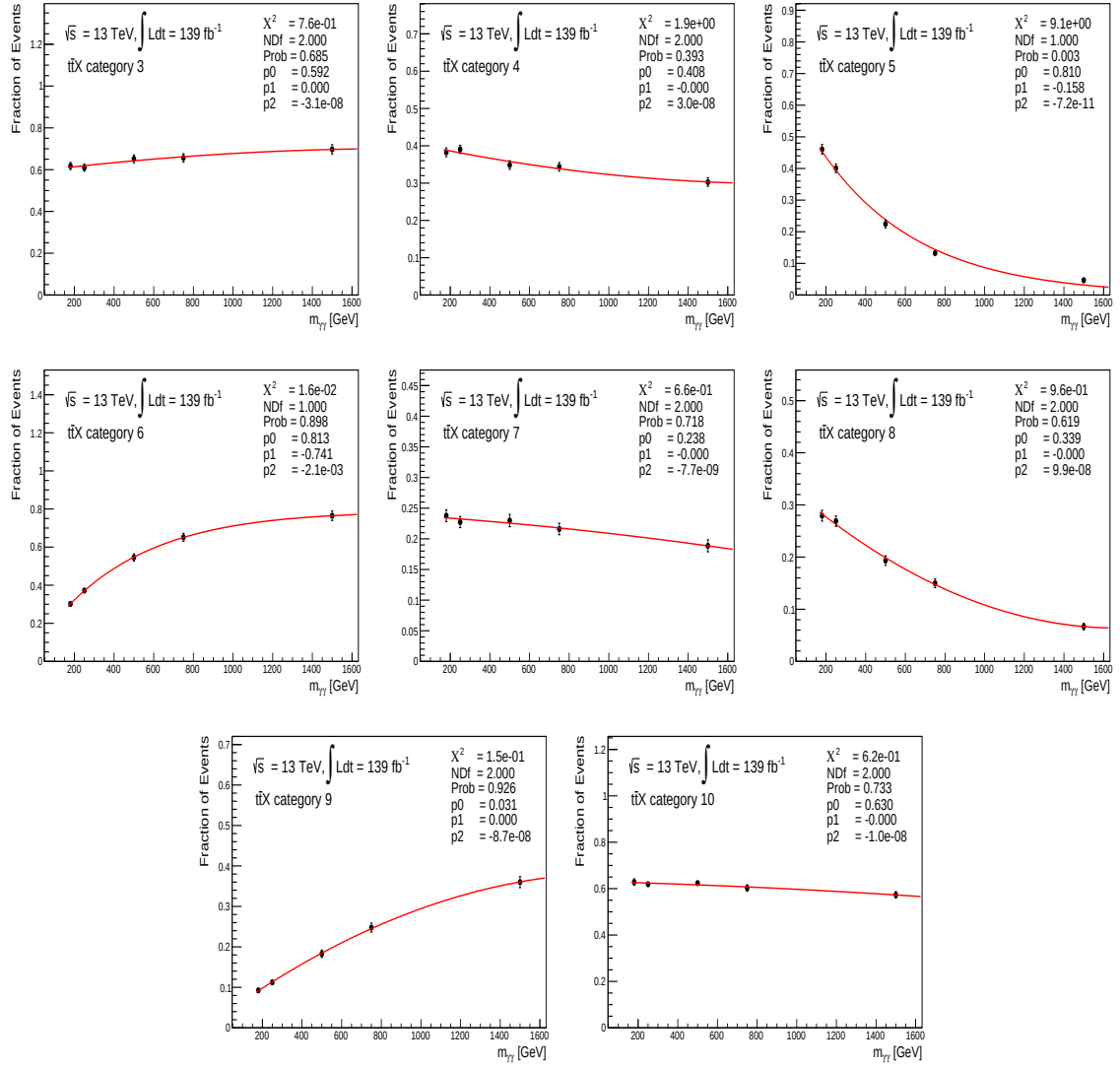


Figure C.12: Fraction of events for the $t\bar{t}X$ signal in the categories 3-10 as a function of the resonance mass.

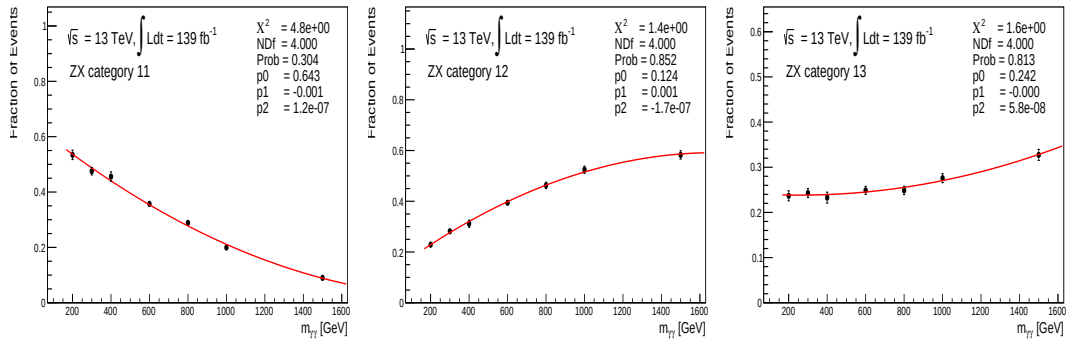


Figure C.13: Fraction of events for the ZX signal in the categories 11-13 as a function of the resonance mass.

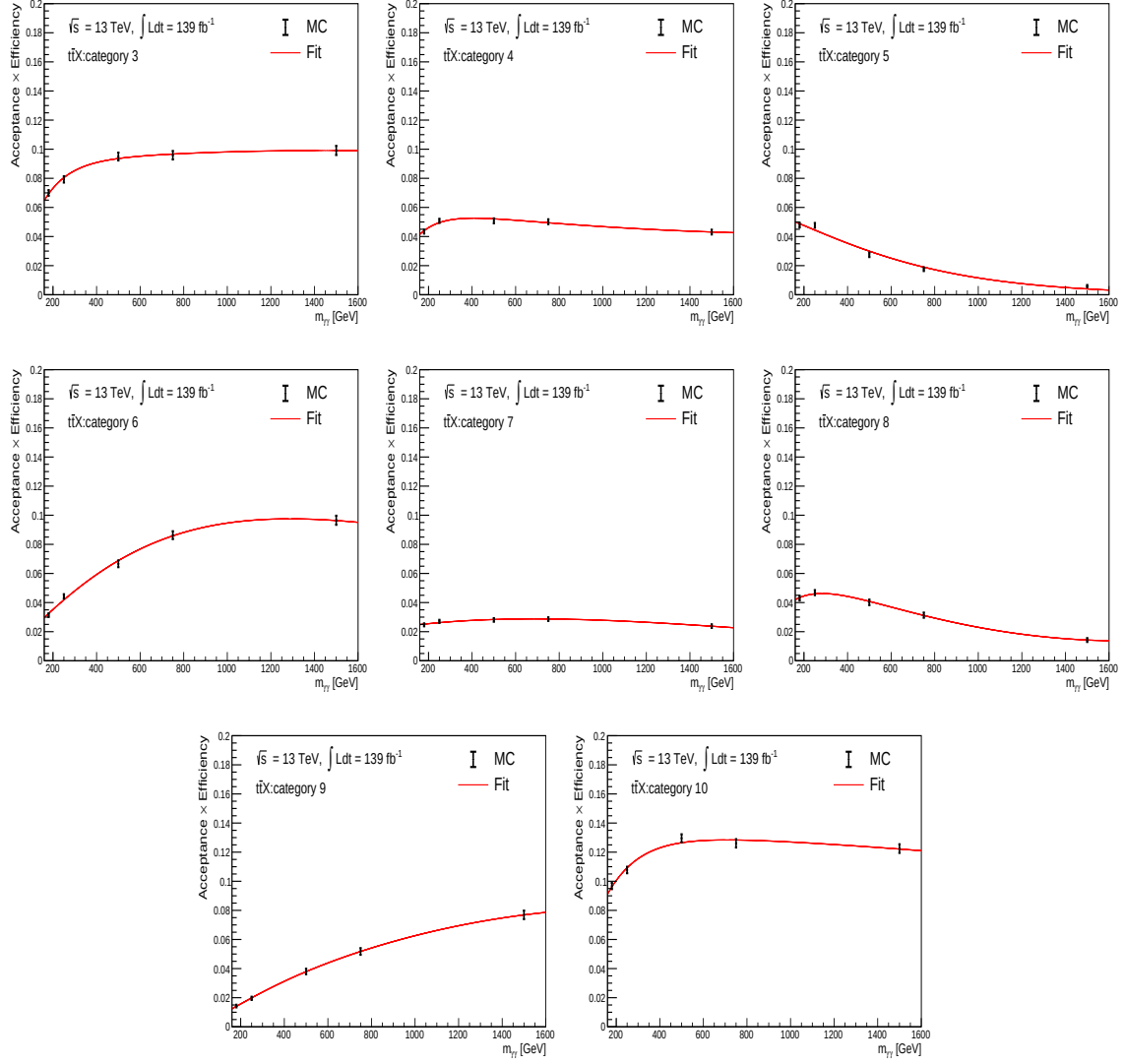


Figure C.14: Acceptance times efficiency for the $t\bar{t}X$ signal in the categories 3-10 as a function of the resonance mass.

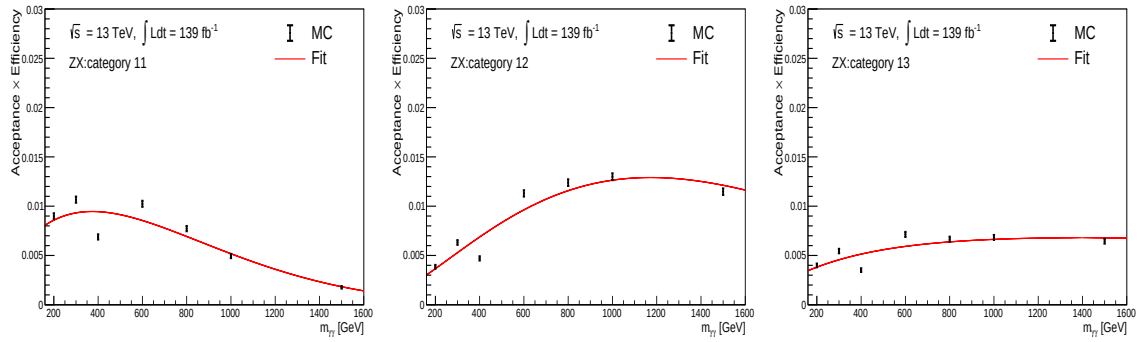


Figure C.15: Acceptance times efficiency for the ZX signal in the categories 11-13 as a function of the resonance mass.

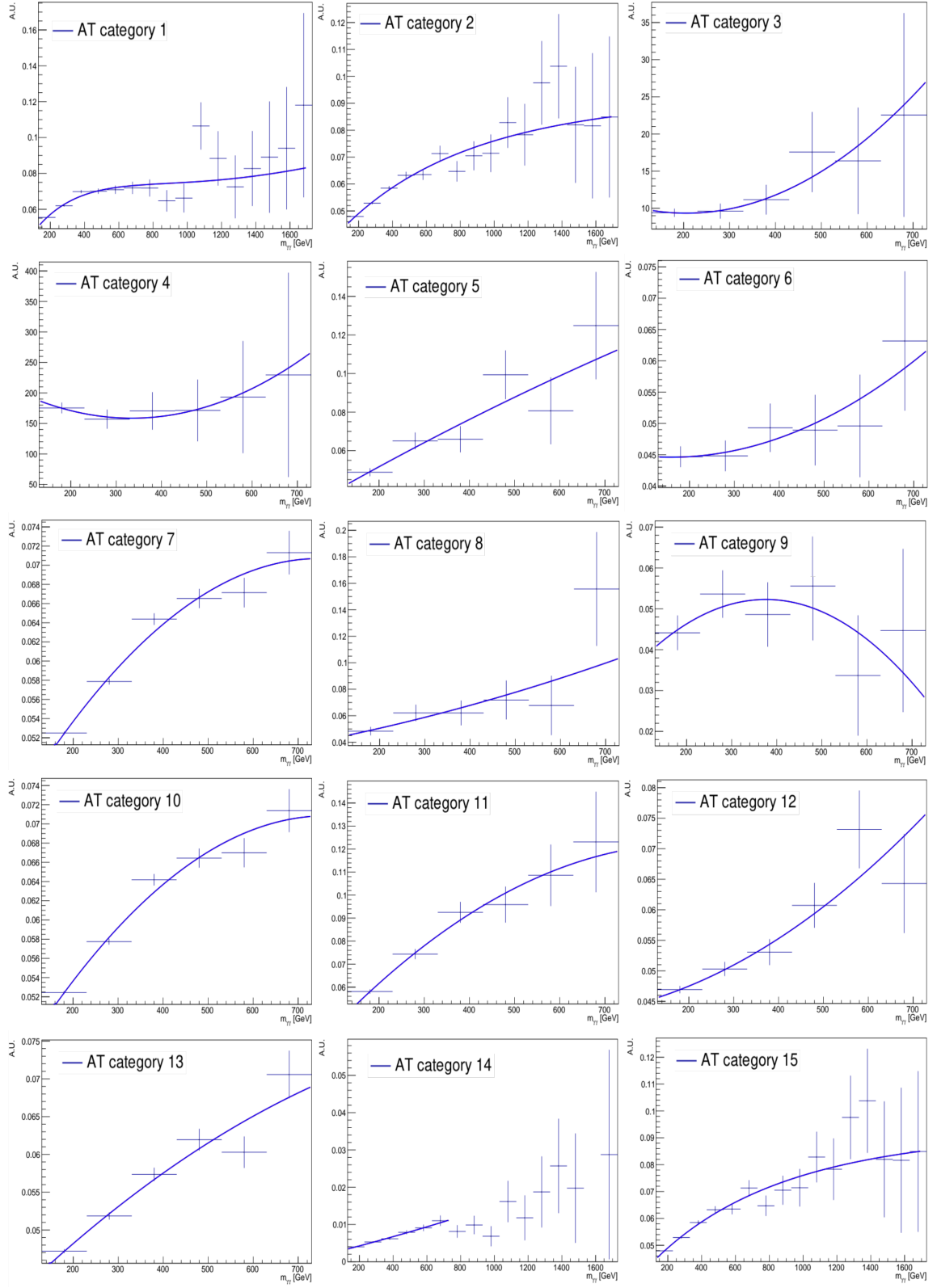


Figure C.16: The ratio of γj sample in signal and control region. The fit is also shown.

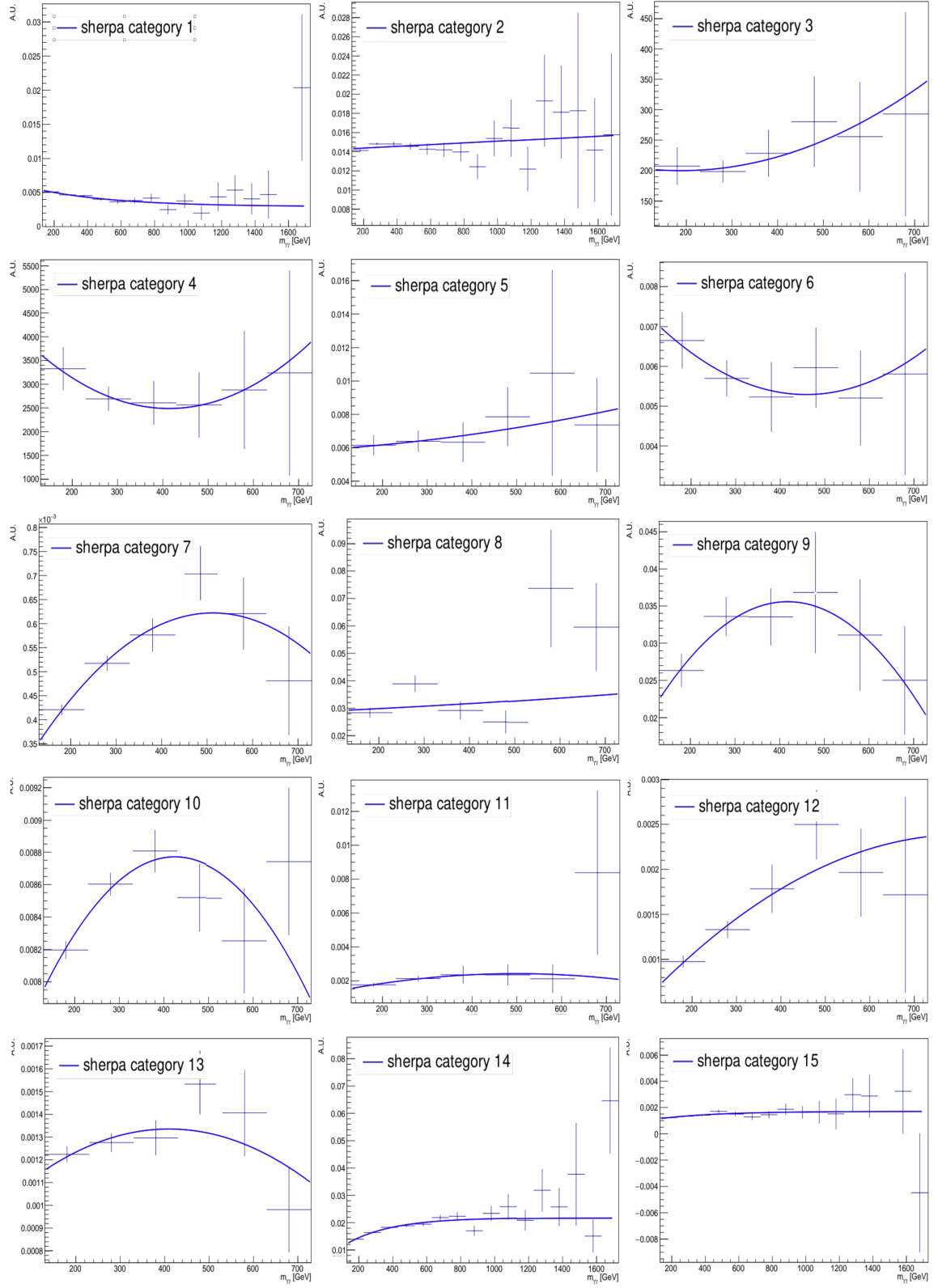


Figure C.17: The ratio of $\gamma\gamma$ sample in signal and control region. The fit is also shown.

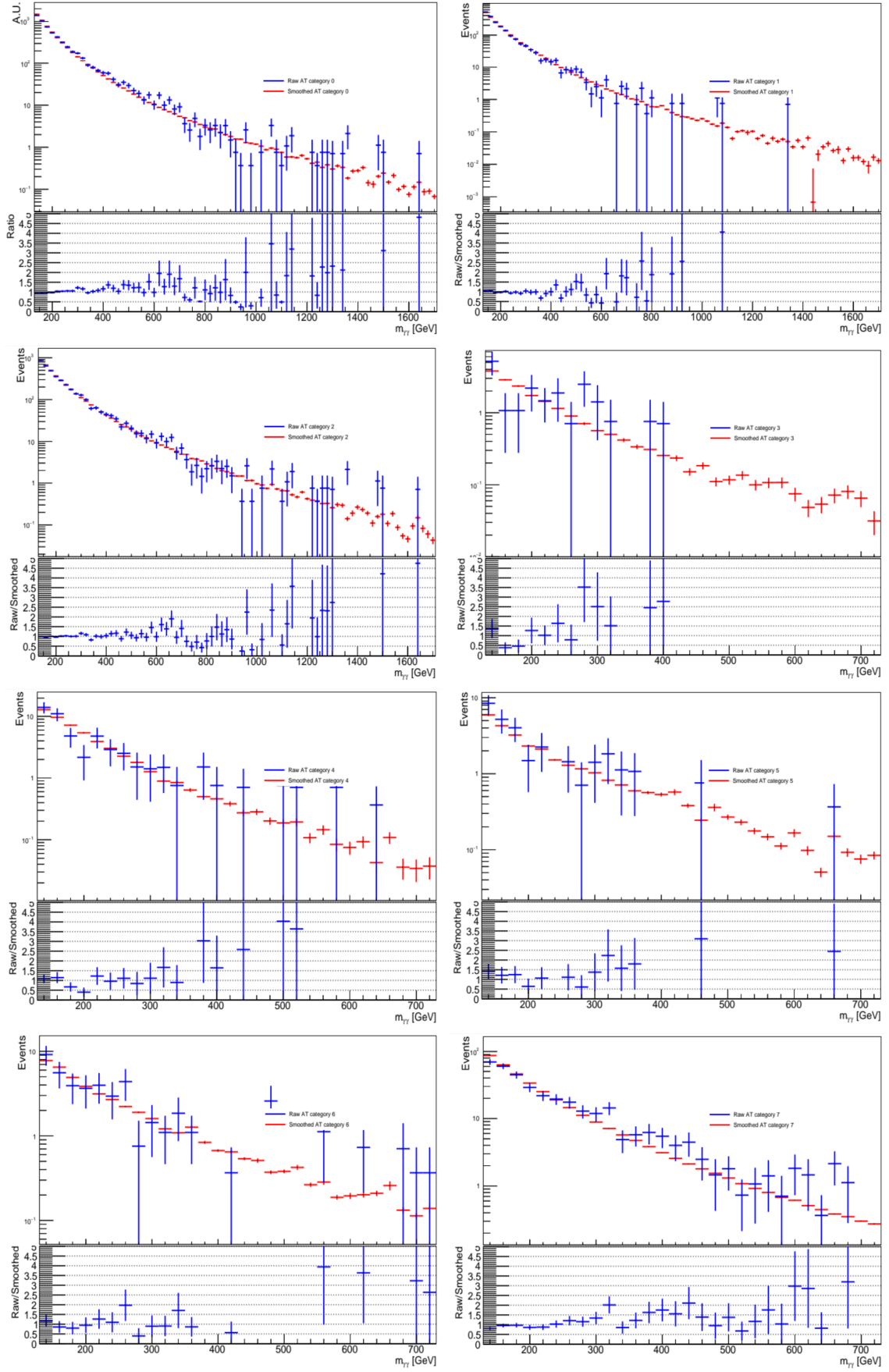


Figure C.18: The smoothed shape and the raw shape of γj sample in categories 0-7.

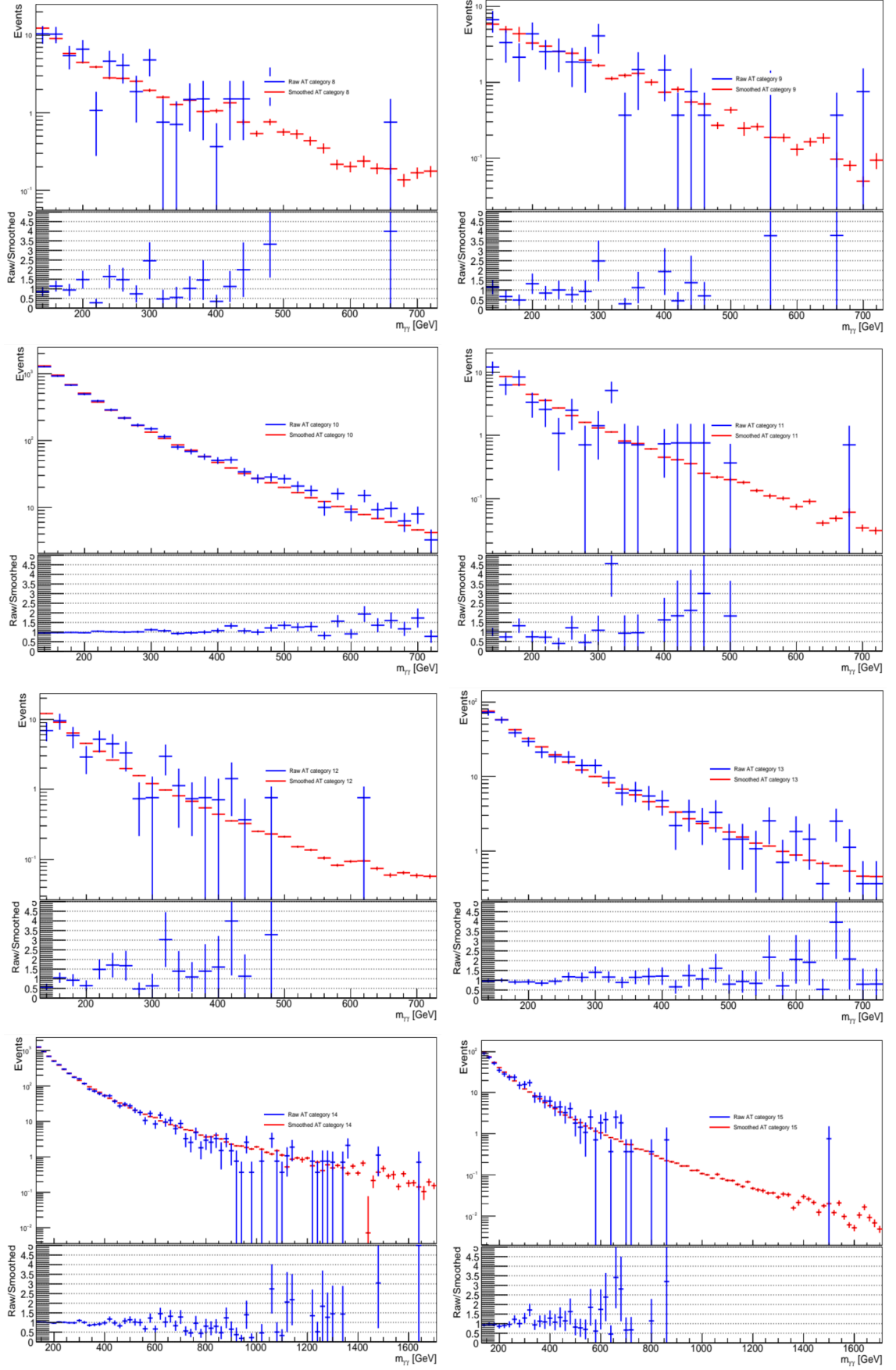


Figure C.19: The smoothed shape and the raw shape of γj sample in categories 8-15.

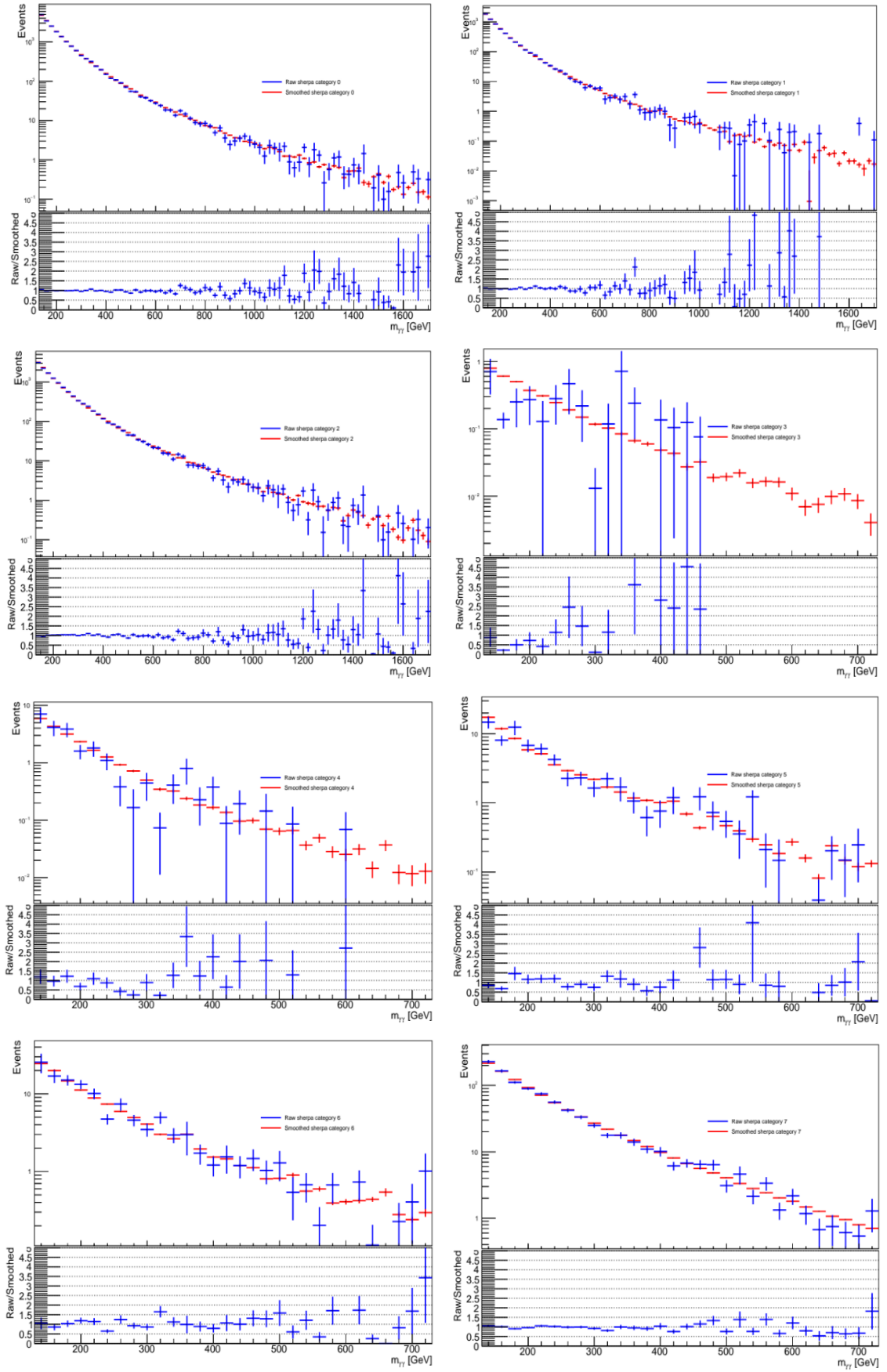


Figure C.20: The smoothed shape and the raw shape of $\gamma\gamma$ sample in categories 0-7.

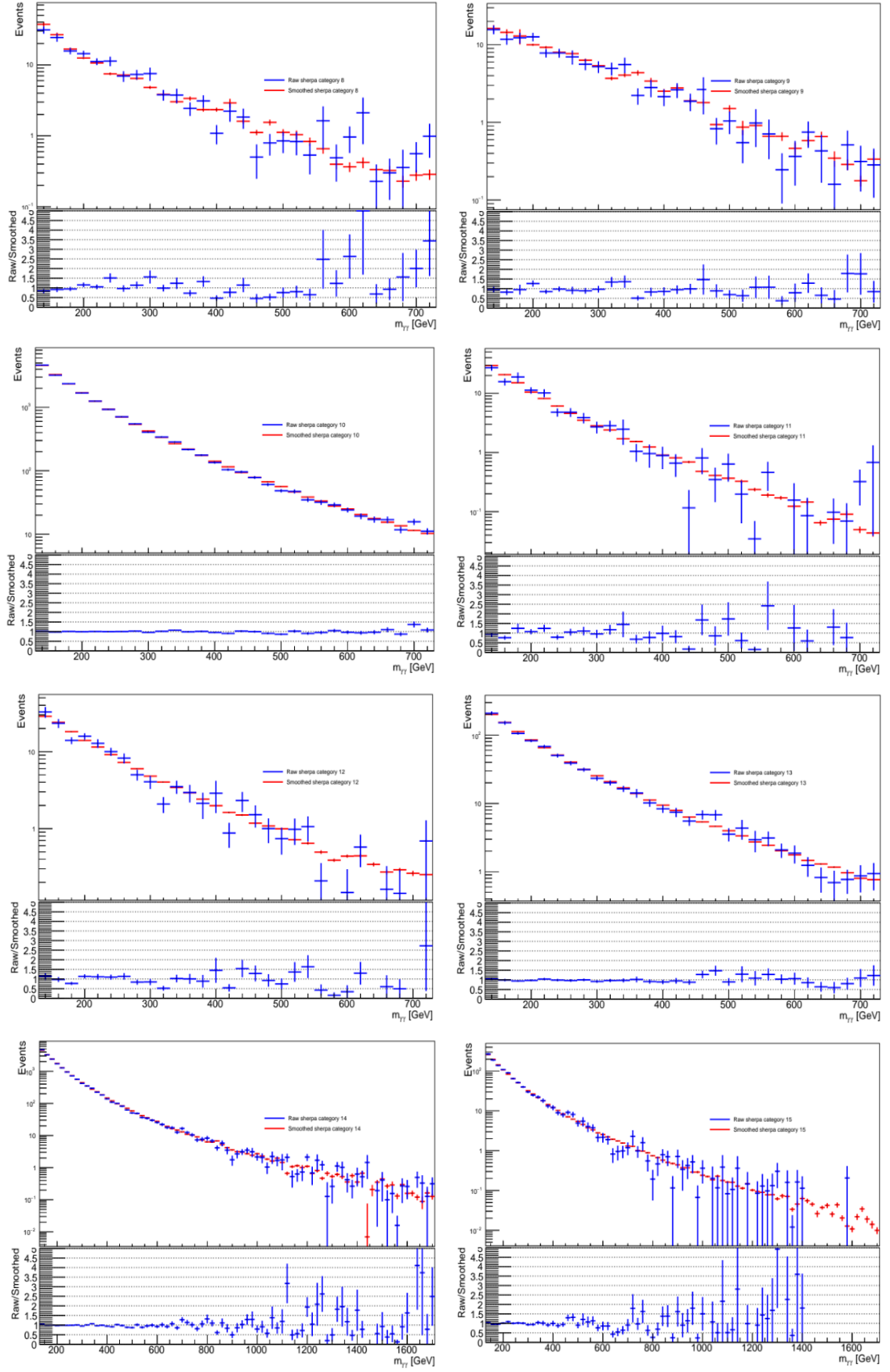


Figure C.21: The smoothed shape and the raw shape of $\gamma\gamma$ sample in categories 8-15.

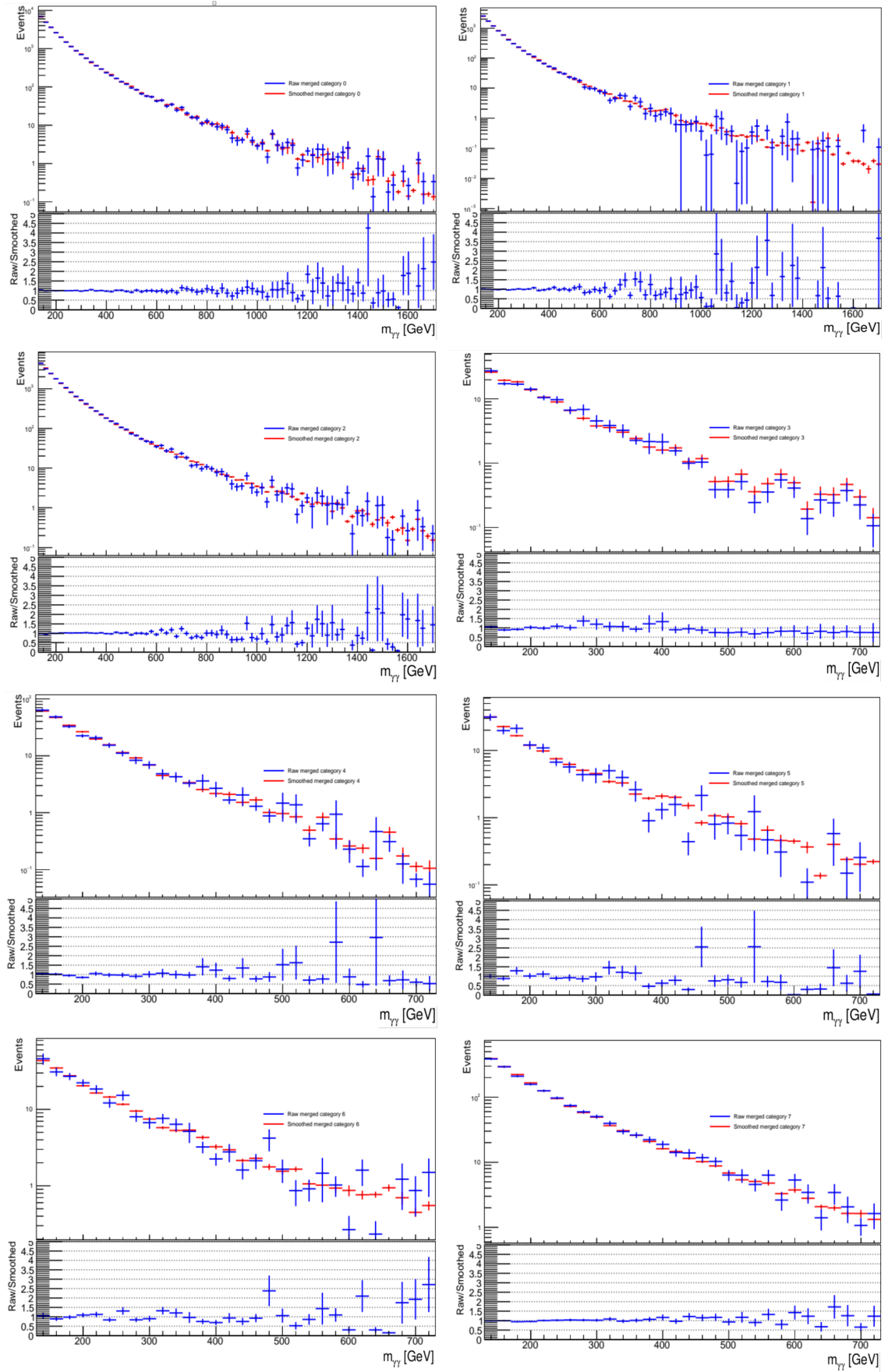


Figure C.22: The smoothed merged shape and the raw merged shape of all the back-ground samples in categories 0-7.

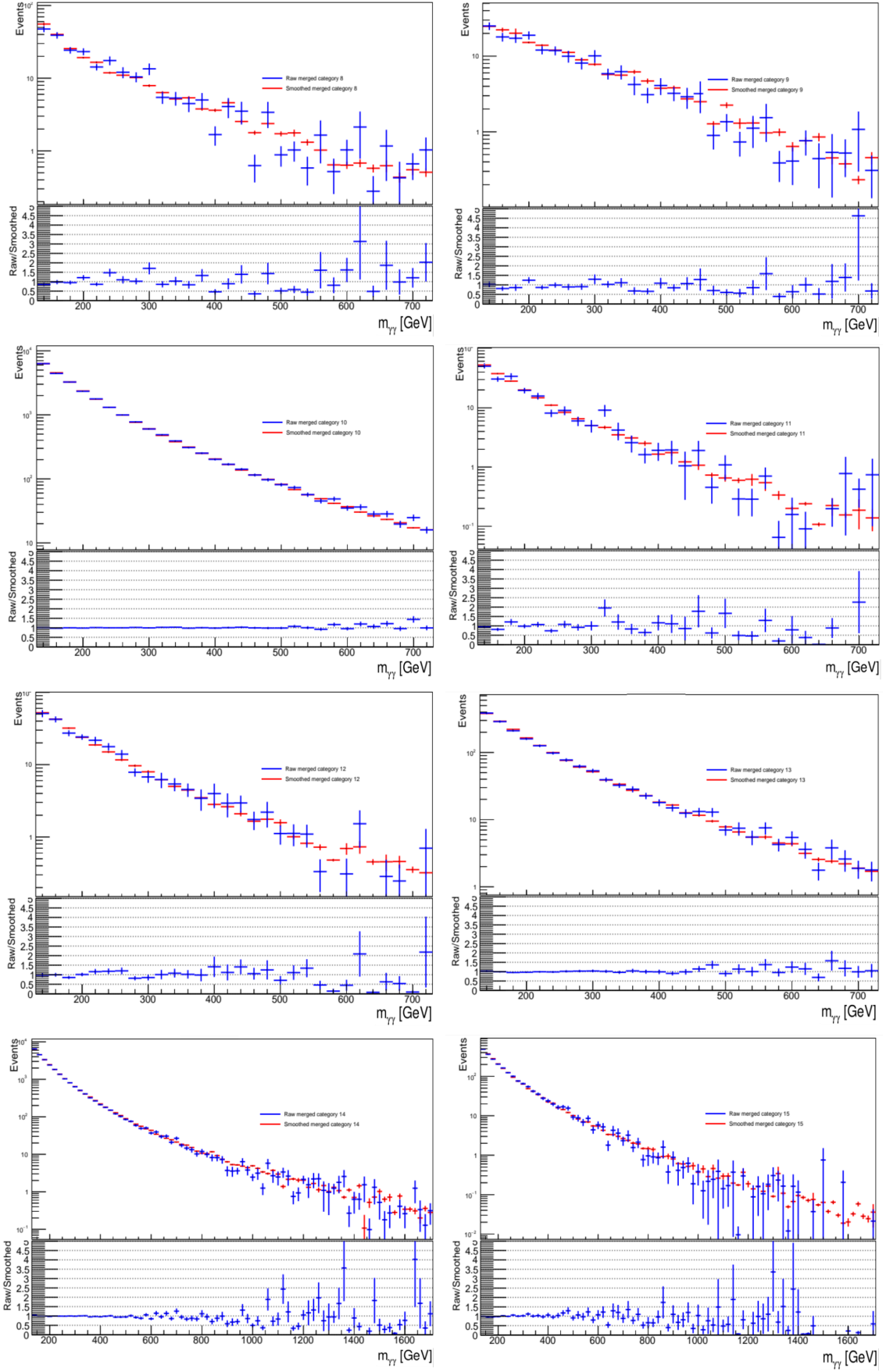


Figure C.23: The smoothed merged shape and the raw merged shape of all the back-ground samples in categories 8-15.

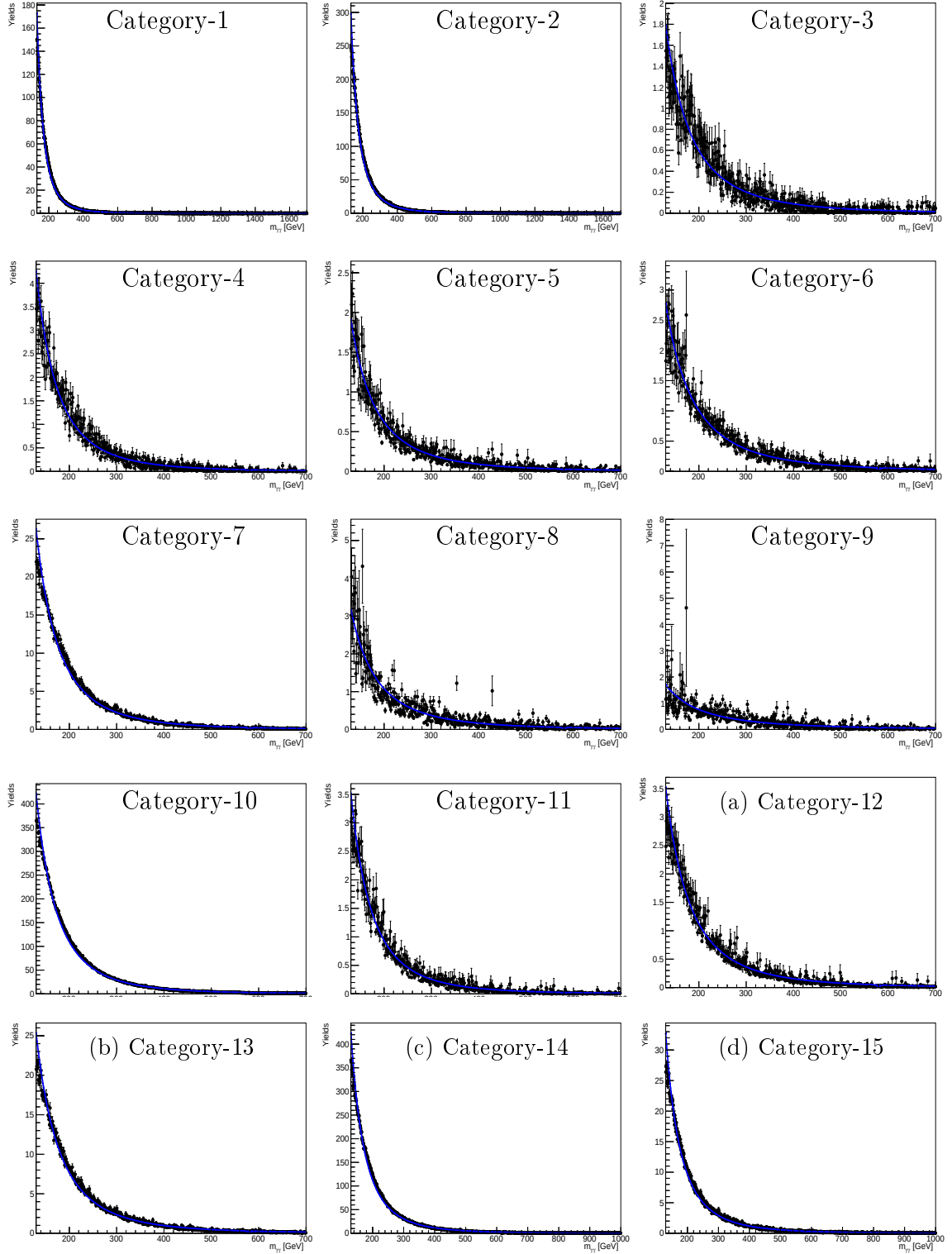


Figure C.24: Example of fitting on the background MC template for category 1-15 using a signal plus background function.

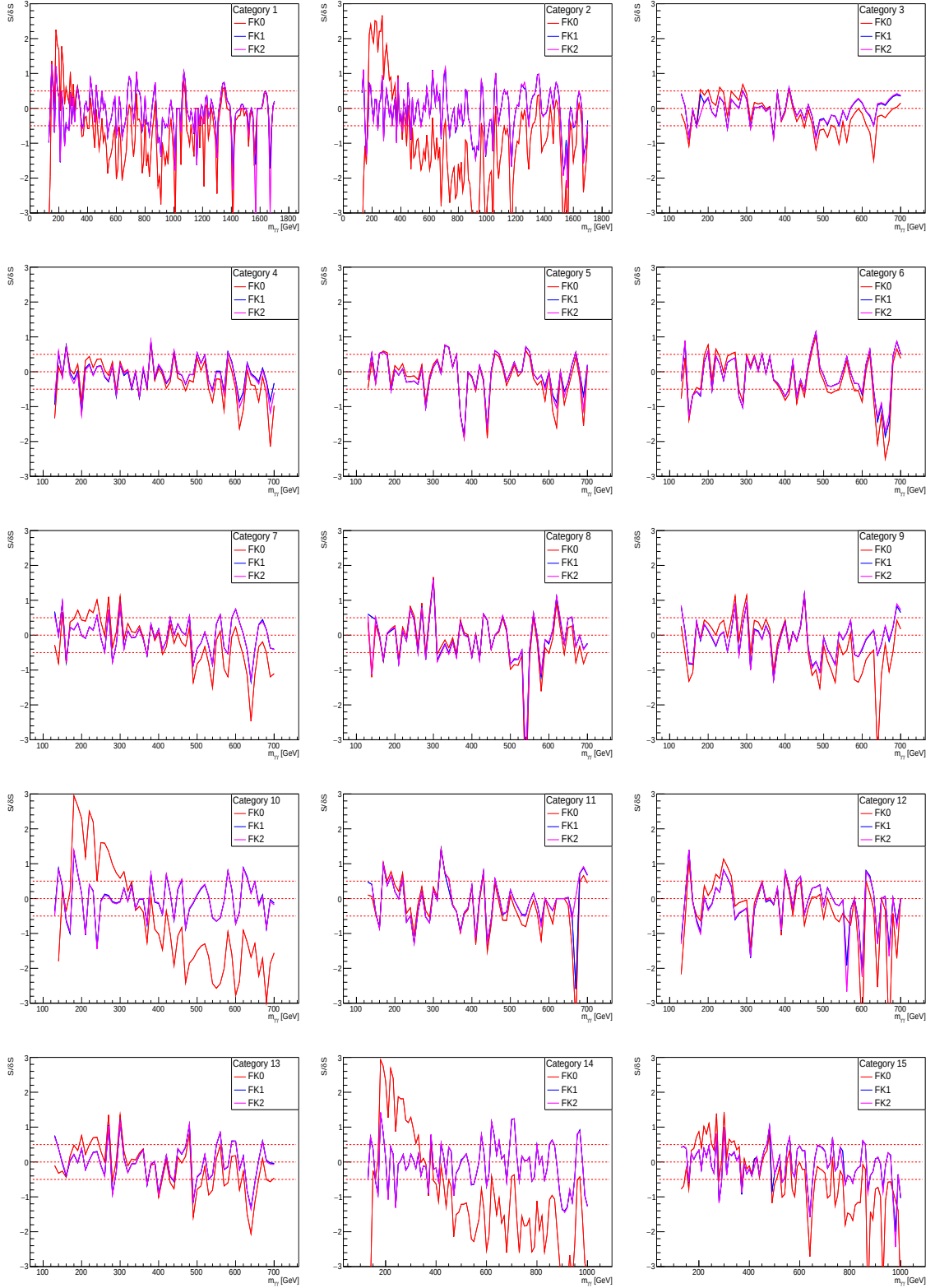


Figure C.25: The $N_{spurious}/\delta N_{spurious}$ as a function of mass for each functional form using raw background.

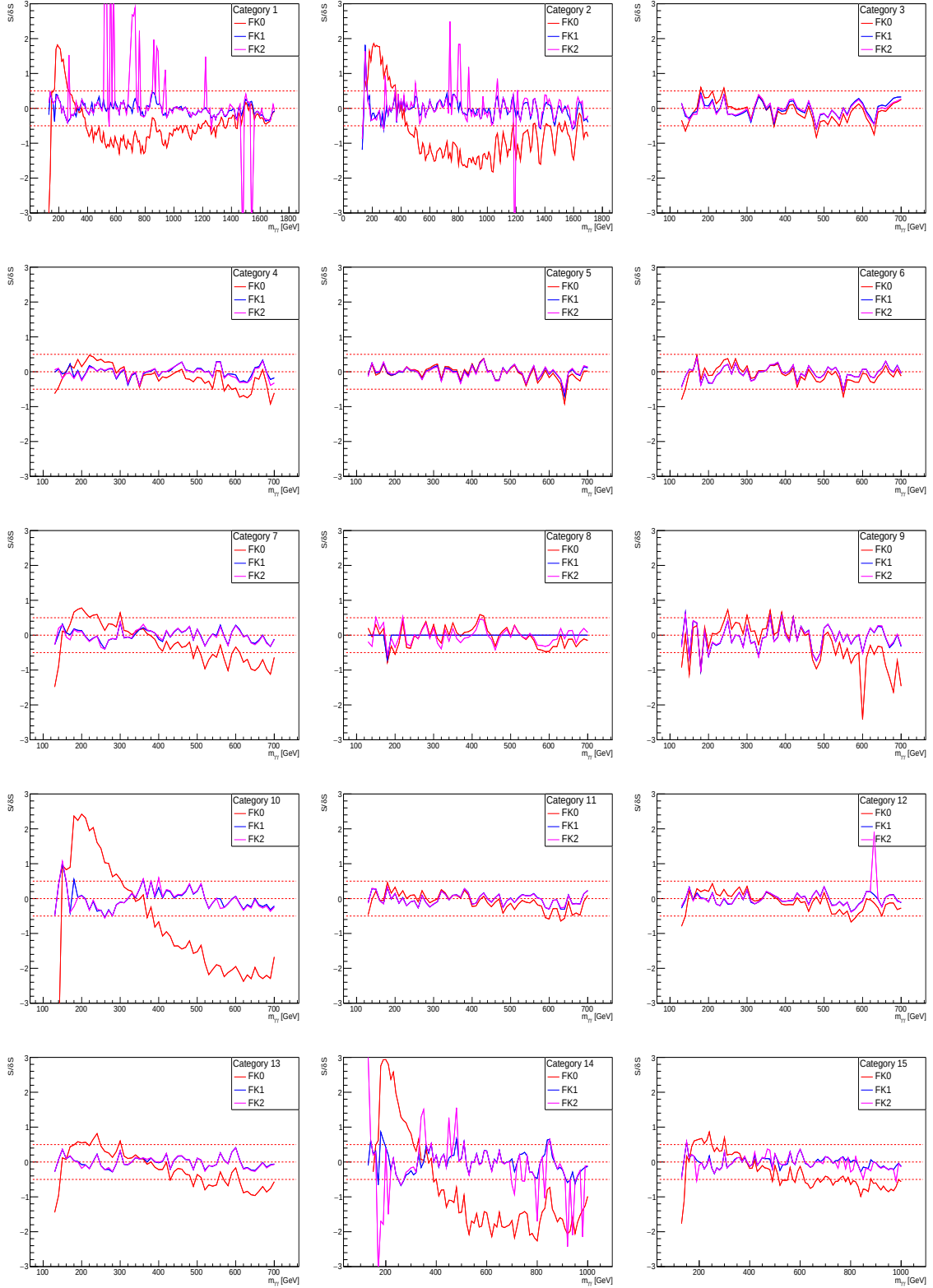


Figure C.26: The $N_{spurious}/\delta N_{spurious}$ as a function of mass for each functional form using smoothed background.

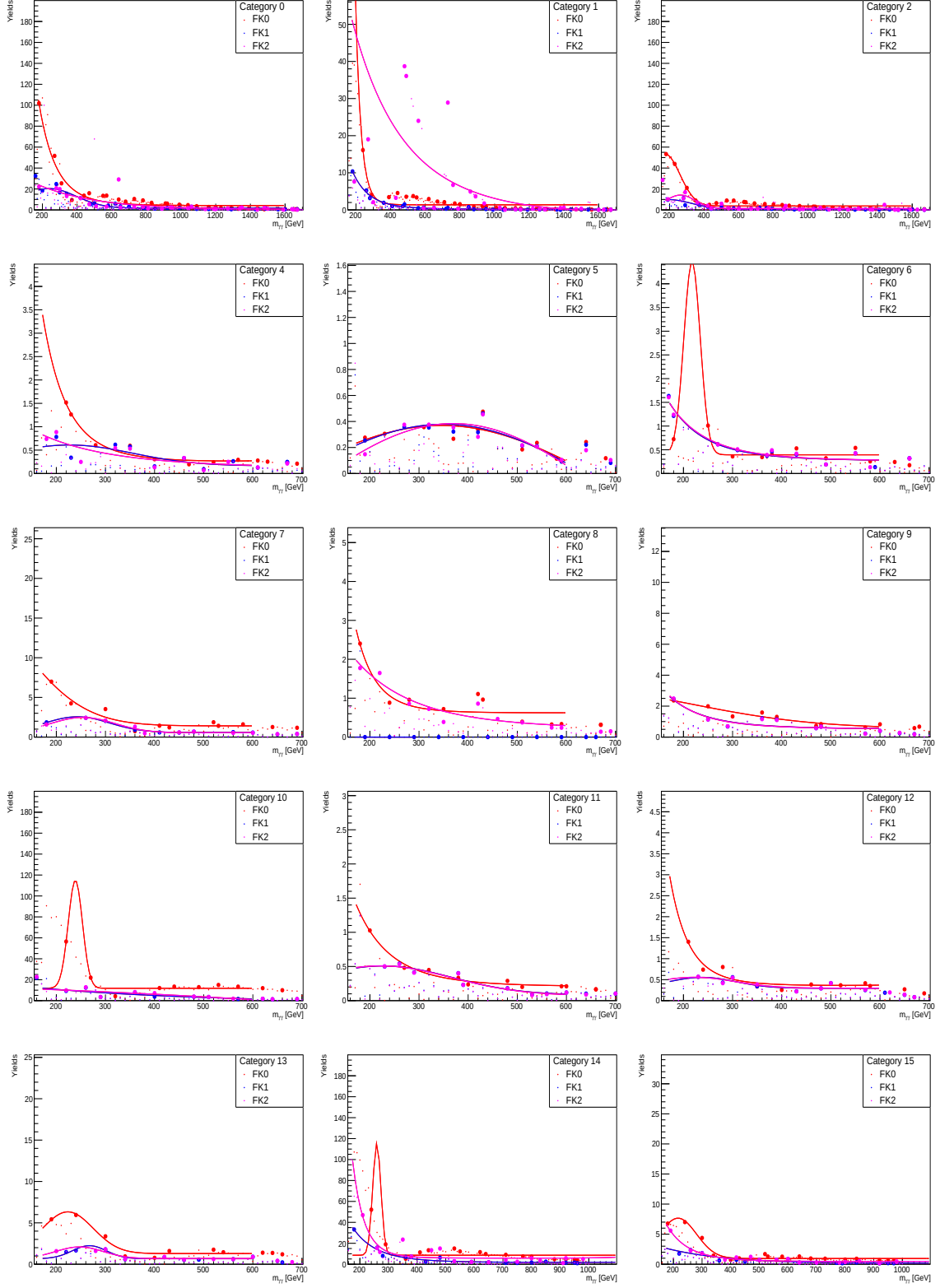


Figure C.27: The $N_{spurious}$ envelop for each functional form.

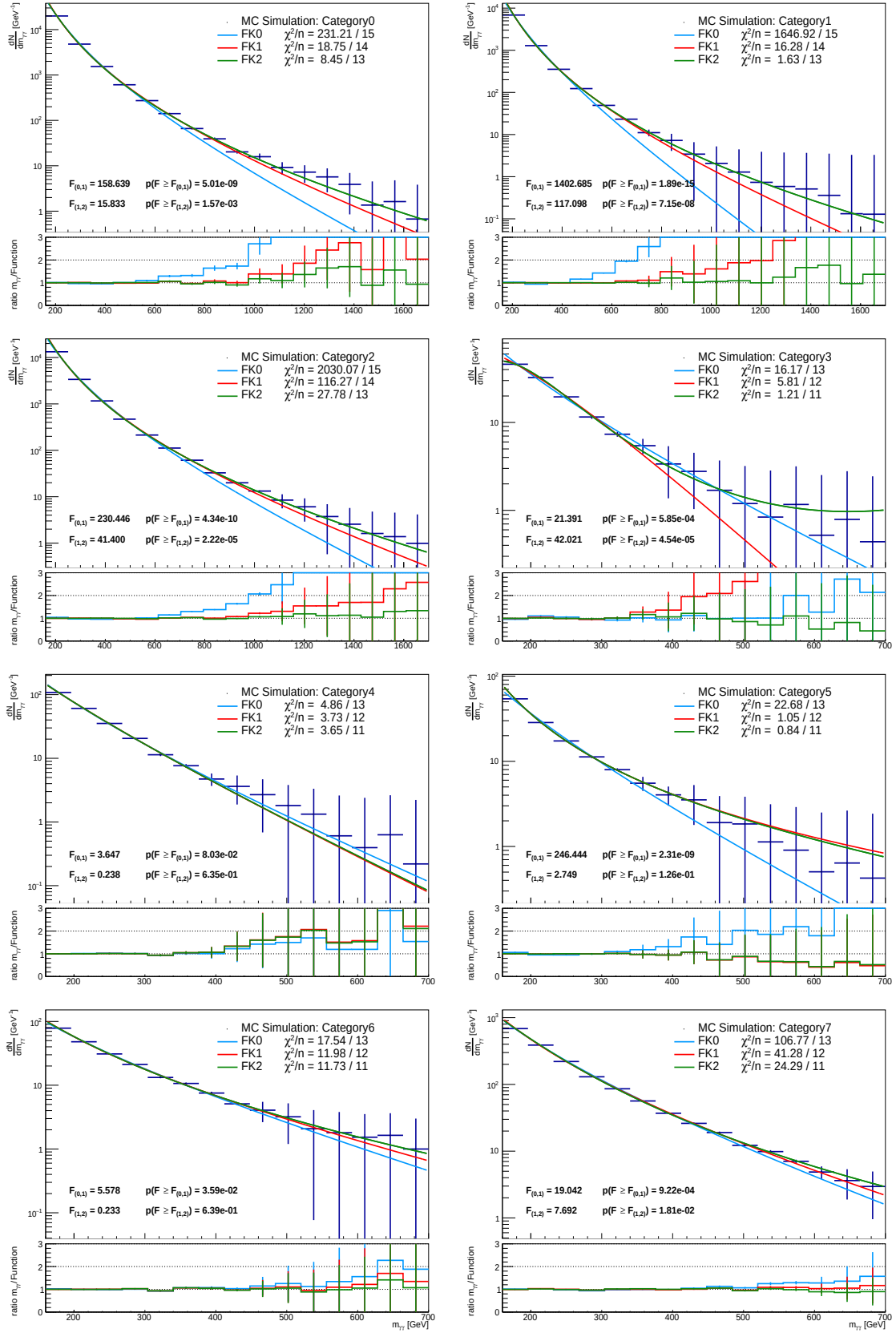


Figure C.28: Fitting on the background MC template for categories 0-7 using background functions.

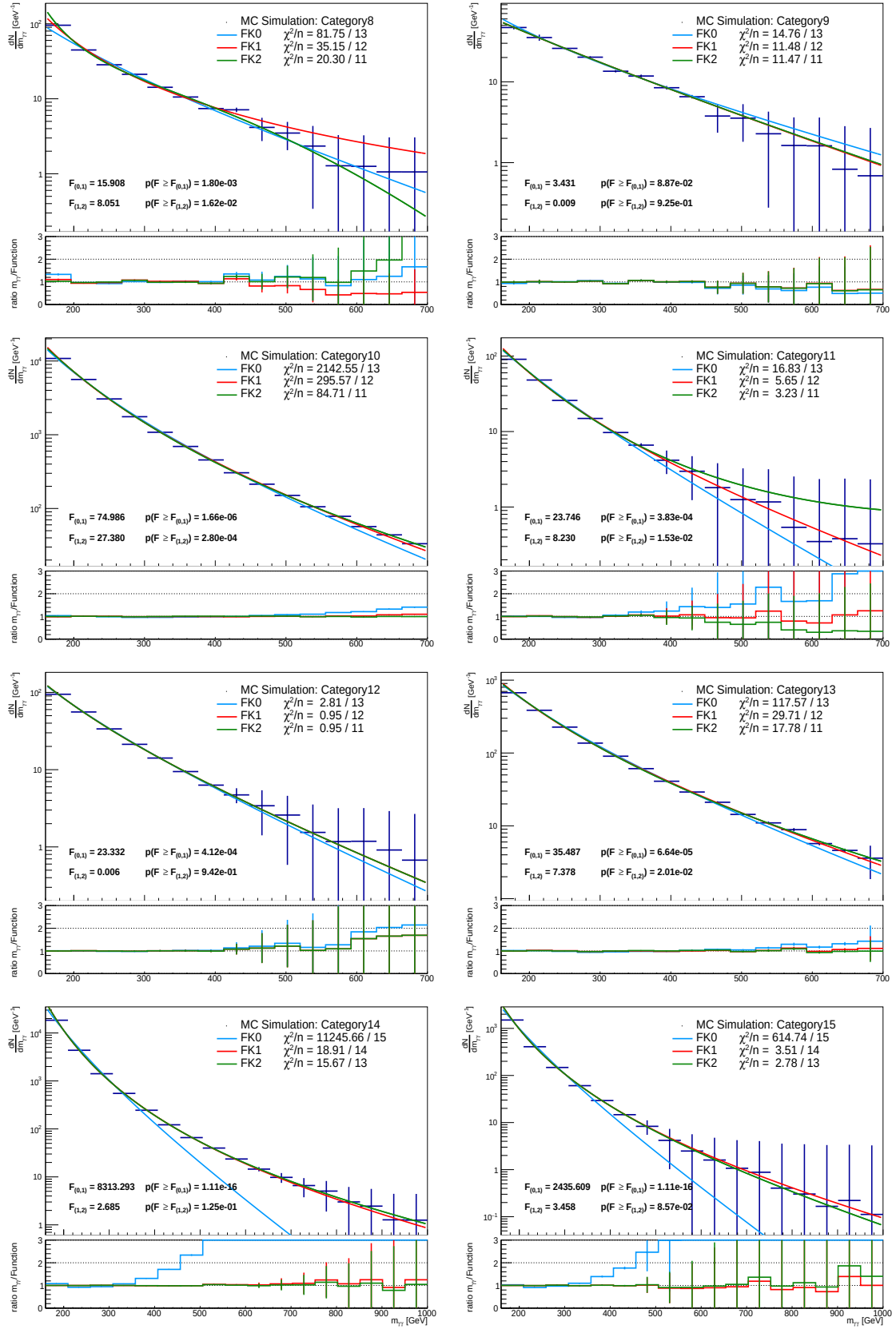


Figure C.29: Fitting on the background MC template for categories 8-15 using background functions.

Appendix D

ADDITIONAL PLOTS FOR SECTIONS 5.9

D.1 SYSTEMATIC UNCERTAINTIES

This appendix shows additional figures in support of the systematic uncertainties discussed in Section 5.9.1. The systematic uncertainties in the signal yields in each category are shown in Figure D.1 to Figure D.7. In each figure, the systematic terms are shown by combining all the nuisance parameters from similar sources, without considering the correlation. In the actual fit, each individual nuisance parameter is taken into account. The figure shows each systematic uncertainty as a function of the resonance mass. The systematic uncertainty in the signal shape is shown in Figure D.9 and Figure D.8.

D.2 STATISTICAL MODEL

Figure D.12-D.19 shows the $m_{\gamma\gamma}$ distribution as well as the analytical fits to the Asimov data obtained from the MC background templates, with the signal mass at 180 GeV. The fit range starts from 130 GeV and ends at 1700 GeV. The scan range of the signals range from 160 to 1600 GeV. The scan step is 1 GeV below 400 GeV, 2 GeV up to 900 GeV, 3 GeV up to 1200 GeV and 5 GeV for the rest.

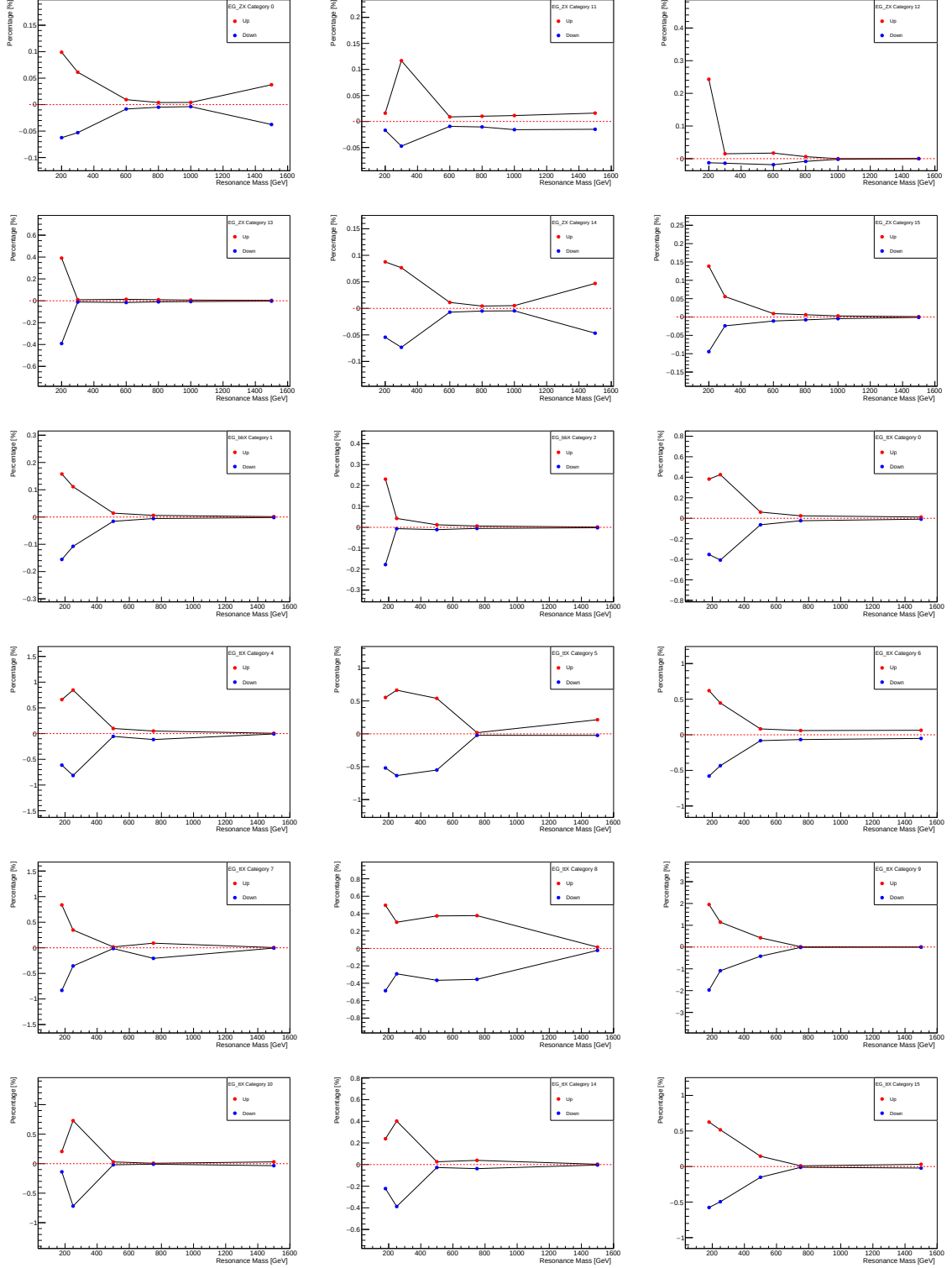


Figure D.1: The systematic uncertainty due to $e - \gamma$ scale and resolution affecting the signal yields as a function of the resonance mass in each category.

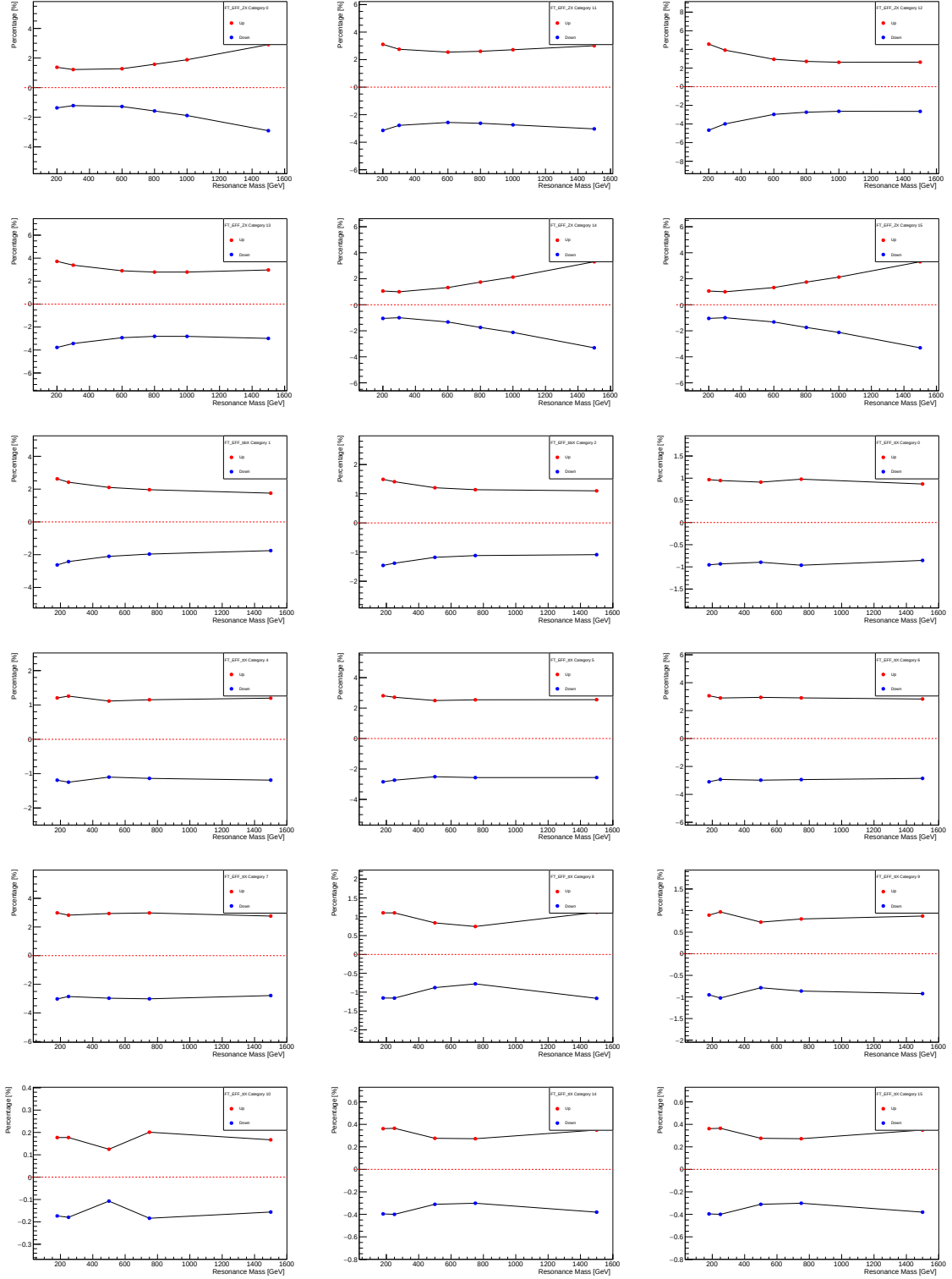


Figure D.2: The systematic uncertainty due to the b -tagging as a function of the resonance mass in each category.

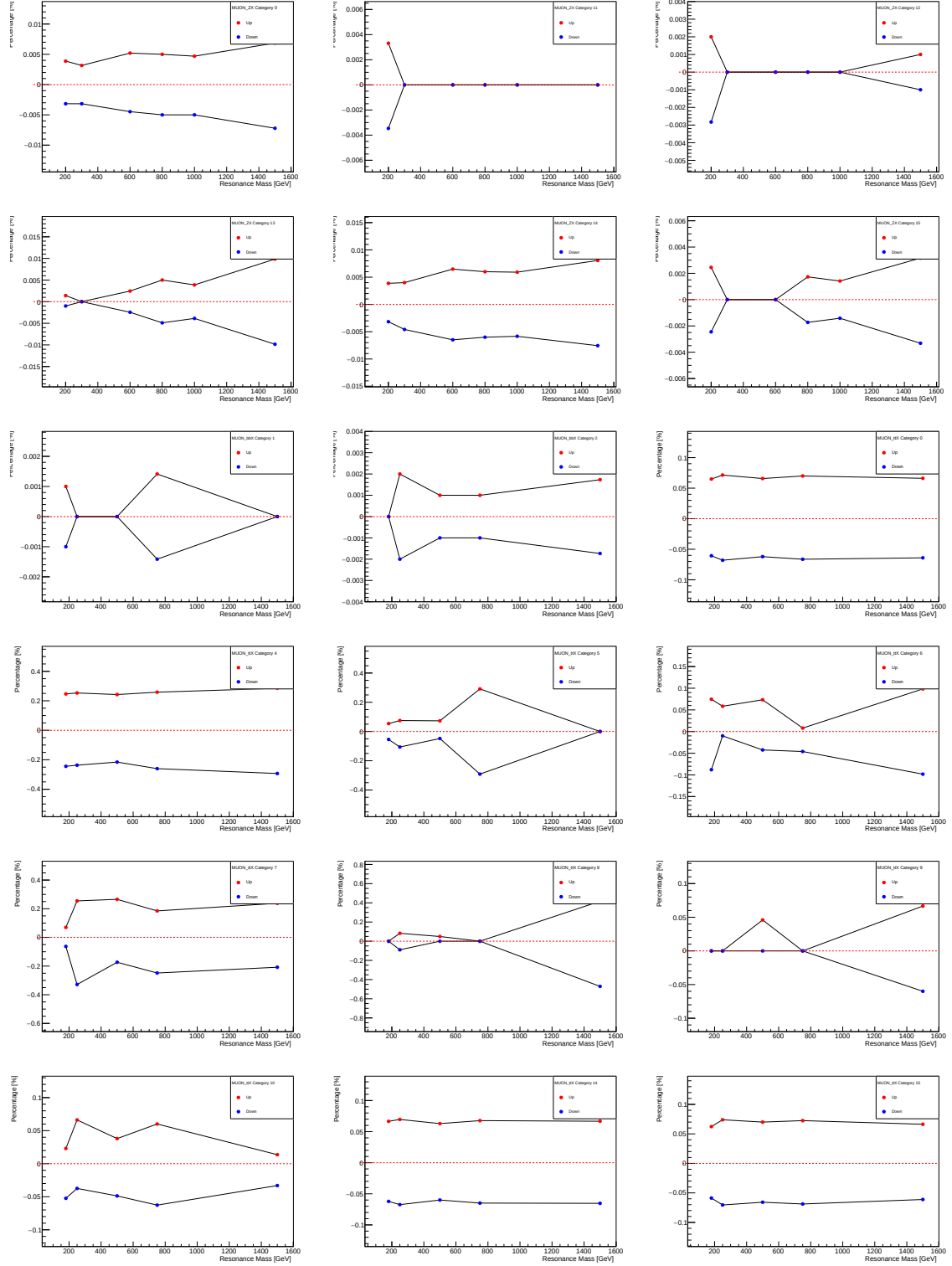


Figure D.3: The systematic uncertainty due to muon selection efficiency as a function of the resonance mass in each category.

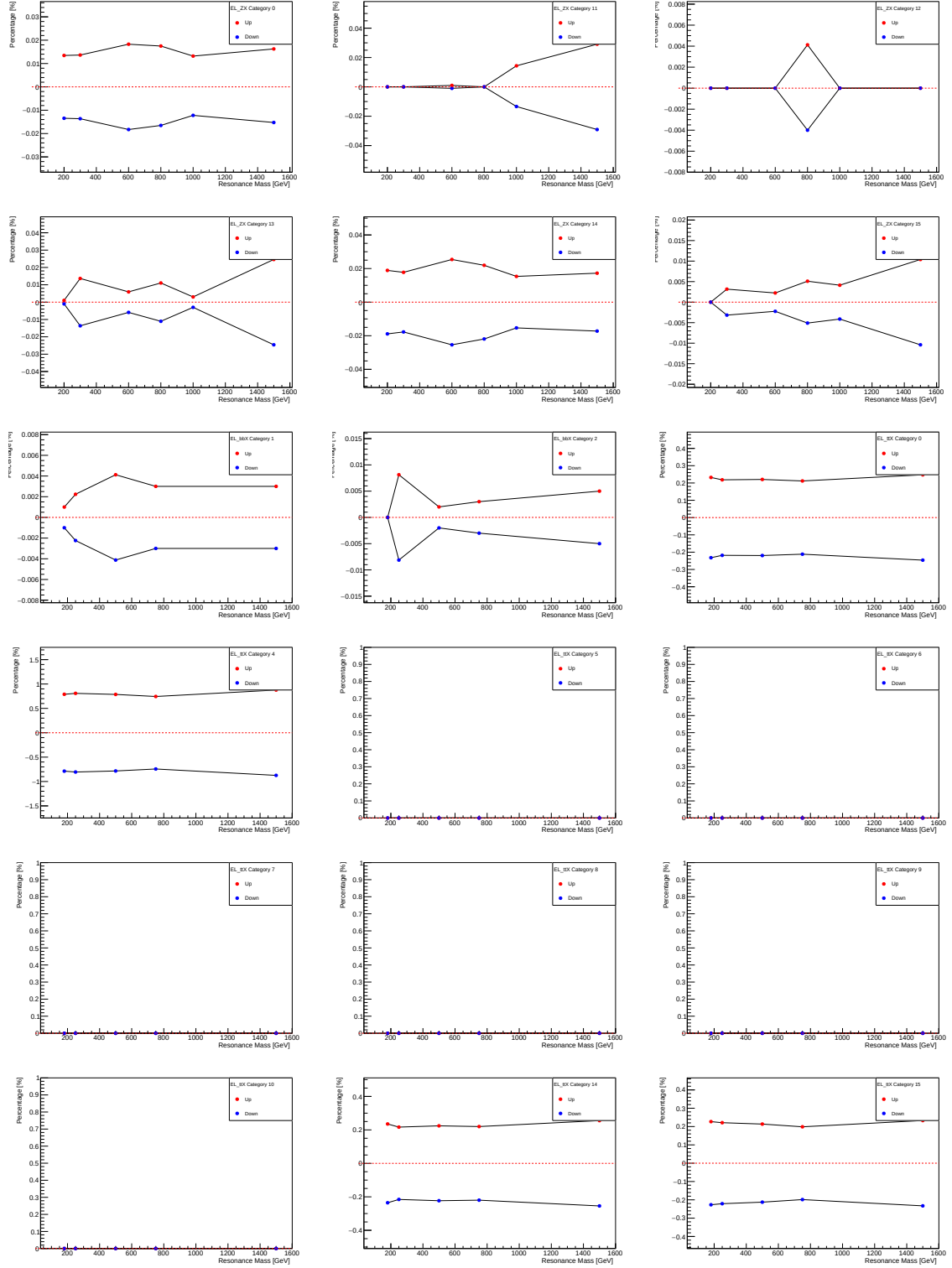


Figure D.4: The systematic uncertainty due to electron selection efficiency as a function of the resonance mass in each category.

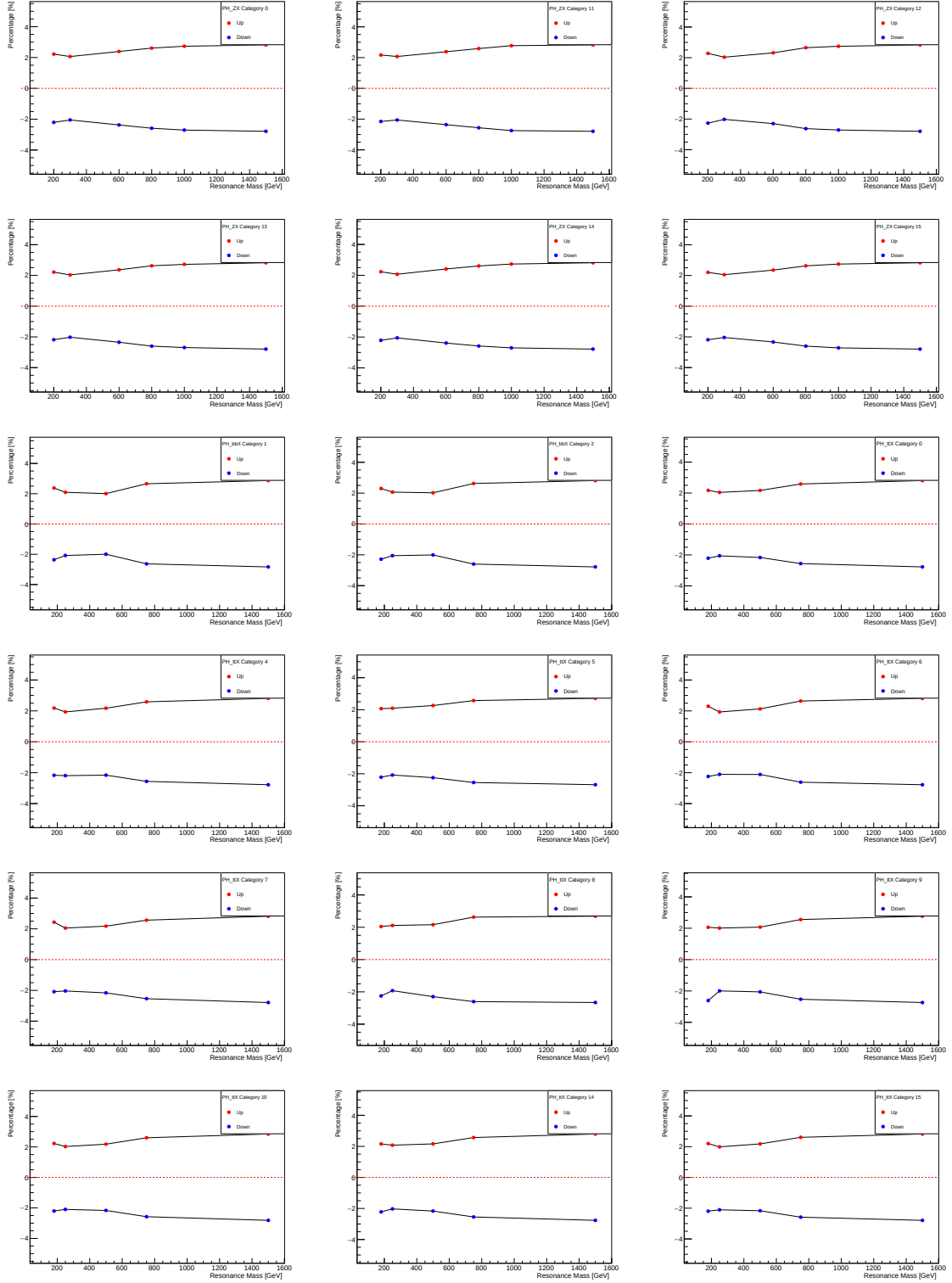


Figure D.5: The systematic uncertainty due to photon selection efficiency as a function of the resonance mass in each category.

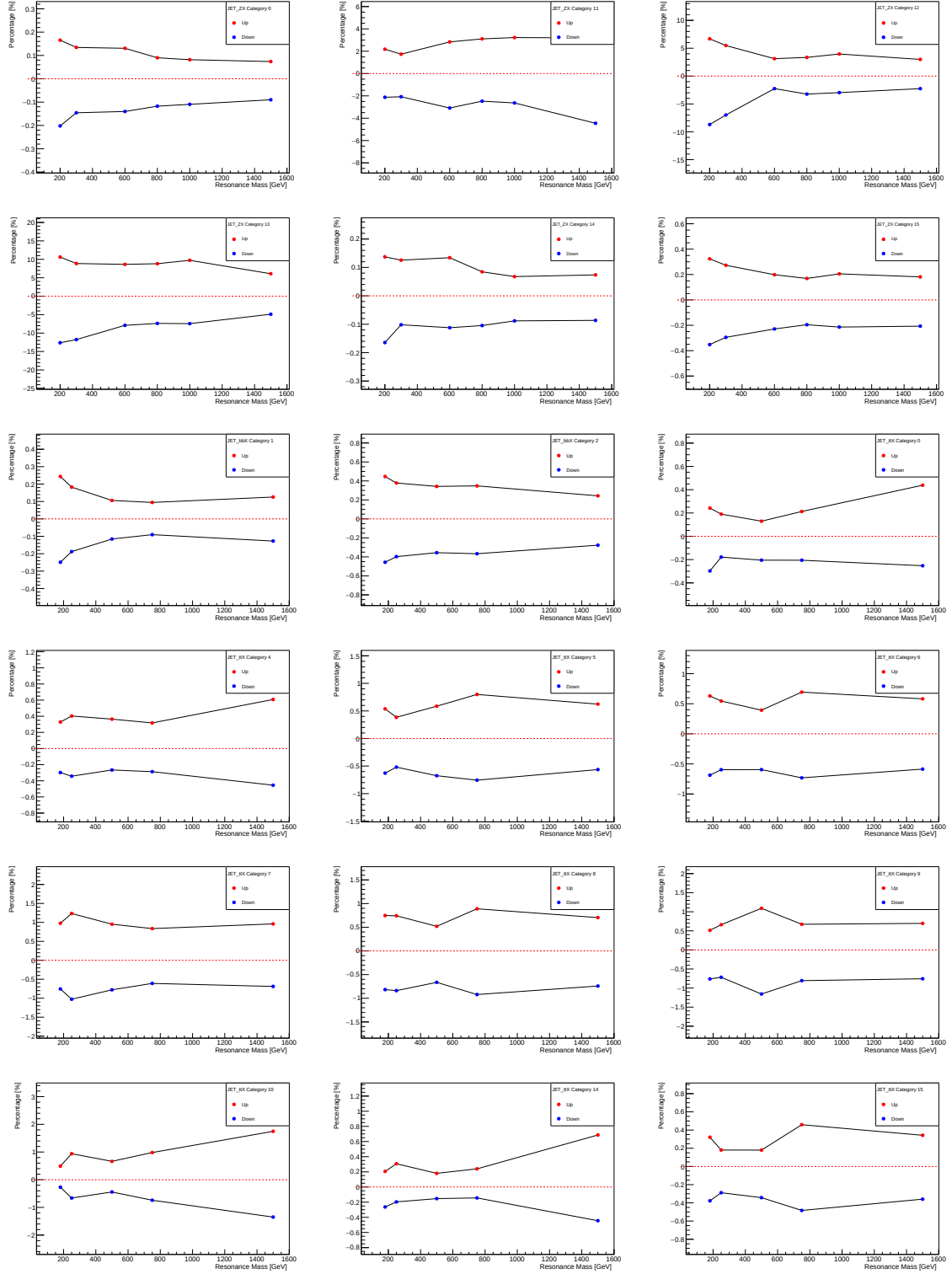


Figure D.6: The systematic uncertainty due to jet energy resolution, energy scale and selection efficiency as a function of the resonance mass in each category.

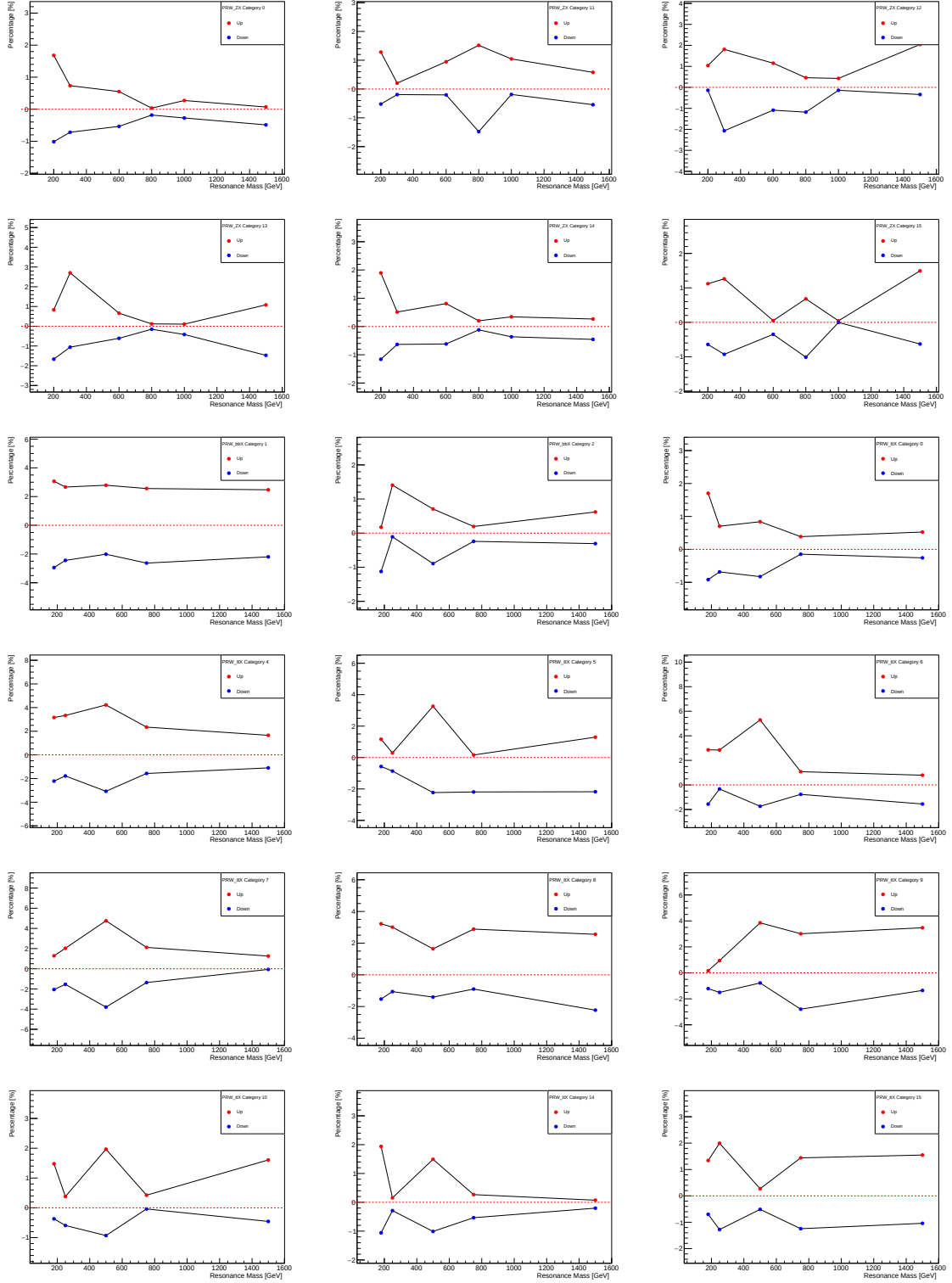


Figure D.7: The systematic uncertainty due to pile-up reweighting as a function of the resonance mass in each category.

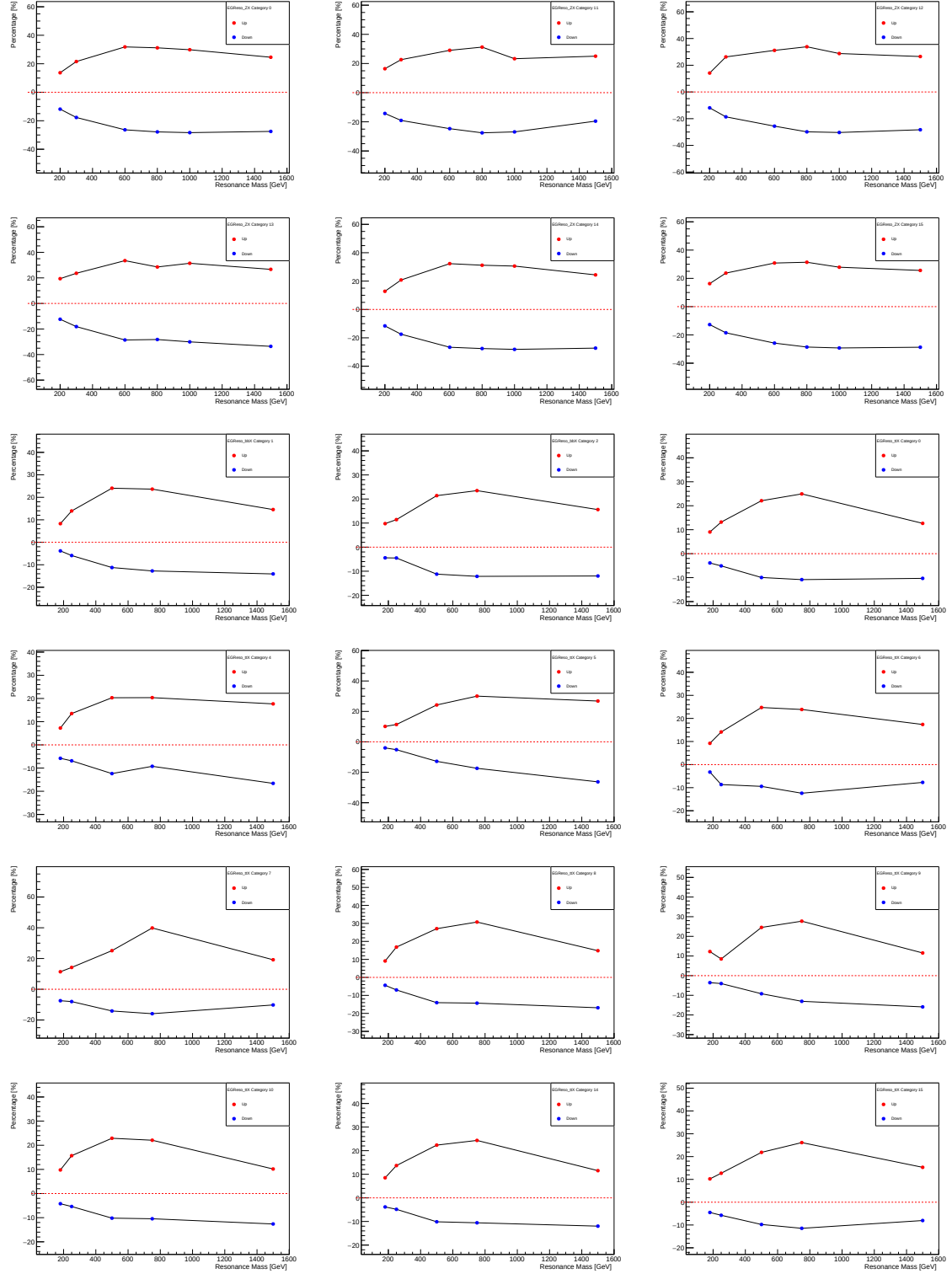


Figure D.8: The systematic uncertainty of $e - \gamma$ resolution in the signal shape as a function of the resonance mass in each category.

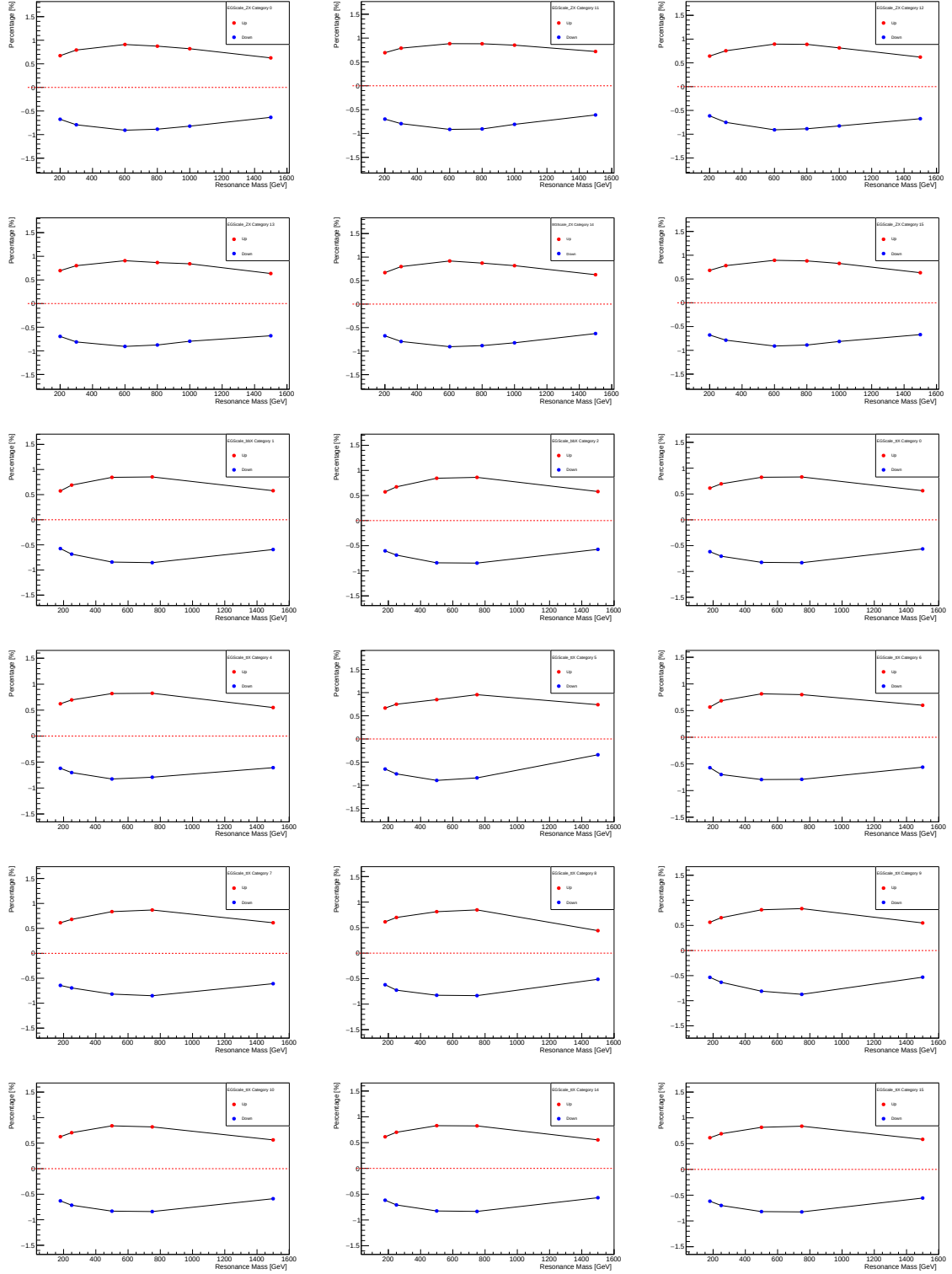


Figure D.9: The systematic uncertainty of $e - \gamma$ scale in the signal shape as a function of the resonance mass in each category.

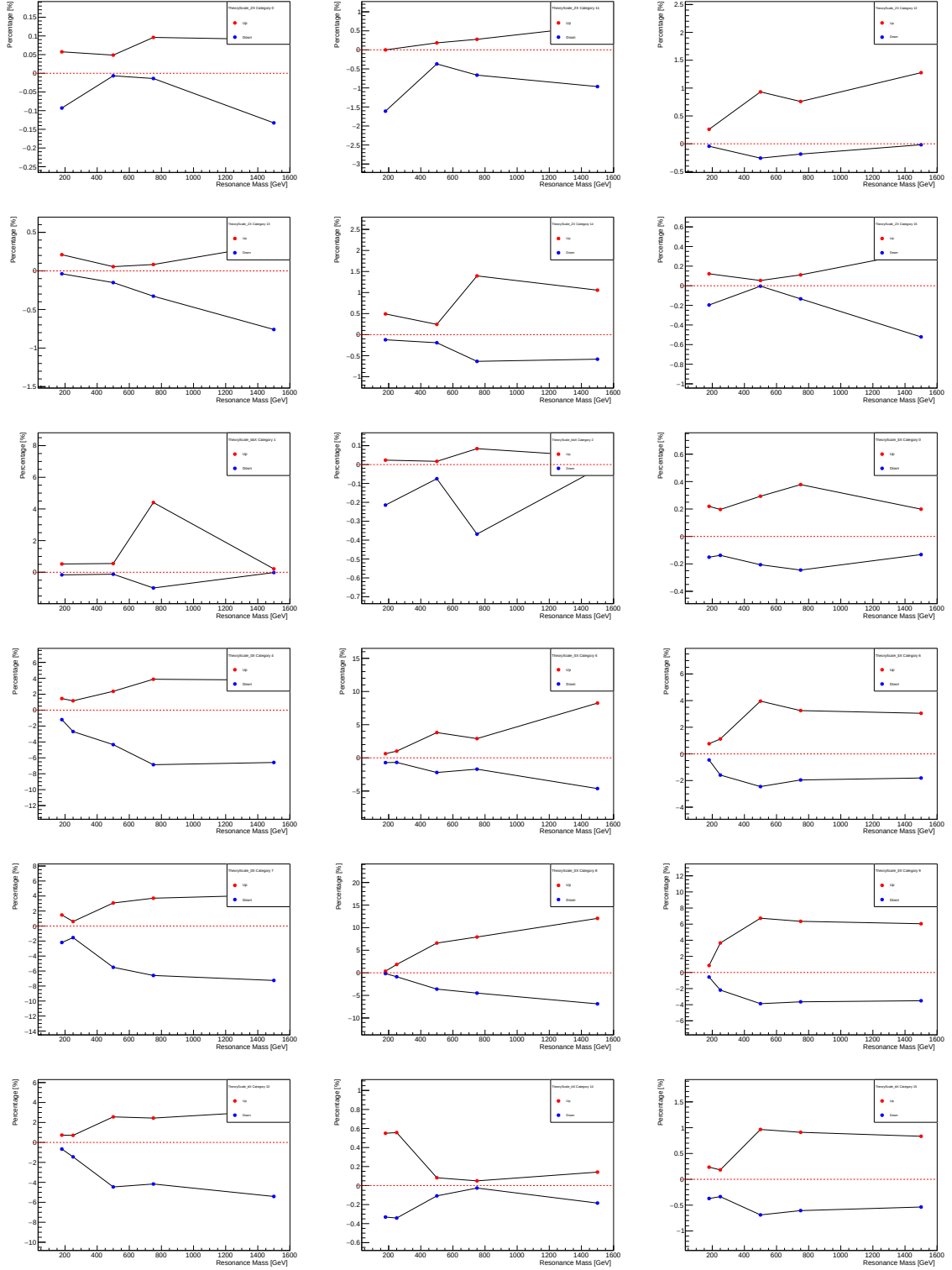


Figure D.10: The scale uncertainty in the migration of the signal yields as a function of the resonance mass in each category.

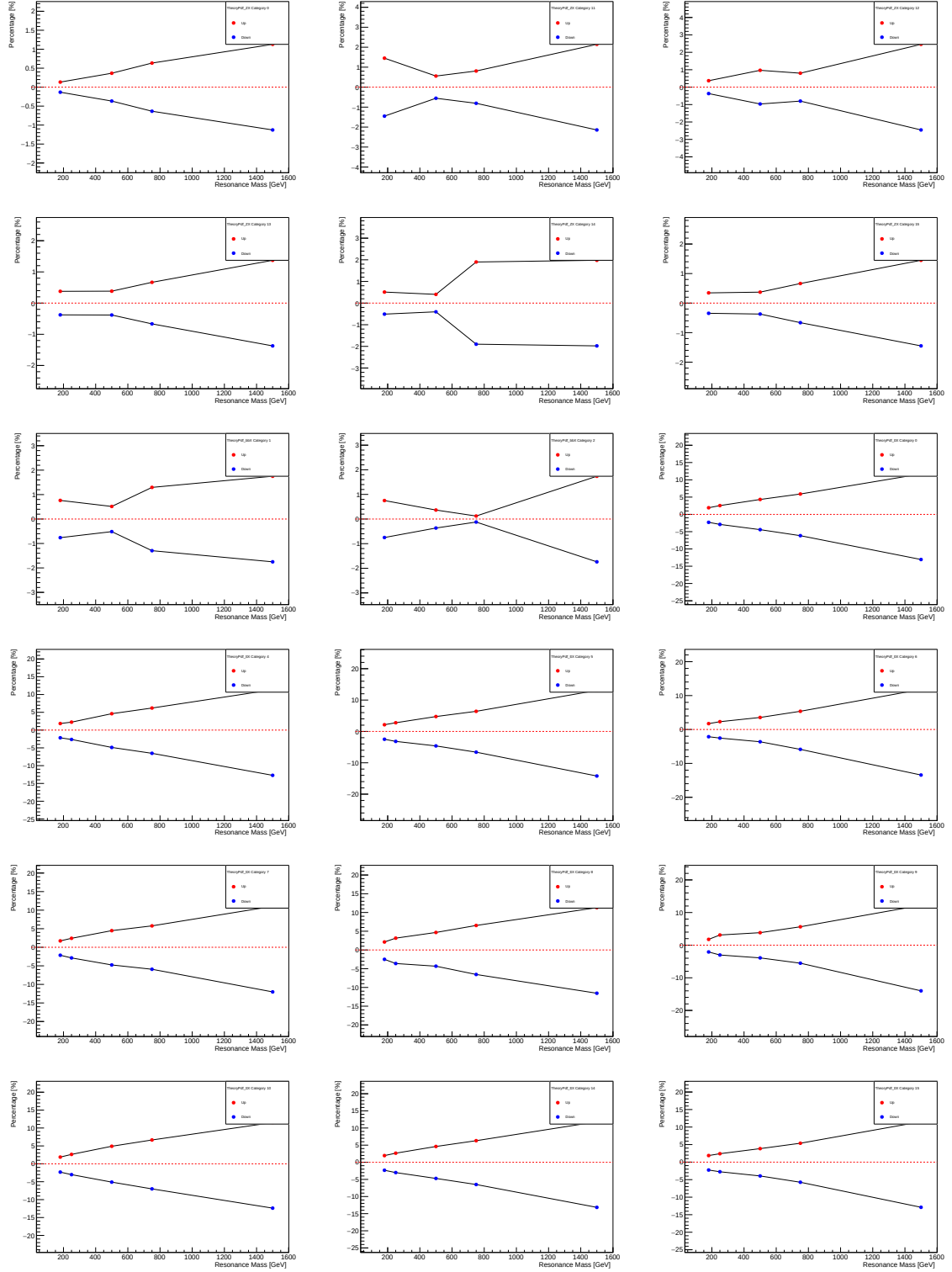


Figure D.11: The PDF+ α_S uncertainty in the migration of the signal yields as a function of the resonance mass in each category.

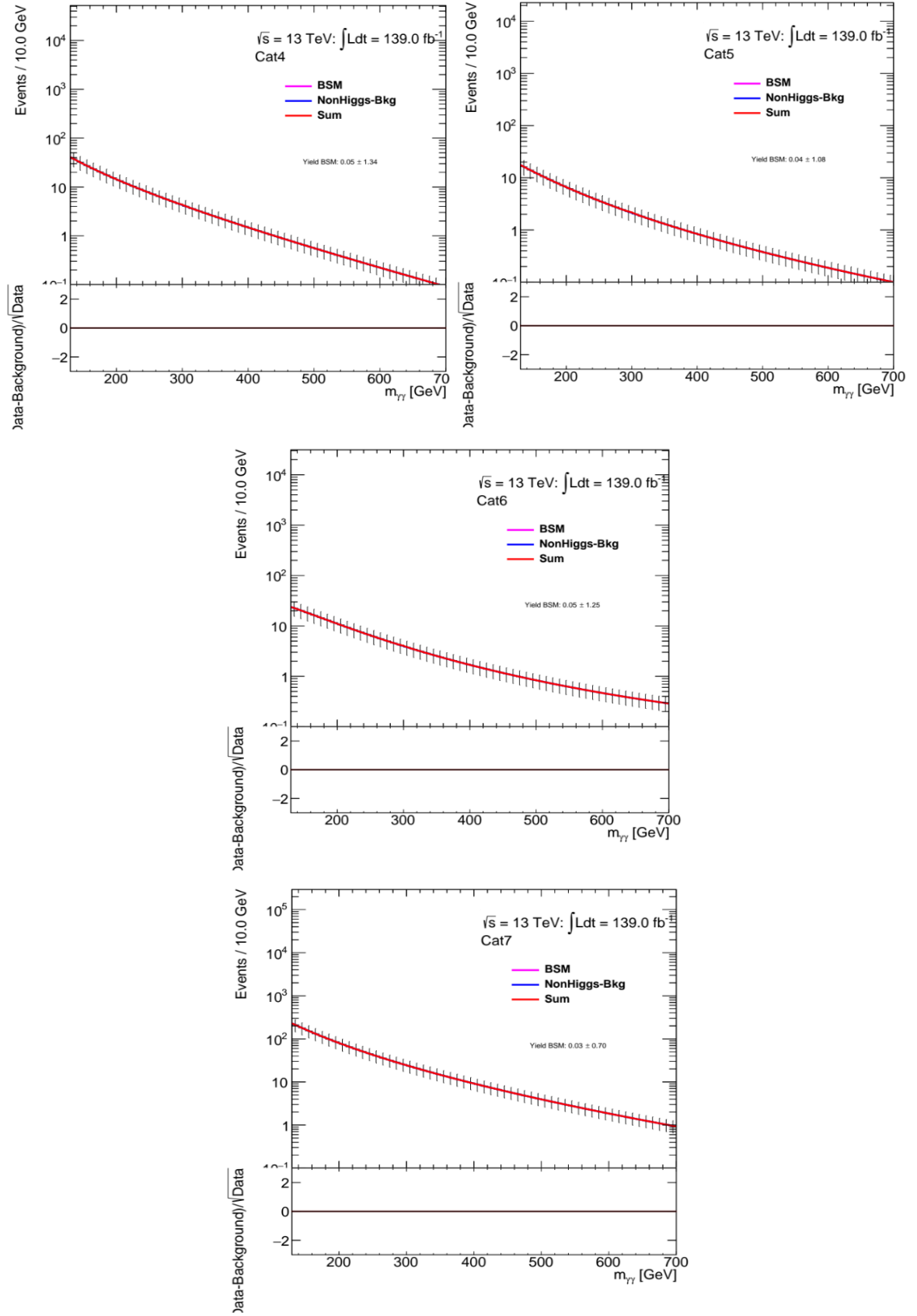


Figure D.12: The fit on the background only Asimov data based on the MC background template in the $t\bar{t}X$ channel with 300 GeV signal.

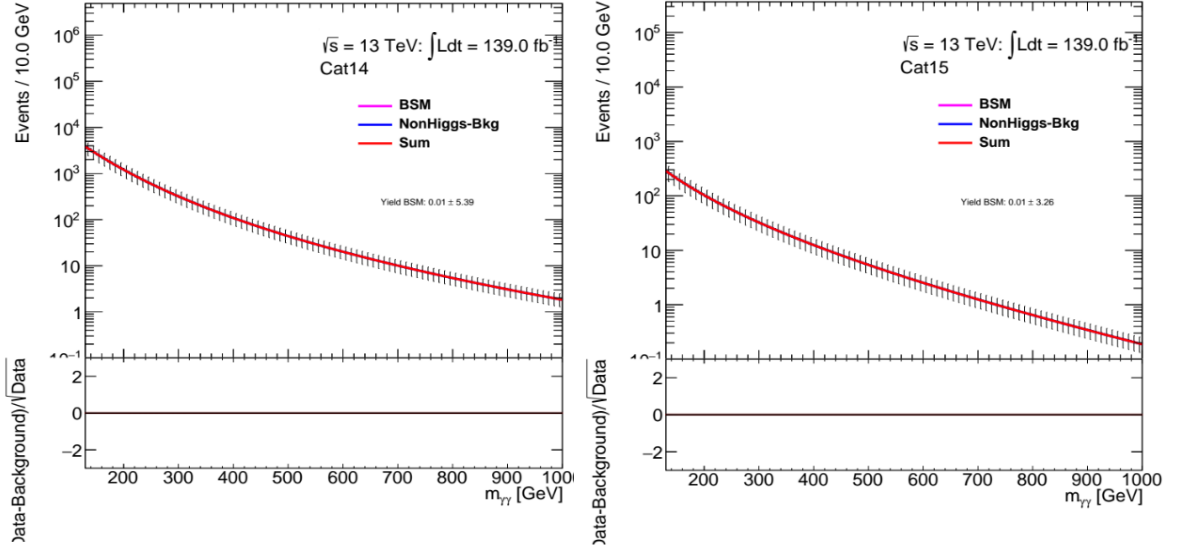


Figure D.13: The fit on the background only Asimov data based on the MC background template in the $t\bar{t}X$ channel with 800 GeV signal.

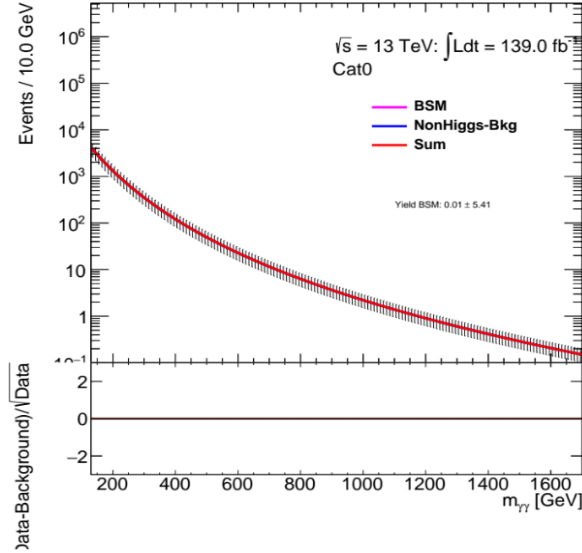


Figure D.14: The fit on the background only Asimov data based on the MC background template in the $t\bar{t}X$ channel with 1200 GeV signal.

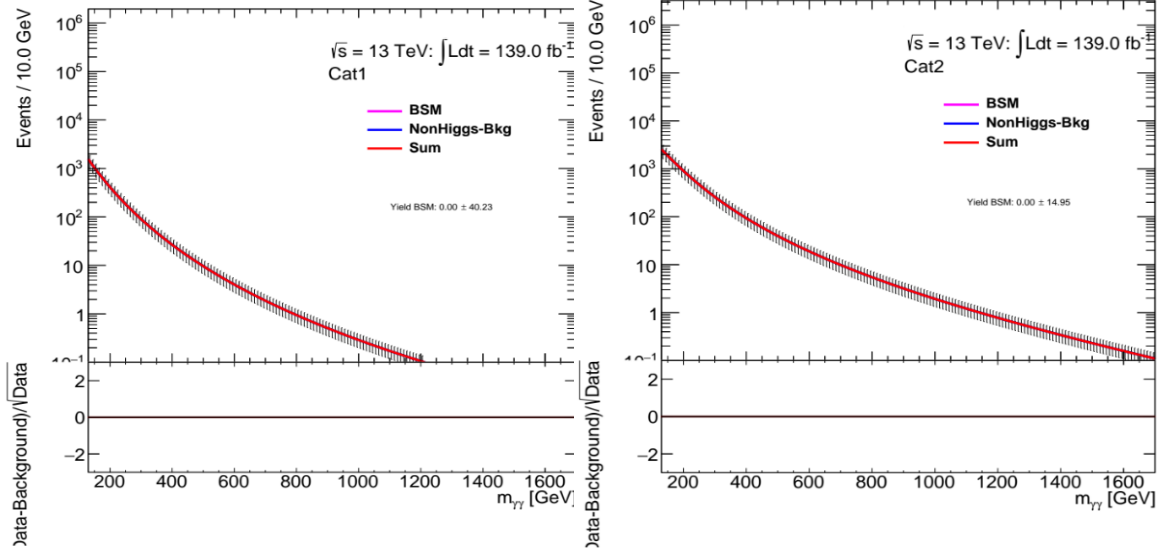


Figure D.15: The fit on the background only Asimov data based on the MC background template in the $b\bar{b}X$ channel with 300 GeV signal.

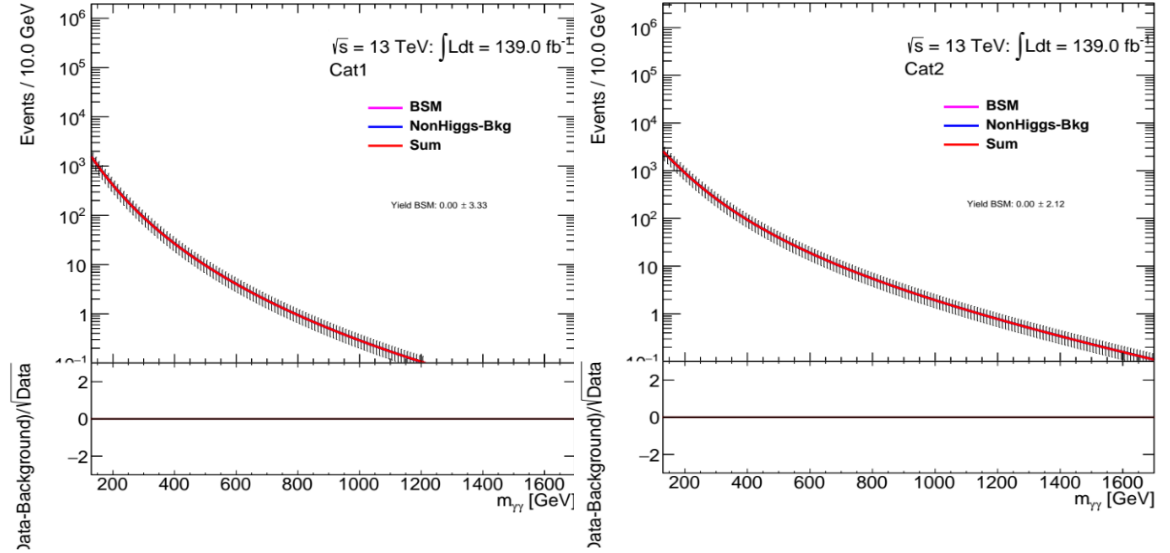


Figure D.16: The fit on the background only Asimov data based on the MC background template in the $b\bar{b}X$ channel with 1200 GeV signal.

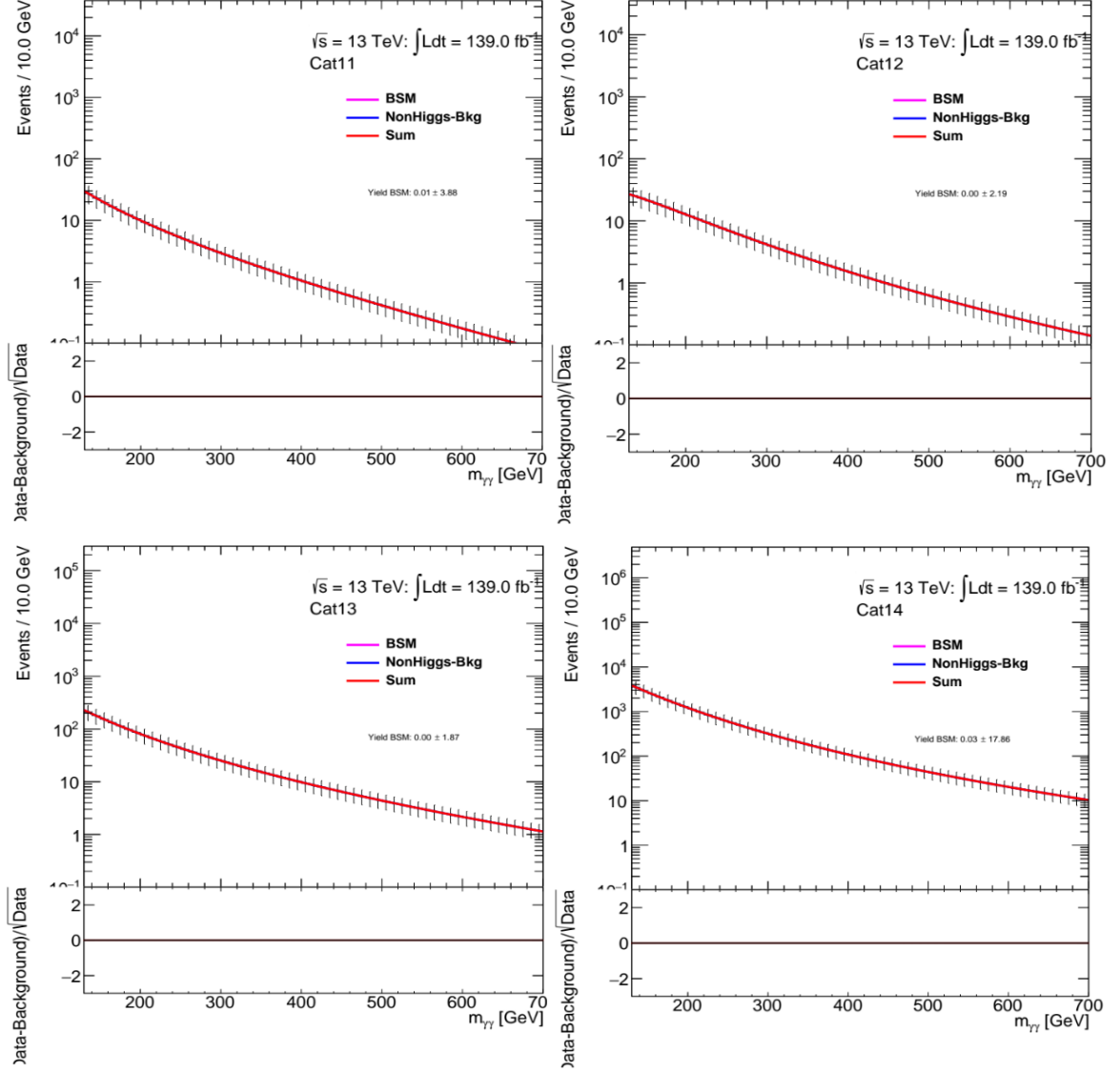


Figure D.17: The fit on the background only Asimov data based on the MC background template in the ZX channel with 300 GeV signal.

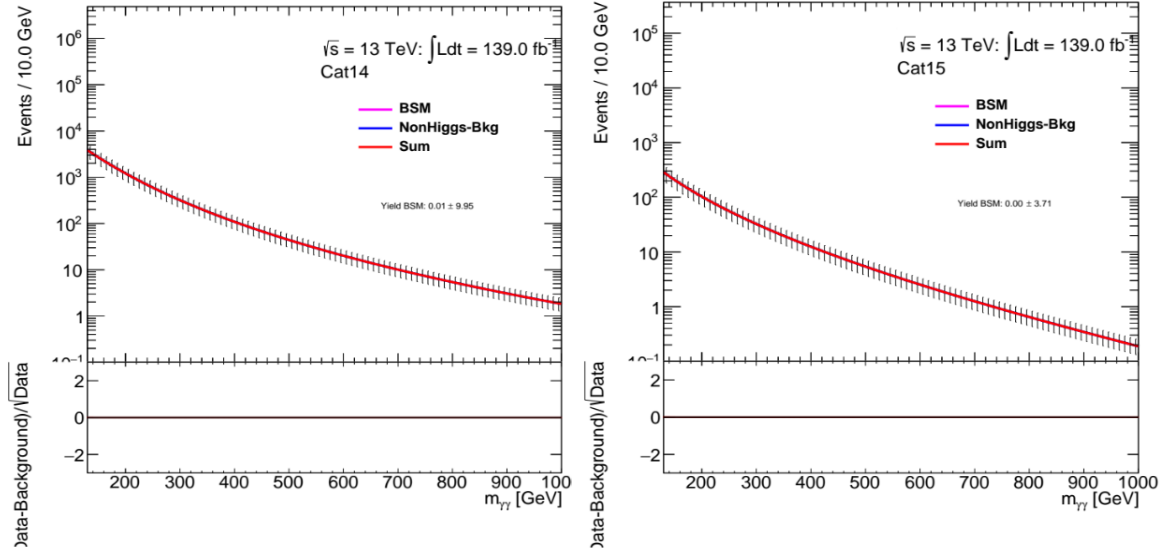


Figure D.18: The fit on the background only Asimov data based on the MC background template in the ZX channel with 800 GeV signal.

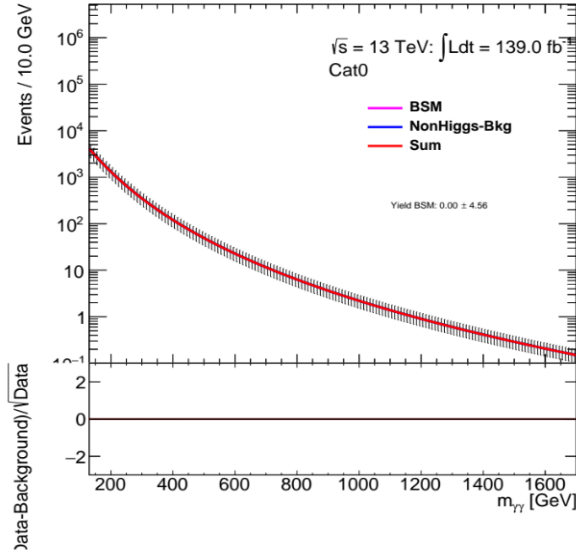


Figure D.19: The fit on the background only Asimov data based on the MC background template in the ZX channel with 1200 GeV signal.

REFERENCES

- [1] Stefan von Buddenbrock, Alan S. Cornell, Abdualazem Fadol, Mukesh Kumar, Bruce Mellado, and Xifeng Ruan. [Multi-lepton signatures of additional scalar bosons beyond the Standard Model at the LHC](#). *J. Phys. G*, 45(11):115003, 2018, 1711.07874. (pages [ii](#), [2](#), [41](#), [42](#), [48](#), [50](#), [52](#), [55](#), [62](#), [63](#), [116](#), [117](#)).
- [2] S. L. Glashow, J. Iliopoulos, and L. Maiani. [Weak Interactions with Lepton-Hadron Symmetry](#). *Phys. Rev. D*, 2:1285–1292, 1970. (pages [1](#), [4](#)).
- [3] Steven Weinberg. [A Model of Leptons](#). *Phys. Rev. Lett.*, 19:1264–1266, 1967. (pages [1](#), [4](#)).
- [4] Abdus Salam. [Weak and Electromagnetic Interactions](#). *Conf. Proc. C*, 680519:367–377, 1968. (pages [1](#), [4](#)).
- [5] ATLAS Collaboration. [Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC](#). *Phys. Lett. B*, 716:1–29, 2012, 1207.7214. (pages [1](#), [20](#), [23](#), [24](#), [25](#)).
- [6] CMS Collaboration. [Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC](#). *Phys. Lett. B*, 716:30–61, 2012, 1207.7235. (pages [1](#), [20](#), [23](#), [24](#), [25](#)).
- [7] G. C. Branco, P. M. Ferreira, L. Lavoura, M. N. Rebelo, Marc Sher, and Joao P. Silva. [Theory and phenomenology of two-Higgs-doublet models](#). *Phys. Rept.*, 516:1–102, 2012, 1106.0034. (pages [2](#), [20](#), [41](#)).
- [8] Margarete Mühlleitner, Marco O. P. Sampaio, Rui Santos, and Jonas Wittbrodt. [Phenomenological Comparison of Models with Extended Higgs Sectors](#). *JHEP*, 08:132, 2017, 1703.07750. (pages [2](#), [41](#)).
- [9] Luigi Delle Rose, Oliver Fischer, and A. Hammad. [Prospects for Heavy Scalar Searches at the LHeC](#). *Int. J. Mod. Phys. A*, 34(23):1950127, 2019, 1809.04321. (pages [2](#), [41](#)).
- [10] Stefan von Buddenbrock, Nabarun Chakrabarty, Alan S. Cornell, Deepak Kar, Mukesh Kumar, Tanumoy Mandal, Bruce Mellado, Biswarup Mukhopadhyaya, and Robert G. Reed. [The compatibility of LHC Run 1 data with a heavy scalar of mass around 270\,GeV](#). June 2015, 1506.00612. (pages [2](#), [41](#), [42](#), [45](#), [55](#), [62](#)).

- [11] Mukesh Kumar, Stefan von Buddenbrock, Nabarun Chakrabarty, Alan S. Cornell, Deepak Kar, Tanumoy Mandal, Bruce Mellado, Biswarup Mukhopadhyaya, and Robert G. Reed. [The impact of additional scalar bosons at the LHC](#). *J. Phys. Conf. Ser.*, 802(1):012007, 2017, 1603.01208. (pages [2](#), [41](#)).
- [12] Stefan von Buddenbrock, Nabarun Chakrabarty, Alan S. Cornell, Deepak Kar, Mukesh Kumar, Tanumoy Mandal, Bruce Mellado, Biswarup Mukhopadhyaya, Robert G. Reed, and Xifeng Ruan. [Phenomenological signatures of additional scalar bosons at the LHC](#). *Eur. Phys. J. C*, 76(10):580, 2016, 1606.01674. (pages [2](#), [41](#), [42](#), [43](#), [45](#), [48](#), [51](#), [52](#), [54](#), [55](#), [62](#)).
- [13] Stefan von Buddenbrock, Alan S. Cornell, Deepak Kar, Mukesh Kumar, Bruce Mellado, and Robert G. Reed. [A heavy scalar of mass 270 GeV and its possible connection to the 750 GeV excess](#). *J. Phys. Conf. Ser.*, 802(1):012001, 2017. (pages [2](#), [41](#), [45](#)).
- [14] Stefan von Buddenbrock, Alan S. Cornell, Mukesh Kumar, and Bruce Mellado. [The Madala hypothesis with Run 1 and 2 data at the LHC](#). *J. Phys. Conf. Ser.*, 889(1):012020, 2017, 1709.09419. (pages [2](#), [41](#), [46](#)).
- [15] Stefan Buddenbrock, Alan S. Cornell, Yaquan Fang, Abdualazem Fadol Mohammed, Mukesh Kumar, Bruce Mellado, and Kehinde G. Tomiwa. [The emergence of multi-lepton anomalies at the LHC and their compatibility with new physics at the EW scale](#). *JHEP*, 10:157, 2019, 1901.05300. (pages [2](#), [41](#)).
- [16] David Galbraith and Carsten Burgard. [The CERN Webfest](#). 2012. (page [5](#)).
- [17] M. Tanabashi et al. [Review of Particle Physics](#). *Phys. Rev. D*, 98(3):030001, 2018. (pages [6](#), [16](#)).
- [18] Raymond Brock et al. [Handbook of perturbative QCD; Version 1.1: September 1994](#). Sept 1994. (page [6](#)).
- [19] T. Nakano and K. Nishijima. [Charge Independence for V-particles](#). *Prog. Theor. Phys.*, 10:581–582, 1953. (page [6](#)).
- [20] M. Gell-Mann. [The interpretation of the new particles as displaced charge multiplets](#). *Nuovo Cim.*, 4(S2):848–866, 1956. (page [6](#)).
- [21] Peter W. Higgs. [Broken symmetries, massless particles and gauge fields](#). *Phys. Lett.*, 12:132–133, 1964. (pages [6](#), [7](#)).
- [22] Peter W. Higgs. [Broken Symmetries and the Masses of Gauge Bosons](#). *Phys. Rev. Lett.*, 13:508–509, 1964. (page [6](#)).

- [23] F. Englert and R. Brout. [Broken Symmetry and the Mass of Gauge Vector Mesons](#). *Phys. Rev. Lett.*, 13:321–323, 1964. (page 6).
- [24] G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble. [Global Conservation Laws and Massless Particles](#). *Phys. Rev. Lett.*, 13:585–587, 1964. (page 6).
- [25] Peter W. Higgs. [Spontaneous Symmetry Breakdown without Massless Bosons](#). *Phys. Rev.*, 145:1156–1163, 1966. (page 6).
- [26] T.W.B. Kibble. [Symmetry breaking in nonAbelian gauge theories](#). *Phys. Rev.*, 155:1554–1561, 1967. (page 6).
- [27] J. Bernstein. [Spontaneous symmetry breaking, gauge theories, the higgs mechanism and all that](#). *Rev. Mod. Phys.*, 46:7–48, 1974. [Erratum: *Rev.Mod.Phys.* 47, 259–259 (1975), Erratum: *Rev.Mod.Phys.* 46, 855–855 (1974)]. (page 6).
- [28] Michael E Peskin and Daniel V Schroeder. [An introduction to quantum field theory](#). Westview, Boulder, CO, 1995. Includes exercises. (pages 6, 9).
- [29] Hideki Yukawa. [On the Interaction of Elementary Particles I](#). *Proc. Phys. Math. Soc. Jap.*, 17:48–57, 1935. (pages 6, 9).
- [30] Jeffrey Goldstone, Abdus Salam, and Steven Weinberg. [Broken Symmetries](#). *Phys. Rev.*, 127:965–970, 1962. (page 8).
- [31] W. Hollik. [Electroweak theory](#). *J. Phys. Conf. Ser.*, 53:7–43, 2006. (page 8).
- [32] G. Rajasekaran. [Fermi and the Theory of Weak Interactions](#). *Resonance J. Sci. Educ.*, 19(1):18–44, 2014, 1403.3309. (page 9).
- [33] Kurt Riesselmann. [Limitations of a standard model Higgs boson](#). In *International School of Subnuclear Physics, 35th Course: Highlights: 50 Years Later*, Sept 1997, hep-ph/9711456. (page 10).
- [34] Abdelhak Djouadi. [The Anatomy of electro-weak symmetry breaking. I: The Higgs boson in the standard model](#). *Phys. Rept.*, 457:1–216, 2008, hep-ph/0503172. (pages 10, 12, 13).
- [35] C. H. Llewellyn Smith. [High-Energy Behavior and Gauge Symmetry](#). *Phys. Lett. B*, 46:233–236, 1973. (page 10).
- [36] John M. Cornwall, David N. Levin, and George Tiktopoulos. [Uniqueness of spontaneously broken gauge theories](#). *Phys. Rev. Lett.*, 30:1268–1270, 1973. [Erratum: *Phys.Rev.Lett.* 31, 572 (1973)]. (page 10).

- [37] Abdesslam Arhrib. [Unitarity constraints on scalar parameters of the standard and two Higgs doublets model](#). In *Workshop on Noncommutative Geometry, Superstrings and Particle Physics*, Dec 2000, hep-ph/0012353. (page 10).
- [38] William J. Marciano, G. Valencia, and S. Willenbrock. [Renormalization Group Improved Unitarity Bounds on the Higgs Boson and Top Quark Masses](#). *Phys. Rev. D*, 40:1725, 1989. (page 10).
- [39] Thomas Hambye and Kurt Riesselmann. [Matching conditions and Higgs mass upper bounds revisited](#). *Phys. Rev. D*, 55:7255–7262, 1997, hep-ph/9610272. (page 12).
- [40] Stephen P. Martin. [A Supersymmetry primer](#). *Adv. Ser. Direct. High Energy Phys.*, 18:1–98, 1998, hep-ph/9709356. (page 13).
- [41] John R. Ellis. [Beyond the standard model for hill walkers](#). In *European School of High-Energy Physics*, Aug 1998, hep-ph/9812235. (page 14).
- [42] Lee Smolin. [What are we missing in our search for quantum gravity?](#) May 2017, 1705.09208. (page 14).
- [43] R. P. Woodard. [How Far Are We from the Quantum Theory of Gravity?](#) *Rept. Prog. Phys.*, 72:126002, 2009, 0907.4238. (page 14).
- [44] Fred Jegerlehner. [The hierarchy problem of the electroweak Standard Model revisited](#). May 2013, 1305.6652. (page 15).
- [45] H. Davoudiasl, J. L. Hewett, and T. G. Rizzo. [Phenomenology of the Randall-Sundrum Gauge Hierarchy Model](#). *Phys. Rev. Lett.*, 84:2080, 2000, hep-ph/9909255. (page 15).
- [46] S. Gariazzo, M. Archidiacono, P. F. de Salas, O. Mena, C. A. Ternes, and M. Tórtola. [Neutrino masses and their ordering: Global Data, Priors and Models](#). *JCAP*, 03:011, 2018, 1801.04946. (page 15).
- [47] B. Ishak. [Neutrino Cosmology](#), by J. Lesgourgues, G. Mangano, G. Miele and S. Pastor. *Contemporary Physics*, 54(3):178–179, 2013. (page 15).
- [48] M. Czakon, M. Zralek, and J. Gluza. [Are neutrinos Dirac or Majorana particles?](#) *Acta Phys. Polon. B*, 30:3121–3138, 1999, hep-ph/9910357. (page 15).
- [49] Susanne Mertens. [Direct Neutrino Mass Experiments](#). *J. Phys. Conf. Ser.*, 718(2):022013, 2016, 1605.01579. (page 15).

- [50] Rabindra N. Mohapatra and Goran Senjanovic. [Neutrino Masses and Mixings in Gauge Models with Spontaneous Parity Violation](#). *Phys. Rev. D*, 23:165, 1981. (page 15).
- [51] Douglas Clowe, Marusa Bradac, Anthony H. Gonzalez, Maxim Markevitch, Scott W. Randall, Christine Jones, and Dennis Zaritsky. [A direct empirical proof of the existence of dark matter](#). *Astrophys. J. Lett.*, 648:L109–L113, 2006, astro-ph/0608407. (page 15).
- [52] Edvige Corbelli and Paolo Salucci. [The Extended Rotation Curve and the Dark Matter Halo of M33](#). *Mon. Not. Roy. Astron. Soc.*, 311:441–447, 2000, astro-ph/9909252. (page 15).
- [53] Richard Massey, Thomas Kitching, and Johan Richard. [The dark matter of gravitational lensing](#). *Rept. Prog. Phys.*, 73:086901, 2010, 1001.1739. (page 15).
- [54] W. Tucker, P. Blanco, S. Rappoport, L. David, D. Fabricant, E. E. Falco, W. Forman, A. Dressler, and M. Ramella. [1e0657-56: a contender for the hottest known cluster of galaxies](#). *Astrophys. J. Lett.*, 496:L5, 1998, astro-ph/9801120. (page 15).
- [55] Volker Springel et al. [Simulating the joint evolution of quasars, galaxies and their large-scale distribution](#). *Nature*, 435:629–636, 2005, astro-ph/0504097. (page 15).
- [56] P. A. R. Ade et al. [Planck 2013 results. I. Overview of products and scientific results](#). *Astron. Astrophys.*, 571:A1, 2014, 1303.5062. (page 15).
- [57] Arvind Rajaraman, William Shepherd, Tim M. P. Tait, and Alexander M. Wijangco. [LHC Bounds on Interactions of Dark Matter](#). *Phys. Rev. D*, 84:095013, 2011, 1108.1196. (page 15).
- [58] Adam G. Riess et al. [Observational evidence from supernovae for an accelerating universe and a cosmological constant](#). *Astron. J.*, 116:1009–1038, 1998, astro-ph/9805201. (page 16).
- [59] S. Perlmutter et al. [Measurements of \$\Omega\$ and \$\Lambda\$ from 42 high redshift supernovae](#). *Astrophys. J.*, 517:565–586, 1999, astro-ph/9812133. (page 16).
- [60] A. D. Sakharov. [Violation of CP Invariance, C asymmetry, and baryon asymmetry of the universe](#). *Pisma Zh. Eksp. Teor. Fiz.*, 5:32–35, 1967. (page 16).
- [61] Makoto Kobayashi and Toshihide Maskawa. [CP Violation in the Renormalizable Theory of Weak Interaction](#). *Prog. Theor. Phys.*, 49:652–657, 1973. (page 16).

- [62] Laurent Canetti, Marco Drewes, and Mikhail Shaposhnikov. [Matter and Anti-matter in the Universe](#). *New J. Phys.*, 14:095012, 2012, 1204.4186. (page 16).
- [63] Jonathan L. Rosner. [CP violation: A Brief review](#). *AIP Conf. Proc.*, 540(1):283–304, 2000, hep-ph/0005258. (page 16).
- [64] Howard E. Haber and Gordon L. Kane. [The Search for Supersymmetry: Probing Physics Beyond the Standard Model](#). *Phys. Rept.*, 117:75–263, 1985. (page 16).
- [65] Ilya F. Ginzburg and Maria Krawczyk. [Symmetries of two Higgs doublet model and CP violation](#). *Phys. Rev. D*, 72:115013, 2005, hep-ph/0408011. (page 18).
- [66] Antonio Pich and Paula Tuzon. [Yukawa Alignment in the Two-Higgs-Doublet Model](#). *Phys. Rev. D*, 80:091702, 2009, 0908.1554. (page 19).
- [67] Sheldon L. Glashow and Steven Weinberg. [Natural Conservation Laws for Neutral Currents](#). *Phys. Rev. D*, 15:1958, 1977. (page 19).
- [68] T. P. Cheng and Marc Sher. [Mass Matrix Ansatz and Flavor Nonconservation in Models with Multiple Higgs Doublets](#). *Phys. Rev. D*, 35:3484, 1987. (page 20).
- [69] Andrzej J. Buras, Maria Valentina Carlucci, Stefania Gori, and Gino Isidori. [Higgs-mediated FCNCs: Natural Flavour Conservation vs. Minimal Flavour Violation](#). *JHEP*, 10:009, 2010, 1005.5310. (page 20).
- [70] J. Hernandez-Sanchez, S. Moretti, R. Noriega-Papaqui, and A. Rosado. [Off-diagonal terms in Yukawa textures of the Type-III 2-Higgs doublet model and light charged Higgs boson phenomenology](#). *JHEP*, 07:044, 2013, 1212.6818. (page 20).
- [71] Chilong Lin, Chien-Er Lee, and Yeou-Wei Yang. [The Two Higgs-Doublet Extension of the Standard Model and S3 Symmetry](#). *J. Phys. C*, 26:180, 1988, 1703.07941. (page 20).
- [72] S. Dittmaier et al. [Handbook of LHC Higgs Cross Sections: 1. Inclusive Observables](#). Jan 2011, 1101.0593. (page 20).
- [73] S. Dittmaier et al. [Handbook of LHC Higgs Cross Sections: 2. Differential Distributions](#). Jan 2012, 1201.3084. (page 20).
- [74] J R Andersen et al. [Handbook of LHC Higgs Cross Sections: 3. Higgs Properties](#). July 2013, 1307.1347. (page 20).
- [75] D. de Florian et al. [Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector](#). 2/2017, Oct 2016, 1610.07922. (pages 20, 22).

- [76] R. Assmann, M. Lamont, and S. Myers. [A brief history of the LEP collider](#). *Nucl. Phys. B Proc. Suppl.*, 109:17–31, 2002. (page 23).
- [77] The LEP 2 Team. [LEP Design Report: Vol.3: LEP2](#). June 1996. (page 23).
- [78] The LEP 2 Team. [LEP Design Report Vol.1: The LEP Injector Chain](#). June 1983. (page 23).
- [79] The LEP Injector Study Group. [LEP Design Report: Vol.2. The LEP Main Ring](#). June 1984. (page 23).
- [80] Herwig Schopper, editor. [Particle Physics Reference Library: Volume 1: Theory and Experiments](#). Springer Nature, Cham, 2020. (page 25).
- [81] Oliver S. Bruning, P. Collier, P. Lebrun, S. Myers, R. Ostojic, J. Poole, and P. Proudlock. [LHC Design Report Vol.1: The LHC Main Ring](#). June 2004. (pages 26, 30).
- [82] O. Buning, P. Collier, P. Lebrun, S. Myers, R. Ostojic, J. Poole, and P. Proudlock. [LHC Design Report. 2. The LHC infrastructure and general services](#). Nov 2004. (page 26).
- [83] M. Benedikt, P. Collier, V. Mertens, J. Poole, and K. Schindl. [LHC Design Report. 3. The LHC injector chain](#). Dec 2004. (page 26).
- [84] [LHC Machine](#). *JINST*, 3:S08001, 2008. (pages 26, 29).
- [85] Esma Anais Mobs. [The CERN accelerator complex. Complexe des accélérateurs du CERN](#). Oct 2016. General Photo. (page 27).
- [86] B. Salvachua. [Overview of Proton-Proton Physics during Run 2](#). In *9th LHC Operations Evian Workshop*, 2019. (page 30).
- [87] ATLAS Collaboration. (page 30).
- [88] A. Augusto Alves, Jr. et al. [The LHCb Detector at the LHC](#). *JINST*, 3:S08005, 2008. (page 30).
- [89] K. Aamodt et al. [The ALICE experiment at the CERN LHC](#). *JINST*, 3:S08002, 2008. (page 30).
- [90] O. Adriani et al. [The LHCf detector at the CERN Large Hadron Collider](#). *JINST*, 3:S08006, 2008. (page 30).
- [91] G. Anelli et al. [The TOTEM experiment at the CERN Large Hadron Collider](#). *JINST*, 3:S08007, 2008. (page 30).

- [92] ATLAS Collaboration. [The ATLAS Experiment at the CERN Large Hadron Collider](#). *JINST*, 3:S08003, 2008. (pages 31, 32).
- [93] ATLAS Collaboration. [ATLAS barrel toroid: Technical design report](#). Apr 1997. (page 31).
- [94] ATLAS Collaboration. [ATLAS endcap toroids: Technical design report](#). Apr 1997. (page 31).
- [95] ATLAS Collaboration. [ATLAS inner detector: Technical design report. Vol. 1](#). Apr 1997. (page 33).
- [96] ATLAS Collaboration. [ATLAS inner detector: Technical design report. Vol. 2](#). Apr 1997. (page 33).
- [97] ATLAS Collaboration. [The ATLAS Inner Detector commissioning and calibration](#). *Eur. Phys. J. C*, 70:787–821, 2010, 1004.5293. (page 33).
- [98] [Technical Design Report for the ATLAS Inner Tracker Pixel Detector](#). Technical Report CERN-LHCC-2017-021. ATLAS-TDR-030, CERN, Geneva, Sep 2017. (page 33).
- [99] ATLAS Collaboration. [The barrel modules of the ATLAS semiconductor tracker](#). *Nucl. Instrum. Meth. A*, 568:642–671, 2006. (page 33).
- [100] ATLAS Collaboration. [The ATLAS semiconductor tracker end-cap module](#). *Nucl. Instrum. Meth. A*, 575:353–389, 2007. (page 33).
- [101] A. Ahmad et al. [The Silicon microstrip sensors of the ATLAS semiconductor tracker](#). *Nucl. Instrum. Meth. A*, 578:98–118, 2007. (page 33).
- [102] ATLAS TRT Collaboration. [The ATLAS TRT barrel detector](#). *JINST*, 3:P02014, 2008. (page 33).
- [103] ATLAS TRT Collaboration. [The ATLAS TRT end-cap detectors](#). *JINST*, 3:P10003, 2008. (page 33).
- [104] ATLAS TRT Collaboration. [The ATLAS Transition Radiation Tracker \(TRT\) proportional drift tube: Design and performance](#). *JINST*, 3:P02013, 2008. (page 33).
- [105] ATLAS Collaboration. [Track Reconstruction Performance of the ATLAS Inner Detector at \$\sqrt{s} = 13\$ TeV](#). *ATL-PHYS-PUB-2015-018*, July 2015. (page 33).

- [106] M. Capeans, G. Darbo, K. Einsweiler, M. Elsing, T. Flick, M. Garcia-Sciveres, C. Gemme, H. Pernegger, O. Rohne, and R. Vuillermet. [ATLAS Insertable B-Layer Technical Design Report](#). Sept 2010. (page 34).
- [107] Joao Pequena. [Computer Generated image of the ATLAS calorimeter](#). Mar 2008. (page 35).
- [108] ATLAS Collaboration. [The ATLAS Experiment at the CERN Large Hadron Collider](#). *JINST*, 3:S08003, 2008. (pages 36, 37).
- [109] A. Henriques. [The ATLAS tile calorimeter](#). In *4th International Conference on Advancements in Nuclear Instrumentation Measurement Methods and their Applications*, IEEE Nucl.Sci.Symp.Conf.Rec., Apr 2015. (page 36).
- [110] ATLAS Collaboration. [ATLAS calorimeter performance Technical Design Report](#). *CERN-LHCC-96-40*, Dec 1996. (page 35).
- [111] ATLAS Collaboration. [ATLAS liquid argon calorimeter: Technical design report](#). Dec 1996. (page 35).
- [112] A. Artamonov et al. [The ATLAS forward calorimeters](#). *JINST*, 3:P02010, 2008. (page 36).
- [113] ATLAS Collaboration. [ATLAS tile calorimeter: Technical design report](#). Dec 1996. (page 36).
- [114] ATLAS Collaboration. [Readiness of the ATLAS Tile Calorimeter for LHC collisions](#). *Eur. Phys. J. C*, 70:1193–1236, 2010, 1007.5423. (page 36).
- [115] C. W. Fabjan and F. Gianotti. [Calorimetry for particle physics](#). *Rev. Mod. Phys.*, 75:1243–1286, 2003. (page 37).
- [116] ATLAS Collaboration. [Commissioning of the ATLAS Muon Spectrometer with Cosmic Rays](#). *Eur. Phys. J. C*, 70:875–916, 2010, 1006.4384. (pages 37, 38).
- [117] ATLAS Collaboration. [ATLAS muon spectrometer: Technical design report](#). June 1997. (page 37).
- [118] F. Bauer et al. [Construction and Test of MDT Chambers for the ATLAS Muon Spectrometer](#). *Nucl. Instrum. Meth. A*, 461:17–20, 2001, 1604.02000. (page 38).
- [119] Theodoros Argyropoulos et al. [Cathode strip chambers in ATLAS: Installation, commissioning and in situ performance](#). *IEEE Trans. Nucl. Sci.*, 56:1568–1574, 2009. (page 38).

- [120] Vasiliki A. Mitsou. [ATLAS silicon microstrip tracker: Operation and performance](#). In *13th ICATPP Conference on Astroparticle, Particle, Space Physics and Detectors for Physics Applications*, Oct 2011, 1110.1983. (page 38).
- [121] A. Ruiz Martínez. [The Run-2 ATLAS Trigger System](#). *J. Phys. Conf. Ser.*, 762(1):012003, 2016. (page 39).
- [122] ATLAS Collaboration. [ATLAS first level trigger: Technical design report](#). June 1998. (page 39).
- [123] Peter Jenni, Marzio Nesi, Markus Nordberg, and Kenway Smith. [ATLAS high-level trigger, data acquisition and controls: Technical design report](#). July 2003. (page 39).
- [124] Yaquan Fang, Mukesh Kumar, Bruce Mellado, Yu Zhang, and Maosen Zhu. [Impact of additional bosons on the exploration of the Higgs boson at the LHC](#). *Int. J. Mod. Phys. A*, 32(34):1746010, 2017, 1706.06659. (pages 41, 46).
- [125] Chuene Mosomane, Mukesh Kumar, Alan S. Cornell, and Bruce Mellado. [Exploring CP-even scalars of a Two Higgs-doublet model in future \$e^-p\$ colliders](#). *J. Phys. Conf. Ser.*, 889(1):012004, 2017, 1707.05997. (page 41).
- [126] S. P. Das, J. Hernandez-Sanchez, S. Moretti, and A. Rosado. [Prospects for discovering a light charged Higgs boson within the NMSSM at the FCC-eh collider](#). June 2018, 1806.08361. (page 41).
- [127] ATLAS Collaboration. [Search for heavy resonances decaying into a \$W\$ or \$Z\$ boson and a Higgs boson in final states with leptons and \$b\$ -jets in 36 fb \$^{-1}\$ of \$\sqrt{s} = 13\$ TeV \$pp\$ collisions with the ATLAS detector](#). *JHEP*, 03:174, 2018, 1712.06518. [Erratum: JHEP 11, 051 (2018)]. (pages 42, 55, 61, 63).
- [128] CMS Collaboration. [Search for a pseudoscalar boson decaying into a \$Z\$ boson and the 125 GeV Higgs boson in \$\ell^+\ell^-b\bar{b}\$ final states](#). *Phys. Lett. B*, 748:221–243, 2015, 1504.04710. (pages 42, 55).
- [129] CMS Collaboration. [Search for a heavy pseudoscalar boson decaying to a \$Z\$ boson and a Higgs boson at \$\sqrt{s} = 13\$ TeV](#). 2018. (page 42).
- [130] Pedro M. Ferreira, Stefan Liebler, and Jonas Wittbrodt. [\$pp \rightarrow A \rightarrow Zh\$ and the wrong-sign limit of the two-Higgs-doublet model](#). *Phys. Rev. D*, 97(5):055008, 2018, 1711.00024. (pages 42, 55).

- [131] CMS Collaboration. [Measurement of the cross section for top quark pair production in association with a W or Z boson in proton-proton collisions at \$\sqrt{s} = 13\$ TeV](#). *JHEP*, 08:011, 2018, 1711.02547. (pages 42, 54, 58).
- [132] CMS Collaboration. [Search for top squarks and dark matter particles in opposite-charge dilepton final states at \$\sqrt{s} = 13\$ TeV](#). *Phys. Rev. D*, 97(3):032009, 2018, 1711.00752. (pages 42, 54).
- [133] Margarete Muhlleitner, Marco O. P. Sampaio, Rui Santos, and Jonas Wittbrodt. [The N2HDM under Theoretical and Experimental Scrutiny](#). *JHEP*, 03:094, 2017, 1612.01309. (pages 43, 44, 46, 48).
- [134] Igor P. Ivanov. [Building and testing models with extended Higgs sectors](#). *Prog. Part. Nucl. Phys.*, 95:160–208, 2017, 1702.03776. (page 43).
- [135] Chien-Yi Chen, Michael Freid, and Marc Sher. [Next-to-minimal two Higgs doublet model](#). *Phys. Rev. D*, 89(7):075009, 2014, 1312.3949. (pages 43, 44).
- [136] Aleksandra Drozd, Bohdan Grzadkowski, John F. Gunion, and Yun Jiang. [Extending two-Higgs-doublet models by a singlet scalar field - the Case for Dark Matter](#). *JHEP*, 11:105, 2014, 1408.2106. (page 44).
- [137] Howard E. Haber and Heather E. Logan. [Radiative corrections to the Z b anti-b vertex and constraints on extended Higgs sectors](#). *Phys. Rev. D*, 62:015011, 2000, hep-ph/9909335. (page 47).
- [138] O. Deschamps, S. Descotes-Genon, S. Monteil, V. Niess, S. T’Jampens, and V. Tisserand. [The Two Higgs Doublet of Type II facing flavour physics data](#). *Phys. Rev. D*, 82:073012, 2010, 0907.5135. (page 47).
- [139] Farvah Mahmoudi and Oscar Stal. [Flavor constraints on the two-Higgs-doublet model with general Yukawa couplings](#). *Phys. Rev. D*, 81:035016, 2010, 0907.1791. (page 47).
- [140] Thomas Hermann, Mikolaj Misiak, and Matthias Steinhauser. [\$\bar{B} \rightarrow X_s \gamma\$ in the Two Higgs Doublet Model up to Next-to-Next-to-Leading Order in QCD](#). *JHEP*, 11:036, 2012, 1208.2788. (page 47).
- [141] M. Misiak et al. [Updated NNLO QCD predictions for the weak radiative B-meson decays](#). *Phys. Rev. Lett.*, 114(22):221801, 2015, 1503.01789. (page 47).
- [142] Rita Coimbra, Marco O. P. Sampaio, and Rui Santos. [ScannerS: Constraining the phase diagram of a complex scalar singlet at the LHC](#). *Eur. Phys. J. C*, 73:2428, 2013, 1301.2599. (page 48).

- [143] ATLAS Collaboration. [Update of the prospects for the \$H \rightarrow Z\gamma\$ search at the High-Luminosity LHC](#). *ATL-PHYS-PUB-2014-006*, May 2014. (page 50).
- [144] Torbjörn Sjöstrand, Stefan Ask, Jesper R. Christiansen, Richard Corke, Nishita Desai, Philip Ilten, Stephen Mrenna, Stefan Prestel, Christine O. Rasmussen, and Peter Z. Skands. [An introduction to PYTHIA 8.2](#). *Comput. Phys. Commun.*, 191:159–177, 2015, 1410.3012. (page 54).
- [145] S. Ovin, X. Rouby, and V. Lemaitre. [DELPHES, a framework for fast simulation of a generic collider experiment](#). Mar 2009, 0903.2225. (page 54).
- [146] Matteo Cacciari, Gavin P. Salam, and Gregory Soyez. [FastJet User Manual](#). *Eur. Phys. J. C*, 72:1896, 2012, 1111.6097. (page 54).
- [147] Matteo Cacciari, Gavin P. Salam, and Gregory Soyez. [The anti- \$k_t\$ jet clustering algorithm](#). *JHEP*, 04:063, 2008, 0802.1189. (pages 54, 70).
- [148] ATLAS Collaboration. [Evidence for the \$H \rightarrow b\bar{b}\$ decay with the ATLAS detector](#). *JHEP*, 12:024, 2017, 1708.03299. (page 60).
- [149] ATLAS Collaboration. [Observation of \$H \rightarrow b\bar{b}\$ decays and \$VH\$ production with the ATLAS detector](#). *Phys. Lett. B*, 786:59–86, 2018, 1808.08238. (page 60).
- [150] CMS Collaboration. [Evidence for the Higgs boson decay to a bottom quark–antiquark pair](#). *Phys. Lett. B*, 780:501–532, 2018, 1709.07497. (page 60).
- [151] CMS Collaboration. [Observation of Higgs boson decay to bottom quarks](#). *Phys. Rev. Lett.*, 121(12):121801, 2018, 1808.08242. (page 60).
- [152] B. Mellado. [Understanding the production of multiple leptons at the LHC](#). *H DAYS2018, Santander*, Sept 2018. (page 62).
- [153] Stefan von Buddenbrock, Alan S. Cornell, Elie D. R. Iarilala, Mukesh Kumar, Bruce Mellado, Xifeng Ruan, and Esra Mohammed Shrif. [Constraints on a 2HDM with a singlet scalar and implications in the search for heavy bosons at the LHC](#). *J. Phys. G*, 46(11):115001, 2019, 1809.06344. (page 63).
- [154] CMS Collaboration. [Search for heavy Higgs bosons decaying to a top quark pair in proton-proton collisions at \$\sqrt{s} = 13\$ TeV](#). *JHEP*, 04:171, 2020, 1908.01115. (page 63).
- [155] CMS Collaboration. [Search for new neutral Higgs bosons through the \$H \rightarrow ZA \rightarrow \ell^+ \ell^- b\bar{b}\$ process in pp collisions at \$\sqrt{s} = 13\$ TeV](#). *JHEP*, 03:055, 2020, 1911.03781. (page 63).

- [156] ATLAS Collaboration. [Search for a heavy Higgs boson decaying into a \$Z\$ boson and another heavy Higgs boson in the \$\ell\ell b\bar{b}\$ final state in \$pp\$ collisions at \$\sqrt{s} = 13\$ TeV with the ATLAS detector](#). *Phys. Lett. B*, 783:392–414, 2018, 1804.01126. (page 63).
- [157] Mirkoantonio Casolino, Trisha Farooque, Aurelio Juste, Tao Liu, and Michael Spannowsky. [Probing a light CP-odd scalar in di-top-associated production at the LHC](#). *Eur. Phys. J. C*, 75:498, 2015, 1507.07004. (page 65).
- [158] CMS Collaboration. [Search for physics beyond the standard model in multilepton final states in proton-proton collisions at \$\sqrt{s} = 13\$ TeV](#). *JHEP*, 03:051, 2020, 1911.04968. (page 65).
- [159] We-Fu Chang, Tanmoy Modak, and John N. Ng. [Signal for a light singlet scalar at the LHC](#). *Phys. Rev. D*, 97(5):055020, 2018, 1711.05722. (page 65).
- [160] Rachid Benbrik et al. [Signatures of vector-like top partners decaying into new neutral scalar or pseudoscalar bosons](#). *JHEP*, 05:028, 2020, 1907.05929. (page 65).
- [161] Simon J. D. King, Stephen F. King, Stefano Moretti, and Samuel J. Rowley. [Discovering the origin of Yukawa couplings at the LHC with a singlet Higgs and vector-like quarks](#). *JHEP*, 21:144, 2020, 2102.06091. (page 65).
- [162] Martin Bauer, Matthias Neubert, and Andrea Thamm. [Collider Probes of Axion-Like Particles](#). *JHEP*, 12:044, 2017, 1708.00443. (page 65).
- [163] Martin Bauer, Mathias Heiles, Matthias Neubert, and Andrea Thamm. [Axion-Like Particles at Future Colliders](#). *Eur. Phys. J. C*, 79(1):74, 2019, 1808.10323. (page 65).
- [164] ATLAS Collaboration. [Search for scalar resonances decaying into \$\mu^+\mu^-\$ in events with and without \$b\$ -tagged jets produced in proton-proton collisions at \$\sqrt{s} = 13\$ TeV with the ATLAS detector](#). *JHEP*, 07:117, 2019, 1901.08144. (page 65).
- [165] CMS Collaboration. [Search for beyond the standard model Higgs bosons decaying into a \$b\bar{b}\$ pair in \$pp\$ collisions at \$\sqrt{s} = 13\$ TeV](#). *JHEP*, 08:113, 2018, 1805.12191. (page 65).
- [166] Johan Alwall, Pavel Demin, Simon de Visscher, Rikkert Frederix, Michel Herquet, Fabio Maltoni, Tilman Plehn, David L. Rainwater, and Tim Stelzer. [Mad-Graph/MadEvent v4: The New Web Generation](#). *JHEP*, 09:028, 2007, 0706.2334. (page 67).

- [167] Richard D. Ball et al. [Parton distributions with LHC data](#). *Nucl. Phys. B*, 867:244–289, 2013, 1207.1303. (page 67).
- [168] Torbjorn Sjostrand, Stephen Mrenna, and Peter Z. Skands. [A Brief Introduction to PYTHIA 8.1](#). *Comput. Phys. Commun.*, 178:852–867, 2008, 0710.3820. (page 67).
- [169] ATLAS Collaboration. [ATLAS Pythia 8 tunes to 7 TeV data](#). *ATL-PHYS-PUB-2014-021*, Nov 2014. (page 67).
- [170] M Beckingham, M. Duehrssen, E. Schmidt, M. Shapiro, M. Venturi, J. Virzi, I Vivarelli, M. Werner, S. Yamamoto, and T. Yamanaka. [The simulation principle and performance of the ATLAS fast calorimeter simulation FastCaloSim](#). Oct 2010. (page 67).
- [171] ATLAS Collaboration. [The ATLAS Simulation Infrastructure](#). *Eur. Phys. J. C*, 70:823–874, 2010, 1005.4568. (page 67).
- [172] S. Agostinelli et al. [GEANT4—a simulation toolkit](#). *Nucl. Instrum. Meth. A*, 506:250–303, 2003. (page 67).
- [173] ATLAS Collaboration. [Electron and photon reconstruction and performance in ATLAS using a dynamical, topological cell clustering-based approach](#). *ATL-PHYS-PUB-2017-022*, Dec 2017. (page 69).
- [174] ATLAS Collaboration. [Electron and photon performance measurements with the ATLAS detector using the 2015–2017 LHC proton-proton collision data](#). *JINST*, 14(12):P12006, 2019, 1908.00005. (pages 69, 102, 103).
- [175] ATLAS Collaboration. [Measurement of the photon identification efficiencies with the ATLAS detector using LHC Run 2 data collected in 2015 and 2016](#). *Eur. Phys. J. C*, 79(3):205, 2019, 1810.05087. (page 69).
- [176] W. Lampl, S. Laplace, D. Lelas, P. Loch, H. Ma, S. Menke, S. Rajagopalan, D. Rousseau, S. Snyder, and G. Unal. [Calorimeter clustering algorithms: Description and performance](#). May 2008. (page 69).
- [177] ATLAS Collaboration. [Muon reconstruction performance of the ATLAS detector in proton–proton collision data at \$\sqrt{s}=13\$ TeV](#). *Eur. Phys. J. C*, 76(5):292, 2016, 1603.05598. (page 70).
- [178] ATLAS Collaboration. [Jet reconstruction and performance using particle flow with the ATLAS Detector](#). *Eur. Phys. J. C*, 77(7):466, 2017, 1703.10485. (page 70).

- [179] ATLAS Collaboration. [Forward Jet Vertex Tagging: A new technique for the identification and rejection of forward pileup jets](#). *ATL-PHYS-PUB-2015-034*, Aug 2015. (page 70).
- [180] ATLAS Collaboration. [Tagging and suppression of pileup jets](#). *ATLAS-CONF-2014-018*, May 2014. (page 70).
- [181] ATLAS Collaboration. [Jet energy measurement and its systematic uncertainty in proton-proton collisions at \$\sqrt{s} = 7\$ TeV with the ATLAS detector](#). *Eur. Phys. J. C*, 75:17, 2015, 1406.0076. (page 70).
- [182] ATLAS Collaboration. [Optimisation and performance studies of the ATLAS \$b\$ -tagging algorithms for the 2017-18 LHC run](#). *ATL-PHYS-PUB-2017-013*, July 2017. (page 70).
- [183] ATLAS Collaboration. [Measurement of Higgs boson production in the diphoton decay channel in pp collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector](#). *Phys. Rev. D*, 90(11):112015, 2014, 1408.7084. (page 87).
- [184] ATLAS Collaboration. [Search for new particles decaying into dijets in proton-antiproton collisions at \$\sqrt{s} = 1.96\$ TeV](#). *Phys. Rev. D*, 79:112002, 2009, 0812.4036. (page 97).
- [185] ATLAS Collaboration. [Luminosity determination in pp collisions at \$\sqrt{s} = 8\$ TeV using the ATLAS detector at the LHC](#). *Eur. Phys. J. C*, 76(12):653, 2016, 1608.03953. (page 102).
- [186] G. Avoni et al. [The new LUCID-2 detector for luminosity measurement and monitoring in ATLAS](#). *JINST*, 13(07):P07017, 2018. (page 102).
- [187] ATLAS Collaboration. [Performance of electron and photon triggers in ATLAS during LHC Run 2](#). *Eur. Phys. J. C*, 80(1):47, 2020, 1909.00761. (page 102).
- [188] ATLAS Collaboration. [Measurement of the Higgs boson production cross section at 7, 8 and 13 TeV center-of-mass energies in the \$H \rightarrow \gamma\gamma\$ channel with the ATLAS detector](#). *ATLAS-CONF-2015-060*, Dec 2015. (page 102).
- [189] ATLAS Collaboration. [Search for dark matter in events with missing transverse momentum and a Higgs boson decaying into two photons in pp collisions at \$\sqrt{s} = 13\$ TeV with the ATLAS detector](#). *JHEP*, 10:013, 2021, 2104.13240. (page 102).

- [190] Glen Cowan, Kyle Cranmer, Eilam Gross, and Ofer Vitells. [Asymptotic formulae for likelihood-based tests of new physics](#). *Eur. Phys. J. C*, 71:1554, 2011, 1007.1727. [Erratum: *Eur.Phys.J.C* 73, 2501 (2013)]. (page 109).
- [191] Alexander L. Read. [Presentation of search results: The CL\(s\) technique](#). *J. Phys. G*, 28:2693–2704, 2002. (page 109).
- [192] ATLAS Collaboration. [High-Luminosity Large Hadron Collider \(HL-LHC\): Technical design report](#). 10/2020, 12 2020. (page 117).
- [193] Catrin Bernius. [HL-LHC prospects from ATLAS and CMS](#). Technical report, CERN, Geneva, 3 2019. (page 117).
- [194] J. Nielsen. [Physics prospects for ATLAS at the HL-LHC](#). *J. Phys. Conf. Ser.*, 1690(1):012156, 10. (page 117).