

The search for new physics in the diphoton decay
channel and the upgrade of the Tile-Calorimeter
electronics of the ATLAS detector.



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Declaration

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

A handwritten signature in black ink, appearing to read 'R. Reed', with a large, stylized initial 'R' and a long, sweeping underline.

Robert Graham Reed

May 8, 2017

To my family, friends and loved ones.

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Abstract

The discovery of the Higgs boson at the Large Hadron Collider in Switzerland marks the beginning of a new era: Physics beyond the Standard Model (SM). A model is proposed to describe numerous Run I features observed with both the ATLAS and CMS experiments. The model introduces a heavy scalar estimated to be around 270 GeV and an intermediate scalar which can decay into both dark matter and SM particles. Three different final state searches, linked by the new hypothesis, are presented. These are the $hh \rightarrow \gamma\gamma b\bar{b}$, $\gamma\gamma + E_T^{\text{miss}}$ and high mass diphoton channels. No significant excesses were observed in any channel using the available datasets and limits were set on the relevant cross sections times branching ratios. The lack of statistics in the $\gamma\gamma b\bar{b}$ analysis prevents any conclusive statement in regard to the excess observed with Run I data. Observing no excess in the $\gamma\gamma + E_T^{\text{miss}}$ channel with the current amount of data is also consistent with the intermediate scalar decaying to SM particles. This could explain the excess of Higgs bosons produced in associations with top quarks in the multilepton final states observed in ATLAS and CMS in Run I and Run II. The work presented provides a deeper understanding on the underlying phenomenology of the hypothesis and provides a foundation for future work. The ATLAS detector underwent a stringent consolidation and validation effort before data taking could commence in 2015. A high voltage board was designed and implemented into a portable test-bench used in the certification and validation process. In addition to these efforts, the electronics on the ATLAS detector are being improved for the Phase-II upgrade program in 2024. A software tool has been designed which integrates the envisioned Phase-II back-end infrastructure into the existing ATLAS detector control system. This software is now an ATLAS wide common tool used by multiple sub-detectors in the community.

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Nomenclature

Acronyms

μ TCA Micro Telecommunications Computing Architecture

$b\bar{b}h$ Higgs production through b quark fusion

ggh Higgs production through gluon gluon fusion

$t\bar{t}h$ Higgs production through t quark fusion

VBF Higgs production through vector boson fusion

Wh Higgs production through W boson associated production

Zh Higgs production through Z boson associated production

ADC Analog to Digital Converter

ALICE A Large Ion Collider Experiment

AMC Advanced Mezzanine Card

ATCA Advanced Telecommunications Computing Architecture

ATLAS A Toroidal LHC Apparatus

CIS Charge Injection System

CME Centre of Mass Energy

CMS Compact Muon Solenoid

CRC Cyclic Redundancy Checking

NOMENCLATURE

CTRL	Control Manager
D	Driver Manager
DAQ	Data Acquisition System
DB	Data Manager
DCS	Detector Control System
DM	Dark Matter
DSS	Data Safety System
EIR	External Interface Reference
EM	Electromagnetic
EV	Event Manager
EW	Electroweak
FPGA	Field-programmable Gate Array
FRU	Field Replaceable Unit
GeV	Gigaelectronvolt
GigaBit Transceiver	GBT
GLIB	Gigabit Link Interface Board
GUI	Graphical User Interface
HL-LHC	High Luminosity LHC
HV	High Voltage
ID	Inner Detector
IP	Interaction Point
IPMB	Intelligent Platform Management Bus
IPMC	Intelligent Platform Management Controller
IPMI	Intelligent Platform Management Interface
JCOP	Joint Control Project

NOMENCLATURE

LAr	Liquid Argon
LED	Light Emitting Diode
LHC	The Large Hadron Collider
LHCb	Large Hadron Collider Beauty
LS	Long Shutdown
MDT	Monitored Drift Tubes
MeV	Megaelectronvolt
MIB	Management Information Base
MobiDICK	Mobile Drawer Integrity Checking System
NLO	Next-to-leading Order
NNLO	Next-to-next-to-leading Order
OID	Object Identification
PCB	Printed Circuit Board
PDF	Parton Distribution Function
PICMG	PCI Industrial Computer Manufacturers Group
PMT	Photo Multiplier Tube
PPr	PreProcessor
PS	Proton Synchrotron
QCD	Quantum Chromodynamics
QED	Quantum Electrodynamics
RF	Radio Frequency
ROD	Read Out Driver
SCADA	Supervisory Control and Data Acquisition
SCT	Semiconductor Tracker
SEU	Single Event Upset

NOMENCLATURE

SFP	Small Form-factor Pluggable
SM	Standard Model, Shelf Manager
SNMP	Simple Network Management Protocol
SPS	Super Proton Synchrotron
SSH	Secure Shell
TCP	Transmission Control Protocol
TeV	Teraelectronvolt
TRT	Transition Radiation Tracker
TTC	Timing, Trigger and Control
UDP	User Datagram Protocol
UI	Interface Manager
vev	Vacuum expectation value
VME	Versa Module Europa

Symbols

η	Pseudorapidity
$\mathcal{B}$	Branching ratio
$\mathcal{L}$	Instantaneous luminosity
σ	Significance or Cross section
$\sqrt{s}$	Centre of mass energy
b	Bottom quark
c	Charm quark
d	Down quark
g	Gluon
h	Standard Model Higgs boson
q	Quarks (u,d,c,s,t,b)

NOMENCLATURE

s Strange quark

t Top quark

u Up quark

$W^{\pm}$ W bosons

Z Z boson

fb^{-1} Inverse femtobarns (Unit of integrated luminosity)

Introduction and Theoretical Motivation

The Standard Model is a well established and successful theory describing fundamental particles and their interactions. The existence of a Higgs boson plays a central part in explaining why other elementary particles have mass. Prior to its discovery in July 2012 the Higgs boson was the last missing piece to the Standard Model. A complete description of the Standard Model is beyond the scope of this work. An overview, with additional details where necessary, will be included to motivate the research presented and provide a coherent picture. Introductory literature is available for an in-depth discussion on the Standard Model [1, 2].

This chapter is structured as follows: a brief overview of the Standard Model and the role of the Higgs boson is summarised in Sections 1.1 and 1.2 and the discovery of the Higgs boson is discussed in Section 1.5. A new hypothesis is proposed in Section 1.6 and the connection between all the analyses in this thesis are outlined in Section 1.7.

1. INTRODUCTION AND THEORETICAL MOTIVATION

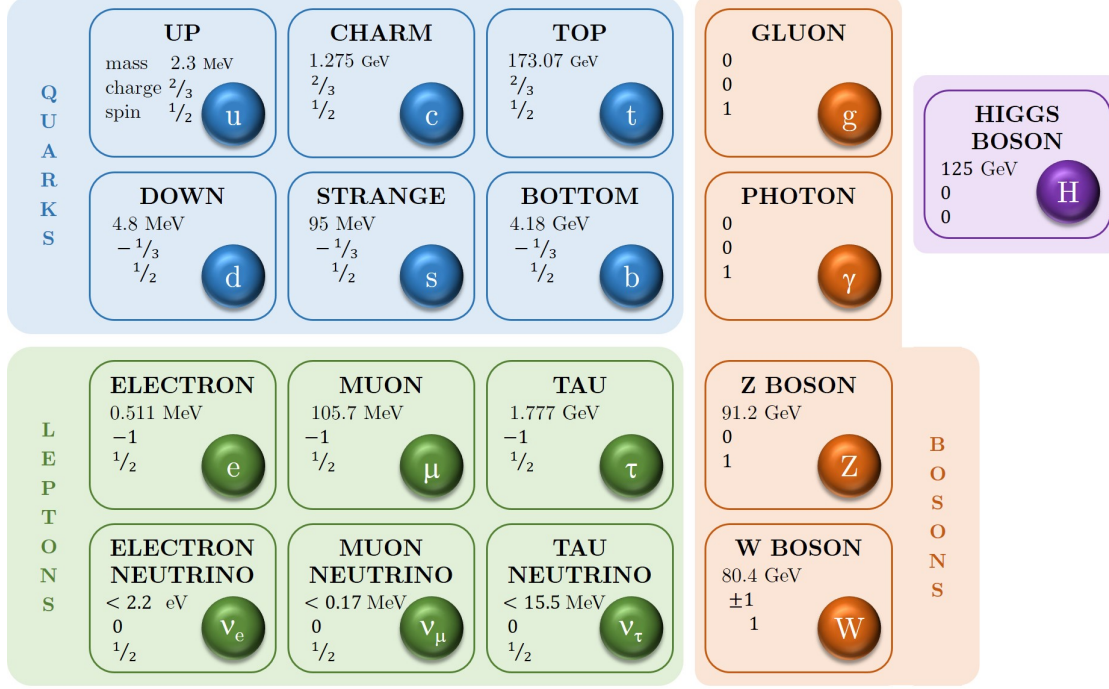


Figure 1.1: Particles and their properties in the Standard Model.

1.1 The Standard Model

The Standard Model (SM) is a successful quantum field theory of elementary particles and their associated interactions. It unifies the electromagnetic, weak and strong forces which account for three of the four fundamental forces with gravity as the exception. The SM comprises three groups of particles: quarks, leptons and bosons shown in Figure 1.1. There are 12 spin $\frac{1}{2}$ particles, known as fermions and their associated anti-particles of opposite charge. Fermions are classified into quarks and leptons where the defining feature is the interaction (or lack thereof) with the strong force.

Quarks, independently proposed by Murray Gell-Mann [3] and George Zweig [4] in 1964, carry colour charge resulting in a strong force binding them together. Quarks combine to form colourless hadrons with a quark and antiquark (called a meson) or three quarks (called a baryon). The most stable baryon is the proton consisting of two up quarks and one down quark. The u , c and t quarks have a charge $+\frac{2}{3}$ while the d , s and b quarks have a charge $-\frac{1}{3}$ resulting in interactions with other fermions through the electromagnetic force. This is also true for the weak force as quarks have an isospin. The strong force binding quarks together prevents individual quarks from being observed through a process called colour

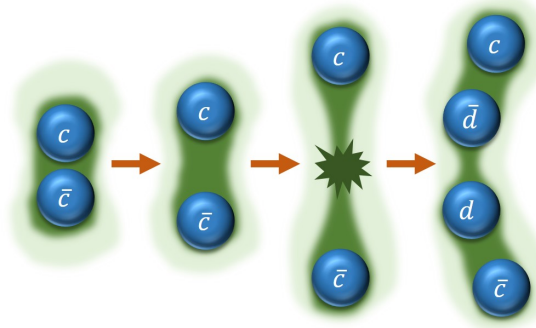


Figure 1.2: A simplified representation for the colour confinement of quarks.

confinement. As two quarks are separated a narrow colour flux tube forms which, unlike the electromagnetic force, strengthens with distance. Before the quarks become isolated it becomes energetically viable for a quark antiquark pair to form which brings the system back into a stable state. The result, when quarks are produced in particle accelerators, is a trail of colour neutral particles appearing as a jet of mesons and baryons. Further discussions of jets will be covered in Section 5.2.4. An illustration of colour confinement is shown in Figure 1.2.

The first lepton, the electron, was discovered in 1897 by Sir Joseph John Thomson [5]. Over 30 years later, in 1930, Wolfgang Pauli proposed an undetected particle, the electron neutrino, was responsible for the difference in the energy, momentum and angular momentum of the initial and final states of a beta decay process [6]. This pairing (electron and the electron neutrino) is also seen for the muon and tau particles. The SM assumes neutrinos are massless but the observation of neutrino oscillations [7, 8], flavour mixing similar to the Cabibbo-Kobayashi-Maskawa matrix for quarks, indicated that a non-zero mass is required which remains an open problem for the SM.

$$\mathcal{L}_{SM} = \mathcal{L}_{Gauge} + \mathcal{L}_{Fermions} + \mathcal{L}_{Yukawa} + \mathcal{L}_{Higgs} \quad (1.1)$$

where each term contains the form:

$$\begin{aligned} \mathcal{L}_{Gauge} &= -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ \mathcal{L}_{Fermions} &= i\bar{\psi}\not{D}\psi + h.c. \\ \mathcal{L}_{Yukawa} &= \bar{\psi}_i y_{ij} \psi_j \phi + h.c. \\ \mathcal{L}_{Higgs} &= |D_\mu \phi|^2 - V(\phi) \end{aligned}$$

Local gauge invariance is required to keep the theory renormalizable. The SM Lagrangian shown in Equation (1.1) is invariant under local transformations of the gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$, where c is colour, L is the left-handedness and Y is the weak hypercharge. $SU(3)$ and $SU(2)_L \times U(1)_Y$ represent

1. INTRODUCTION AND THEORETICAL MOTIVATION

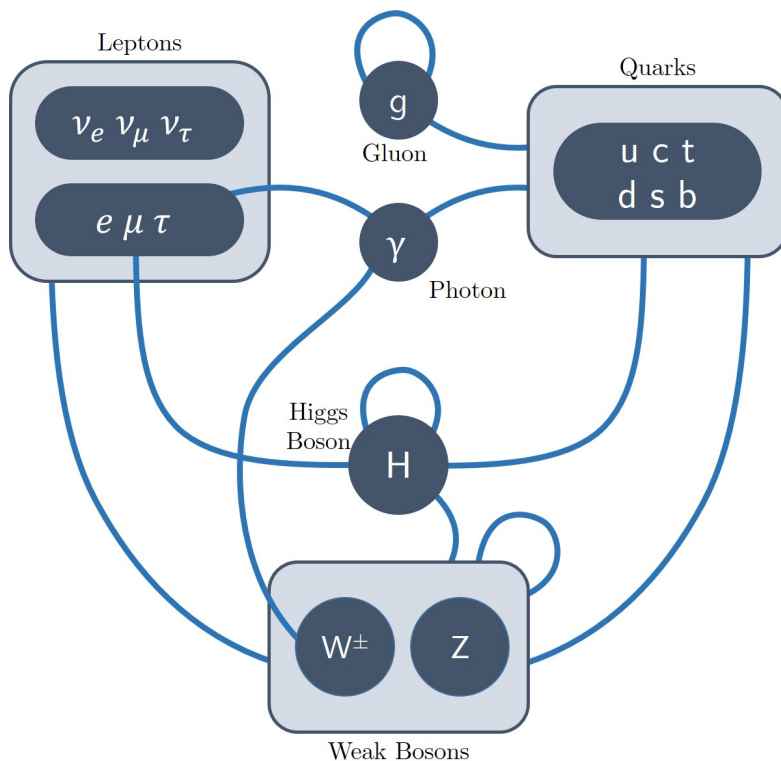


Figure 1.3: A summary of the interactions between the Standard Model particles.

the gauge groups for the strong and electroweak (EW) forces respectively. Local gauge invariance is preserved through the introduction of a covariant derivative leading to the prediction of spin-1 gauge bosons. The strong force (Quantum Chromodynamics, QCD) is mediated by eight massless gluons while the EW force comprises the electromagnetic force (Quantum Electrodynamics, QED), mediated by massless photons, and the weak force, mediated by massive $W^\pm$ and Z bosons (after EW symmetry breaking). The interactions between all particles is summarised in Figure 1.3.

Local $SU(2)_L \times U(1)_Y$ gauge invariance forbids massive fermions and gauge bosons. In order to get around this problem a new field, with a specific potential, is introduced that keeps the full Lagrangian but not the vacuum invariant under $SU(2)_L \times U(1)_Y$ symmetry. This is called spontaneous symmetry breaking of a local gauge invariant theory and introduces a fundamental scalar, the Higgs Boson.

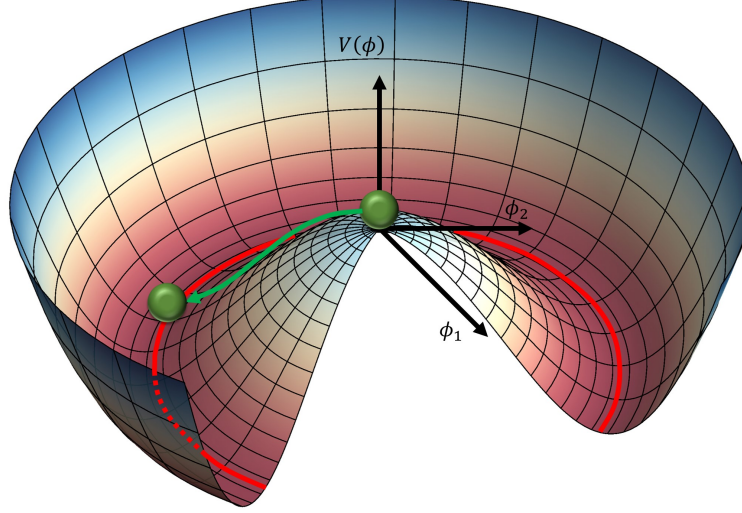


Figure 1.4: The “Mexican hat” potential illustrates spontaneous symmetry breaking.

1.2 The BEH Mechanism

The Brout-Englert-Higgs Mechanism solves the problem of massless fermions and bosons from the gauge invariance of their respective fields. Additional scalar fields are added to the theory which couple with the electroweak gauge fields. A specific potential is chosen that respects both the gauge invariance of the Lagrangian and $SU(2)_L \times U(1)_Y$ symmetry but has a minimum that does not correspond to the zero value of the field. A “Mexican hat potential” of a complex field ϕ

$$V(\phi) = \mu^2(\phi^\dagger\phi) + \lambda(\phi^\dagger\phi)^2 \quad (1.2)$$

is rotationally symmetric. Setting $\mu^2 < 0$ and $\lambda > 0$ in Equation (1.2) the minimum lies on a circle with radius $\nu = \sqrt{-\mu^2/\lambda}$ which does not correspond to the zero value. When a point is chosen on the ground state (moving from the origin, an unstable state, to the ground state) one can say the rotational symmetry has been spontaneously broken. This is illustrated in Figure 1.4.

A result of the spontaneous symmetry breaking is the non-zero value of the scalar fields, called the vacuum expectation value (vev). The scalar field couples to fermion and gauge fields which is ultimately expressed as mass terms for their corresponding mediators. Gauge bosons are specified by the vev and couplings to the gauge symmetry leading to a massive particle constrained by the theory. Fermions depend on coupling parameters that are included by hand. The previously massless weak bosons and fermions are now treated as massive particles whilst still being described in a gauge invariant manner. One of the additional scalar fields

1. INTRODUCTION AND THEORETICAL MOTIVATION

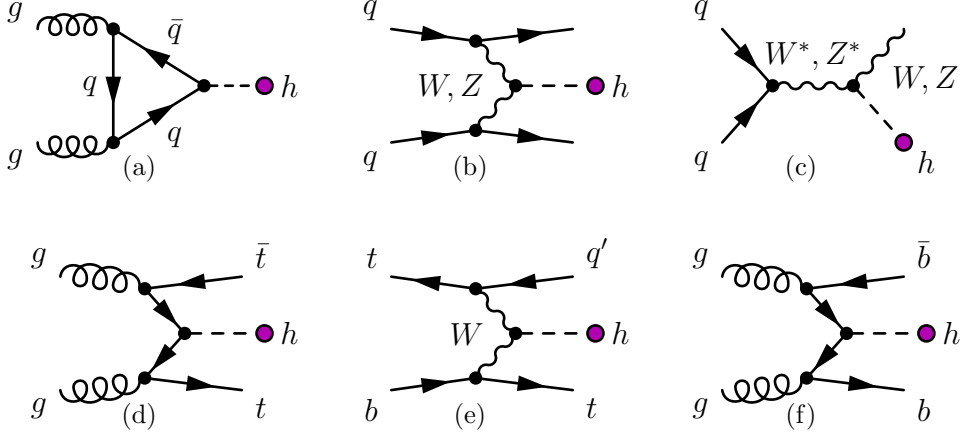


Figure 1.5: Various production modes of the Higgs boson. Gluon fusion (a), Vector boson fusion (b), WZ associated production (c), $t\bar{t}$ associated production (d), single top production (e), and $b\bar{b}$ fusion (f).

couples similarly to the vev resulting in a massive spin-zero neutral boson, the Higgs boson. The Higgs mass is not predicted by the SM but can be measured if it were to be observed. It was a profound moment in scientific history when such an observation was made in July 2012.

1.3 Higgs Boson Production and Decay Modes

Higgs boson production modes at the Large Hadron Collider are shown as Feynman diagrams in Figure 1.5. The cross sections and uncertainties of each production mechanism is provided by the LHC Cross Section Working Group [9–11]. The overall production rates as a function of the Higgs mass are shown in Figure 1.6a.

Gluon Fusion (ggh) shown in Figure 1.5a is the most common form of Higgs production at $\sqrt{s} = 8$ TeV. Higher order corrections introduce quark and gluon radiation resulting in additional objects. The ggh production cross section is computed to next-to-next-to-next-to-leading order (N³LO) [12–15] with electroweak (EW) corrections calculated to next-to-leading order (NLO) [16–18].

Vector Boson Fusion (VBF) shown in Figure 1.5b has a unique feature of two heavy forward jets separated by large pseudorapidity forming from the outgoing hard scattered quarks. The VBF production cross section has been calculated with full NLO QCD and EW correction [15, 19–21] and with accurate approximations for NNLO QCD corrections [15, 22].

1.3. HIGGS BOSON PRODUCTION AND DECAY MODES

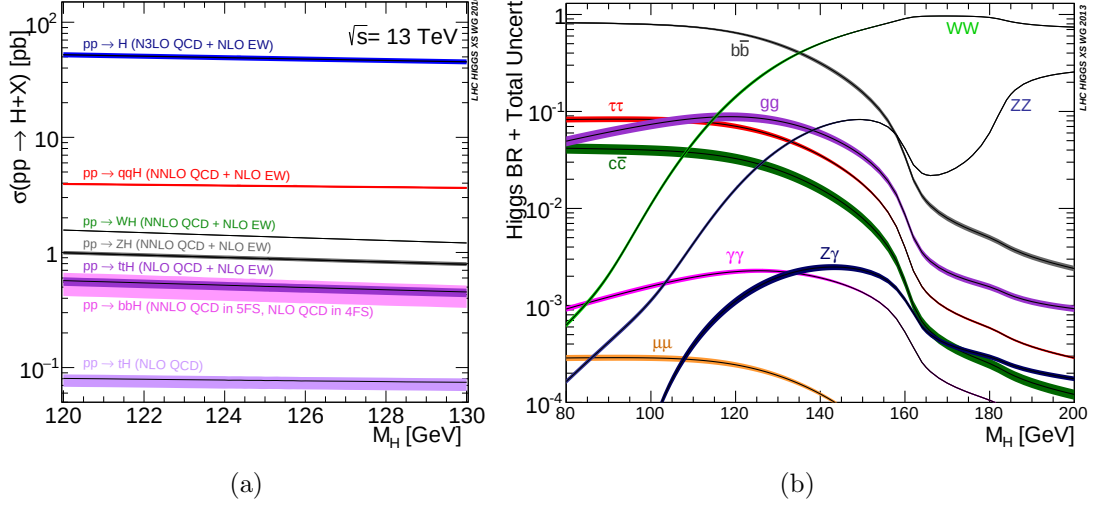


Figure 1.6: The production (left) and decay (right) modes of the Higgs boson. [11].

WZ Associated Production (Wh , Zh) shown in Figure 1.5c is also called “Higgsstrahlung” due to the radiation of a Higgs boson analogous to that of Bremsstrahlung. It is the third most common production mechanism. This process is identified by leptonic activity (from the weak bosons interaction with leptons Figure 1.3), missing energy (through the decay to neutrinos) and the reconstruction of dijet masses, m_{jj} , close to the mass of the W and Z bosons. The cross sections have been calculated with NLO [23] and NNLO corrections [24, 25].

Top Associated Production ($t\bar{t}h$ and th) shown in Figures 1.5d and 1.5e has one of the lowest rates of Higgs boson production at the LHC. Both single and double top production is difficult to measure due to the many final states with b quarks and leptons. The cross sections are calculated to NLO [15, 26–29] with NLO EW and QCD corrections.

bb Fusion ($b\bar{b}h$) shown in Figure 1.5f has a cross section calculated with two flavour schemes. The four flavour scheme (4FS), computed at NLO [30, 31], and a five flavour scheme (5FS) computed at NNLO [32]. The 5FS EW corrections are shown to be small in Ref [33] and are ignored. The 4FS can be viewed as gluon splitting similar to the $t\bar{t}h$ process while the 5FS has the b quarks added into the parton distribution function (PDF) for the two incoming protons.

The Higgs boson couples to other particles as discussed in Section 1.2. The probability for any given decay is, among others, largely dependent on the strength

1. INTRODUCTION AND THEORETICAL MOTIVATION

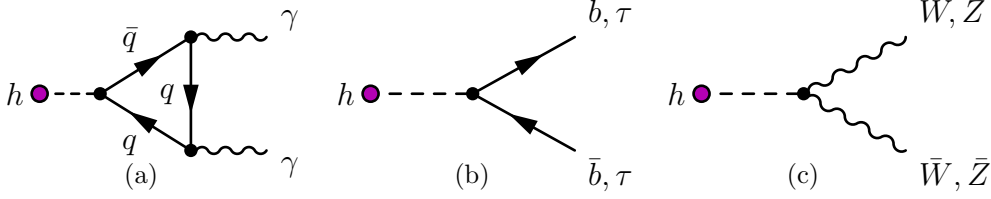


Figure 1.7: Three main decay modes of the Higgs boson. Diphoton decay (left), fermionic decays (middle) and W/Z decays (right).

of the interaction, the mass of the particle and the Higgs mass itself. The branching ratios are calculated as a function of the Higgs mass using programs such as HDECAY [34, 35] and PROPHECY4F [36, 37]. The results are summarised in Figure 1.6b. The discovery of the Higgs at a mass of 125 GeV provides a rich collection of possible decays with the relevant ones illustrated in Figure 1.7.

Diphoton decay ($h \rightarrow \gamma\gamma$), shown in Figure 1.7a, forms the bulk of this thesis.

It has a small branching ratio of $\mathcal{B}_{\gamma\gamma} \approx 0.00228$ but due to its clean triggering and low background it has a good selection efficiency. The quark loop is typically massive virtual particles such as top or bottom quarks but can also be replaced with a W boson loop. A detailed explanation of the identification and selection of photons is provided in Chapter 5 and is used for the majority of searches presented in this work.

Fermionic decays ($h \rightarrow b\bar{b}, \tau\tau$), shown in Figure 1.7b, are two of the more common decays with a branching ratio of $\mathcal{B}_{b\bar{b}} \approx 0.57$ and $\mathcal{B}_{\tau\tau} \approx 0.06$. These decays are useful in determining the Higgs coupling to different quark types and leptons. Although the branching ratios are high, these decay channels tend to be difficult to distinguish from their large background processes. The $b\bar{b}$ decay is studied in combination with the diphoton decays in Chapter 6.

W/Z decays ($h \rightarrow WW, ZZ$), shown in Figure 1.7c, are included for their relevance to the Higgs boson discovery in Section 1.5. The $ZZ \rightarrow 4\ell$ decay has a very high signal to background ratio and tends to be very pure but suffers from low statistics. The WW decay has the second highest branching ratio but has a poor mass resolution due to neutrinos in the final state. It has a similar rate to diphoton decay after applying the selection efficiency.

1.4 Higgs Boson Pair Production

In addition to the singular Higgs boson production mentioned in Section 1.3 it is also possible to have the generation of two Higgs bosons in a process called

1.4. HIGGS BOSON PAIR PRODUCTION

pair production. Figures 1.8a and 1.8b are the two leading mechanisms for Higgs pair production in the SM. A future goal of the LHC is to measure the Higgs self-coupling, λ_{hhh} shown in Figure 1.8b, but due to the destructive interference of the “box diagram”, in Figure 1.8a, the production rate is a factor of $\sim 10^3$ lower than the single SM Higgs [11, 38], making such a measurement very challenging. However, a wide variety of new physics models can enhance this production rate making it an interesting channel to analyse. Enhancements fall into two basic categories: Non-resonant and resonant production.

1.4.1 Non-resonant Di-Higgs Boson Production

Larger enhancements in the non-resonant case can be achieved in a number of ways. Modifying any of the SM couplings would vary the expected di-Higgs production rate. Simply “turning off” the self-coupling λ_{hhh} would result in a doubling of the di-Higgs rate in gluon-gluon fusion, and changing its sign would lead to a quadrupling of the rate [38]. Enabling a direct $t\bar{t}hh$ vertex would likewise lead to a significant enhancement of the $pp \rightarrow hh$ rate [39]. This process would be similar to Figure 1.8b but with a single vertex and without the intermediate Higgs. There is also the option of including light colored scalars [40] and, of course, there are many other possibilities that remain.

1.4.2 Resonant Di-Higgs Boson Production

Resonant production allows for potentially significant enhancements with striking features that are well defined for a physics analysis. In two Higgs doublet models (2HDM) [41] there are four additional scalars to the Higgs boson. The heavier neutral scalar Higgs, often denoted “ H ”, may decay into its lighter Higgs boson partner “ h ”. The rate corresponding to this decay is the ratio $\tan \beta$ of the vacuum expectation values (vevs), the mixing between light and heavy scalars ($\sin(\beta - \alpha)$), and the so called type of model. Single Higgs measurements constrain the parameter space but even near the alignment limit, the region where $\cos(\beta - \alpha) = 0$ and the light scalar h closely resembles the SM Higgs, the $H \rightarrow hh$ cross section times branching ratio may be several picobarns [42]. A combination of numerous hh channels was recently published by ATLAS which provides exclusions to the phase space [43]. In addition to the 2HDM approach there are many other resonant models that can exist. This is represented in Figure 1.8c where “ X ” is a new intermediate particle. This thesis proposes a new model, called the Madala hypothesis, which can account for an enhanced di-Higgs production. This is discussed in Section 1.6.

1. INTRODUCTION AND THEORETICAL MOTIVATION

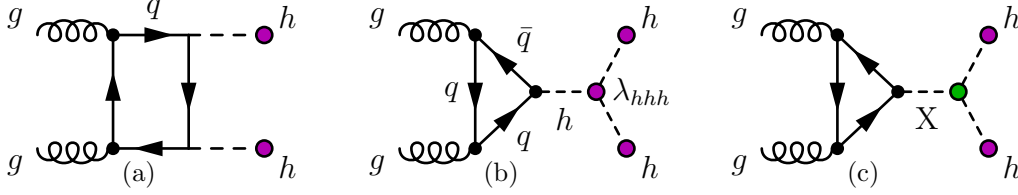


Figure 1.8: Leading order production modes for SM Higgs pair production through. a) Heavy quark loop and b) Higgs self-coupling. The total SM contribution is the combination of the two which has a significant destructive interference. BSM Higgs pair production can occur by changing the SM couplings in a) and b) or through an intermediate particle, X, called a resonance.

1.5 The Discovery of the Higgs Boson

ATLAS and CMS are two general purpose detectors which had the primary goal of searching for the Higgs boson when the facility came online in 2011. In July 2012 both ATLAS [44] and CMS [45] reported an observation of a Higgs-like boson with a mass of 125 GeV. The discovery was made using $4.6 - 4.8 \text{ fb}^{-1}$ and 5.1 fb^{-1} of integrated luminosity recorded by ATLAS and CMS at a centre of mass energy of $\sqrt{s} = 7 \text{ TeV}$, in 2011, in combination with $5.8 - 5.9 \text{ fb}^{-1}$ and 5.3 fb^{-1} at $\sqrt{s} = 8 \text{ TeV}$, in 2012, respectively. A combination of $h \rightarrow \gamma\gamma$, $h \rightarrow ZZ$ and $h \rightarrow W^+W^-$ observations are used to derive a probability, p_0 , that the measured signal is a background only fluctuation. The smaller p_0 the more significant the observation. Figure 1.9a shows the discovery plot for the local p-value reaching a minimum at approximately 125 GeV with a significance close to 6σ . An updated measurement shown in Figure 1.9b was performed using the full 2012 dataset [46] with the significance further increasing to 10σ . The mass of the Higgs boson is well measured allowing additional constraints to be applied to more complex models that go beyond the Standard Model.

1.6 The Madala Hypothesis

Since the discovery of the Higgs boson attention has been directed in two general directions: 1) experimental measurements to analyse the compatibility of data to the SM predictions, and 2) theoretical work in understanding how any new physics would be revealed. The University of the Witwatersrand High Energy Physics Group (Wits HEP Group) in collaboration with the Harish-Chandra Research Institute (HRI) have developed a model which provide an explanation for multiple features observed in Run 1 from both ATLAS and CMS. This is achieved by introducing a heavy scalar, H , which couples to a dark matter candidate (DM), χ ,

1.6. THE MADALA HYPOTHESIS

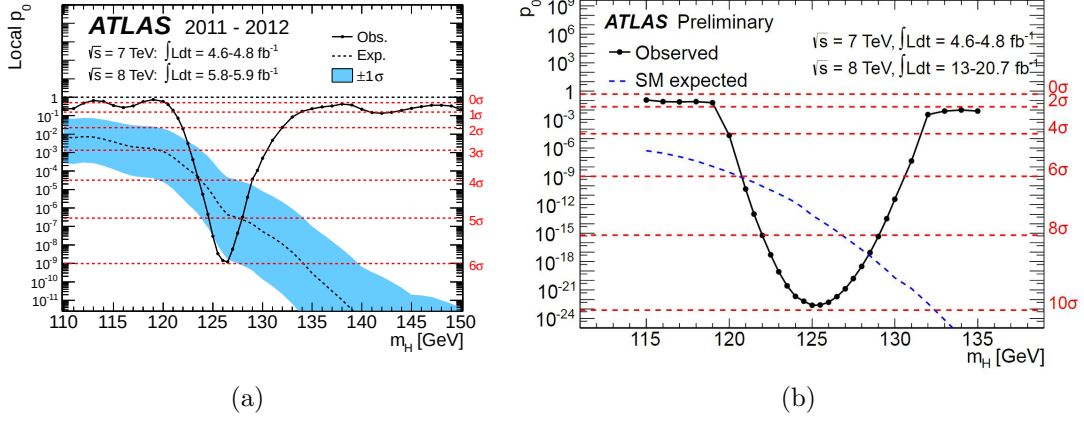


Figure 1.9: The ATLAS background only p-value discovery plot (left) [44] and an updated ATLAS measurement of local background only p-value with additional luminosity (right) [46]

through an intermediate scalar, S . This section will give an overview of the Madala Hypothesis. A detailed discussion is provided in Refs. [47, 48].

The Madala hypothesis, an isiZulu word for ‘old one’, considers a number of measurements summarised in Table 1.1. This includes the Higgs boson transverse momentum, p_T^h , searches for di-Higgs resonances, Higgs production in associated with top quarks and VV resonances from both ATLAS and CMS. In order to describe the p_T^h a heavy scalar H is introduced which can decay into at least one Higgs boson: $H \rightarrow hh$ and $H \rightarrow h\chi\chi$, where χ is the DM candidate, which leads to the production of a Higgs boson with missing energy. It must be noted that this assumes dark matter is produced 100% of the time, which may not be the case and could alternatively include any SM particle. The features seen in data, particularly the p_T^h shown in Figure 1.10, can be explained by a simple extension to the SM. The Lagrangian can be written as:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{BSM}}, \quad (1.3)$$

where $\mathcal{L}_{\text{SM}}$ is described in Equation (1.1) and new physical processes are described in $\mathcal{L}_{\text{BSM}}$. For simplicity, the new interactions are described using an effective theory. The Higgs boson is assumed to have SM interactions with other particles. The proposed BSM Effective Lagrangian involving the new scalars is given as:

$$\mathcal{L}_{\text{BSM}} \supset \mathcal{L}_H + \mathcal{L}_Y + \mathcal{L}_T + \mathcal{L}_Q, \quad (1.4)$$

where $\mathcal{L}_Y$, $\mathcal{L}_T$ and $\mathcal{L}_Q$ are the Yukawa, trilinear and quartic interactions respectively.

1. INTRODUCTION AND THEORETICAL MOTIVATION

Result	Publication	
Differential Higgs boson p_T spectra	ATLAS	Fiducial cross section measurements on $h \rightarrow \gamma\gamma$ [49] and $h \rightarrow ZZ^* \rightarrow 4\ell$ [50]
	CMS	Fiducial cross section measurements on $h \rightarrow \gamma\gamma$ [51] and $h \rightarrow ZZ^* \rightarrow 4\ell$ [52]
Di-Higgs boson resonance searches	ATLAS	Limits on $H \rightarrow hh \rightarrow b\bar{b}\tau\tau$, $\gamma\gamma WW^*$, $\gamma\gamma b\bar{b}$ and $b\bar{b}b\bar{b}$ [43]
	CMS	Limits on $H \rightarrow hh \rightarrow \gamma\gamma b\bar{b}$ [53], $b\bar{b}\tau\tau$ [54] and multi-lepton [55]
Top associated Higgs boson production	ATLAS	Limits on $h \rightarrow \gamma\gamma$ [56] Measurements on: Multi-lepton decays [57] and $h \rightarrow b\bar{b}$ [58]
	CMS	Measurements on: Multi-lepton decay channels, $h \rightarrow \gamma\gamma$ and $h \rightarrow b\bar{b}$ [59]
$H \rightarrow VV$ decays	ATLAS	Limits on $H \rightarrow WW$ [60] and ZZ [61]
	CMS	Limits on $H \rightarrow WW$ and ZZ [62]

Table 1.1: A list of the experimental results initially used to constrain the relevant parameters in the Madala hypothesis [47].

They are defined as:

$$\mathcal{L}_H = -\frac{1}{4} \beta_g \kappa_{hgg}^{\text{SM}} G_{\mu\nu} G^{\mu\nu} H + \beta_V \kappa_{hVV}^{\text{SM}} V_\mu V^\mu H, \quad (1.5)$$

$$\mathcal{L}_Y = -\frac{1}{\sqrt{2}} \left[y_{ttH} \bar{t}tH + y_{bbH} \bar{b}bH \right], \quad (1.6)$$

$$\mathcal{L}_T = -\frac{1}{2} v \left[\lambda_{Hhh} Hhh + \lambda_{h\chi\chi} h\chi\chi + \lambda_{H\chi\chi} H\chi\chi \right], \quad (1.7)$$

$$\begin{aligned} \mathcal{L}_Q = & -\frac{1}{2} \lambda_{Hh\chi\chi} Hh\chi\chi - \frac{1}{4} \lambda_{HHhh} HHhh \\ & - \frac{1}{4} \lambda_{hh\chi\chi} hh\chi\chi - \frac{1}{4} \lambda_{HH\chi\chi} HH\chi\chi, \end{aligned} \quad (1.8)$$

where H and χ denote the heavy scalar the Madala boson and the DM candidate respectively, and $v = 246$ GeV is the vacuum expectation value giving rise to the W and Z -boson masses. A simultaneous fit on the results listed in Table 1.1 is used to calculate a minimised χ^2 as a function of the mass of H . Figure 1.12 shows the best fit to be $m_H = 272_{-9}^{+12}$ GeV. Examples of fits at the minimised χ^2 can be seen in Figure 1.10.

The effective theory, represented in Figure 1.11a, makes no attempt to explain the origin of the $H \rightarrow h\chi\chi$ coupling. The proposed scalar, S , is assumed to mediate this interaction and decay into a pair of DM particles, as $S \rightarrow \chi\chi$, shown in Figure 1.11b. It must be noted that this treats the branching ratio of $S \rightarrow \chi\chi$ as 100% but may not be this high which would give rise to other SM decay modes. Treating S as a real scalar introduces rich possibilities for new search channels and phenomenology. The mass range $m_h \leq m_S \leq m_H - m_h$, with $m_S \geq 2m_\chi$, allows for new processes such as $H \rightarrow hS$, $H \rightarrow hh$ and $H \rightarrow SS$. In cases where $m_S \geq m_H - m_h$ this would lead to off shell processes such as $H \rightarrow S^*h^*$. It is important to realise that all decay modes (jets, leptons, photons, bosons, DM, etc.) of S are possible.

One can gain a deeper insight into the effective decay in Figure 1.11a by introducing two scalars, S and χ , into a two Higgs doublet model (2HDM) as described in Ref [48]. The outcome is five new scalars: the heavy scalar H , the intermediate S , a pseudoscalar A , and two charged Higgs bosons, $H^\pm$. Table 1.2 shows the rich number of possible final decay states of the five scalars and the Higgs boson.

1.7 Connecting the Dots

Although each analysis presented in this thesis is interesting in its own right, it is important to clarify how they are linked together. The simple answer is through

1. INTRODUCTION AND THEORETICAL MOTIVATION

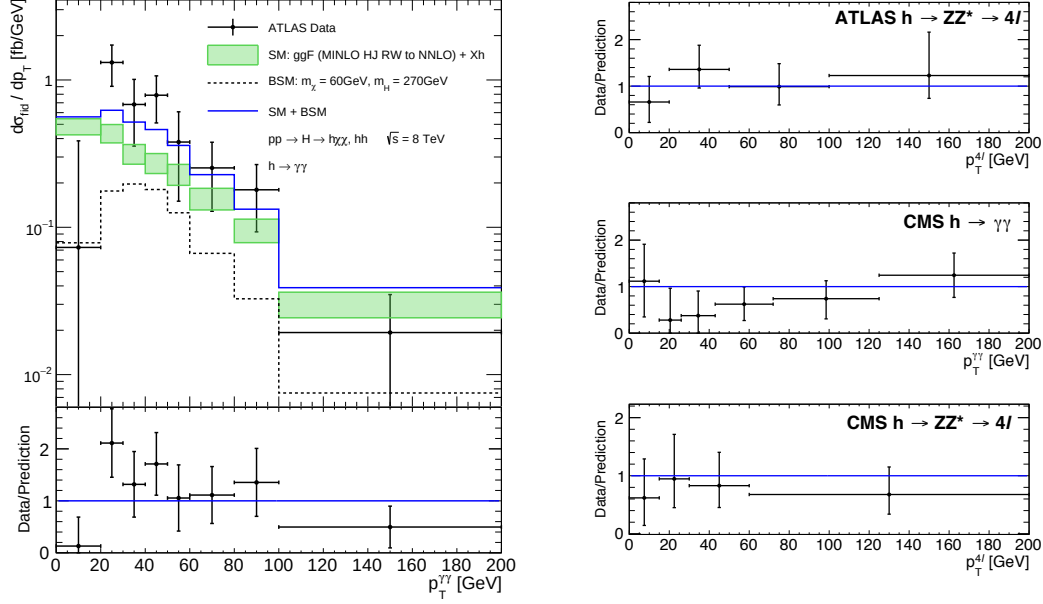


Figure 1.10: Fits to the fiducial differential distributions of the Higgs boson transverse momentum using the ATLAS diphoton [49] (left), the ATLAS $h \rightarrow ZZ^* \rightarrow 4\ell$ [50] (top right), the CMS diphoton [51] (middle right) and CMS $h \rightarrow ZZ^* \rightarrow 4\ell$ [52] (bottom right) decays. The ratio plots are between data and the Madala hypothesis. The fits are performed globally to all results listed in Table 1.1.

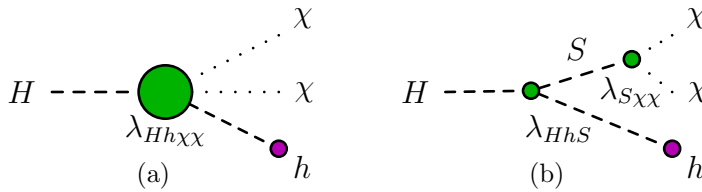


Figure 1.11: Representative Feynman diagrams of the Madala hypothesis described in Equation (1.3). On the left is the decay of a heavy scalar, H , through the effective quartic vertex, $\lambda_{Hh\chi\chi}$, and on the right due to an additional scalar, S .

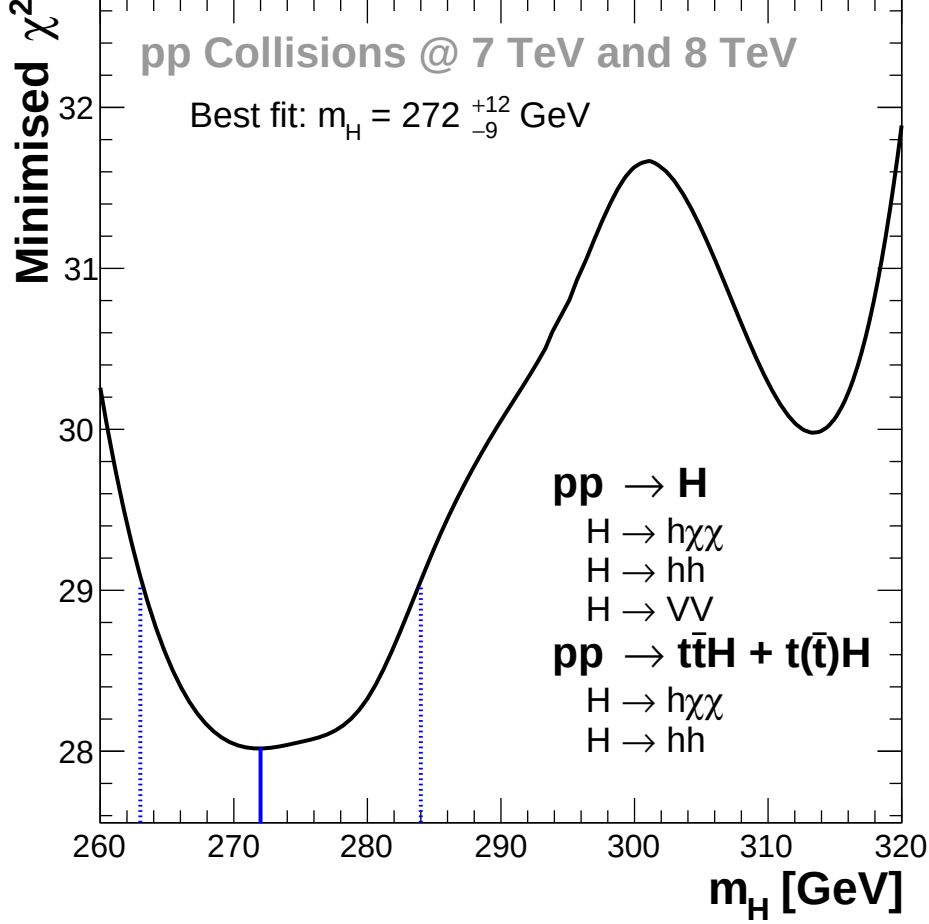


Figure 1.12: A scan of minimised χ^2 values as a function of m_H . This was calculated by minimising a χ^2 with contributions from all results in Table 1.1 as described in Ref. [47]

S. No.	Scalars	Decay modes
D.1	h	$b\bar{b}, \tau^+\tau^-, \mu^+\mu^-, s\bar{s}, c\bar{c}, gg, \gamma\gamma, Z\gamma, W^+W^-, ZZ$
D.2	H	D.1, hh, SS, Sh
D.3	A	D.1, $t\bar{t}, Zh, ZH, ZS, W^\pm H^\mp$
D.4	$H^\pm$	$W^\pm h, W^\pm H, W^\pm S$
D.5	S	D.1, $\chi\chi$

Table 1.2: The list of decay modes of the 2HDM scalars and S [48].

1. INTRODUCTION AND THEORETICAL MOTIVATION

the Madala hypothesis. In Section 1.6 a new heavy boson, called the Madala boson (H), is proposed. The BSM Lagrangian in Equation (1.4) indicates the possibility of an additional mechanism for Higgs boson pair production discussed in Section 1.3; a new real intermediate scalar, S, with similar Higgs-like decay modes and a dark matter candidate, χ , which would manifest itself as missing energy.

The diphoton channel has a very clean final state providing a high selection efficiency. This, combined with a precise reconstructed mass, makes it an ideal channel to search for new physics. Since the Higgs boson, the intermediate scalar, S, and the Madala boson can all decay into photons, it is natural to search for final states that share this common decay mode. This allows transfer of skills between different analysis and less time to get acquainted with technicalities.

In early 2015, ATLAS observed an excess of 3σ in the $hh \rightarrow \gamma\gamma b\bar{b}$ final state [63] which sparked the idea behind the Madala hypothesis. The Madala boson has two interesting decay modes to reach this four object final state: $H \rightarrow hh \rightarrow \gamma\gamma b\bar{b}$ and $H \rightarrow Sh \rightarrow \gamma\gamma b\bar{b}$, with the latter having $S \rightarrow b\bar{b}$ and $h \rightarrow \gamma\gamma$. Chapter 6 is a search for $hh \rightarrow \gamma\gamma b\bar{b}$ where the focus is on resonant and non-resonant Higgs boson pair production. The best fit mass in Figure 1.12 of $m_H = 272$ GeV falls within the search range of the $\gamma\gamma b\bar{b}$ study.

An important feature of the Madala hypothesis is the explanation of the enhanced intermediate diphoton transverse momentum ($p_T^{\gamma\gamma}$), seen in Figure 1.10. The introduction of a dark matter particle, χ , can provide the “recoil” against the Higgs boson and explain the increased $p_T^{\gamma\gamma}$ spectrum. The dark matter particles would pass through the detector unseen but would manifest themselves as missing energy. Chapter 7 searches for the production of a Higgs boson with missing transverse energy in the context of the Madala hypothesis with $H \rightarrow Sh \rightarrow \gamma\gamma + E_T^{\text{miss}}$.

In December 2015 ATLAS measured a rather startling excess, at 750 GeV, in the search for high mass diphoton resonances [64]. If the Madala hypothesis is embedded into a 2HDM, such as in Ref. [48], it has the potential to explain this excess, but will not be the focus of this chapter. The high mass study in Chapter 8 will investigate the jet differential properties of the 750 GeV excess and, since the Madala boson can also decay to photons, will search for signs of the Madala boson around 270 GeV.

Experimental Apparatus: The LHC and the ATLAS Detector

The Large Hadron Collider (LHC) is the frontier of collider physics. It boasts extremely complex and sophisticated systems from a wide range of scientific fields, including physics, mechanical engineering, civil engineering, electrical engineering and information technology. This chapter will provide a general overview with more detail to areas directly relevant to this thesis.

2. THE LHC AND THE ATLAS DETECTOR

2.1 The Large Hadron Collider

The LHC [65–67] lies in a tunnel 27 km in circumference approximately 100 m beneath the French and Swiss border near lake Geneva. Protons are accelerated through a series of systems before being injected into the main LHC ring. The injection system consists of pre-existing accelerators [65]. Protons are extracted by ionising hydrogen gas and directed into the Linac2 where they are accelerated to 50 MeV before being inserted into the Proton Synchrotron (PS) Booster. The PS Booster supplies the PS with 1.6 GeV protons after which they are accelerated to 26 GeV for insertion into the Super Proton Synchrotron (SPS). The SPS is the final pre-acceleration stage providing 450 GeV protons to the main LHC ring. The whole process takes just under five minutes and is repeated until 2 808 bunches¹ are circulating per beam in the LHC. Once this is complete the radio frequency (RF) system accelerates each beam up to 6.5 TeV, totalling 13 TeV.

The LHC is divided into eight sectors with each sector separated by a straight section nearly 530 m in length. The midpoints of straight sections are home to the worlds most advanced particle detectors as well as auxiliary machinery such as beam collimators,² access and dump³ sites. Figure 2.1 illustrates what is located at each arc of the LHC. Octant 1 contains the injection from the SPS as well as the ATLAS [69] detector. On either side of ATLAS are the ALICE [70] and LHCb [71] experiments in octants 2 and 8 respectively. Collimators are located at opposite ends in octets 3 and 7. The RF acceleration cavities and beam dump site are in octants 4 and 6, respectively, followed by the CMS experiment [72] located at the opposite side to ATLAS in octant 5.

The total energy of the LHC, 13 TeV or 6.5 TeV per beam, is limited to the physical radius of the ring as well as the strength of the superconducting bending magnets. In total there are 1 232 bending dipole magnets which require up to 12 000 Amperes. Providing this much current to the magnets cannot be done quickly resulting in a ramp time of around 20 minutes. Luminosity is used to characterise the performance of an accelerator and detector. It is defined as the number of collisions that can be produced per area per second. Higher luminosity values mean more collisions are detected resulting in larger datasets to analyse. This can be approximated by the number of bunch crossings per second divided by the effective cross section of the bunch. This is written as:

$$\mathcal{L} \approx \frac{N^2 f}{A_{\text{eff}}} = \frac{N^2 f}{4\pi\sigma_{\text{IP}}^2} \approx 10^{34} \text{ cm}^{-2}\text{s}^{-1} \quad (2.1)$$

¹Multiple bunches are inserted per injection taking approximately 30 minutes in total.

²A device which narrows a beam of particles.

³A process of removing energetic particles from an accelerator. Interestingly, the total energy of each beam at the LHC is ~ 360 MJ or equivalently 85 kg of TNT per beam [68]. This energy must be removed safely and quickly.

2.1. THE LARGE HADRON COLLIDER

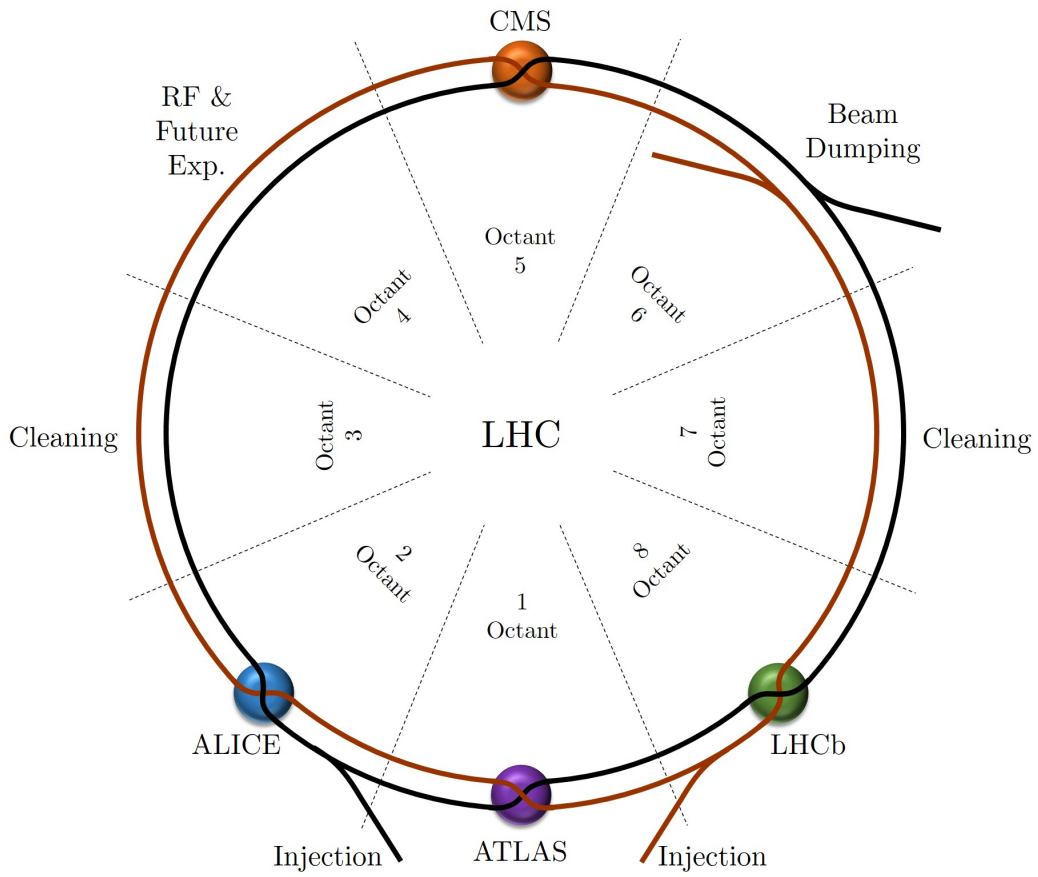


Figure 2.1: Layout of the main LHC ring. Protons are injected at 450 GeV from the Super Proton Synchrotron and finally accelerated to 6.5 TeV per beam.

2. THE LHC AND THE ATLAS DETECTOR

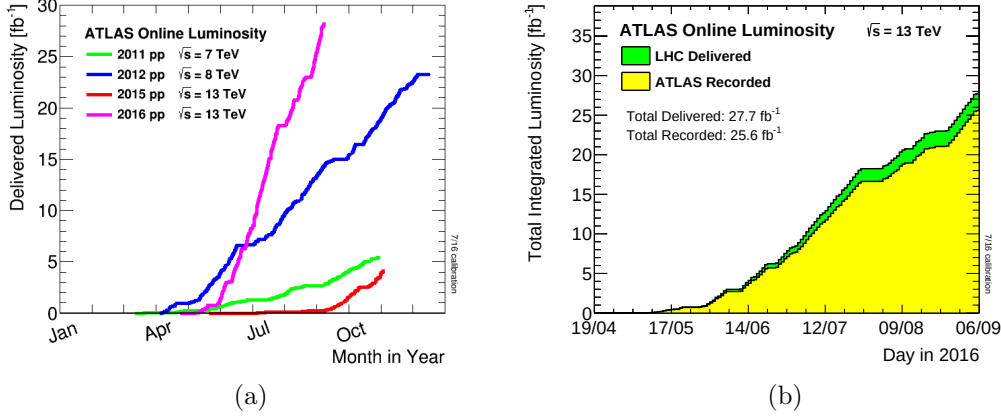


Figure 2.2: a) The total integrated luminosity delivered by the LHC over four years of operation and b) the total recorded luminosity by the ATLAS detector up to September, 2016 [73].

where $N = 10^{11}$ is the number of protons per bunch (squared because a proton could interact with any proton in the oncoming bunch), $f = 40$ MHz (bunch crossing of 25 ns) and $\sigma_{\text{IP}} = 16$ microns is the transversal size of the bunch at the interaction point.

In 2016, at the time of writing, the design luminosity in Equation (2.1) was surpassed with a record instantaneous luminosity of $1.2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. As a result of the higher luminosity, the rate of data collection, shown in Figure 2.2a, has been significantly higher compared to other years.¹ Figure 2.2b shows the total integrated luminosity provided by the LHC and recorded by the ATLAS detector for the 2016 period.

2.2 The ATLAS Detector

The ATLAS (A Toroidal LHC Apparatus) detector [69], illustrated as a cutaway diagram in Figure 2.3, was originally proposed in 1994 [74] as a general purpose particle detector. Over a decade of work saw the ATLAS detector progress from its expected performance [75] to actual measurements on collision data [76] as well as cosmic rays [77]. The detector has a cylindrical symmetry providing coverage of almost 4π in solid angle.²

¹The rate of data collection for 2016 is almost double that of 2012. Resulting in an equivalent integrated luminosity in half the time, an amazing feat.

²Solid angle is the two-dimensional angle in three-dimensional space. 4π equates to a surface that completely covers a sphere.

2.2. THE ATLAS DETECTOR

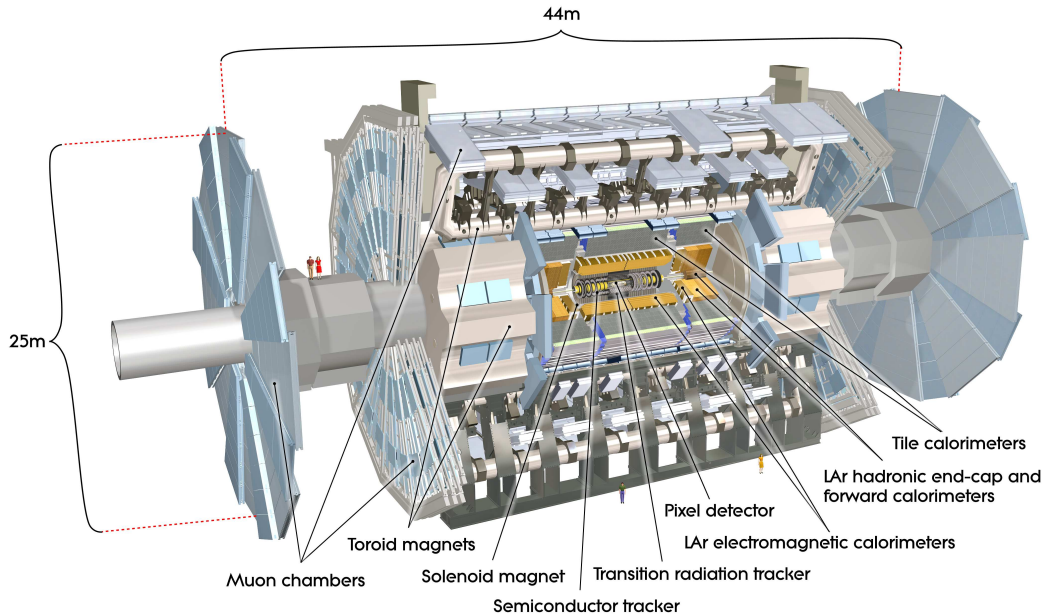


Figure 2.3: Cutaway representation of the ATLAS detector [78].

ATLAS uses a right-handed coordinate system originating at the designed interaction point (IP). The x-axis points from the IP to the center of the LHC ring, the y-axis points upwards and the z-axis points along the beam pipe. There are three main spacial properties, among others, that are used throughout this thesis: 1) Transverse plane in the x-y direction, 2) the azimuthal angle around the beam pipe (ϕ) and 3) the pseudorapidity¹ $\eta \equiv -\ln(\tan(\theta/2))$, where θ is the polar angle between the particle and the positive direction of the beam axis.

ATLAS comprises three concentric sub-detectors centred around the interaction point and a trigger system to select interesting events:

The Inner Detector [79–81] employs two technologies providing detailed tracking for vertex reconstruction and identification using millions of channels. The Pixel detector [82, 83] and the semiconductor tracker (SCT) [84–86] use silicon and microstrips to detect ionising radiation. The Transition Radiation Tracker (TRT) [87–89] is a straw tracker using a xenon, carbon dioxide and oxygen gas filled tube with a gold-plated wire fixed in the middle. The total coverage of the ID extends out to $|\eta| < 2.5$. A representation of the layout can be seen in Figure 2.4a.

The ATLAS Calorimeters are grouped into four unique systems which pro-

¹In the limit that the particle travels close to the speed of light, or the mass is negligible, the pseudorapidity converges to the definition of rapidity as $y \equiv \frac{1}{2} \ln \left(\frac{E+p_z}{E-p_z} \right)$

2. THE LHC AND THE ATLAS DETECTOR

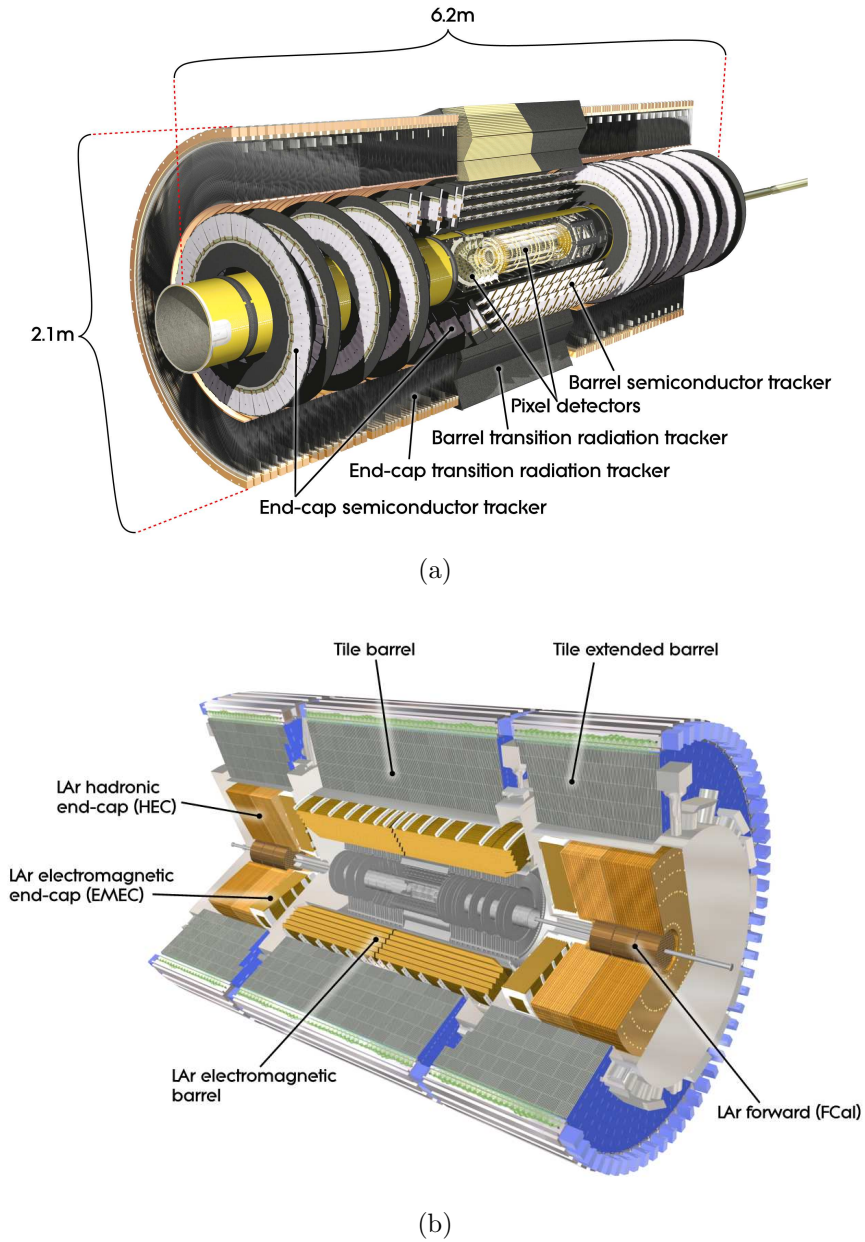


Figure 2.4: a) The Inner Detector and b) The Electromagnetic and Hadronic calorimeters [78].

vide the means to measure electromagnetic and hadronic energy in the range $\eta < 4.9$. The four systems include the Liquid Argon Electromagnetic Calorimeter, The Tile Calorimeter, the Hadronic Endcap Calorimeter and Forward Calorimeter. The diphoton studies presented in Chapters 5 to 8 use the Electromagnetic Calorimeter to identify photons so additional information can be found in Section 2.2.1. Similarly, Chapters 3 and 4 involve the consolidation and upgrade of the Tile Calorimeter, therefore, more detail is provided in Section 2.2.2. The Hadronic Endcap provides coverage for the range $1.7 < |\eta| < 3.2$ and the forward calorimeter completes the final range with $3.1 < |\eta| < 4.9$. The accepted maximum range is considered to be $|\eta| < 4.5$ for reasons related to jet reconstruction discussed in Section 5.2.4. The layout of the four subsystems is seen in Figure 2.4b.

The Muon System comprises four different technologies: Monitored Drift Tube chambers (MDT), Cathode Strip Chambers (CSC), Resistive Plate Chambers (RPC) and Thin Gap Chambers (TGC) which, when combined with immense toroid magnets powered by a 205 kA current, can perform precise momentum measurements [90, 91]. The Muon system, shown in Figure 2.3, and the Calorimeters are used in conjunction to estimate the amount of missing energy carried away by undetected particles such as neutrinos or possibly new non-interacting particles like dark matter. Muons are used for b -jet reconstruction and corrections in Chapter 6 as well as in the missing energy reconstruction in Chapter 7.

The Trigger and Data Acquisition System is responsible for identifying interesting events and storing them to disk. Numerous areas of the trigger system have been updated in order to improve the trigger rates required for the data taking conditions in Run II. Events will be written to disk at 1 kHz (compared to 600 Hz in Run I) totalling around 1.5 GB/s. This factor of 2.5×10^{-5} is achieved using the new two stage system consisting of a hardware and software level called the level-1 (L1) trigger and high level trigger (HLT), respectively. The L1 accept is processed using custom electronics to find regions of interest (ROI) using the calorimeter and muon systems within a latency of 2.5 μ s. The HLT uses information from the ROI on custom computer farms taking on average 0.2 s to make a decision. Events are then reconstructed using the full event information and stored on disk at a rate of 1 kHz.

2.2.1 The Liquid Argon Electromagnetic Calorimeter

Particles passing through material usually undergo a process called showering, a cascading of secondary particles, which is characterised by the initiating particle. In

2. THE LHC AND THE ATLAS DETECTOR

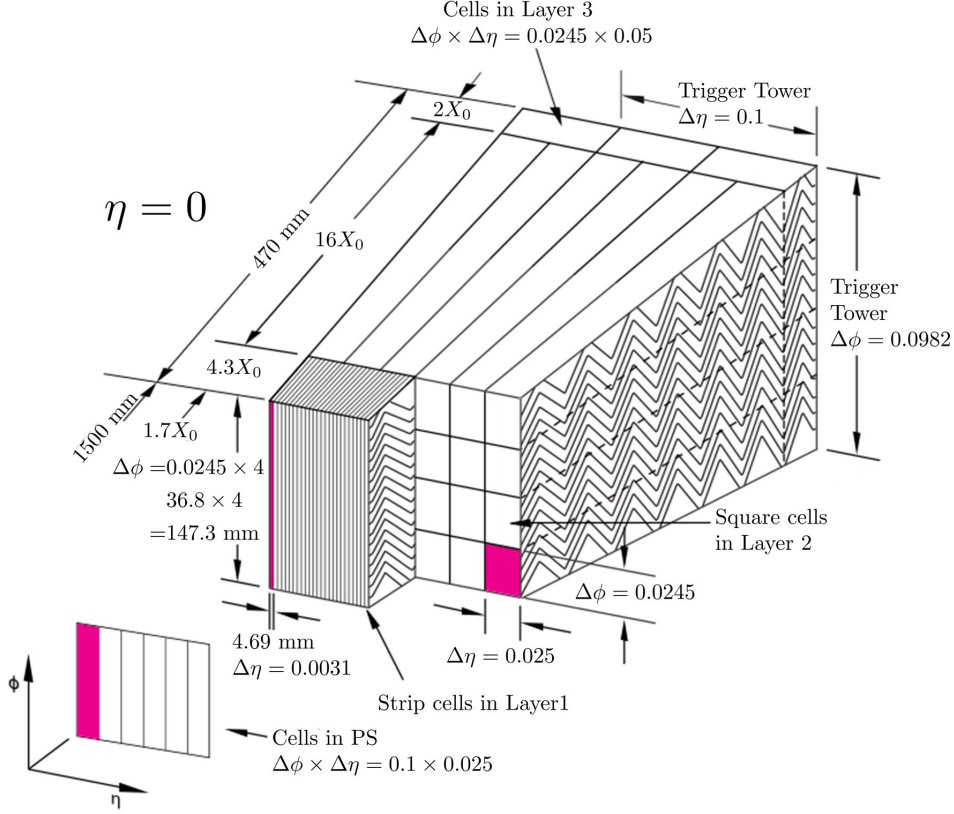


Figure 2.5: A schematic of the EM liquid argon calorimeter. The shape allows almost perfect symmetry in the azimuthal plane. A finer granularity is used in the first layer to allow identification of neutral pions from photons.

the Liquid Argon (LAr) Electromagnetic (EM) Calorimeter [92] incoming photons and electrons lose energy by undergoing multiple $\gamma \rightarrow e^+e^-$ conversions and $e^\pm \rightarrow e^\pm\gamma$ Bremsstrahlung emissions. A depth parameter, X_0 , is defined as the distance an electron must travel to lose $1/e$ of the initial energy due to Bremsstrahlung or the distance a photon must travel to have a 54% probability to be converted into an electron-positron pair. Ideally, full containment of the shower is required to measure the total energy deposition. To achieve this lead absorbers are added in conjunction with liquid argon. Ionising radiation creates currents in the liquid argon which is sampled using Kapton¹ electrodes.

The EM calorimeter is separated in the longitudinal η direction allowing photons to be traced towards the main vertex in a technique called “pointing”. This is a

¹Kapton is a radiation hard and non-conducting polymer at extremely low temperatures [93] making it ideal for use in a liquid argon environment.

useful technique in the event of an unconverted¹ photon which leaves no tracks in the inner detector. The accordion geometry, providing complete azimuthal symmetry, can be seen in Figure 2.5. The first layer contains a fine granularity of strips to assist in neutral pion rejection. The second layer has a larger granularity and records most of the energy deposition of an EM shower [69]. The third and final layer provides a last measurement before the hadronic calorimeter. The total coverage of the calorimeter is $|\eta| < 3.2$ but since the fine strips end at $|\eta| < 2.4$ photon identification cannot reliably extend passed this. The different components combine to make an excellent tool for accurate identification and reconstruction of photons (a procedure explained in Chapter 5).

2.2.2 The Tile Calorimeter

The central hadronic calorimeter, $|\eta| < 1.7$, is called the Tile Calorimeter. It is a hollow cylinder with an inner radius of 2.28 m and outer radius of 4.23 m. The central barrel is 5.56 m long and covers the range $|\eta| < 1.0$ with two extended barrels, 2.91 m, on either end to cover $0.8 < |\eta| < 1.7$. Each barrel comprises 64 wedge-shaped modules with two sets on either end of the long central barrel. When hadronic particles pass into the material they produce a shower of additional particles which are called jets. The main design goal of the Tile Calorimeter is to identify and measure the energy of jets. This is achieved using an active layer of plastic scintillators sandwiched between steel absorber plates as can be seen in Figure 2.6. Multiple tiles are grouped together to form cells. Light from the cell, emanating from particles interacting with the scintillator, is directed through wavelength shifting fibre optics to a photomultiplier tube (PMT) to generate an electrical signal. Two drawers are combined to form a super-drawer reading out a single wedge with 48 PMTs. In total there are 256 super-drawers with approximately 10000 channels. The electronics which process the PMTs output are separated into regions on and off the detector which are called the front-end and back-end electronics.

Front-end electronics are contained in retractable drawers inserted into the outer radius of the modules as shown in Figure 2.6. There are four main components: The PMTs, amplifiers, digitizers and an interface board to transmit data off the detector and receive information from the back-end. Chapter 3 details the consolidation and validation of the front-end electronics after the first long shutdown and before data taking started in 2015.

Back-end electronics are housed in the counting room separate from the detector. This is a low radiation zone which allows easy access. The back-end receives

¹A photon which has not converted into an electron positron pair.

2. THE LHC AND THE ATLAS DETECTOR

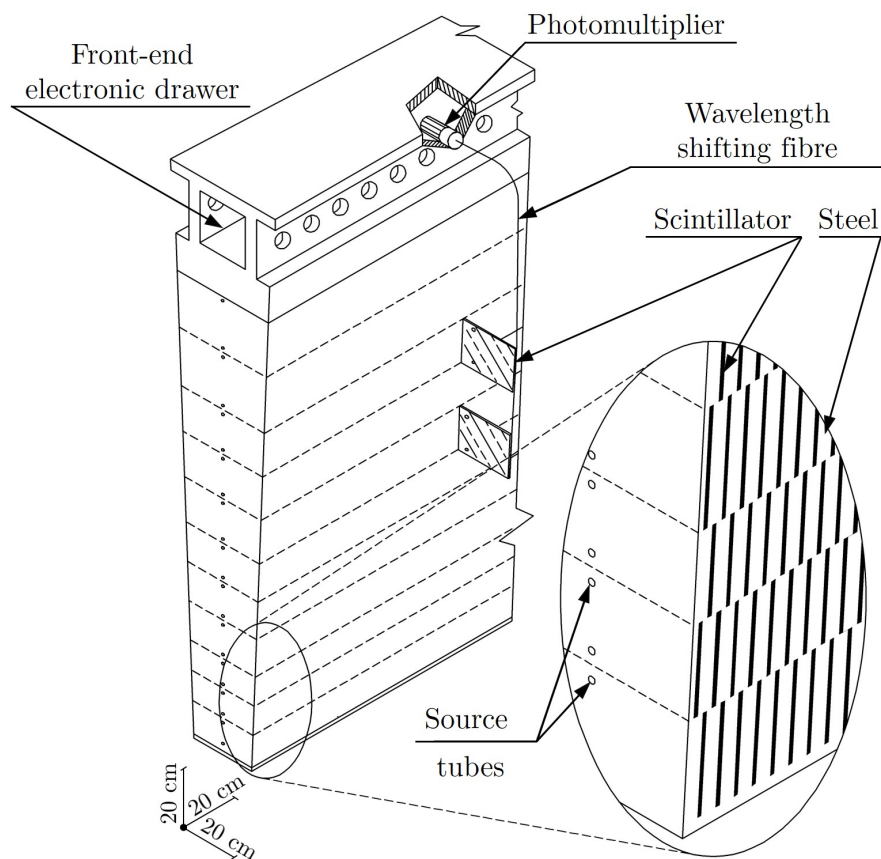


Figure 2.6: A schematic of a Tile Calorimeter wedge-shaped module showing the plastic scintillators sandwiched between steel absorbers. The front-end electronics drawer is located in the outer radius to read out the photomultiplier tubes.

digitized data through redundant optical fibres links and prepares the data for further processing downstream. The auxiliary hardware housing the electronics will be improved for the Phase II upgrade during the third long shutdown. Chapter 4 describes the integration of this new hardware into the existing detector control system and data taking in general. The back-end electronics also act as an interface to the front-end allowing transfer of information such as trigger and timing or the execution of commands changing the detector state.

2.3. THE UPGRADE OF THE LHC AND THE ATLAS DETECTOR

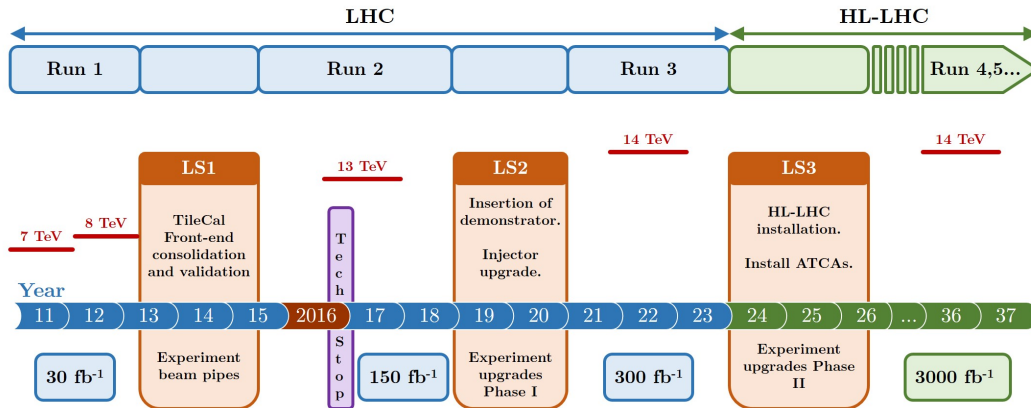


Figure 2.7: A timeline showing the foreseen operations and upgrades of the LHC and ATLAS detector [95].

2.3 The Upgrade of the LHC and the ATLAS Detector

The LHC is envisioned to operate till the late 2030's. A timeline of the projected operations can be seen in Figure 2.7. The LHC schedule accommodates multiple upgrade phases and technical stops since hardware is continuously stressed in high radiation environments and the employed technology keeps advancing. After a successful Run I the LHC went into the first long shutdown (LS1) for maintenance and upgrades. During LS1 the Tile Calorimeter was required to undergo consolidation of the front-end electronics and to validate the performance before Run II could start. The first stage, Phase 0,¹ allowed the required preparations to record collisions at an increased centre of mass energy of 13 TeV as well as a reduction in the bunch crossing time from 50 ns to 25 ns. The second long shutdown (LS2) is scheduled to begin in early 2019 starting the upgrade phase (Phase I upgrade). During this phase ATLAS will, among others, improve the muon system (the largest sub-detector) and prepare the detector for a doubling of the designed luminosity. The increase in the luminosity will be possible by upgrading the LHC PS Booster and collimators [94].

Following LS2, the LHC is expected to deliver over 300 fb⁻¹ by 2023. At this point an extensive replacement of hardware for both the accelerator and all detectors [96] will commence. The motivation for the ATLAS Phase II upgrade in 2023 [97] is summarised as follows:

- The trigger rate (number of events accepted per second) will increase by a

¹The upgrade numbering may get confused with the shutdown numbering. Phase 0, 1 and 2 refer to the upgrade phases for the shutdown periods LS1, LS2 and LS3, respectively.

2. THE LHC AND THE ATLAS DETECTOR

factor of five to 500 kHz requiring a redesign of the entire readout systems.

- A larger dataset will allow significant improvements in precise measurements and also open the window to rare interactions, such as the Higgs boson self coupling.
- New complex theories require more sophisticated object reconstruction and identification.
- The majority of hardware would be approaching 15 – 20 years of operation and would benefit from an upgrade. Electronics continue to shrink in size and increase in performance.
- Radiation damage will be more significant for the higher luminosities expected in Run 3. Components must be able to withstand these demanding conditions.
- Pileup, the number of interactions per bunch crossing, will increase dramatically requiring better granularity in some detectors.

Preparations for the Phase II upgrade of the Tile Calorimeter are already under way and will be discussed in Chapter 4.

2.4 The Detector Control System

The ATLAS Detector Control System (DCS) [98] has the task of ensuring the safe and coherent operation of the detector and all its components. The DCS manages what state the detector is required to be in whether its for access, calibration or data taking. It must continuously monitor and archive hardware information and alert the operators if any abnormal behaviour is observed. The DCS can automatically attempt to recovery from an unplanned change of state to maintain smooth operations. If automated recovery is unsuccessful the detector will shutdown relevant systems to prevent any further damage. Online operational information must be managed and presented to the expert with a level of detail that is both minimal and useful for easy global overseeing. The requirements of the DCS are summarized as follows:

- Unrelated systems should not be dependent on each other.
- Scalability to accommodate upgrades, prototypes and expansions.
- Remote monitoring and control due to the difficulty of physical access to the detector 100 m underground in high radiation environments.

2.4. THE DETECTOR CONTROL SYSTEM

- Graphical displays of the detectors' online status with the options to view detailed information if desired.
- Automated response for recoverable situations.
- Triggering alarms or emergency procedures if needed.
- Flammable gas/liquid and smoke detections.
- Error handling.
- A synergy between the Data Acquisition System (DAQ) and DCS to ensure good quality physics data.
- Integrate with the Detector Safety System (DSS) to maintain a safe environment in the detector complex.

A Joint Controls Project (JCOP) [99] was established to facilitate the collaboration between major detector systems such as the DCS, DAQ and DSS. The JCOP framework is designed and built on a SCADA¹ tool called WinCC (previously known as PVSS²). The JCOP framework is not a complete control system but a well organised set of tools allowing one to be built. Developers are able to reuse existing packages which minimise the learning curve and accelerates productivity.

The DCS has dedicated electronics connected to the front-end allowing direct control over the hardware. The control process is facilitated by the back-end software. In order to satisfy the requirements listed above, the DCS back-end is structured in a three level hierarchy as shown in Figure 2.8. The global control stations (GCS) provide the overall control of the detector. The GCS provides high level monitoring and controls all the sub-detectors. The GCS summarises all statuses from sub-components and presents it graphically to the operator. Each sub-detector has a dedicated Sub-detector Control Stations (SCS). The role of the SCS is to micromanage all sub-systems in the Local Control Station (LCS) and validate commands issues by the GCS. The LCS is the lowest level in the back-end system and is specific to the sub-system it belongs to. The LCS is responsible for reading out the front-end equipment and executing commands from higher levels. Chapter 4 discusses the integration of new back-end infrastructure into the DCS for the Phase II upgrade.

¹SCADA stands for Supervisory Control And Data Acquisition. Generally these are commercial software systems which are widely used in a wide range of industries. Examples include mining, material processing, data centres and large experiment controls.

²Prozeß, Visualisierungs und Steuerungs-System made by ETM a subsidiary of Siemens.

2. THE LHC AND THE ATLAS DETECTOR

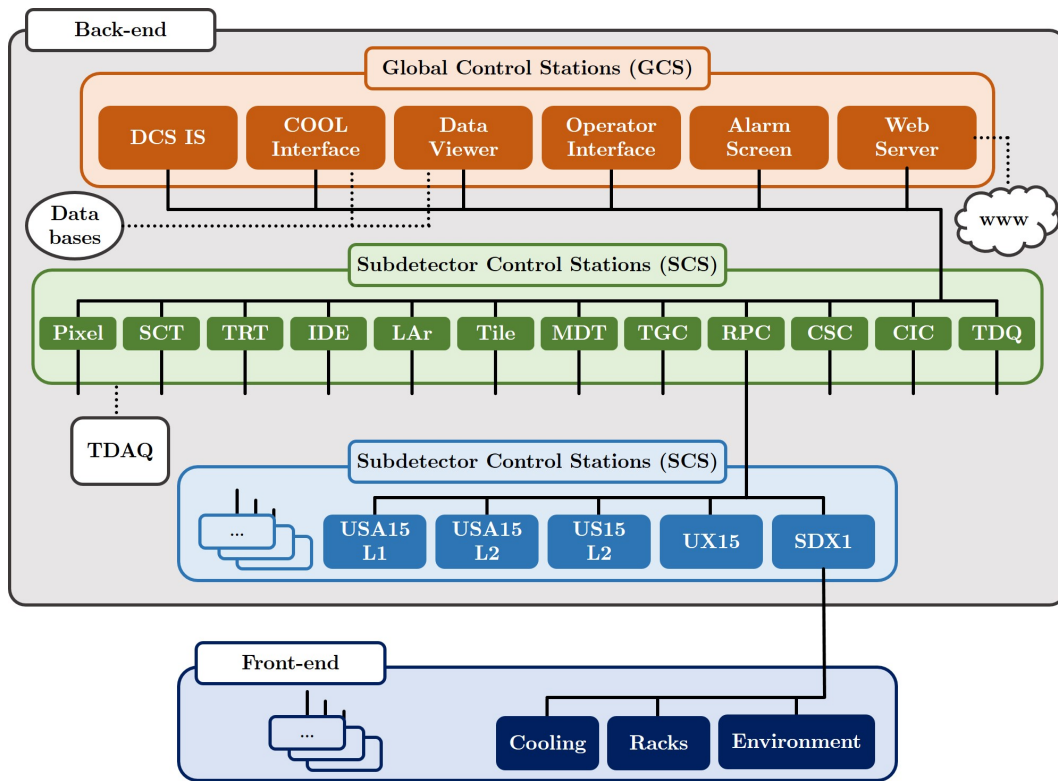


Figure 2.8: Layout of the Detector Control System.

Run II Consolidation of the Tile Calorimeter Front-End Electronics

In March 2013, the LHC entered the first long shutdown (LS1) following the discovery of the Higgs boson in July 2012. The LS1 lasted two years providing sufficient time to prepare the Tile Calorimeter front-end electronics for a centre of mass energy (CME) of 13 TeV. The Tile Calorimeter community used this time to repair and improve many systems from issues found during Run I. This included corrupted data, persistent tripping of low voltage power supplies and channels with high noise to signal ratios. On completion of any needed maintenance, the super-drawer underwent a stringent consolidation and validation process, which was performed both before and after closing the module. In 2010 a mobile drawer integrity checking system (MobiDICK) was developed to extend the lifetime of the existing test-bench. The MobiDICK design has been upgraded for LS1 and additional units were produced to consolidate all aspects of the front-end electronics while experts still had physical access to the detector. This section describes the MobiDICK unit and details the upgrade of the high voltage board used to power the PMTs on the drawer. The work presented was performed at the High Throughput Electronics Laboratory (HTEL) at the University of the Witwatersrand.

3. RUN II CONSOLIDATION OF THE TILE CALORIMETER FRONT-END ELECTRONICS

3.1 Mobile Drawer Integrity Checking System

The Mobile Drawer Integrity Checking System (MobiDICK) [100] was originally based on a Versa Module Europa (VME) system [101]. A VME bus is a standardized way to connect multiple components together while maintaining modularity. The back-end electronics, which connect and process signals from the front-end, are housed in large VME crates. In 2010 a portable version was designed in 2010 to extend the lifetime of the test-bench. The portable version assisted the commissioning of the front-end electronics allowing experts to fully diagnose a drawer of electronics while still having physical access. The main reasons for the design of a new MobiDICK unit were:

- At the time there were only three units available. Due to the tight time constraints of LS1 all four modules of the Tile Calorimeter were required to be checked at the same time.
- VME and some other components were fairly outdated making the replaceability and repairs almost impossible.
- Technology keeps progressing and the size of components is shrinking. The new unit would be much lighter and easier to manoeuvre.
- The technologies employed would provide practical knowledge about products, devices and techniques that could be used for the Phase II upgrade in 2024.
- The original units were rather cumbersome due to the number of boards required to operate the VME crate combined with the overall weight and size of the VME crate. This trait made them difficult to use in the cramped spaces found in the ATLAS detector.
- New diagnostic tests were developed.

The new unit, called MobiDick4 [102], has a completely new design, intended to replace the VME system, utilising programmable logic. The VME modules are emulated on a field-programmable gate array¹ (FPGA) evaluation board to simplify the design. The internal connectivity of the different components is shown in Figure 3.1. The main components are described below.

The motherboard provides an interconnect between all subcomponents. It uses a Xilinx ML507 evaluation board which includes a Virtex-5 FPGA with a PowerPC 440 microprocessor which executes the tests. The evaluation board is used to simplify the overall design.

¹A field-programmable gate array is an integrated circuit designed to be configured after manufacturing which can contain millions of programmable logic blocks with variable interconnects.

3.1. MOBILE DRAWER INTEGRITY CHECKING SYSTEM

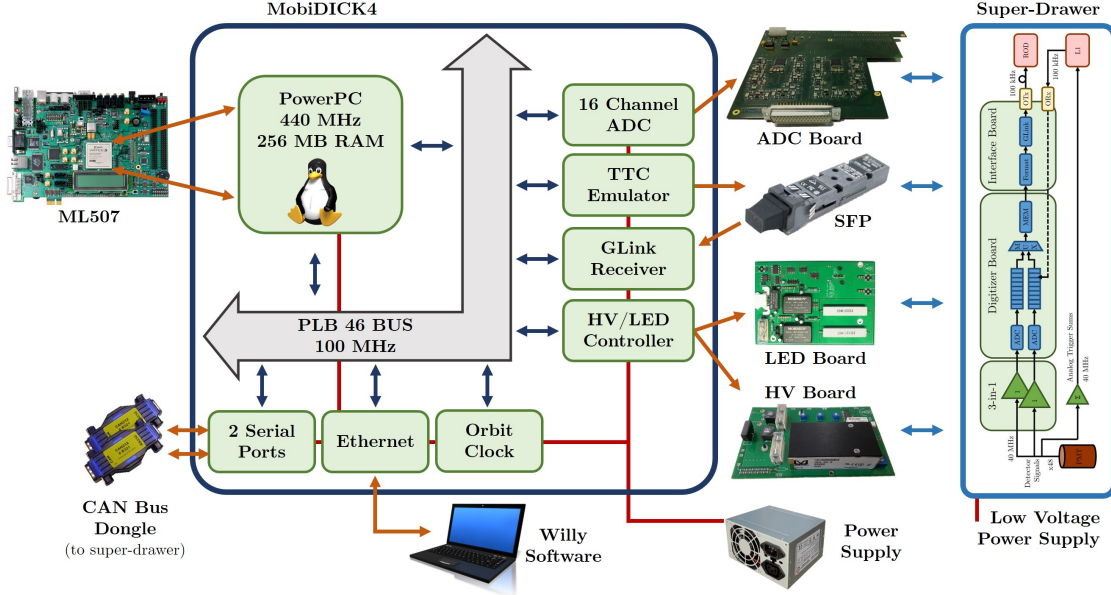


Figure 3.1: Sketch of the MobiDICK-4 test-bench system. Adapted from Ref [102].

An analog to digital conversion (ADC) board to digitize the analog trigger and muon outputs received from the front-end electronics. It uses two 12-bit ADC chips from Texas Instruments to digitize 16 input channels at a rate of 40 MSps.

A Light Emitting Diode (LED) board to generate a 20 ns pulse to drive the LEDs used to test the PMTs. This board was redesigned and built in the HTEL in South Africa.

A high voltage (HV) board to provide -830 V to power the PMTs located on the super-drawer during testing. This board was redesigned and built in the HTEL in South Africa.

CAN bus dongles to control the HVmicro board through the motherboards two serial ports using the Controller Area Network (CAN) bus. The HVmicro board on the super-drawer regulates the high voltage applied to the PMTs and controls the ADC-I boards to provide integrated data on the PMT currents.

User software is installed on an external laptop which connects to the unit providing a graphical interface to perform the relevant tests. In keeping with the MobiDICK theme the software is nicknamed ‘Willy’.

The geometry of the new MobiDICK4, shown in Figure 3.2a, is significantly smaller than the previous version. The overall dimensions are 40 cm in length, 35 cm

3. RUN II CONSOLIDATION OF THE TILE CALORIMETER FRONT-END ELECTRONICS

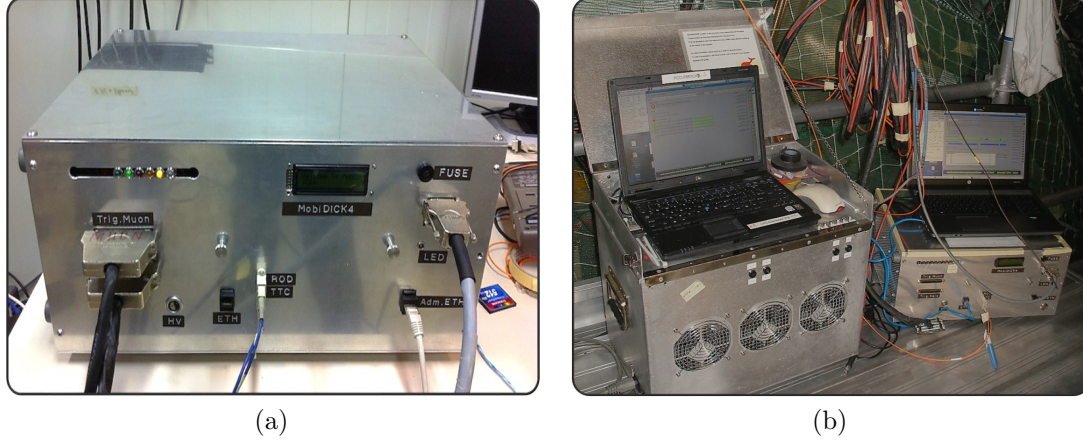


Figure 3.2: a) The new MobiDICK4 unit and b) a side-by-side comparison of the new and old systems.

in breadth and 20 cm in height, resulting in a weight roughly 20% of the original at 4 kg. The size comparison can clearly be seen in Figure 3.2b. The MobiDICK unit performs a total of 14 different tests which constitutes the certification process. These are summarised from Ref [103] as:

1. **Communication with motherboard.** The first test checks if there is any communication with the main motherboard on the front-end electronics.
2. **Trigger tower charge injection test.** A Charge Injection System (CIS) is used to check the response of the adder summation card with respect to a known injected charge. The adder card is used to sum the analog PMT signals which is used for triggering. The CIS system allows the PMTs to be bypassed.
3. **Data integrity test.** The quality of the digital read-out must be validated. There are five sub-tests performed with different read-out modes and calibration modes.
4. **Digitizer charge injection test.** This test checks the functionality of the digitizer using the CIS and looks at the linearity of the response.
5. **Noise test.** The digitizer produces noise which must be measured to check the data integrity. The high voltage is turned off for this test to allow the measurement of electronic noise.
6. **Noise test with HV.** Similar to the test above but with the high voltage power supply which feeds the PMTs switched on. An increase in the noise is expected.

3.2. THE UPGRADED HIGH VOLTAGE BOARD

7. **Fast test.** Level one accept triggers are sent by MobiDICK to the front-end with a rate of 100 kHz and checked in real time using a cyclic redundancy checking¹ (CRC) code to validate data integrity.
8. **Communication with HV CAN.** Determine if communication with the HVmicro boards is working using the CAN bus interface.
9. **Communication with HVOpto card.** This test checks the correct operation of the high voltage distribution system using the CAN bus interface.
10. **HV regulation test.** The high voltage distribution is tested using a predefined voltage value stored in the HVmicros' EEPROM.²
11. **Integrator readout test.** The noise level and linearity of the ADC-I are checked by injecting a predefined signal into the ADC-I board and reading the response through the CAN bus.
12. **Integrator readout test with HV.** The Integrator readout test is performed with the high voltage supply turned on. An increase in the noise is once again expected.
13. **Digitizer stuck bit test.** Failures in the front-end digitizer boards could result in bits getting stuck. All bits are flipped multiple times with a fixed procedure and any stuck bits are identified.
14. **LED test.** The LED test injects a known light pulse into the PMT and measures the final output of the electronics. This tests the entire front-end system including the PMT response. The readout is done through the small form-factor pluggable (SFP) module.

3.2 The Upgraded High Voltage Board

In order to successfully run all the certification tests, the MobiDICK unit must provide a high voltage source to power the PMTs and HV systems on the electronics drawer. It was envisioned to produce four new upgraded MobiDICK units, which meant additional HV boards had to be manufactured. The new HV boards were based off the original design by Clermont-Ferrand [104] but incorporated numerous upgrades made following its installation in 2010. These upgrades include the addition of an isolating optocoupler,³ DC/DC power converter, dual DIP pins for

¹Cyclic redundancy check is an error detecting code usually used in digital communication to identify if raw data has been corrupted.

²Electrically Erasable Programmable Read-Only Memory. The contents can be erased and re-programmed using a pulsed voltage.

³An optocoupler or opto-isolator is an electrical component that transmits a signal between two isolated circuits using light.

3. RUN II CONSOLIDATION OF THE TILE CALORIMETER FRONT-END ELECTRONICS

LED connectors and other minor improvements to assist the usage and maintenance of the board. The design and manufacturing process is described below.

3.2.1 Logical Design and Component Layout

One of the first steps in the design process for any electronic device is the circuit diagram. In the case of the HV Board the previous circuit diagrams were available in PDF format and on paper. The upgrades mentioned above were first included into the paper schematics and then captured into an electronic version using a commercial product called OrCAD Capture [105]. Schematics in OrCAD Capture produce a netlist which can be exported to other software packages for simulation or component placement. A netlist is a collection of logical relationships between different pins of the electrical components and the conductors that intersect them. A net is the conductor which connects two or more component terminals. The schematics of the HV design can be seen in Figures A.2 to A.4 and the associated Bill Of Material with component information in Tables A.1 and A.2. OrCAD Capture includes a component information system, a central database which links footprints¹ or simulation data to the circuit symbol in the schematic.

Once the schematics were completed the layout of the board and all components was considered. The netlist from Capture were exported into the OrCAD PCB designer software [106]. PCB designer allows for manual or automated track placing, board level analysis and design rule checks (DRC). The size of the HV Board was kept the same since mechanical mounting points in the MobiDICK case was already specified. A dual layer board was used. A single large ground plane was added to the top layer of the board which made grounding components through vias² or directly to the plane easier and provided a simpler design overall. The power lines, located on the bottom layer, were routed before all components were placed so they were as simple as possible. Each component and its corresponding tracks were all placed by hand. The circuit board top and bottom layouts, showing all tracks and components, can be seen in Figure 3.3. A 3D rendering of the design for each layer is shown in Figure 3.4. The DRC provides warnings and errors for any condition that violates the schematic design. This extends to the footprint package geometry (size and shape of a component) overlapping or being in close proximity to something in its surroundings. Once all DRCs were fixed the production could begin.

¹A component footprint is the geometric layout of pins or pads that electrically and physically connect a component to the PCB.

²A via is a vertical interconnect access. A hole from one level to another with conducting material on the inner diameter providing a connection.

3.2. THE UPGRADED HIGH VOLTAGE BOARD

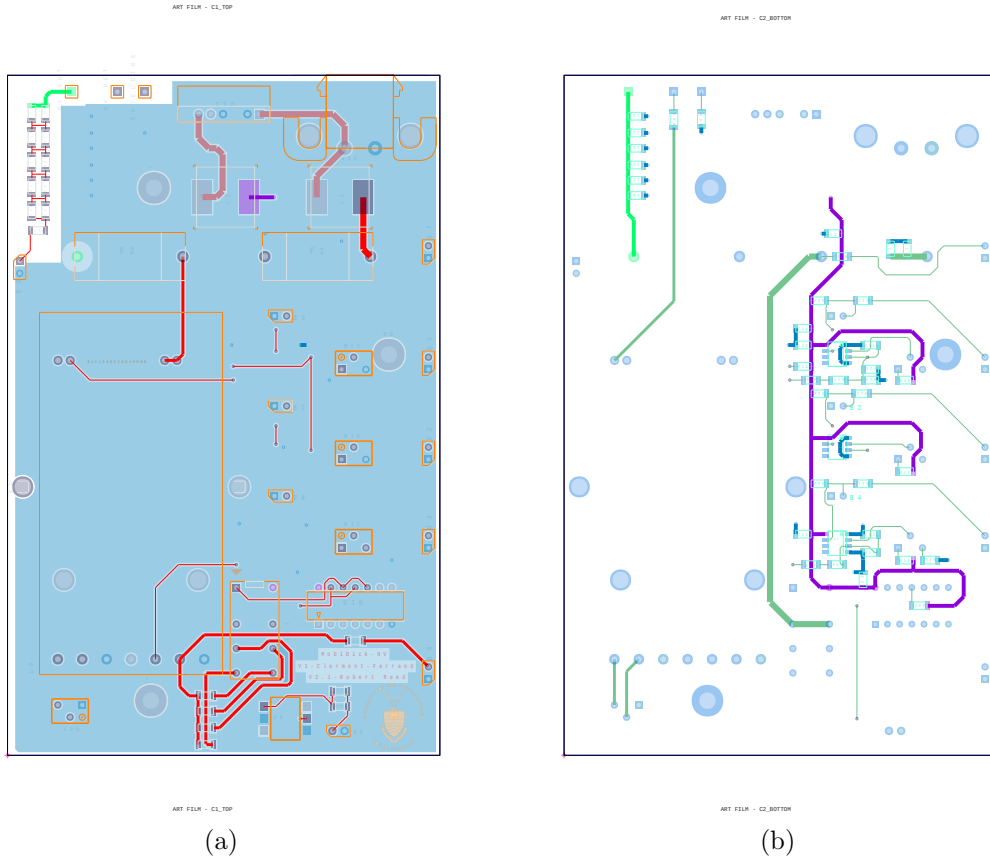


Figure 3.3: Layout of the HV Board from the a) top view and b) bottom view.

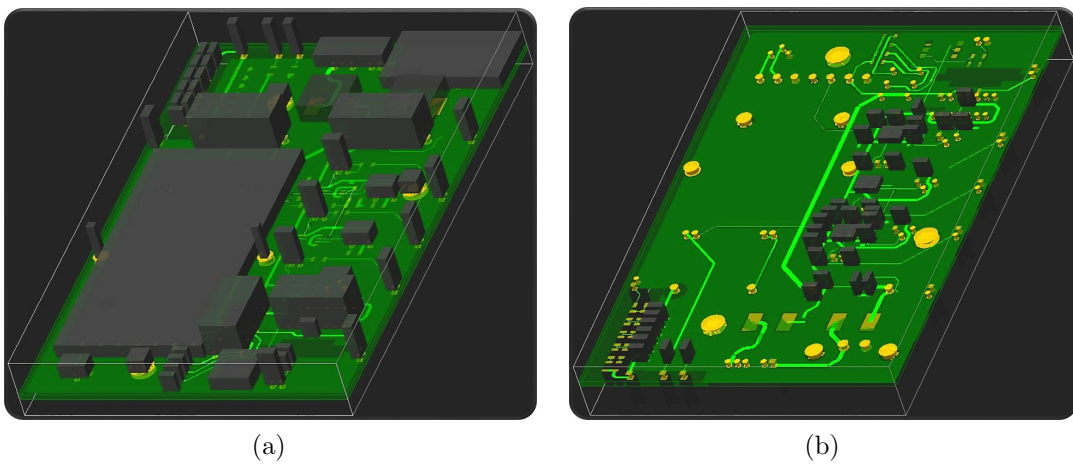


Figure 3.4: 3D rendering of the HV Board from the a) top view b) bottom view.

3. RUN II CONSOLIDATION OF THE TILE CALORIMETER FRONT-END ELECTRONICS

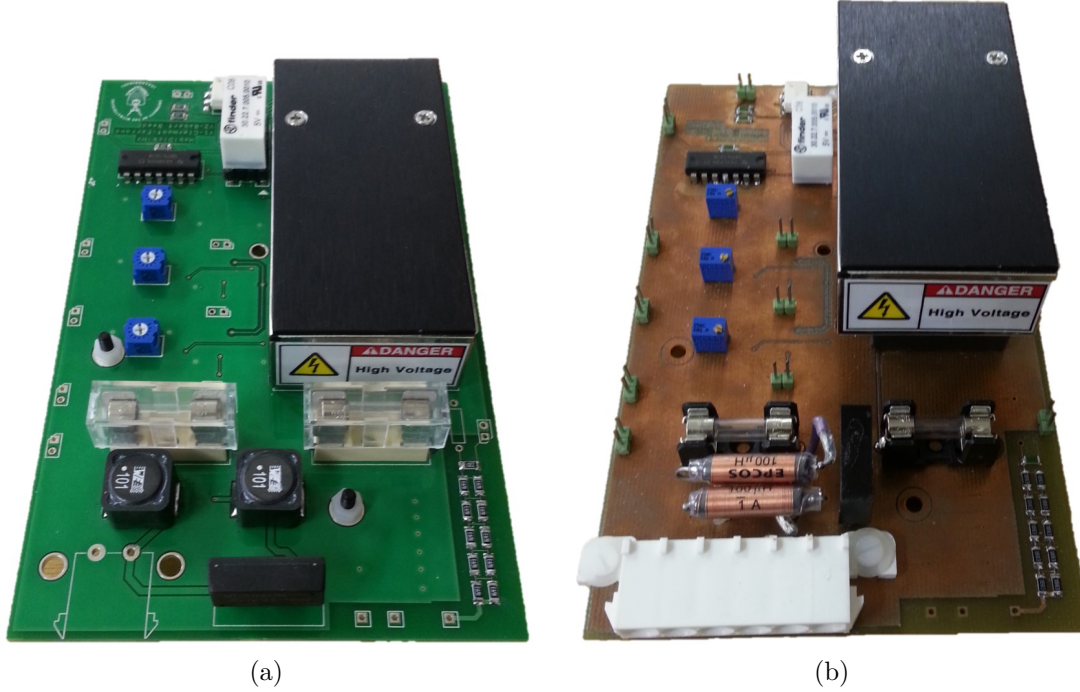


Figure 3.5: a) The final High Voltage Board and b) the first prototype produced at the HTEL at the University of the Witwatersrand.

3.2.2 Production

The manufacturing progressed in two stages with a prototype being produced first followed by the main production. The prototype PCB was manufactured in Valencia at the Instituto de Física Corpuscular (IFIC) [107] for logistical and turn around reasons. The components were soldered by hand starting with the smallest such as resistors and capacitors before moving onto the larger relays and fuse casings. The typical component size can be seen in Figure A.1. The prototype is used for the initial power up of the board after which any design changes can be implemented before the final production begins. The final version can be seen in Figure 3.5a and the prototype in Figure 3.5b.

A labelled diagram of the HV Board can be seen in Figure 3.6. A commercial high voltage biasing supply, manufactured by Ultravolt [108], is used to convert 24 V to a range from 0 to -1000 V (inverted). It is important that the MobiDICK unit is able to control the high voltage state. To achieve this an input signal of 3.3 V, via an optocoupler, is used to flip a relay switch supplying the Ultravolt with 24 V. The output voltage is configured using a variable resistor connected to the control pin of the Ultravolt. Additional circuitry, using comparators, provide feedback

3.2. THE UPGRADED HIGH VOLTAGE BOARD

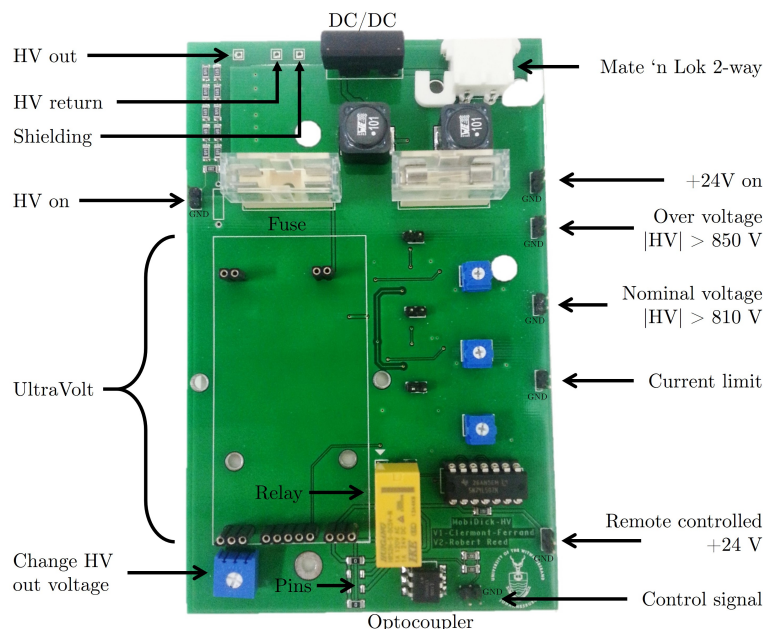


Figure 3.6: Labeled HV Board produced at the HTEL at the University of the Witwatersrand.

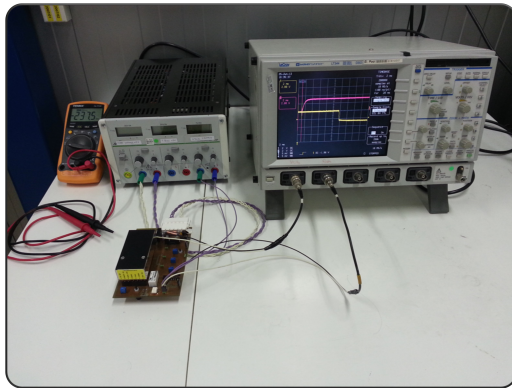
regarding the operational state of the high voltage cell. LEDs are connected to the DIP pins along the edge of the board which illuminate depending on the presence of the 24 V input and voltage, current and presence of the output. Off-the-shelf components were sourced for the entire design with the intention to reduce cost and increase availability.

3.2.3 Testing and Characterising

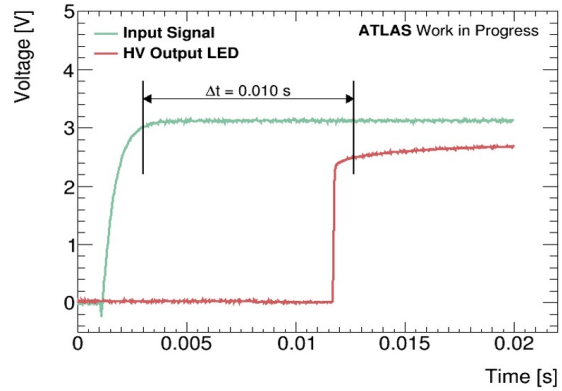
Before the PCB was powered on, a multimeter was used to search for any possible short circuits, particularly around the solder region. Connecting the power with the Ultravolt unmounted allowed for the checking of all input voltages to the relay and confirm the optocoupler was performing correctly with the input 3.3 V switch. The Ultravolt was then placed on the board, powered on using the input signal and the output measured to confirm if it was working. The outcome of the prototype power on test identified an issue with the filter capacitors on the HV output line. The breakdown voltage was being exceeded causing the capacitor to become electrically conducting resulting in the HV out shorting to ground (a problem enhanced due to the small size of the components). This was simple to fix by replacing the capacitors with a higher voltage rating.

After the board was performing as designed, and producing -830 V, the time

3. RUN II CONSOLIDATION OF THE TILE CALORIMETER FRONT-END ELECTRONICS

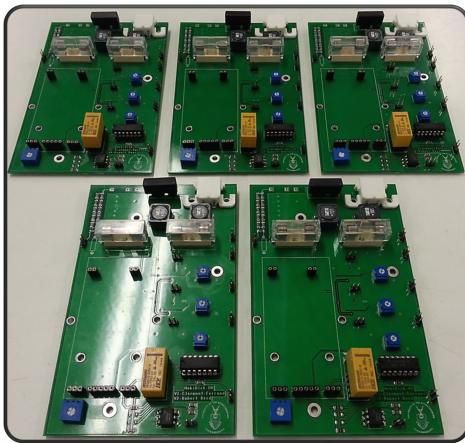


(a)

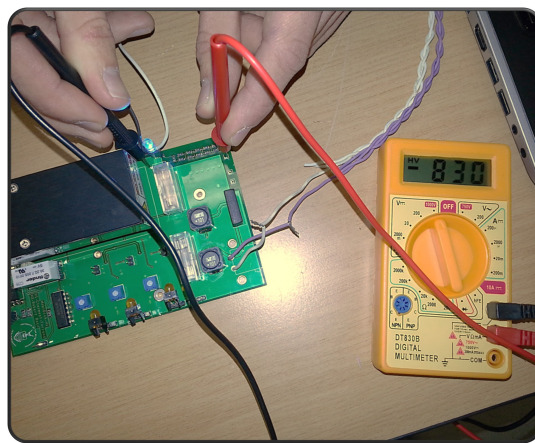


(b)

Figure 3.7: a) The signal propagation time test setup and b) time delay from input signal till nominal HV output.



(a)



(b)

Figure 3.8: a) Final production of five HV boards and b) example of a smoke test for each board before shipping.

3.2. THE UPGRADED HIGH VOLTAGE BOARD

delay between the input signal and the HV output was measured. It is useful to identify the latency so that any tests being performed by the MobiDICK unit will wait the adequate time before starting. The setup used for this can be seen in Figure 3.7a. A 500 MHz Waverunner oscilloscope recorded 250 000 samples to a log file for later processing. The results can be seen in Figure 3.7b. The green line indicates the input 3.3 V signal and the red line indicates the voltage measured on the HV on LED terminal.¹ The delay between the input and output is measured to be approximately 0.01 s and is mostly due to the mechanical relay switch. Although this is slow in electrical terms, it is sufficient for the needs of the MobiDICK.

Following the success of the initial prototyping five additional HV Boards were produced in South Africa, shown in Figure 3.8a. Each board was configured to produce the desired -830 V, shown in Figure 3.8b, and tested for any defects. Following the quality checks the boards were shipped to CERN for installation in the MobiDICK units to be used in the consolidation efforts.

3.2.4 Conclusion

A cost effective upgrade to the high voltage board for the mobile drawer integrity checking system (MobiDICK) has been designed, tested, installed and documented. There are now four additional units, MobiDICK04 to MobiDICK07, using the upgraded HV board. The new MobiDICK design allows for easier handling in a cramped environment, a trait making the consolidation effort more convenient and less physically straining. All 256 tile calorimeter front-end drawers were checked, maintained and validated, during the LS1, using the MobiDICK units. This resulted in a successful consolidation phase ensuring data taking was possible in 2015. The HV board is also included in a portable test-bench for the upgraded front-end electronics called Prometeo [109], a unit similar to MobiDICK in functionality but intended for the Phase II upgrade in 2024.

¹It is not connected directly to the HV out pin since the oscilloscope is not designed to measure such a high voltage. Instead, the HV on LED has a series of parallel resistors connected directly to the HV out which reduce the voltage to a measurable level.

Integrating Back-end Infrastructure into the ATLAS Detector Control System for the Phase II Upgrade

The High Luminosity LHC presents numerous difficulties to overcome. New operating conditions such as high radiation levels and increased data rates will require drastic changes in the current detector readout system. As a result, a multiphase upgrade program has been established which has been discussed in more detail in Section 2.3. The Phase II upgrade, in 2023, will see a complete redesign of the front-end electronics on the Tile Calorimeter. The section will introduce the proposed front-end architecture and the relocation of key components to the back-end infrastructure which is foreseen to be based on an Advanced Telecommunication Computing Architecture (ATCA) standard. A detailed explanation will be provided on the development of a new software tool that integrates the ATCA infrastructure into the existing Detector Control System (DCS).

4.1 The Phase II Tile Calorimeter Front-End Electronics

The fundamental requirements for the Phase II upgrade include a full digital level-1 trigger, increased radiation tolerance, much higher data rates and the use of more reliable data protocols for transmission such as the GigaBit Transceiver protocol (GBT) [110]. The full list of requirements for the entire ATLAS detector can be found in the scoping document in Ref. [111]. The existing signal chain can be seen in Figure 4.1a. Detector signals from the PMTs are shaped and amplified using a 3-in-1 card [112]. The 3-in-1 cards also send an analog¹ signal over approximately 70 m of cable to the off-detector trigger processor. Following digitization the signals are stored in a pipeline and, following a level one trigger signal, formatted to be sent off the detector to the Read Out Drivers (RODs) for further processing.

The most effective method to reduce component damage and Single Event Upsets² (SEUs) from exposure to high radiation doses is to remove the device from the radiation environment entirely. Naturally, this is not always entirely practical. Two major goals of upgrading the electronics is to relocate sensitive components off the detector and to provide fully digitized data at the sampling rate of 25 ns or 40 MHz to the back-end system. This equates to a bandwidth increase from 205 Gbps to 40 Tbps (80 Tbps if including redundancy) [114] which is an increase by a factor of 200 (400). Figure 4.1b shows the signal chain for the Phase II upgrade. The detector signals from the PMTs undergo signal conditioning and digitizing immediately. There are currently three options available for this initial stage. They are the Modified 3-in-1 board, Charge Integrator and Encode (QIE) boards and a Front-end for Atlas TileCal Integrated Circuit (FATALIC) board. The functionality and differences of these three options are discussed in Ref. [115]. The digitized data is formatted on the Daughter Board (DB) using a robust GBT format before being transmitted off the detector at a full sampling rate of 40 MHz. The digital pipelines are relocated to the Tile PreProcessor (PPr) which is located off the detector. The Tile PPr performs numerous functions such as: data processing; Timing, Trigger and Control (TTC); Detector Control System (DCS) management and communication to front-end electronics; data reconstruction and transmission for further processing; and preprocessing digitized trigger information for level 0 triggering. The Tile PPr is a double mid-size Advanced Mezzanine Card (AMC), which is envisioned to be housed in an Advanced Telecommunications Computing Architecture (ATCA) chassis or a miniature variant called Micro Telecommunications Computing Architecture (μ TCA). A picture of the Tile PPr

¹This analog signal over 70 m of cable can cause as much as 350 MeV of noise.

²A Single Event Upset (SEU) in a radiation environment is a change of state that is caused by ionising radiation passing through a sensitive electronic device.

4.1. THE PHASE II TILE CALORIMETER FRONT-END ELECTRONICS

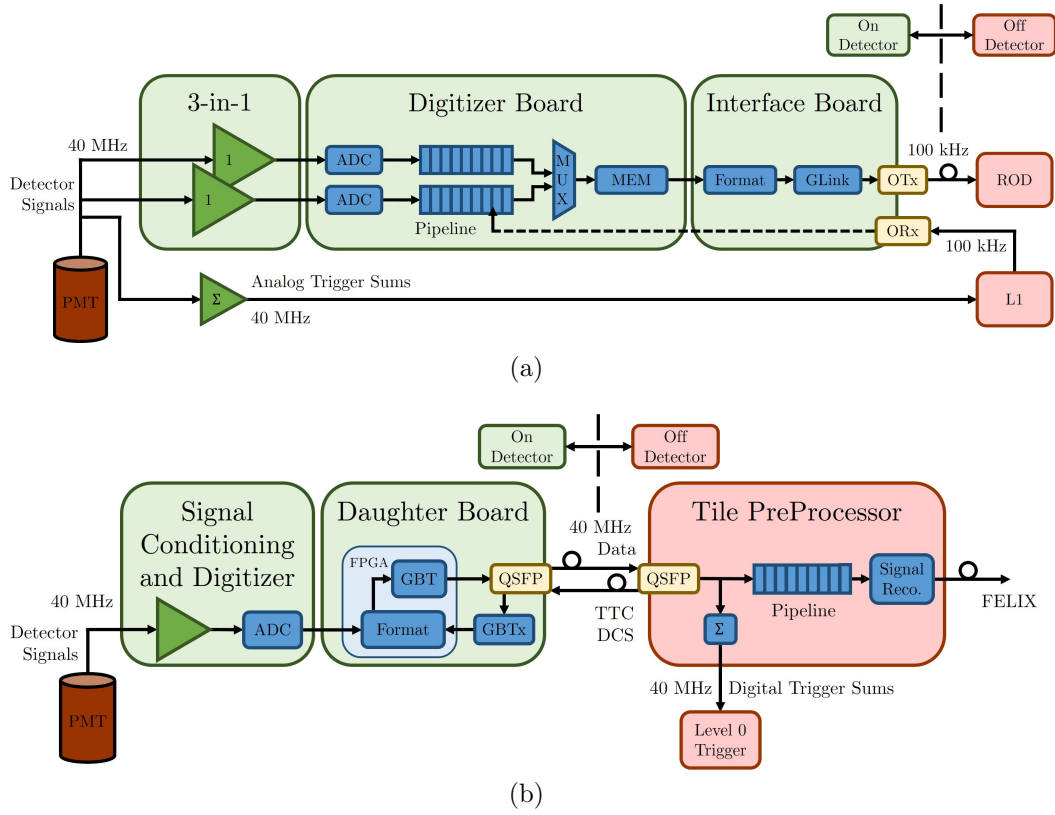


Figure 4.1: a) Diagram detailing the current front-end electronics and b) the upgraded front-end electronics for Phase II. Blocks in red correspond to the off detector electronics.

4. ATCA BACK-END INTEGRATION INTO THE DCS

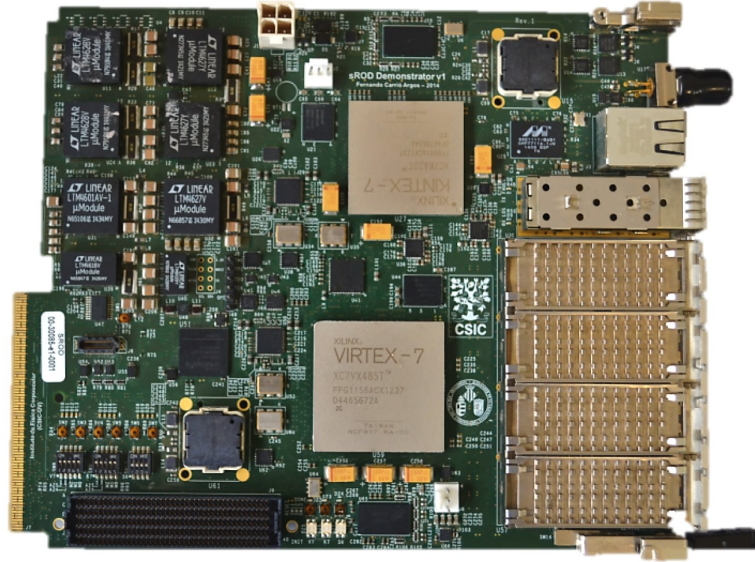


Figure 4.2: A picture of the Tile Calorimeter Preprocessor produced by Trax Interconnect in South Africa [113].

can be seen in Figure 4.2. The next section introduces the ATCA standard and the components needed to integrate the back-end system into the existing DCS.

4.2 The Advanced Telecommunications Computing Architecture Specification

The ATCA specification was developed by the PCI¹ Industrial Computer Manufacturers Group (PICMG) [116] in 1994. PICMG is a consortium, consisting of over 200 companies, with the intention to develop and implement specifications and guidelines for open standards relating to computing architecture and interconnects. ATCA falls into the PICMG 3.x specification which focuses on industrial communications equipment but has also been extended into applications for military and space industries. The latest specification includes the latest interconnect and processing technologies while further improving reliability, availability and serviceability. Recently, research related specifications have been added such as WG.x and PICMG 3.7 which will focus on minimising the effort and time required to set up a system for physics research. The ATCA standard provides mechanical

¹Peripheral Component Interconnect. A bus standard developed by Intel Corporation.

4.2. THE ATCA SPECIFICATION

specifications, backplane architectures, interconnect fabrics, blade¹ specification and shelf management guidelines. There are numerous benefits to using the ATCA specification which are summarised in the following points:

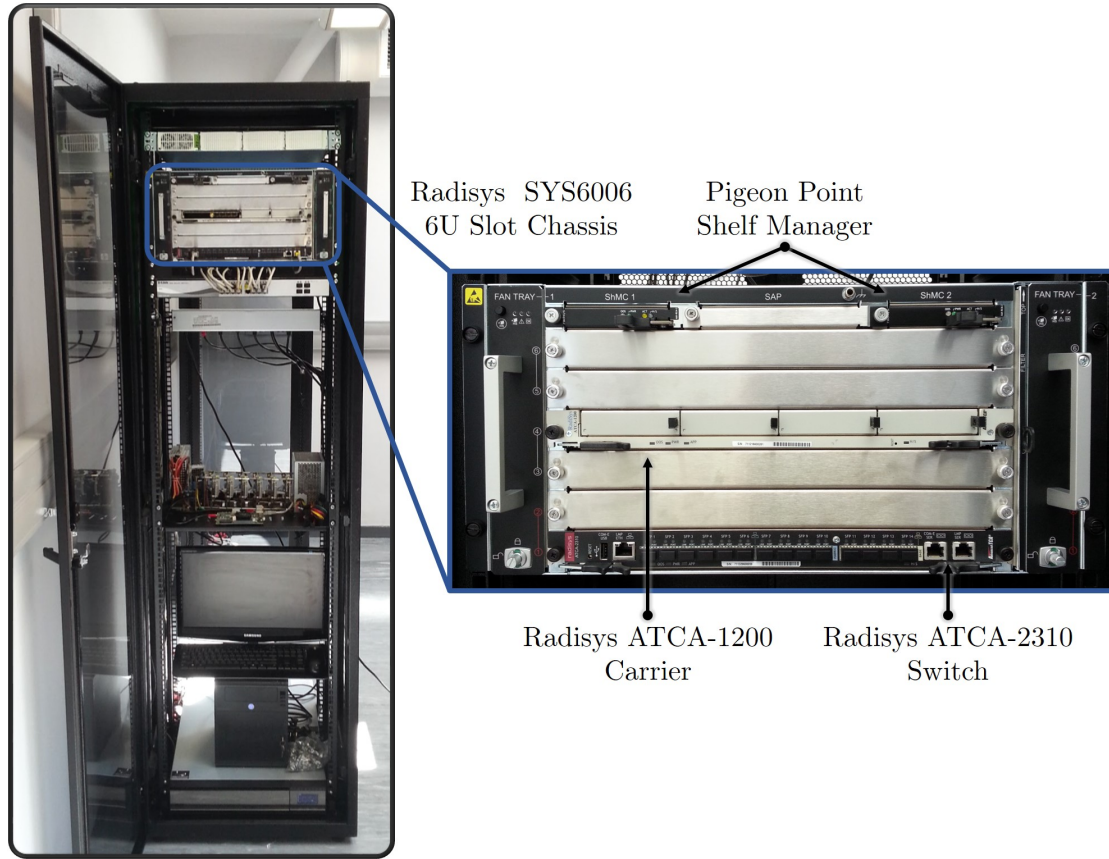
- **Expenditure.** A unified hardware platform removes propriety obstacles allowing for more competition. Competition and demand ultimately drive costs down.
- **Availability, reliability and serviceability.** These three aspects are inherent in the specification due to the nature of the industries its serving. The availability in terms of both the “uptime” of the device and how easy it is to acquire the product. Reliability that errors or faults are minimized through redundancies and error checking. Serviceability by easy problem diagnoses, intervention and replacements.
- **Modularity and hot-swapping.** The modularity comes in the form of independent blades and individual AMC cards. Each component is powered independently allowing hot-swapping. This is a process where the power to the chassis is left on while a single blade or AMC can be removed. Hot-swapping allows the replacement of a faulty component without shutting down the whole system.
- **Scalability and “time to market”.** The modularity of the ATCA specification lends itself to a scalable system. As demand grows additional modules can be inserted into the chassis as desired. A custom AMC can be designed in a far shorter time since all auxiliary components are already supplied and specified (Size of board, housing, power and connectivity etc).
- **Advanced monitoring and control.** Through the shelf manager and numerous protocols a system manager can have full access to every detail about the contents of the ATCA chassis (and the chassis itself). This allows advanced monitoring at a detailed level. Through the Intelligent Platform Management Controller (IPMC), located on all blades and AMCs, all devices in the chassis can be controlled remotely. This extends to external system managers which connect to the shelf manager through various protocols² over an Ethernet network.

A picture of the ATCA chassis from the HTEL at the University of the Witwatersrand that is used for the work presented in this chapter can be seen in Figure 4.3a. This system has a Radisys [117] SYS6000 six slot chassis with up to 40 Gbps backplane interconnection. It is a horizontal design (due to its compact size) with

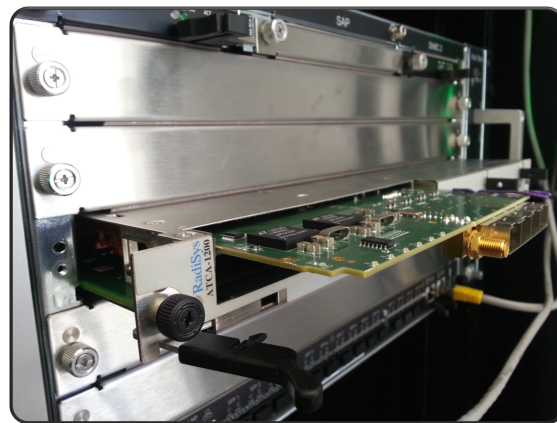
¹ATCA blades are individual drawers that can be inserted into the ATCA Chassis. These blades can be processor boards, switches, carrier boards or custom devices.

²RMCP, HTTP, SNMP etc. These are discussed in later subsections.

4. ATCA BACK-END INTEGRATION INTO THE DCS



(a)



(b)

Figure 4.3: a) Labelled picture of the ATCA chassis and components that were used in this work at the HTEL at the University of the Witwatersrand. Further details provided in text. b) Picture of a Gigabit Link Interface Board (GLIB) partially extracted from the carrier board in Slot 4 of the ATCA chassis. This board was used for development purposes.

4.2. THE ATCA SPECIFICATION

two ShM and two fan trays. In addition to the chassis there is a 10 Gbps switch blade (ATCA-2310) located in slot 1 which provides point-to-point connectivity, for all blades, using a dual star¹ topology. A four slot AMC carrier blade (ATCA-1200) is used to house a Gigabit Link Interface Board (GLIB) [118]. The GLIB card is an evaluation board, with high speed optical links, for testing GBT-based connections. This board is used as it has the same physical dimension and memory management controller that is used by the PPr which, at the time, was still in development but, more importantly, it provided a working AMC to assist development. Figure 4.3b shows the GLIB board partially inserted into the extracted carrier board. The following subsections describe the ShM and protocols used in order to facilitate the advanced monitoring and control of the ATCA chassis system.

4.2.1 The ATCA Shelf Manager

The Shelf Manager (ShM) is the central controlling unit for the entire ATCA chassis. Generally, there are two physical ShM inserted into a dedicated slot in the ATCA chassis. This is for redundancy on a physical and logical level. The ShM controls the behaviour of the blades and Field Replaceable Units (FRUs), manages cooling to each component, and monitors the health of all devices. A FRU is usually a subcomponent of a system, like a processing board, that can be easily replaced while on site. The ShM can be configured to take corrective measures in response to a change of state of any subcomponent and alert a higher level system manager, for e.g. the Detector Control System in ATLAS, if any thresholds are surpassed.

The ShM has a challenging role to fulfil; a role made more difficult with the dynamic nature of the contents its trying to administrate. Firstly, the ShM must identify what is inserted into the chassis and what resources are needed (power, cooling, connectivity etc). Secondly, each component should be treated differently and the ShM must automatically determine how to handle it. The low level communication with the different components is not specified in the ATCA standard. A separate specification called the Intelligent Platform Management Interface (IPMI), an Intel driven effort [119], provides a standardized method for the Shelf Manager to interact with boards and FRUs. Using the ATCA and IPMI specifications the ShM can determine what is present in the shelf and the corresponding information needed to operate the device; such information is usually stored on the FRU itself.

Figure 4.4a shows a picture of the Shelf Manager used in the ATCA system. Figure 4.4b is a schematic of the internal and external connectivity. The System Manager, in this case the DCS, connects to the ShM via an Ethernet connection.

¹A dual star topology has two central nodes connected to every other node. In the ATCA, slots one and two are connected to every other slot.

4. ATCA BACK-END INTEGRATION INTO THE DCS

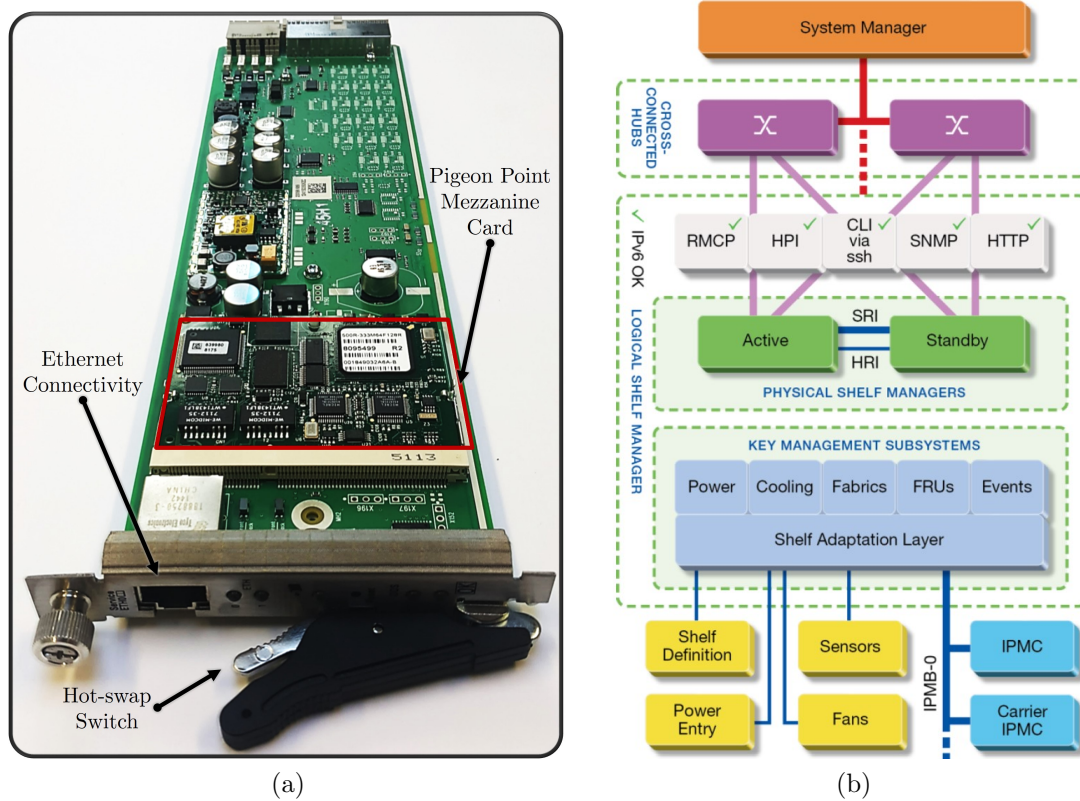


Figure 4.4: a) A picture of the Pigeon Point Shelf Manager. This device controls the blades and all field replaceable units in the chassis. The Shelf Manager also acts as an interface for management and diagnostic information of the system. b) A schematic of the Shelf Managers' internal and external connectivity.

There are five protocols that can be used: Remote Management Control Protocol (RMCP), Hardware Platform Interface (HPI), Command Line Interface (CLI), Simple Network Management Protocol (SNMP), and Hyper Text Transfer Protocol (HTML). Each has their own merit but a detailed comparison will digress from the work being presented. The SNMP approach is used for two main reasons. Firstly, its supported by the proprietary SIMATIC WinCC Open Architecture [120], a Supervisory Control And Data Acquisition (SCADA) and Human-Machine Interface (HMI) system produced by Siemens [121], which forms the foundation of the DCS in ATLAS. This means any development can be coded directly within the WinCC framework. Secondly, the Pigeon Point Mezzanine has a well defined SNMP mapping structure to retrieve information from the ATCA chassis. There are two physical ShMs present, with one on standby, which have a set of logical management subsystems to manage Power, FRUs, Cooling etc. The ShMs use a dual Intelligent Platform Management Bus (IPMB) that acts as an interface to the intelligent FRUs. This setup provides some powerful out-of-band management features.

4.2.2 Out-of-band Management

Out-of-band management is a term which describes the use of a dedicated channel for managing network devices. No software is required to be operating on the device and no operating system is needed to be up and running. This allows for remote reboot, shutdown, powering on and hardware monitoring of voltages, fan speeds, temperatures etc. There are three key components that are required for out-of-band management using SNMP with an ATCA chassis. These are:

- A network management station**, which is usually a software package that has various applications it can deploy to monitor and control. In this case we have a comprehensive DCS that fulfils this role. The DCS is described in Section 2.4.
- A software agent**, which has local knowledge of the management information and can represent it in an SNMP format. The Pigeon Point Mezzanine card has a sophisticated design to collect and present the information in an SNMP compliant way.
- A managed device**, which constitutes all components of the ATCA chassis, including the ShM itself, that are to be controlled.

Pigeon Point Mezzanine

Pigeon Point management products, like the Mezzanine card in Figure 4.4a [122], were the first intelligent platform devices designed from the ground up for the

4. ATCA BACK-END INTEGRATION INTO THE DCS

ATCA specification. PICMG 3.x specifies the required extensions to the IPMI standard which Pidgeon Point has incorporated into their devices. Pigeon Point have developed a system which adds a huge proportion of the new specifications, from both IPMI 2.0 and ATCA 3.x, into a single product which fully supports the extensions and maps them to other platform architectures. This allows a standardized way to communicate with ATCA systems from different manufacturers and also systems like the μ TCA.

Simple Network Management Protocol

The SNMP is a widely used Internet standard for collecting and organizing information about managed devices through a network. It can also modify information to control the state of a device. SNMP uses a Management Information Base (MIB) to expose interactive objects with a well defined identifier. The identifiers are defined using a subset of Abstract Syntax Notation One (ASN.1) called the Structure of Management Information Version 2. The structure of an Objected Identification (OID) is based on a tree-like design. It consists of a string of numbers separated by a period. Each number usually has a name associated to it which starts off very generic and gets more specific as we move further down the tree. Below is an example of the OID number for the “present” state of the carrier board:

$$\text{Carrier hotswap state OID} = 1.3.6.1.4.1.16394.2.1.1.4.1.2.3 \quad (4.1)$$

Each company has their own unique identifier. In this case Pigeon Point have the number 16394. Every sensor that is populated by the Pigeon Point ShM will have the numbers 1.3.6.1.4.1.16394.2.1.1 preceding it. This is usually referred to as the `ROOT_OID` and the names of each number are shown in Table 4.1.

The company is responsible for specifying the numbering after their unique ID, which is product specific; a leading cause for non-standard ways of accessing information. For example two different manufacturers of an ATCA chassis may have a reversed numbering for two components (lets say power and cooling) which means the numbering is required to be known in advance. This is exactly what the Pigeon Point Mezzanine prevents as it defines the mapping from the OID structure to the IPMI standard and covers all aspects of an ATCA shelf with the possibility of dynamically adding custom sensors. This means there is always a predefined structure to fetch the information that is of interest. The mappings are described in the External Interface Reference (EIR) [123] ,for the Pigeon Point ShM, which has over 50 pages dedicated to SNMP OIDs. A sample of the first few rows of a table for the board variables is shown in Table 4.2.

Using Table 4.2 we can construct the example from Equation (4.1) by setting `<Index>= 2` for the “present” status and `<SlotNum>= 3` to indicate which blade we are querying. Every sensor (standard or custom) can be identified in this manner.

4.2. THE ATCA SPECIFICATION

Table 4.1: Names for each identifier in ROOT_OID.

Identifier	Name
1	Iso
3	org
6	dod
1	internet
4	private
1	enterprise
16394	PigeonPoint
2	products
1	chassis-management
1	ipm-sentry-shelf-manager

Table 4.2: Example table of blade OIDs taken from the Pigeon Point EIR.

Variable	Index	Type	Access Mode	Description
board-index	1	INT	Read-Only	Equal to slot number
board-present	2	INT	Read-Only	1 Board present 0 Otherwise
board-healthy	3	INT	Read-Only	1 Board present and healthy 0 Not present and or not healthy

OID = <ROOT_OID>.4.1.<Index>.<SlotNum> - See text.

4. ATCA BACK-END INTEGRATION INTO THE DCS

This is incredibly important since numerous ATCA chassis will be used throughout ATLAS and it would require far too many man-hours to map the required sensors if there is no consistency in the naming convention. This solution is ideal since the convention is coherent across different ATCA manufacturer products and various architectures like the μ TCA systems.

4.2.3 WinCC and the SNMP Driver

WinCC makes use of the modern Object Orientated Programming, often called OOP, which makes use of classes with data fields and properties. Significant reduction in the implementation time is only achieved if the entire workflow is designed in an object orientated manner. This is true for WinCC which, as any programmer would testify, is a sought-after feature in any modern application.

The manager concept of WinCC Open Architecture

WinCC uses dedicated, autonomous program components for all key functions. These are called managers whose task is specific and predefined. Such examples include database management, archiving or Graphical User Interfaces (GUIs). Figure 4.5 shows the logical design of WinCC. This is summarised as:

- **Event Manager (EV)** is the keystone of the WinCC software. All operations are mediated through the EV. Peripheral devices send information of an updated sensor to the EV which is processed and converted into an event. The EV will then update the corresponding values and forward it to any of the other components such as GUIs, Control Script or alerts for processing. Sometimes, this requires reactive measures which are sent back to the EV and then forwarded to the respective driver which interprets the command and acts on the hardware.
- **Driver Manager (D)** connects multiple processes together. An example is an SNMP driver which executes given SNMP commands and receives and processes outputs from the query before presenting the values to the EV.
- **Data Manager (DB)** stores changes of data point values in a database for archiving and historical information.
- **Control Manager (CTRL)** is a runtime environment that is dedicated to programs written in the powerful WinCC scripting language. This language is based on a Java type structure and most of the work presented in this chapter is based on it.
- **Interface Manager (UI)** controls all the graphical display of process states.

4.3. THE FWATCA FRAMEWORK

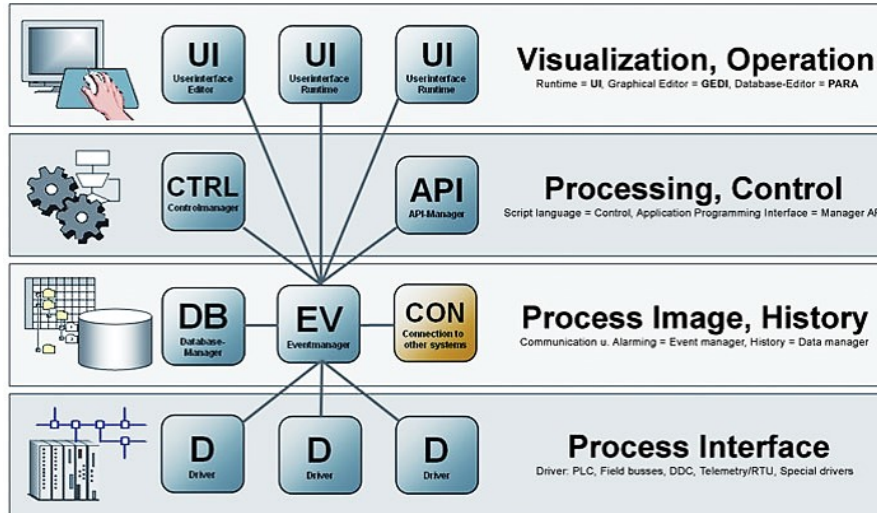


Figure 4.5: A conceptual design of the WinCC SCADA software [120]. Its central component is the event manager which allows event based processing which is extremely efficient.

- **Other managers** exist that offer additional features like redundancy, web servers, simulation etc.

The SNMP Driver

The SNMP Driver falls under the “Process Interface” category. The main role of the Driver is to initiate a SNMP query to a targeted device, wait for the response and then process the returned information for the EV. Figure 4.6 shows the SNMP driver in the WinCC console and the corresponding information used to configure it. The EV contains an internal real-time database built on the object oriented datapoint concept. A datapoint is the basic data container of a variable which can have any primary data type in computing such as a: Strings, integers, floats, booleans or arrays of said types. Datapoints form the central role of most WinCC tools. The next section details how these datapoints are created and configured.

4.3 The fwATCA Framework

The ATCA chassis, when fully equipped, may have tens of thousands of sensors. These can be axillary related, like voltages, or more sophisticated, like packet loss in a communication fabrics. In the previous sections we have established a protocol, through a WinCC manager, that allows for the retrieval of a sensor value. Through

4. ATCA BACK-END INTEGRATION INTO THE DCS

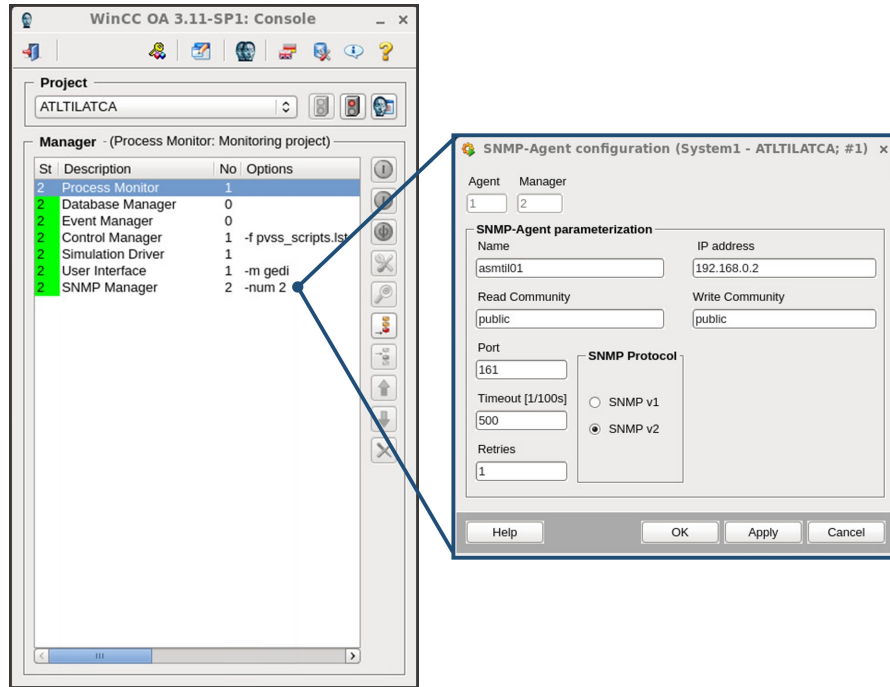


Figure 4.6: An example of the WinCC SNMP driver and the settings used.

the Pigeon Point Mezzanine, and the mapping convention it supplies, there is a standardized way of accessing this information. WinCC provides an event driven framework based on datapoints, which represent any type of data structure, with the ability to be updated with a sensors value via the SNMP protocol. The final task is to put all of these attributes together into a framework which is convenient, easy to use and compatible across different ATCA manufacturers. This gave rise to the integration framework tool simply called fwATCA. The original scope of this work was intended to cover the implementation of the new PPr into the ATCA chassis. It soon became clear that there was a lack of software tools for any sort of ATCA support in ATLAS. This was mostly due to the cutting-end technology and the brevity of the ATLAS communities exposure to it. The main purpose of the fwATCA framework is the generation of datapoints with the correct configurations in a graphical format for the user. This can be broken down to five main design features.

Search the shelf for content. This includes dynamically changing elements such as custom boards.

Sort the information. The Pigeon Point mappings provide a convenient categorisation based on the component type such as power supply, blade or fan trays. This is summarised in Table 4.3.

4.3. THE FWATCA FRAMEWORK

Create the datapoints. Datapoints must be created with the correct datatype, SNMP OID and naming convention. There are two categories of datapoints: Standard and Custom. Standard refer to the sensors that are located in the ATCA chassis itself while custom sensors are placed on the insertable devices. The main difference being the availability. Standard sensors are always available for polling while custom sensors have the potential to be unavailable (removed from the chassis). Along with creation the user may also want to delete datapoints that are no longer needed or obsolete.

Configure the datapoints. This largely refers to a human readable text added to the description of the datapoints. The text is automatically generated but can be manually edited by the user if required.

Post process raw results. Some sensors return a data type called a masks. Masks are required to be decoded to understand their meaning. Some sensors return string types, even if they represent floats or integers, and must be converted into the correct type if they are to be used by the WinCC software later on.

4.3.1 Search and Sort

The search process is achieved using a method called an SNMP walk. This is an SNMP Get request which takes a parent OID as a parameter and then queries everything that falls within this parent container by stepping into each subdirectory. The result from the walk is returned in a large array which can be looped over to fetch the individual values and OID numbers. The walk command is executed by the SNMP agent that is created in the WinCC console during the setup as seen in Figure 4.6. This manager sends the query, collects the results and presents them to the WinCC software as an array in datapoint format. A proof of concept for the SNMP communication can be seen in Figure B.1. It was important to test the software on multiple ATCA chassis but impractical to purchase two systems due to the costs involved. The solution was to connect to an ELMA [124] six slot chassis located at CERN. This posed a few technical challenges since the SNMP manager in WinCC uses a User Datagram Protocol (UDP) and in order to connect securely to CERN one must use an encrypted Secure Shell (SSH) connection which uses the Transmission Control Protocol (TCP). A multipurpose relay program called socat [125] forwards the UDP connection to a TCP transmission on both ends of the networks. A diagram of the setup can be found in Figure B.2

The sorting of information can be achieved by leveraging on the Pigeon Point OID mappings. A summary of the categorisation can be seen in Table 4.3 with component type and the OID structure. The number of components in a category can be determined using the walk command and querying the parent OID. The

4. ATCA BACK-END INTEGRATION INTO THE DCS

Table 4.3: Table of the OID categories.

Category	SNMP OID Mapping
Shelf	<ROOT_OID>.6.1.2.<Index>
	<ROOT_OID>.36.<Index>.0
Shelf Managers	<ROOT_OID>.35.1.<Index>.<smNum>
Power Supplies	<ROOT_OID>.44.1.<Index>.<psNum>
Power Entry Modules	<ROOT_OID>.43.1.<Index>.<pemNum>
Fan Trays	<ROOT_OID>.33.1.<Index>.<ftNum>
Blades (Slots)	<ROOT_OID>.32.1.<Index>.<slotNum>
FRUs	<ROOT_OID>.2.1.<Index>.<IPMB>.<fruID>
Custom Sensors	<ROOT_OID>.3.1.<Index>.<IPMB>.<sensorID>

The numbers in the OID maps above are not variables and are predefined in the EIR [123]

<ROOT_OID> = See Equation (4.1) and text.

<Index> = Variable number. See Ref. [123].

<smNum> = Shelf Manager Number. Usually only two.

<psNum> = Power Supply Number.

<pemNum> = Power Entry Module Number.

<ftNum> = Fan Tray Number.

<slotNum> = Slot (Blade) Number.

<IPMB> = Intelligent Platform Management Bus Identifier.

<fruID> = Field Replaceable Unit Identifier.

<sensorID> = Sensor Identification.

4.3. THE FWATCA FRAMEWORK

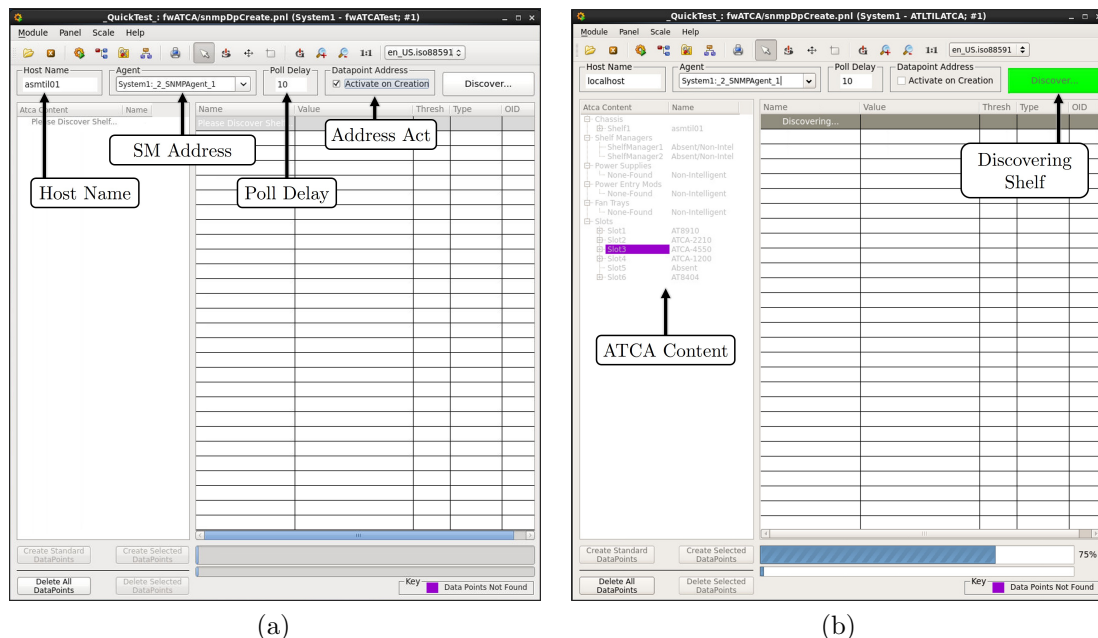


Figure 4.7: a) Setup of fwATCA panel to initiate the ATCA search and b) the discovering process in action. The ATCA content is partially populated with the discovered items.

size of the returned array contains the number of devices found. Figure 4.7a shows the settings needed to begin the discovery of the ATCA content. There can be multiple ShM addresses stored (accessible from the drop down menu) using the SNMP manager shown in Figure 4.6 and incrementing the agent number. Simply selecting a new ShM address allows the expert to work on a different chassis. A time interval between queries can be set by the poll time. The address activation options allows the automatic enabling of the SNMP OID polling on creating of the datapoint. This is a useful option when debugging. Figure 4.7b is an example of an ongoing discovery process. The ATCA content is populated into a tree table based on the category currently being polled. The different branches in the tree serve to satisfy the sorting of the information.

4.3.2 Create

The datapoint creation process is straight forward once the searching and sorting stages are done. When the code searches for the content it appends the information into a large array. This array has the datapoint type, name and OID for each standard sensor. The array is looped over and the corresponding datapoint is

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4.3. THE FWATCA FRAMEWORK

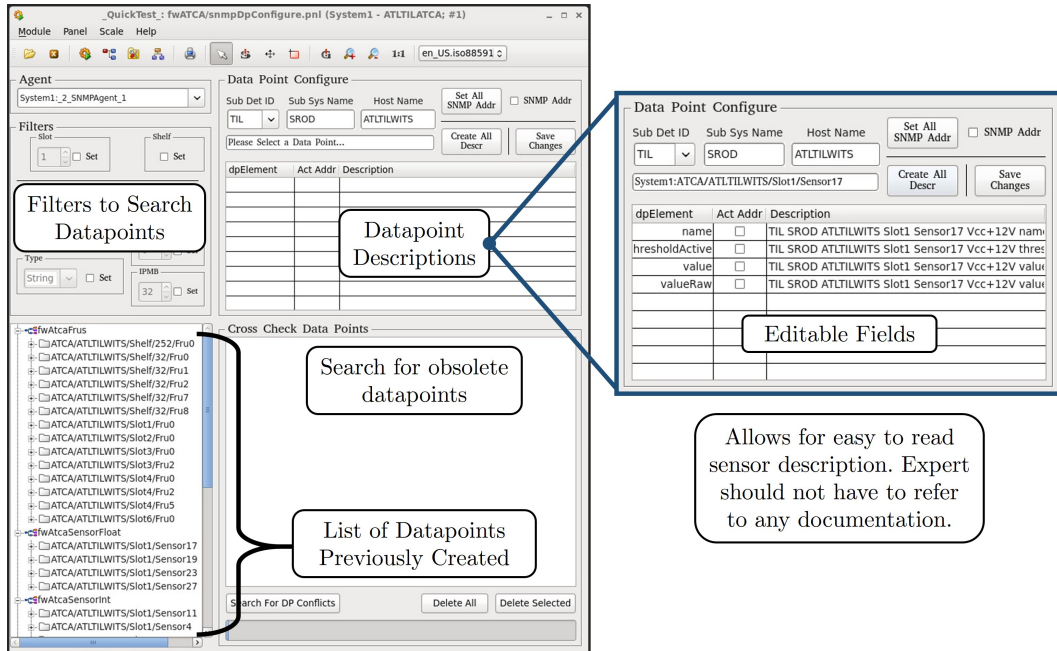


Figure 4.9: Configure

various editable fields. The second is to search for obsolete datapoints that are no longer required in the database. The user can filter the already created datapoints making searching easier and auto generate all the human readable descriptions. Obsolete datapoints arise when a component is permanently removed from the ATCA chassis and the associated datapoints no longer have any sensors to poll.

4.3.4 Post Processing

The final feature of the fwATCA framework is the post processing of datapoints. Some sensors have formats that are incompatible with the data types used by WinCC. For example most custom sensors return their value in a string format. It is possible to query the sensor for the type of data it should return (int, float, bool etc) and then convert the string format accordingly. This is done using an independent script which is executed if there is a value change in any of the datapoints requiring processing. Figure 4.10a shows the control manager with the option to execute the fwATCA_postProcess.ctl script. During creation of custom sensors (or any sensor requiring processing) the value returned is labeled "valueRaw" to illustrate its unprocessed. An additional element called "value", with the corresponding data type, is also created. This value element is updated by the post processing script based on the valueRaw string. In other words the value element does not have any OID address that populates the field but is rather

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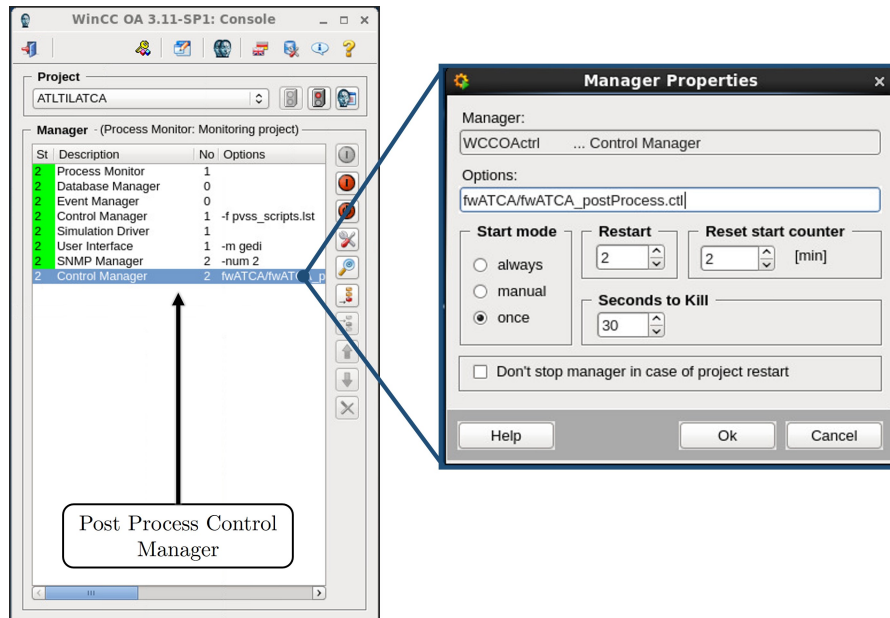
updated by an external script which casts a raw string into the required format. An example of this can be seen in Figure 4.10b where the value and valueRaw have different trailing zeros. In the case of a float the trailing zeros would be removed.

4.4 Adoption and Conclusions

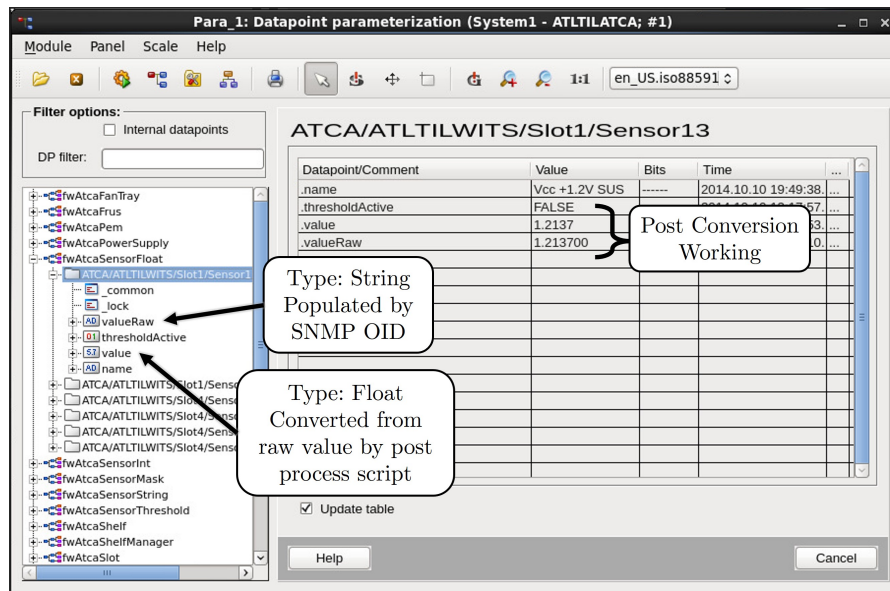
The fwATCA framework quickly transformed from a project specific tool into an ATLAS wide common framework. It forms the foundation work for all future ATCA related activities in ATLAS by allowing the expert to easily search an ATCA for content, sort the information into categories, create the datapoints and configure the description to suit their needs. It is a structured design that will allow quick and easy implementation by different detectors in ATLAS. The functionality of the code has been expanded by other groups in ATLAS providing alarm handling, archiving, Finite State Machine (FSM) generation and generic objects to be used in GUI development. The fwATCA framework provides Tile Calorimeter, and other sub-detector, experts with the necessary tools to integrate custom ATCA compliant hardware, like the Tile PPr, into the existing DCS software. The fwATCA integration tool has been adopted by many subsystems in ATLAS. This is no surprise since any monitoring or control of ATCA platforms via the DCS WinCC software requires the core datapoints to be created in the first place. Since the first version went live numerous groups showed interest in furthering the development of the code. Figure 4.11 shows a full hardware monitoring page for the Cathode Strip Chamber sub-detector in ATLAS. This panel uses the internal datapoints and maps them to a GUI. In this panel we can see all the datapoints previously created: Custom sensors on the right, fan trays, power entry modules, and slot (blade) sensors in the middle. The CSC group also added individual panels for generic use, a FSM generating tool and a service tool for alarm handling and archiving.

The fwATCA framework is adaptable to future releases of WinCC since the core functionality is the processing of the output from the SNMP walk. The output is specified by the SNMP protocol and would only change with an entirely new standard. With that said, there is a new version of SNMP available called SNMP_V3, which is already supported by WinCC and fwATCA.

4.4. ADOPTION AND CONCLUSIONS



(a)



(b)

Figure 4.10: a) Post process manager executing the processing script and b) an example of the working script.

4. ATCA BACK-END INTEGRATION INTO THE DCS

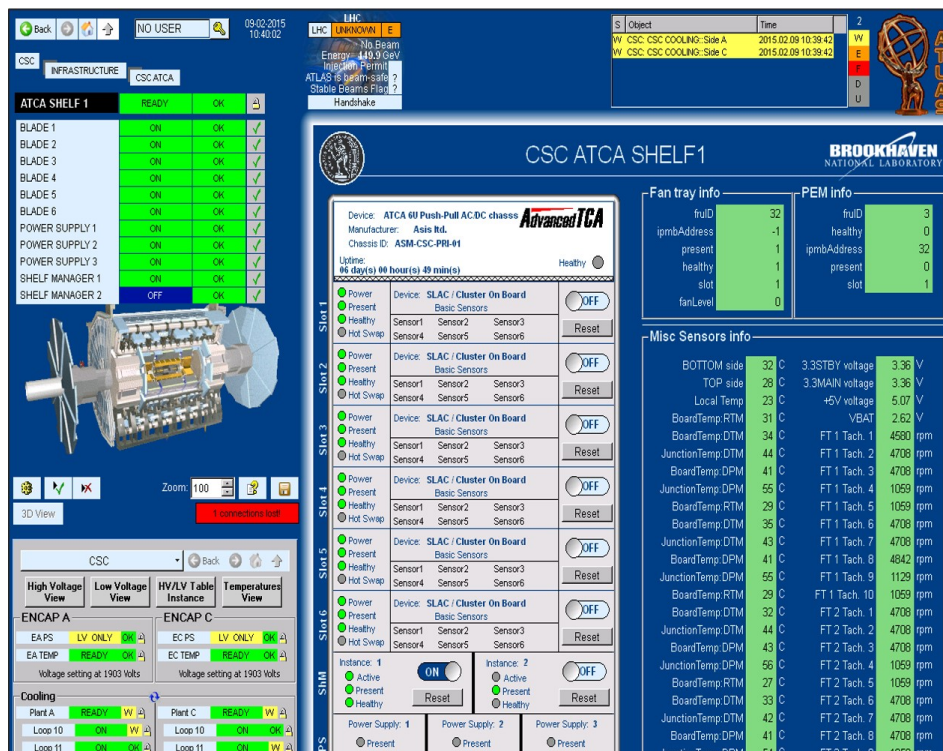


Figure 4.11: Adoption of fwATCA to build monitoring panels for the Cathode Strip Chambers control system in the DCS. [Taken from the CSC group meeting with permission.]

Introduction to the Diphoton Analysis

The diphoton decay channel played a crucial role in the discovery of the Higgs boson in 2012. The high diphoton invariant mass resolution, simple and smooth continuum background, and good signal efficiency make the diphoton channel a perfect candidate for precise Higgs boson measurements and searches for new physics. The three analyses presented in Chapters 6 to 8 are extensions to the nominal diphoton analysis. In order to reduce repetition for the coming chapters, an outline will be given of the object and event selection for the nominal $h \rightarrow \gamma\gamma$ analysis. The analysis software tool will also be included as it forms the basis of code development for the three proceeding analyses.

5.1 Analysis Software in ATLAS

The diphoton analysis framework, called `HGamAnalysisFramework`, is built on an object orientated data analysis framework called ROOT [126]. A large proportion of the work presented in Chapters 6 to 8 was made possible by the development of analysis dependant code built onto the `HGamAnalysisFramework`. A brief overview of the coding environment will be given to alleviate the technical information in the analysis chapters.

5.1.1 The ATLAS Event Data Model

The central ATLAS control framework for all data processing, called Athena, is based on the GAUDI framework [127] and written in the C++ language. It comprises numerous individual packages and totals over 6.5 million lines of code. Athena can be used for every aspect of an analysis from event generation, event reconstruction all the way to final data analysis. Athena carries a level of complexity which makes final data analysis rather difficult to perform.

The Event Data Model (EDM) for Run I can be seen in Figure 5.1a. The event reconstruction, performed by Athena, produces data in the Analysis Object Data (AOD) format; the most complete representation of data available for physics analysis. AODs are produced in the Petabyte scale making them too cumbersome to work with directly. AODs are skimmed (removing events), slimmed (removing types or collections of data) and thinned (removing specific objects) to reduce the total size of the dataset. The output is a Derived Physics Data (D3PD) file which is readable by ROOT and thus avoiding the Athena framework. D3PDs are then further processed with CP tools to produce a reduced ROOT data file called an ntuple. Ntuples are the final dataset used by an analysis (which must use CP tools for final calibrations) to produce final physics results. Some major drawbacks to this first EDM are:

- The effort to maintain and produce D3PDs for an analysis group is considerable. This is largely due to the manual intervention required at stages such as book-keeping, merging and submission of jobs.
- Building a D3PD is very CPU intensive due to the additional object reconstruction over and above the AOD information.
- Many D3PDs overlap between groups. Similar (same) data uses valuable disk space. Fixes implemented after reconstruction require precious CPU time.
- Cannot reprocess some information in a D3PD that require the full EDM since the information is not available once converted from AOD to D3PD. In particular B-Tagging and Vertex reconstruction cannot be reprocessed.

5.1. ANALYSIS SOFTWARE IN ATLAS

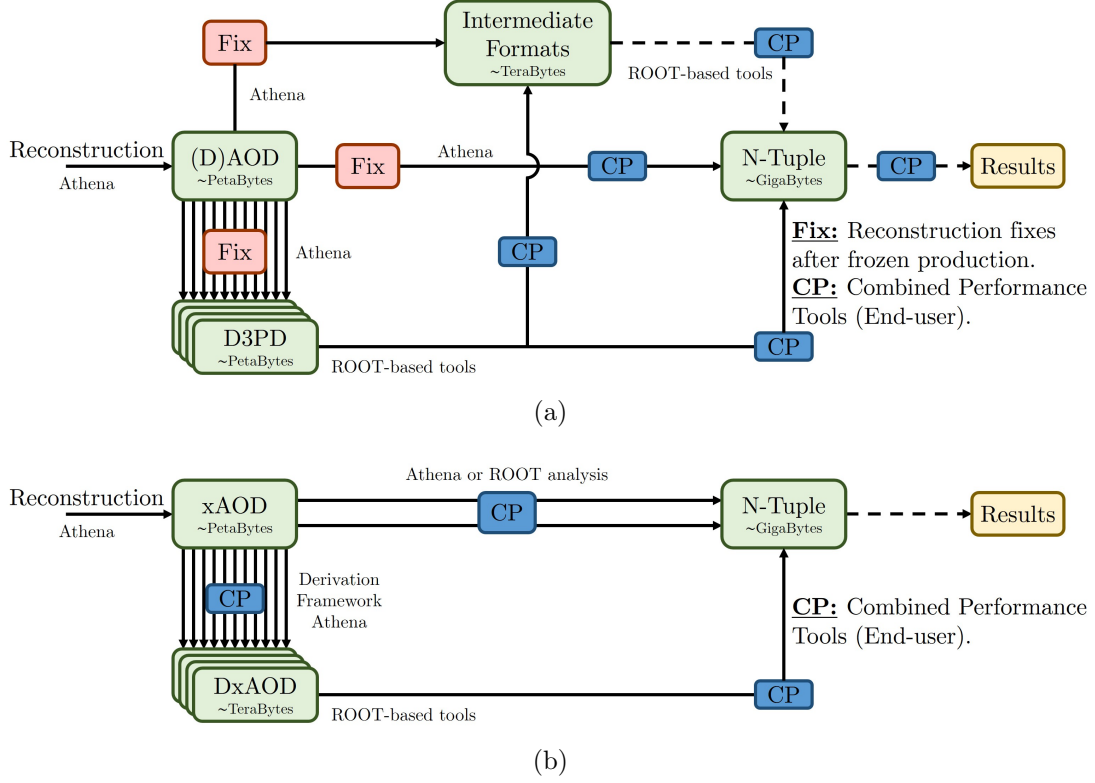


Figure 5.1: a) A flow diagram representing the analysis model used in Run I which had numerous short comings (see text) and b) the improved analysis model used for Run II.

- The AODs and D3PDs require dedicated tools which have large overlap in functionality.

The long shutdown provided the opportunity to improve on the EDM and implement changes learnt during the first data taking period. Figure 5.1b shows the improved EDM using a new data format called xAOD which is compatible with both Athena and ROOT simplifying the overall process. The new EDM satisfies the following general criteria:

- One common data format to combine the AOD and D3PD EDM formats. Derived datasets (DxAODs) use the same format and can be processed with the same tools.
- Keeping things simple with inheritance structures (less code replication) and easier Input/Output (IO).
- Software packaging and version control with easy to install dependencies.

5. INTRODUCTION TO THE DIPHOTON ANALYSIS

- Friendly to new users. Simple to set up and run in ROOT. Able to perform a complete analysis using the full power of the available software packages on a device such as a laptop.

The new xAOD format makes complete use of the object orientated approach. The `xAOD::IParticle` virtual class provides access to an object's four momentum and is a standard way of accessing all variables stored in the auxiliary store. The `IParticle` base class is extended by interface classes for each physical object (photons, electrons, jets, etc.) which can be seen in Figure 5.2. Particles are stored in `DataVector` class, called "containers", which are essentially large vectors containing a dynamic number of templated `IParticle` classes. Every object type has its corresponding container type. For example photons are collected in a `PhotonContainer` which is actually a vector of photon objects defined as `DataVector<xAOD::Photon>`. This is similar for other objects including event information. `DataVectors` can be populated at compile time (information known beforehand, such as components of the four momentum, will always exist) and during run time (dynamic information dependent on unknown circumstances like analysis specific boolean decisions) which allows for flexibility. Objects can have references ("ElementLinks") to other objects such as links to the calorimeter clusters that seed the object or properties about the shower shapes etc. This is incredibly useful because any correction that is needed at a later stage can access the desired information from the object class directly. This can be illustrated by comparing the required input parameters to correct the energy of a photon in both the Run I and Run II approach. Figure 5.3a shows a method that returns the corrected energy of a photon but required over 20 different input parameters. This method returns the corrected energy **only** for an electron and a similar method is required for other objects with slightly different input parameters. Figure 5.3b shows a method that can apply **all** corrections to an object and only requires a single input parameter. This is possible because all required information is accessible as a property of the object class by utilising the element links and base classes it inherits. The function is templated, meaning any object can be passed to it and the corresponding method can then be called to apply the object specific corrections. This method changes the properties of the object itself meaning nothing is required to be returned. Properties can be accessed at a later stage from the object directly.

The final difficulty to overcome was developing a coding structure which can be read by both ROOT and Athena. The central part of Athena is the usage of an "algorithm", a piece of code with a particular function, based off the `Algorithm` class. The `Algorithm` class has been incorporated in a C++ format for ROOT and an analysis level code can now make use of it.

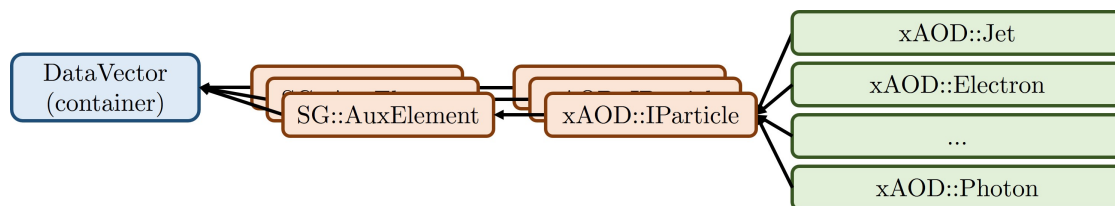


Figure 5.2: Simplified example of object orientated inheritance for particles in xAODs.

The class has three main methods¹ summarised below:

1. *Initialize()* - Run once at the start of the algorithm. Used to setup initial configurations that are not required to be repeated.
2. *Execute()* - A single method that is executed for every event that is in an xAOD dataset. This is where the actual object and event selection takes place.
3. *Finalize()* - Run once at the end of the algorithm. This is used to save output files or histograms.

Using the object orientated structure combined with the inheritance for particles and internal links to other containers, a simplified analysis framework can, relatively easily, be built. It is more intuitive (and less error prone) to deal with physical objects for new users which helps the readability and understanding of code.

5.1.2 The HGamAnalysisFramework

The diphoton analysis framework, which is used in other analyses like $Z\gamma$, encapsulates the underlying design philosophy of the new xAOD format. It provides a skeleton into which developers can plug in their code and provides the majority of common functionality and communication between different components. It is a centrally developed framework that provides a standardised tool that is easily adapted for more specific use cases. This allows different analyses, who use the HGam framework, to compare results on an even footing and with minimal duplication of effort. The **HGamAnalysisFramework** provides the required tools to develop code which can be used to slim, skim and thin DxAODs into smaller mini xAODs called MxAODs. These smaller files can be run on a laptop and average between 50 to 100 MB in size.

¹There are other methods in the Algorithm which will be discussed in the relevant chapters where necessary.

5. INTRODUCTION TO THE DIPHOTON ANALYSIS

```
1 // Function to get the correct energy of a photon.
2 // Object properties must be passed as parameters
3 double getCorrectedEnergyPhoton(
4     unsigned int runnumber,
5     PATCore::ParticleDataType::DataType dataType,
6     float rawcl_Es0,
7     float rawcl_Es1,
8     float rawcl_Es2,
9     float rawcl_Es3,
10    float cl_eta,
11    float cl_phi,
12    float cl_E,
13    float cl_etaCalo,
14    float cl_phiCalo,
15    float ptconv,
16    float ptlconv,
17    float pt2conv,
18    int convtrk1nPixHits,
19    int convtrk1nSCTHits,
20    int convtrk2nPixHits,
21    int convtrk2nSCTHits,
22    float Rconv,
23    egEnergyCorr::Scale::Variation scaleVar
24    = egEnergyCorr::Scale::None,
25    egEnergyCorr::Resolution::Variation resVar
26    = egEnergyCorr::Resolution::None,
27    egEnergyCorr::Resolution::resolutionType resType
28    = egEnergyCorr::Resolution::SigmaEff90,
29    double varSF = 1.0 ) const;
```

(a)

```
1 // Function to apply corrections to an object.
2 // Object properties accessible via class.
3 CorrectionCode applyCorrection(xAOD::Photon& myPhoton);
4
5 // Accessing corrected energy from an object.
6 double photonE = myPhoton->E();
```

(b)

Figure 5.3: a) Example code from the Run I EDM approach to fetch the corrected energy of a photon. There are over 20 different variables passed as parameters while b) is a method, using the new Run II object orientated approach, that applies all corrections to the photon with just single object as a parameter. An example of accessing properties of an object (before or after corrections applied) is also shown.

5.1. ANALYSIS SOFTWARE IN ATLAS

Table 5.1: Table of core components in the HGam framework.

Filename	Function	Description
Config.cxx	Core	Reads and processes information from a config file used to configure the analysis framework.
HgammaAnalysis.cxx	Core	Provides the core functionality for the diphoton analysis. Initialises all handlers, tools and extension classes. Sets all initial configurations.
HGamVariables.cxx	Core	Initialising the variables to save to the event information for writing to file.
HistogramStore.cxx	Core	Class to manage histograms used throughout the analysis code.
RunUtils.cxx	Core	Helper class to configure the job with the correct algorithm. This requires the correct format (local, GRID or parallel) to be specified and the sample files to be run over.
TruthUtils.cxx	Core	Provides core functionality for the truth handler.

5. INTRODUCTION TO THE DIPHOTON ANALYSIS

Table 5.2: Table of the different object handlers in the HGam framework.

Filename	Function	Description
ElectronHandler.cxx	Handler	Functions to manage electrons.
ETmissHandler.cxx	Handler	Functions to manage missing energy.
EventHandler.cxx	Handler	Functions to manage event information.
JetHandler.cxx	Handler	Functions to manage jets; including flavour tagging which the author implemented from the experience gained in the $\gamma\gamma b\bar{b}$ analysis.
MuonHandler.cxx	Handler	Functions to manage muons.
OverlapRemovalHandler.cxx	Handler	Provides overlap removal of objects with one another.
PhotonHandler.cxx	Handler	Functions to manage photons.
TruthHandler.cxx	Handler	Functions to manage truth information.
VarHandler.cxx	Handler	Provides utility functions to calculate, store and fetch variables of interest (mass of diphotons, number of jets etc.).

Table 5.3: Table of the different extensions to the HGam framework.

Filename	Function	Description
HGamCategoryTool.cxx	Extension	Category tool for the $t\bar{t}h$ analysis.
HgammaUtils.cxx	Utility	A helper class with useful functions.
HGamMETCatTool.cxx	Extension	Category tool for the E_T^{miss} analysis.
HHyybbTool.cxx	Extension	Category tool for the $\gamma\gamma b\bar{b}$ analysis.

5.2. OBJECT IDENTIFICATION AND SELECTION

The `HGamAnalysisFramework` can be split into three components: core constituents, handlers and extensions. The core components, summarised in Table 5.1, provide the structural framework which addresses dataset management, initialisation and configuration of all HGam components (handlers, extensions, etc.), histogram management and implementing the algorithms. The core `HgammaAnalysis` class has, among others, the `initialise`, `execute` and `finalise` methods discussed earlier. HGam handlers, summarised in Table 5.2, provide numerous functionality for specific object types. Some features include calibration, identification, isolation, selections and systematic shifts. The handlers also provide the end-user with an interface to access the collection of objects for any further studies that are required. The extensions to the `HGamAnalysisFramework`, summarised in Table 5.3, are additional classes that are either for general use (such as a utility class) or analysis specific. The author was responsible for two extension that provide the classification and categorisation of events for the $hh \rightarrow \gamma\gamma b\bar{b}$ and $h \rightarrow \gamma\gamma + E_{\text{T}}^{\text{miss}}$ analyses. These tools will be discussed in more detail in Chapters 6 and 7. The overall inheritance is discussed in Section 6.5.

A tool was developed, called `HGamTools`, which incorporates all aspects of the `HGamAnalysisFramework` to produce a central MxAOD that can be used by multiple analyses. This file has the nominal diphoton selection and additional information computed at run time.

5.2 Object Identification and Selection

The nominal diphoton analysis forms the basis of many other analyses. These analyses use the clean diphoton signature and combine it with additional object selections. The HGamma group follow the recommendations from the combined performance (CP) groups. CP groups are dedicated to optimise object identification and selection. The analysis strategy for object definition and selection are summarised from Ref. [128]. Although photons are the focal point of the $h \rightarrow \gamma\gamma$ analysis, other objects will be described for completeness.

5.2.1 Photons

Photons form the basis of all the analyses presented in this work and as a result will be emphasised. The reconstruction [129] of photons (and electrons) is initiated when the transverse energy, E_{T} , in the EM Calorimeter is greater than 2.5 GeV in an area defined by $\Delta\eta \times \Delta\phi = 0.075 \times 0.125$. The reconstruction algorithm is tasked to classify the clusters into electrons, unconverted photons and converted photons. Candidate clusters that have tracks in the ID are initially identified as electrons and those that have no tracks are classified as unconverted photons. Photons may

5. INTRODUCTION TO THE DIPHOTON ANALYSIS

convert into an electron-positron pair in the presence of matter and will have a conversion vertex along the electron tracks. If there are two opposite sign tracks forming a vertex the conversion is said to be a two-track conversion. Single-track conversions are identified by no b-layer hits and not requiring a second track. There are two methods to identify late conversions and asymmetric conversions (one track has majority of the energy) which are called “back-tracking” and “single-tracking”. In the nominal $h \rightarrow \gamma\gamma$ analysis approximately a third of final events are converted photons with more than half of those being single-track converted.

Cluster sizes of $\Delta\eta \times \Delta\phi = 0.075 \times 0.175$ in the barrel region of the calorimeter and $\Delta\eta \times \Delta\phi = 0.125 \times 0.125$ in the calorimeter endcaps are used to measure the photon energy. There is a four step correction process using both simulation and data driven calibration factors [130]. The simulation has been updated for Run II data taking conditions and is found to be similar to Run I results [130] with an improvement in the crack region due to the additional scintillating detectors added to this area [131]. The data-driven calibration factors for the absolute energy scale are determined from $Z \rightarrow e^+e^-$ events collected during 2015. The correction is derived from the energy calibration factors in $Z \rightarrow e^+e^-$ events and adjusting the electron energy resolution such that the width of the reconstructed Z peak matches the width observed in data [131].

In general jets are produced in abundance compared to photons and a sophisticated identification system is required to reject jets and accept photons. This is done using the shape of the showers induced by the photons, electrons and jets in the EM calorimeter [132]. Photons have a narrow shower that is generally well contained. Jets tend to have broader shapes with most of the energy deposited in the Hadronic Calorimeter. Two levels of identification are used based on ten distinct shape discriminating variables. The first is a loose ID level which exploits four of the ten variables. These variables relate to the hadronic calorimeter and the second sampling layer of the EM calorimeter. The second is a tight ID level, the default for all diphoton analyses, which uses all the variables and applies tighter requirements on those used in the loose ID. Tight and loose IDs are tuned differently depending on the conversion status of the photon. A summary of the discriminating variables can be found in Ref. [132]. The identification efficiency of converted (unconverted) photons range from 90% to 98% (85% to 95%) between 25 GeV and 200 GeV. Small corrections are applied to the shower shape variables for photons in MC which account for the slight differences between data and simulation.

An important aspect in efficiently selecting photons is how isolated the photon is from other particles and the activity surrounding it. Jets occur with relatively large numbers of constituents making it look “messy” while photons tend to be well contained. Isolation uses a $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ cone making a solid angle around the area of interest. The photon and any noise are removed from isolation calculation. The calorimeter isolation is computed as the sum of transverse energies

5.2. OBJECT IDENTIFICATION AND SELECTION

of positive topological clusters in the calorimeter within a cone of $\Delta R = 0.2$ centered around the photon candidate. The track isolation is computed as the scalar sum of the transverse momenta [133] of all tracks in a cone of $\Delta R = 0.2$ with $p_T > 1$ GeV which pass a loose track quality criteria and originate from the diphoton primary vertex. Sometimes identifying the diphoton primary vertex can be difficult particularly in the case of unconverted photons which leave no track. Tracks from converted photon candidates associated to the conversion are removed and the total calorimeter isolation is required to be less than 5% (6.5%) of the photon transverse energy. The efficiency of the calorimeter isolation ranges from 83% to 97% (84% to 97%) for converted (unconverted) photons between 25 GeV and 200 GeV that pass the isolation requirements. The efficiency of the track isolation ranges from 93% to 97% (96% to 100%) for converted (unconverted) photons between the same energy ranges and isolation requirements as before.

5.2.2 Electrons

The reconstruction and identification of electrons follows closely to the methods described for photons. After all, converted photons are dealt with by measuring the electron positron pair. EM calorimeter clusters that have a matching track in the ID are considered to be electron candidates. Corrections are applied using dedicated calibration factors and are required to have $p_T > 10$ GeV and located in the central region defined by $|\eta| < 2.47$ but rejecting candidates in the “crack” region $1.37 < |\eta| < 1.52$. Electrons must satisfy a significance of $|d_0|/\sigma(d_0) < 5$ with respect to the primary vertex and $|z_0 \sin \theta| < 0.5$ mm and the loose identification criteria [134] which are retuned for Run II conditions. Electrons are also required to pass the requirements on the track and calorimeter isolation such that the achieved combined efficiency should be 99% over the p_T range.

5.2.3 Muons

Muons are reconstructed from tracks in the inner detector and the muon spectrometer. These are complimented by candidates solely built from the muon spectrometer which are originating from the interaction point [135]. Muons are required to have $p_T > 10$ GeV and $|\eta| < 2.7$ that pass the medium identification criteria. Muons undergo a similar track isolation which is 99% efficient over the p_T range.

5.2.4 Jets

Jets are reconstructed using the anti- k_t algorithm [136] with distance parameter $R = 0.4$. All jet candidates are required to have $|\eta| < 4.4$ and $p_T > 25$ GeV. The reconstruction uses three dimensional topological clusters from the EM calorimeter.

5. INTRODUCTION TO THE DIPHOTON ANALYSIS

Jets are corrected for soft energy. The jets are corrected on an event-by-event basis for soft energy depositions caused from pileup [137] and are calibrated using both simulation and data-driven factors [138, 139]. A jet vertex tagging (JVT) algorithm [139, 140] is used to determine if jets coincide with the diphoton vertex which aids in rejecting pile-up interactions. The JVT algorithm supersedes the former jet vertex fraction (JVF) discriminant [140]. Jets are required to have a JVT score larger than 0.64. Central jets with $p_T < 60$ GeV and $|\eta| < 2.4$ use a medium identification working point which has an efficiency over 92% for non-pileup jets for $p_T > 30$ GeV.

5.2.5 Missing Transverse Energy

The missing energy in a collision is calculated using the conservation of momentum. A useful quantity is the missing energy transverse to the beam, usually denoted E_T^{miss} , because the initial beam of particles, before a collision, have nearly zero transverse momentum and any E_T^{miss} measured may be indicative of an undetected particle carrying away the balance of energy. The E_T^{miss} vector is calculated as the negative vector sum of the three momenta of all particles in the event. The different components that build the missing energy are calculated in the x and y plane separately and summed to give the total missing energy [141, 142]. The terms used to calculate the $E_{x,y}^{\text{miss}}$ terms can be seen in Equation (5.1) and the summation for each term is illustrated in Equation (5.2).

$$E_{x,y}^{\text{miss}} = E_{x,y}^{\text{miss},e} + E_{x,y}^{\text{miss},\gamma} + E_{x,y}^{\text{miss},\mu} + E_{x,y}^{\text{miss},jets} + E_{x,y}^{\text{miss},SoftTerm} \quad (5.1)$$

$$E_{x,y}^{\text{miss},k} = - \sum_{i=0}^{N_k} (\vec{p}_i)_{x,y} \quad k = jets, e, \gamma \dots \quad (5.2)$$

Using the two transverse momentum components calculated in Equation 5.1, the E_T^{miss} magnitude and its direction in the transverse plane, ϕ , can be calculated as in Equation (5.3).

$$\begin{aligned} E_T^{\text{miss}} &= \sqrt{(E_x^{\text{miss}})^2 + (E_y^{\text{miss}})^2} \\ \phi^{\text{miss}} &= \arctan(E_y^{\text{miss}} / E_x^{\text{miss}}) \end{aligned} \quad (5.3)$$

An interesting parameter to study is the scalar sum of the components, $\sum E_T$, which indicates the scattering deepness or hardness of the objects. Pileup events have more objects resulting in a larger $\sum E_T$. The sum is simply the magnitude of each component added together as in Equation (5.4).

$$\sum E_T = \sum E_T^{\text{miss},e} + \sum E_T^{\text{miss},\gamma} + \sum E_T^{\text{miss},\mu} + \sum E_T^{\text{miss},jets} + \sum E_T^{\text{miss},SoftTerm} \quad (5.4)$$

5.3. DIPHOTON EVENT SELECTION

Low energy energy particles constitute the SoftTerm missing energy component. A track-based soft-term (TST) is reconstructed from low- p_T tracks associated to the diphoton primary vertex of the event. Since jets form the bulk of the missing energy calculation, it is important to use the standardised jet selection. In 2016 the LHC achieved record breaking instantaneous luminosities. The increase in proton-proton collisions, and subsequent pileup, results in a degradation of the E_T^{miss} performance. To facilitate the increased pileup, the variable $S_{E_T^{\text{miss}}} = E_T^{\text{miss}} / \sum E_T$ is introduced. This makes use of the scalar sum which will increase with pileup and result in a smaller significance.

5.2.6 Overlap Removal

During reconstruction a single object candidate is built for every object type (electrons, jets, photons, etc.) so that no information is lost. This means, for example, that a jet can also be reconstructed as a photon and vice versa. An object is determined by satisfying numerous criteria. These criteria may overlap from object to object meaning there can be two definitions which refer to the same physical object. It is extremely important that when an object is classified according to a set definition that the same object is removed from the other collections. This is called overlap removal. In the diphoton analysis, photons have the utmost priority and form the keystone of the overlap removal strategy. All candidate photons passing the cuts are given priority and all other objects which overlap are removed. This is done in the following order:

1. Remove electrons within $\Delta R = 0.4$ of any photon.
2. Remove jets within $\Delta R = 0.4$ of any photon.
3. Remove jets within $\Delta R = 0.2$ of any electron.
4. Remove muons within $\Delta R = 0.4$ of any photon or jet. Removing the muon over the jet is a matter of convention.
5. Remove electrons within $\Delta R = 0.4$ of any jet.

5.3 Diphoton Event Selection

Events are selected by requiring two photons that pass the loose trigger where the leading photon must have $p_T > 35$ GeV and the subleading photon must have $p_T > 25$ GeV. All photons must be in the central region of the detector with $|\eta| < 2.37$ (excluding the crack region, $1.37 < |\eta| < 1.52$) that satisfy the loose photon identification criteria. The trigger was measured to be over 99% efficient based on 2015 data. The two hardest photons (highest p_T) are considered

5. INTRODUCTION TO THE DIPHOTON ANALYSIS

the diphoton pair and are used to identify the diphoton primary vertex. The primary vertex is reconstructed using a neural-network algorithm that uses tracks, vertex information and information of the photons in the EM calorimeter and ID [143]. The neural network selects the diphoton vertex within 0.3 mm of the true $h \rightarrow \gamma\gamma$ vertex in 87% of gluon fusion simulated samples. The performance is evaluated using $Z \rightarrow e^+e^-$ events from both data and simulation and is found to be satisfactory. When a diphoton vertex is different from the hardest vertex (vertex from the hardest particles) the direction of the pair of photons is altered providing a much better diphoton mass resolution. The two photon candidates are required to satisfy a relative p_T cut that is dependant on the invariant mass of the diphoton object. The leading photon should satisfy $p_{T\gamma 1}/m_{\gamma\gamma} > 0.35$ and the subleading should satisfy $p_{T\gamma 2}/m_{\gamma\gamma} > 0.25$. Each photon should satisfy the tight identification and isolation requirements and fall in the mass window $105 < m_{\gamma\gamma} \leq 160$ GeV. Additional criteria are imposed based on the detector performance. No event is kept if there is any incomplete or corrupt data from any part of the detector. This is achieved by requiring the event to pass the good runs list (GRL). Table 5.4 summarises the various event selection criteria. Each selection is called a “cut” and if all are satisfied we have the nominal events, with two photons, for the $h \rightarrow \gamma\gamma$ analysis.

5.4 Monte Carlo Simulation

In the diphoton analysis Monte Carlo (MC) samples are used to determine the shape of the signal model, to calculate the rate of SM Higgs boson production, and to derive systematic uncertainties. MC generators have been updated for the 2015 pileup and 13 TeV CME conditions. Higgs boson production and decay modes and their higher order corrections, discussed in Section 1.3, are incorporated in various MC software programs to simulate events on a large scale.

5.4.1 Signal Samples

The ggh and VBF signal samples are generated with POWHEG [144–146] using the CT10 parton distribution function (PDF) [147]. The parton level events are passed to PYTHIA 8 [148] for showering, hadronization and multiple parton interactions using the AZNLO set of data tuned parameters [149]. In 2015, POWHEG-on-the-fly (OTF) was incorporated into the ATLAS generation software allowing the application of PYTHIA 8 at generation level of the parton events and effectively simplifying MC production to a single step. The Zh and Wh parton level events are generated using PYTHIA 8 while $t\bar{t}h$ and $b\bar{b}h$ events are generated with MG5_aMC [150]. Zh , Wh and $t\bar{t}h$ are generated with the NNPDF2.3LO PDF [151] and the

5.4. MONTE CARLO SIMULATION

Table 5.4: Table of the nominal event selection cuts for the diphoton analysis.

Cut Name	Details
No Duplicates	Remove events which are duplicated in a sample.
Pass Trigger	Pass the g35_loose_g25_loose trigger.
GRL	Data should pass the good runs list.
Detector DQ	The data should be of good quality with no errors or incomplete information.
Has PV	The diphoton object should satisfy the vertex reconstruction.
2 Loose Photons	Two loose identified photons should be present.
$e - \gamma$ ambiguity	Events with ambiguous photons are rejected.
Trigger Match	The HGamma framework has the option to enable more than one trigger. Match the trigger to g35_loose_g25_loose trigger.
Identification	Two photon candidates should pass the tight identification.
Isolation	Two photon candidates should pass the isolation.
Relative p_T	The leading pair of photons are required to have a transverse momentum that is 35% (25%) or more of the diphoton mass. $p_{T\gamma 1}/m_{\gamma\gamma} > 0.35$ and $p_{T\gamma 2}/m_{\gamma\gamma} > 0.25$
Mass Window	$105 < m_{\gamma\gamma} \leq 160$ GeV

5. INTRODUCTION TO THE DIPHOTON ANALYSIS

Table 5.5: MC signal samples for nominal $\gamma\gamma$ analysis.

Process	Generator	N _{Events}	Details
ggh	POWHEG + PYTHIA8	2M	100k for m_h 105 $\rightarrow$ 145 GeV
VBF	POWHEG + PYTHIA8	1M	50k for m_h 105 $\rightarrow$ 145 GeV
Wh	PYTHIA8	100k	30k for m_h 105 $\rightarrow$ 145 GeV
Zh	PYTHIA8	100k	30k for m_h 105 $\rightarrow$ 145 GeV
$t\bar{t}h$	aMC@NLO	1M	30k for m_h 100 $\rightarrow$ 150 GeV
$b\bar{b}h$	aMC@NLO (ybyt+yb2)	100k	30k for m_h 100 $\rightarrow$ 150 GeV

A14 parameter set [152]. $t\bar{t}h$ and $b\bar{b}h$ are interfaced to PYTHIA 8 for showering, hadronization and Multi-Parton Interactions (MPI). The particle-level Higgs boson events, from signal samples, are passed through a Geant 4 [153, 154] simulation of the ATLAS detector [155] and reconstructed using the same analysis software that is used for real data. This is called Full Simulation (FS). The pile-up events are simulated as minimum bias events by PYTHIA. The pile up includes minimum bias, cavern background radiation, beam gas and beam halo effects. In addition to in-time pileup, bunch crossings before and after the hard scattering (called out-of-time pileup) may affect the detector. Table 5.5 summarises the six main signal samples used for the diphoton analysis. Each production mechanism has multiple samples corresponding to a range of $m_{\gamma\gamma}$ values from 105 to 145 GeV in steps of 5 GeV.

5.4.2 Background Samples

The continuum background is generated with SHERPA [156] with the same CT10 PDF as the signal samples. The $h \rightarrow \gamma\gamma$ events are generated with up to three additional partons in the final state. The $V\gamma$ and $V\gamma\gamma$ samples are also generated with SHERPA and contain up to two additional partons. All samples are passed through FS as with the signal samples. The only exception is with the exceptionally large (100M) diphoton plus three jet sample which is passed through the fast simulation [155]. This is for feasibility reasons. Pileup is included as before with the signal samples. Table 5.6 summarises the background MC samples used in the nominal $\gamma\gamma$ analysis. Due to the sheer size of samples they are spliced into sub files based on either $m_{\gamma\gamma}$, p_T^γ or the transverse momentum of the jet, p_T^j .

5.4. MONTE CARLO SIMULATION

Table 5.6: MC background samples for nominal $\gamma\gamma$ analysis.

Process	Generator	N _{Events}	Details
$\gamma\gamma$ +0,1,2 jets	SHERPA	1M	Slicing $m_{\gamma\gamma}$ 0, 55, 100, 160 GeV
$\gamma\gamma$ +0,1,2 jets	SHERPA	500k	Slicing $m_{\gamma\gamma}$ 160, 250, 400, 650, 1000 GeV
$\gamma\gamma$ +0,1,2 jets	SHERPA	500k	Slicing $m_{\gamma\gamma}$ 1000 $\rightarrow$ 2500 every 500 GeV
$\gamma\gamma$ +0,1,2 jets	SHERPA	100k	Slicing $m_{\gamma\gamma}$ 2500 $\rightarrow$ 5000+ every 500 GeV
$\gamma\gamma$ +0,1,2,3 jets	SHERPA	5M	Slicing $m_{\gamma\gamma}$ 100 to 160 GeV
$\gamma\gamma$ +0,1,2,3 jets	SHERPA	100M	Slicing $m_{\gamma\gamma}$ 100 to 165 GeV
γj +0,1,2 jets	SHERPA	20M	Slicing p_T^γ 35, 70 GeV, b ; $c \cancel{b}$; $e \cancel{b}$ filter
γj +0,1,2 jets	SHERPA	2M	Slicing p_T^γ 70, 140 GeV, b ; $c \cancel{b}$; $e \cancel{b}$ filter
γj +0,1,2 jets	SHERPA	10M	Slicing p_T^γ 140, 280 GeV, b ; $c \cancel{b}$; $e \cancel{b}$ filter
γj +0,1,2 jets	SHERPA	1M	Slicing p_T^γ 280, 500 GeV, b ; $c \cancel{b}$; $e \cancel{b}$ filter
γj +0,1,2 jets	SHERPA	200k	Slicing p_T^γ 500, 1000 GeV, b ; $c \cancel{b}$; $e \cancel{b}$ filter
γj +0,1,2 jets	SHERPA	100k	Slicing p_T^γ 1000, 2000 GeV, b ; $c \cancel{b}$; $e \cancel{b}$ filter
jj	PYTHIA	2M	JZNW, N = 0 $\rightarrow$ 8
jj	PYTHIA	500k	JZNW, N = 9 $\rightarrow$ 12

b = b -quark filter

$c \cancel{b}$ = c -quark filter and b -quark veto

$e \cancel{b}$ = c -quark veto and b -quark veto

JZNW = Represents the p_T slice of jets. The larger N the larger the p_T slice.

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5.4.3 Pileup Reweighting

Pileup events occur when two bunches of protons collide in the LHC and multiple protons interact. The number of interactions per bunch crossing, μ , is dependent on the operating conditions of the LHC. Monte Carlo samples are generated with a broad range of μ so that all possible conditions would be encompassed. This was needed because it was the first time the LHC was operating at such energies and the pileup was not easily predicted. MC samples are reweighted such that the average number of interactions, $\langle\mu\rangle$, is the same as seen in data. This has the undesired consequence of reducing the effective statistical power of the sample. More accurate pileup estimates result in less aggressive reweighting values and more powerful statistics in a given sample. In 2015 the $\langle\mu\rangle$ was much less than initially thought which resulted in numerous zeros for the reweight values. This led to a loss of up to 80% of the statistical power of MC samples. This was resolved by reprocessing the MC samples with more accurate pileup numbers after analysing initial datasets.

5.5 Conclusion

Numerous flaws in the ATLAS software were exposed following the success of the discovery of the Higgs boson in Run I. The cross-platform xAOD data structure and object orientated approach was established in order to overcome these challenges. The HGamAnalysisFramework includes these new features to provide the end-user with an adaptable, centrally developed, common framework that implements the object identification and event selection required to perform a photon based analysis. The author contributed to the development of the HGamAnalysisFramework by assisting with the HGamTools and JetHandler packages. Chapters 6 to 8 build on this framework extensively. The object identification and event selection presented in this chapter form the foundation of the analyses in Chapters 6 to 8.

A Search for Higgs Boson Pair Production in the $\gamma\gamma b\bar{b}$ Final State

The $hh \rightarrow \gamma\gamma b\bar{b}$ decay channel is an interesting one to study for two main reasons. Firstly, in late 2014 the first results of the di-Higgs boson resonance, at $\sqrt{s} = 8$ TeV, announced an excess of events around 300 GeV, with a significance of 3.0σ . Secondly, the excess can be explained by the Madala hypothesis in Section 1.6, which describes the possibility of two new scalar particles. The $hh \rightarrow \gamma\gamma b\bar{b}$ search presented in this thesis serves three purposes: To verify if the excess seen in Run I will be observed again, set limits on the resonant and non-resonant Higgs boson pair production cross sections, and to search for evidence for the decays predicted by the Madala hypothesis, namely $H \rightarrow hh \rightarrow \gamma\gamma b\bar{b}$. There can also be a contribution from the intermediate scalar, S , from $H \rightarrow Sh \rightarrow \gamma\gamma b\bar{b}$ where S or h can both decay to $b\bar{b}$.

6. HIGGS BOSON PAIR PRODUCTION IN $\gamma\gamma b\bar{b}$ EVENTS

6.1 Introduction

The di-Higgs boson production modes are enhanced resonantly or non-resonantly, as discussed in Section 1.4, by many extensions to the Standard Model. The $\gamma\gamma b\bar{b}$ channel is a very appealing final state to study due to the clean diphoton trigger, relatively small backgrounds, and excellent diphoton mass resolution. It is also important in the range from 260 to 400 GeV, where QCD backgrounds and combinatorics make other channels like $4b$ and $b\bar{b}\tau\tau$ rather challenging. The primary reason of interest is the excess of 3.0σ observed by ATLAS in the Run 1 results using 20 fb^{-1} of 8 TeV data and whether this can be explained using the Madala hypothesis or not. The branching ratio of the Madala into two Higgs bosons is not large, as can be seen in Ref. [47], but could be dominated by $H \rightarrow Sh$ with S decaying into $b\bar{b}$. Figure 6.1a shows the diphoton invariant mass, $m_{\gamma\gamma}$, in the signal region with an insert of the control region used to constrain the background shape. Figure 6.1b shows the constrained four-object invariant mass, $m_{\gamma\gamma jj}$, with an insert showing the control region for the four-object to constrain the background shape. The local probability of the background-only hypothesis and the 95% CL upper limits are shown in Figures 6.2a and 6.2b respectively. The significance of the excess is reduced to 2.1σ after applying the look elsewhere effect¹). These results have been combined with other di-Higgs boson analyses ($hh \rightarrow b\bar{b}\tau\tau$, $\gamma\gamma WW^*$, $\gamma\gamma b\bar{b}$, $b\bar{b}b\bar{b}$) reducing the excess at 300 GeV to 2.0σ .

The analysis strategy to select two photons mirrors the nominal diphoton analysis discussed in Chapter 5. The object definitions and event selection are kept the same in order to take advantage of the HGamAnalysisFramework and experience of the HGam community. The primary goal of this analysis is the verification of the Run 1 excess therefore, wherever possible, cuts and strategies are kept as similar as possible with the Run 1 approach. The only major changes occur in the b -tagging techniques which has been updated due to the insertion of the new b -layer in ATLAS. The same selection is applied when studying the non-resonant and resonant categories with exception of an additional cut on the $m_{\gamma\gamma b\bar{b}}$ for the resonant production and the statistical model used to interpret the results.

6.2 Data and Simulated Samples

The full 2015 proton-proton dataset is used in this analysis. The data was collected at $\sqrt{s} = 13\text{ TeV}$, by the ATLAS detector, corresponding to an integrated luminosity of $3.2 \pm 0.2\text{ fb}^{-1}$. All events are required to belong to good quality luminosity blocks

¹The look-elsewhere effect is a phenomenon in statistics where a statistically significant result may arise by chance due to the large parameter space. This is compensated for and generally decreases the local significance.

6.2. DATA AND SIMULATED SAMPLES

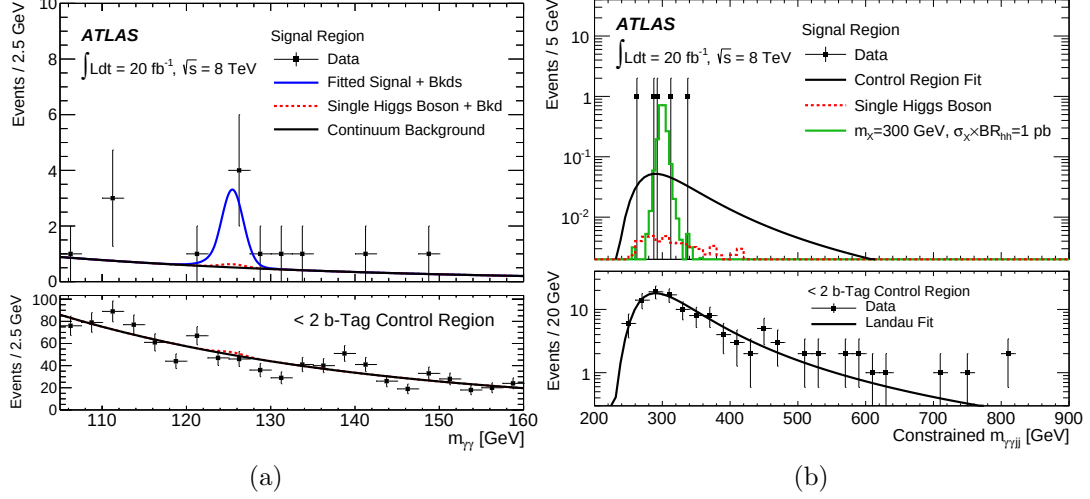


Figure 6.1: a) Diphoton invariant mass spectrum for data and the corresponding fitted signal and background in the signal region for the non-resonance search. The diphoton invariant mass spectrum (lower plot) in the continuum background from events with fewer than two b-tags and the corresponding fitted curve, the shape of which is also used in the upper plot. b) The constrained four-object invariant mass, $m_{\gamma\gamma jj}$, for data events in the resonance signal region. The expected backgrounds are also shown. A narrow width resonance at 300 GeV is displayed for comparison only. The diphoton invariant mass spectrum (lower plot) in the continuum background from events with fewer than two b-tags and the corresponding fitted curve, the shape of which is also used in the upper plot [63].

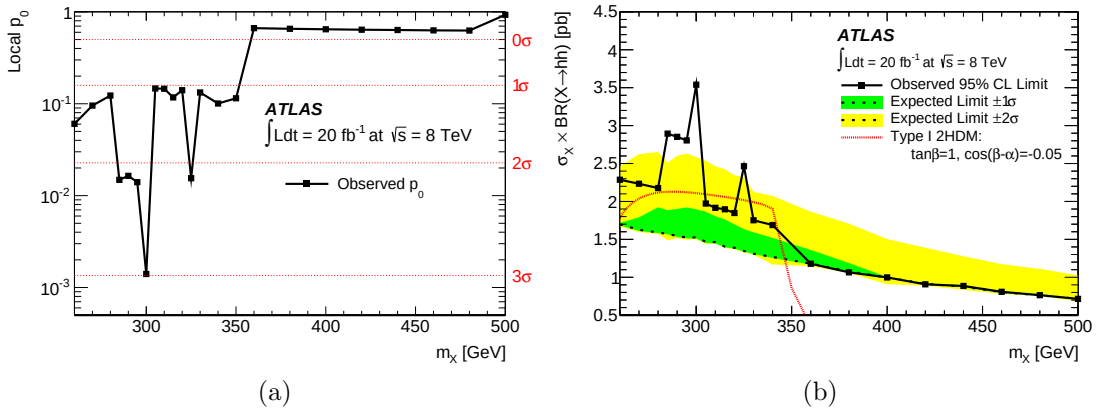


Figure 6.2: a) Local probability (p_0) of the background-only hypothesis in the resonance analysis, as a function of the resonance mass, m_X . SM branching ratios of the daughter Higgs boson decays are assumed. b) A 95% CL upper limit on the cross section times branching ratio of a narrow resonance decaying to pairs of Higgs bosons as a function of m_X [63].

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which satisfy the detector quality and triggering criteria. Accurately modelling the background is a non-trivial exercise therefore, whenever possible, data-driven methods are used to estimate backgrounds. Simulation samples are required for SM single Higgs bosons, which are considered backgrounds in this study, and di-Higgs signal samples. Background MC samples are generated for cross checks and optimisation studies which assists in the understanding of the non-resonant, continuum $m_{\gamma\gamma}$ background.

6.2.1 Monte Carlo Signal Samples

Two dedicated signal simulations are used for the non-resonant and resonant case.

Non-resonant models

The MADGRAPH5 [157] team has implemented a SM di-Higgs model, shown in Table 6.1, with LO and NLO accuracy [158]. The LO model is showered and hadronised with PYTHIA8 while the NLO uses HERWIG. The two Higgs bosons are forced to decay into a pair of b -quarks and photons. A filter is implemented that requires one of each. A comparison between the LO and NLO distributions showed that the LO sample predicts a harder p_T distribution, which is expected due to the non-resonant box diagram having a negative interference with the triangle diagram. It does not affect the jet multiplicity.

Resonant models

A 2HDM heavy scalar, decaying to two Higgs bosons, is used in the resonant study. MADGRAPH5 is used to produce a gluon initiated state at LO. The samples are generated with a natural width of 10 MeV at numerous resonance masses, shown in Table 6.1, with the scalar being forced to decay to two SM Higgs bosons. The two SM Higgs bosons are then decayed, showered and hadronised using PYTHIA8 and a generator-level filter to ensure one decays to photons and the other to a pair of b -quarks.

6.2.2 Monte Carlo Background Samples

The background samples are grouped into continuum (background) samples, single Higgs boson backgrounds and everything else.

Continuum background

The continuum background consists of jets and photons. These events are generated with MADGRAPH5 and showered and hadronised using PYTHIA8. Table 6.2 lists

6.2. DATA AND SIMULATED SAMPLES

Table 6.1: MC signal samples for the $\gamma\gamma b\bar{b}$ analysis.

Process	Generator	N _{Events}	Details
$X \rightarrow hh \rightarrow \gamma\gamma b\bar{b}$	MADGRAPH5 + PYTHIA8	100k	Generated with $m_X = 275$ GeV.
$X \rightarrow hh \rightarrow \gamma\gamma b\bar{b}$	MADGRAPH5 + PYTHIA8	100k	Generated with $m_X = 300$ GeV.
$X \rightarrow hh \rightarrow \gamma\gamma b\bar{b}$	MADGRAPH5 + PYTHIA8	100k	Generated with $m_X = 325$ GeV.
$X \rightarrow hh \rightarrow \gamma\gamma b\bar{b}$	MADGRAPH5 + PYTHIA8	100k	Generated with $m_X = 350$ GeV.
$X \rightarrow hh \rightarrow \gamma\gamma b\bar{b}$	MADGRAPH5 + PYTHIA8	100k	Generated with $m_X = 400$ GeV.
LO non-res. $\gamma\gamma b\bar{b}$	MADGRAPH5 + PYTHIA8	100k	SM non-resonant production at LO.
NLO non-res. $\gamma\gamma b\bar{b}$	MADGRAPH5_AMC@NLO + HERWIG	200k	SM non-resonant production at NLO.

the different processes and the composition of photons and jets. There are no k-factors available in literature for these samples but from experience in Run I showed they are in the order of 2. These samples are at LO since NLO is not available. The analysis is not sensitive to the overall normalisation, which is data driven, but only to the relative difference in the shapes between the different background processes.

Single-Higgs Boson Background

The six SM Higgs boson production models (ggh , VBF, Wh , Zh , $t\bar{t}h$ and $b\bar{b}h$) discussed in Section 5.4 are treated as backgrounds. All rates for these productions are taken from the Yellow Report 3 [11].

Other Background Samples

Additional background samples are considered for completeness but have little influence on the signal regions. These samples have substantially smaller yields, in the signal region, compared to the ones mentioned above. These are listed in Table 6.3.

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Table 6.2: MC continuum background samples for the $\gamma\gamma b\bar{b}$ analysis.

Process	Generator	N _{Events}	Simulation
$\gamma\gamma b\bar{b}$	MADGRAPH5 + PYTHIA8	395k	Full and Fast Simulation.
$\gamma b\bar{b}j$	MADGRAPH5 + PYTHIA8	200k	Fast Simulation.
$\gamma\gamma b\bar{j}$	MADGRAPH5 + PYTHIA8	196k	Fast Simulation.
$\gamma b\bar{j}j$	MADGRAPH5 + PYTHIA8	200k	Fast Simulation.
$\gamma\gamma j\bar{j}$	MADGRAPH5 + PYTHIA8	180k	Fast Simulation.
$\gamma j\bar{j}j$	MADGRAPH5 + PYTHIA8	198k	Fast Simulation.

Table 6.3: Additional MC background samples for the $\gamma\gamma b\bar{b}$ analysis.

Process	Generator	k-Factor
$t\bar{t}$	POWHEG + PYTHIA8	1.0
$W^+(\ell\nu)W^-(qq)$	SHERPA	0.91
$W^+(qq)W^-(\ell\nu)$	SHERPA	0.91
$W(\ell\nu)Z(qq)$	SHERPA	0.91
$W(qq)Z(\ell\ell)$	SHERPA	0.91
$W(qq)Z(\nu\nu)$	SHERPA	0.91
$Z(qq)Z(\ell\ell)$	SHERPA	0.91
$Z(qq)Z(\nu\nu)$	SHERPA	0.91

6.3 Object Selection

The object selection in the $\gamma\gamma b\bar{b}$ analysis mirrors the nominal diphoton analysis and the previous Run I $\gamma\gamma b\bar{b}$ study. The differences arise from new techniques that were developed specifically for Run II conditions. Two major changes were the rejection of pileup jets using the new JVT method, discussed in Section 5.2.4, which replaced the older JVF technique and the new b -tagging algorithms developed for the new insertable b -layer, discussed below.

6.3.1 Photons

The photon selection is identical to the nominal diphoton analysis described in Section 5.2.1. This drives the event selection to benefit from the clean trigger and good mass resolution.

6.3.2 Leptons

Muons are selected in order to reconstruct leptonic b -hadron decays with the optimal resolution. The only difference with respect to the nominal selection in Section 5.2.3 is a lower p_T threshold of 4 GeV instead of 10 GeV. The muon correction is discussed in Section 6.6.2. The primary reason to reconstruct electrons is to reject jets that originate from them. This is performed in the overlap removal stage discussed in Section 5.2.6. The selection criteria for electrons is unchanged from the nominal diphoton analysis.

6.3.3 Jets

The selection of jets differs to the nominal selection for b -tagging reasons. Only jets in the ID, $|\eta| < 2.5$, are considered due to the tracking requisite for b -tagging. Events are categorised by the number of b -jets present. More detail is provided in Section 6.4.

6.3.4 b -Tagging

Jets that are seeded by a b -quark are called b -tagged jets or b -jets. A multivariate algorithm (MV2), based on the combination of 24 outputs from three basic algorithms, provides a single output used to determine a jet's flavour. The three algorithms are the Impact Parameter algorithms (IP2D and IP3D), Secondary Vertex Finding algorithm (SV), and Decay Chain Multi-Vertex algorithm (JetFitter) [159]. The training of the MV2 is performed on approximately five million $t\bar{t}$ MC events and numerous efficiency working points are calculated. The optimisation of this

6. HIGGS BOSON PAIR PRODUCTION IN $\gamma\gamma b\bar{b}$ EVENTS

working point is investigated in Section 6.6. Following the training a Calibration Data Interface (CDI) file is generated which contains scale/efficiency factors and systematic uncertainty information. Efficiency scale factors are applied in MC to tagged jets depending on the flavour of corresponding truth jet (b, c, τ or light flavour). An “inefficiency” scale factor is applied to untagged jets. The `MV2 BTaggingEfficiencyTool` provides a list of systematics that affect the tagging process. The overall uncertainties are computed by first constructing a covariance matrix corresponding to each uncertainty and then summing them to produce a total covariance matrix. This is a symmetric, positive-definite matrix and can be treated as an eigenvalue problem. The eigenvalue value solutions indicate the direction of the variation and the square root provides the size of the variation. These values are stored in a CDI file.¹

6.4 Event Selection

The $\gamma\gamma b\bar{b}$ event selection begins with the nominal $\gamma\gamma$ selection discussed in Section 5.3. The event is then considered if there are at least two central jets with $|\eta| < 2.5$. The event is categorised depending on how many b -jets are in the event. If there are zero then the event is classified as a 0-tag event and constitutes a control region (CR). A new category (compared to Run 1) has been added for events with a single b -jet called 1-tag. The sensitivity gain was rather limited and it was decided later to drop this category. It will be included for completeness but will not be a focus. Events with two b -jets, 2-tag, belong to the signal region (SR). It must be noted that the b -jets in the 1 and 2-tag categories do not necessarily have to be the leading pair. Events with three or more b -jets are rejected so as not to overlap with other hh analyses like the $4b$ analysis [160]. Once the two jets, corresponding to the b -tag category, are selected they are required to satisfy kinematic cuts. The leading (subleading) jet is required to have $p_T^j > 55(35)$ GeV and the invariant mass of the di-jet system must fall between $95 > m_{jj} < 135$ GeV. Table 6.4 summarises the cuts for the $\gamma\gamma b\bar{b}$ analysis.

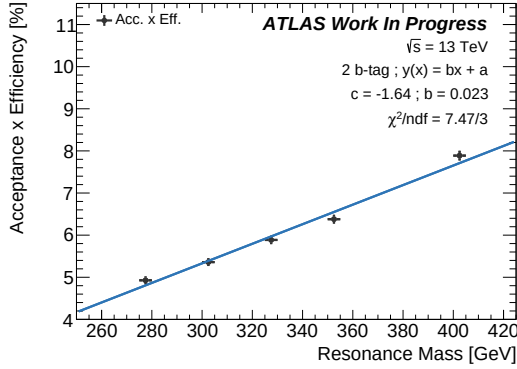
Table 6.5 shows the cutflow for the 275 GeV sample using the 85% b -tagging working point. The implementation of the cutflow code is described in Section 6.5. The cutflow tables for other resonance masses (and non-resonant SM sample) can be found in Tables C.1 to C.6. The total combined efficiency for the signal is in the order of 4-7% for the resonance hypotheses. An interpolation on the efficiency, using 1st and 2nd order polynomials, is performed to extract values for resonance masses that have not been simulated. Examples for the 2-tag category can be seen in Figure 6.3. The one tag case can be found in Figure C.1.

¹The CDI file, at the time of the analysis, was the `2016-Winter-13TeV-MC15-CDI-February14_v2.root` file.

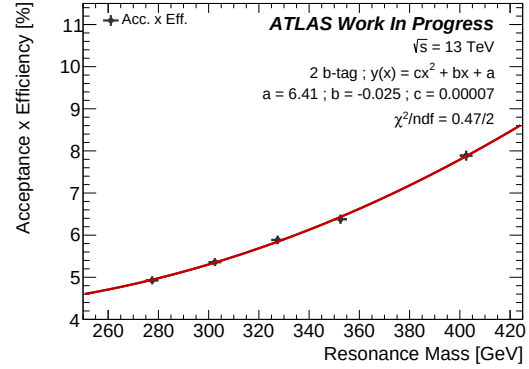
6.4. EVENT SELECTION

Table 6.4: Table of the nominal event selection cuts for the $\gamma\gamma b\bar{b}$ analysis.

Cut Name	Details
Nominal $\gamma\gamma$ Cuts	Apply all standard $\gamma\gamma$ cuts from Table 5.4.
Two Central Jets	Only consider jets with $ \eta < 2.5$ and reject event if there are less than two.
b -Tagging Categories	Count number of b -tagged jets and specify category. Select two jets depending on the category.
Jet p_T Cuts	Require leading (subleading) $p_T^j > 55(35)$ GeV.
Di-jet Mass Window	Require di-jet mass to be near the Higgs boson. $95 > m_{jj} < 135$ GeV.



(a)



(b)

Figure 6.3: Efficiency of the full selection as a function of the generated resonance mass for 2 b -tag category. The efficiency is fitted with a 1st order (a) and 2nd order (b) polynomial allowing interpolation for missing generated resonance masses. The 1 b -tag efficiency plots can be found in Figure C.1.

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Table 6.5: Cutflow for 275 GeV resonant sample for the 2-tag category with 85% b -tagging working point.

Cuts	2 b -tag Category		
	Weighted Events	Error	Efficiency
N_{xAOB}	100000	348	-
N_{DxBOD}	100000	316	-
All Events	32.000	0.128	100.0
No Duplicates	32.000	0.128	100.0
Pass Trigger	20.359	0.102	63.6
GRL	20.359	0.102	63.6
Detector DQ	20.359	0.102	63.6
Has PV	20.359	0.102	63.6
2 Loose Photons	17.226	0.094	53.8
$e - \gamma$ Ambiguity	17.082	0.094	53.4
Trigger Match	16.962	0.093	53.0
Tight ID	14.547	0.087	45.5
Isolation	12.138	0.079	37.9
Rel. p_{T} Cuts	11.114	0.076	34.7
$m_{\gamma\gamma} \in [105, 160]$ GeV	11.100	0.076	34.7
2 Cen. Jets	7.680	0.063	24.0
b -tagging	3.564	0.043	11.1
b -jet p_{T} Cuts	2.186	0.033	6.8
$m_{b\bar{b}}$ Cut	1.577	0.028	4.9

6.5 HH2yybb Analysis Framework

The $hh \rightarrow \gamma\gamma b\bar{b}$ analysis started in early 2015 when the `HGamAnalysisFramework` was in its early stages of development. This made the implementation of the `HH2yybb` framework more challenging by having to adapt to a rapidly changing base class. The `HGamTools` package, mentioned in Section 5.1.2, had only incorporated the photon handler with some basic selections. This combined with the early 2015 time scale for $\gamma\gamma b\bar{b}$ meant a dedicated $\gamma\gamma b\bar{b}$ framework was required to serve the initial needs of the analysis. The design and coding of the `HH2yybb` framework was led by the author and ended up with more than 3500 lines of code. The inheritance of the framework is shown in Figure 6.4. The `HH2yybb` framework inherits from the `HGamAnalysisFramework`, which allows access to object handlers. `HGamAnalysisFramework` inherits from the `Algorithm` class and provides access to the run methods. Object handlers use tools, wrapped into a single `AnalysisBase`, developed by the ATLAS Software Group (ASG) to calibrate objects.

The first item on the agenda was to develop the ability to identify b -jets using the flavour tagging techniques discussed in Section 6.3.4. The `JetHandler`, in its early development, did not have b -tagging functionality so it was implemented in the `HH2yybb` framework first and subsequently incorporated into the `JetHandler` for the `HGam` community. Once b -tagging was available, the development of the full framework could begin. The algorithm structure, which includes the `initialise()`, `execute()` and other methods, is used to manage how and when the relevant code is executed. The functionality of each method is described below:

fileExecute() - At the moment a file is opened (possible to run over multiple files) the Bookkeeping container is accessed to retrieve information about any rejection of events between the xAOD and DxAOD levels. This information is stored for every new file and is used in the `finalize()` method. This is important when calculating efficiencies.

initialize() - This method fetches the configuration file and applies the settings. The settings include which files to run over, which cuts to apply, the value of the cuts, which variables to save, what corrections to apply, object selection criteria etc.

createOutput() - After all tools are initialised the desired output histograms are created. All properties of the histograms are set such as the x-axis range, labels, bins, etc. These histograms are filled event-by-event during the `execute` method. The histograms contain object (kinematic, multiplicities, etc.) and event (cutflows, pileup, etc.) information.

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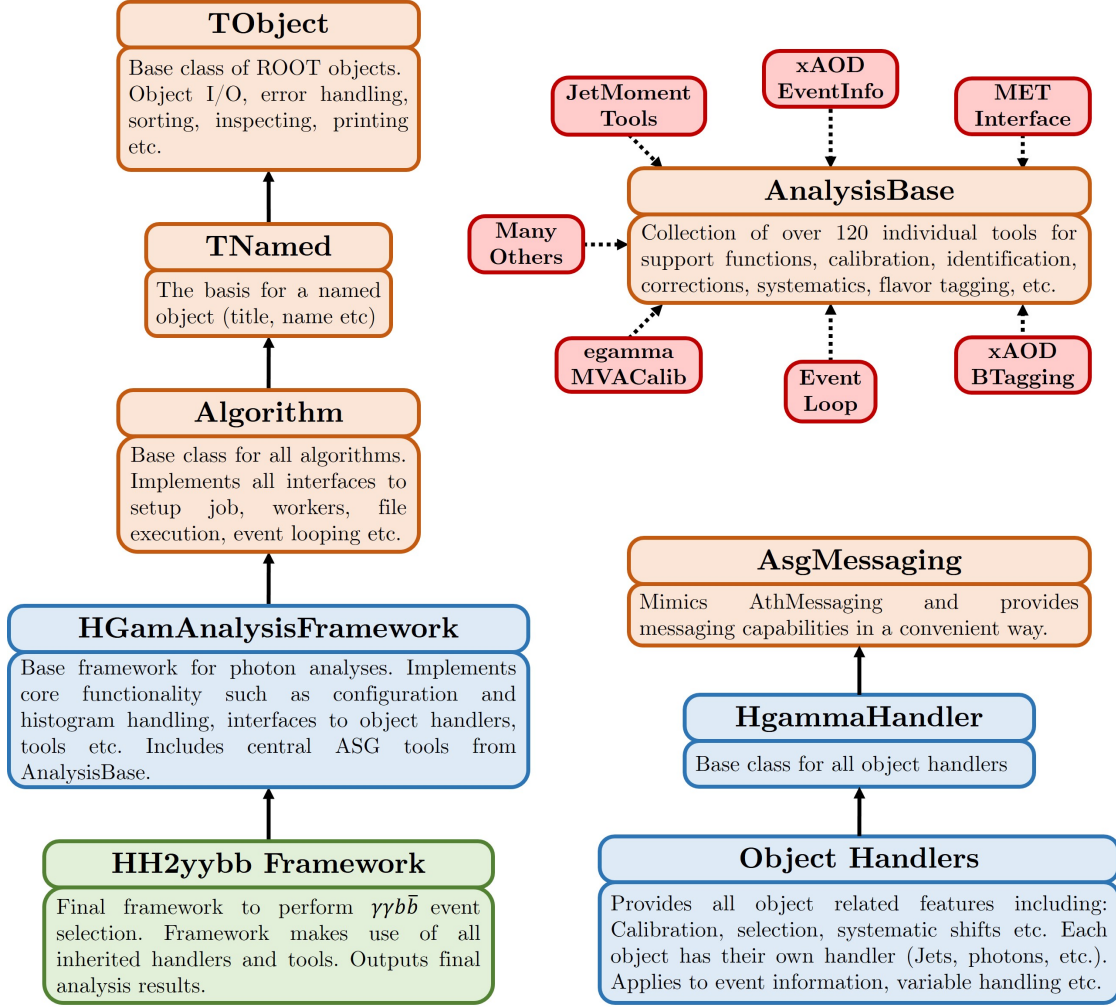


Figure 6.4: Inheritance structure of the HH2yybb framework. The HH2yybb framework (shown in green) was developed solely by the $\gamma\gamma b\bar{b}$ group of which the author was the lead developer. The HGamAnalysisFramework (shown in blue) was developed by the HGam community, including the contributions relating to b -tagging in the JetHandler by the author. The rest (shown in orange and red) are maintained by official ROOT developers and the ASG community.

6.5. HH2yybb ANALYSIS FRAMEWORK

execute() - The execute method is carried out for every event in the file. This method contains the majority of the code required to perform the object and event selection. The work flow is carried out as follows:

1. If there is a new file add the Bookkeeping information (first loop only).
2. Two photons passing the nominal selection are chosen. This utilises the photon handler which returns the corrected candidate photons. A cutflow number is returned depending on which of the twelve selection cuts fail.
3. All cutflows (one for each b -tag category) are filled up to the failed cut number.
4. Jets, electrons and muons are retrieved and corrected by the object handlers from the `HGamAnalysisFramework`. Overlap removal is applied as per Section 5.2.6.
5. Two candidate jets are selected as per the following process:
 - (a) A muon correction is applied to all candidate b -jets. This is discussed in Section 6.6.2.
 - (b) The number of b -jets is counted depending on the b -tag working point. This determines the b -tag category. The selection of the jets is different for the three categories. For 0-tag events the leading pair of untagged jets are selected. For 1-tag events, the b -jet and leading untagged jet are selected and the pair is then sorted by p_T . 2-tag events have both b -jets selected. Anything else is rejected.
 - (c) Once two candidate jets are selected the pair is then required to pass the jet p_T and dijet mass window cuts.
6. The cutflows for the relevant b -tag category is filled from the diphoton mass window cut onwards.
7. The scale factors of the four objects required to build the $\gamma\gamma b\bar{b}$ object are then multiplied into the total event weight. This is required before any filling of histograms.
8. The selected object containers are saved and ready for writing to disk.
9. The histograms previously created are then filled. The dijet mass is saved before and after it is constrained to 125 GeV. The mass constraint is discussed in Section 6.6.3.
10. Write all histograms and object containers to MxAOD file.

finalize() : Save bookkeeping cut info into the btag category cutflow histograms and delete tools still in memory.

The output MxAOD contains all the required information to perform the $\gamma\gamma b\bar{b}$ analysis. This includes the cutflow histogram providing the final event yields and

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efficiencies. Table 6.5 shown in Section 6.4 was generated by printed the bins of the cutflow histograms from the MxAOD. The output MxAOD also contains histograms for quick and easy comparisons. Figure 6.5 shows basic kinematic plots of five signal samples. These samples include a SM non-resonant production and four resonance masses of 275, 300, 325 and 350 GeV. Additional plots can be found in Figures C.2 to C.4.

6.6 Object Corrections and Event Selection Optimisations

In an attempt to be consistent with the $\gamma\gamma b\bar{b}$ Run I result most of the optimisation techniques were kept the same. The insertion of the new b -layer in the ATLAS detector gave rise to a new b -tagging technique and naturally an optimisation of the working point was required. The $h \rightarrow b\bar{b}$ decays tend to have a wide mass resolution, which is largely due to imprecise measurement of the constituent b -jets, and is made worse by the semi-leptonic b decays. There are two main techniques that may be used to correct the energy resolution. Firstly, if a muon is found within a ΔR cone of a b -tagged jet then the four momentum of the muon is added to the jet, this is done before the kinematic cuts. Secondly, after the selection of the dijet its mass is scaled to 125 GeV in a mass constraint.

6.6.1 B-Tagging Working Points

The b -tagging working point was studied by applying the full event selection on single-Higgs boson MC samples (Table 5.5), resonant pair production samples (Table 6.1) and the SM continuum backgrounds (Table 6.2) with different b -tagging working points ranging from 60% to 85%. A mass window on $m_{\gamma\gamma b\bar{b}}$ is chosen that contains 95% of the signal events. The window size is dependent on the resonance mass. A Landau function is fitted to the four object mass for signal samples and integrated in the 95% window to determine the number of signal events. The $m_{\gamma\gamma b\bar{b}}$ from background samples is fitted with a Crystal ball convoluted with a Gaussian and integrated in the same 95% window to determine the number of background events. The figure of merit used for the optimization, given by the Asimov approximation to the Poisson formula [161], is shown below:

$$Z = \sqrt{2\left((s+b)\ln\left(1 + \frac{s}{b}\right) - s\right)}, \quad (6.1)$$

where s is the number of signal events and b is the number of background events. This equation also represents the significance of a signal for a counting experiment. Samples are normalised to their cross sections (with k-factors for background

6.6. OBJECT AND EVENT SELECTION OPTIMISATIONS

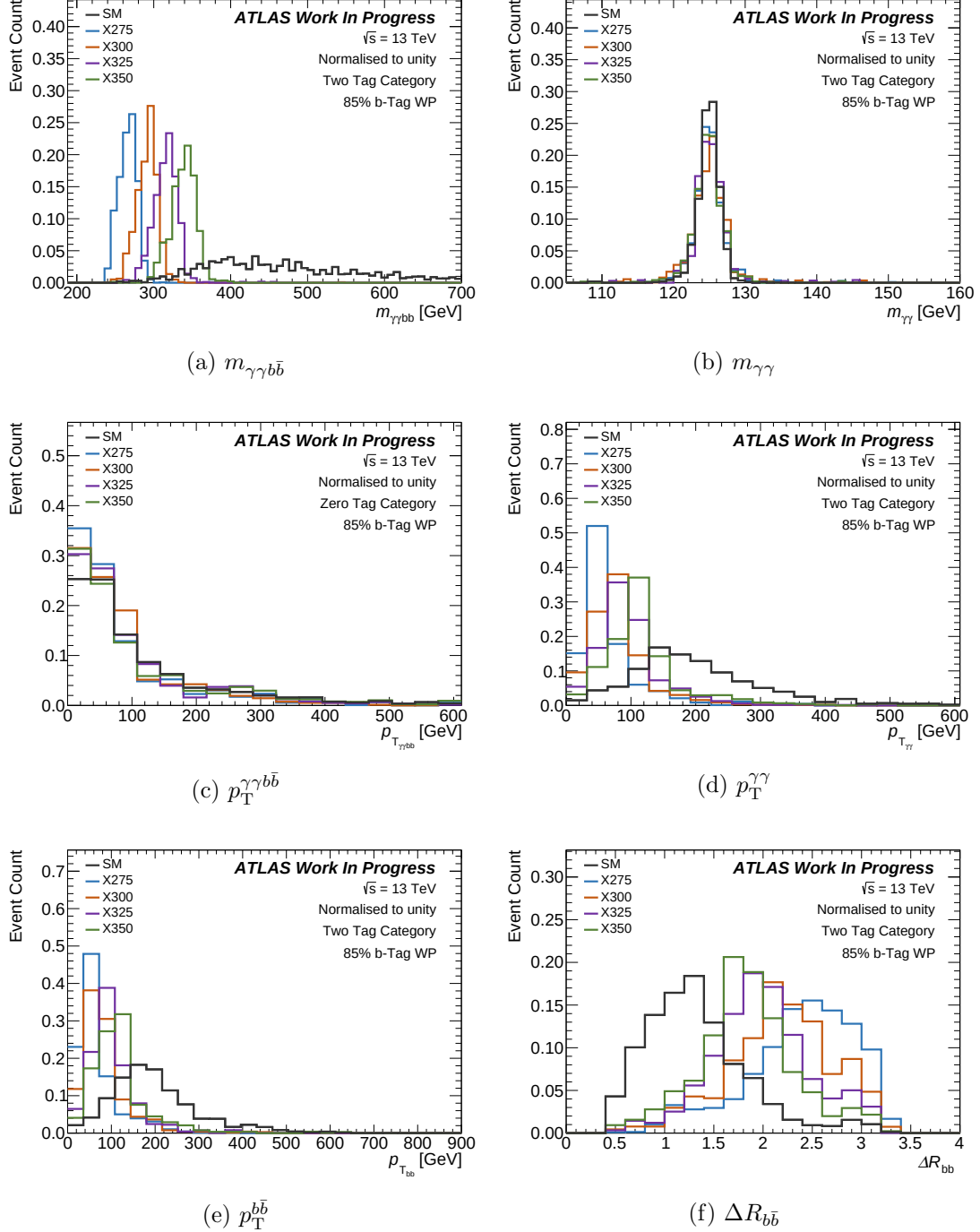


Figure 6.5: Basic kinematic properties produced by the HH2yybb framework. Five signal sample are shown: Four resonance samples with masses of 275, 300, 325, 350 GeV and a SM non-resonant production model shown (black). Additional distributions are shown in Appendix C.

6. HIGGS BOSON PAIR PRODUCTION IN $\gamma\gamma b\bar{b}$ EVENTS

Table 6.6: Results of the b -tagging optimisation with different working points.

Working Points	Significance	
	1-tag	2-tag
60%	0.41	1.59
70%	0.43	1.82
77%	0.43	1.87
85%	0.44	2.01

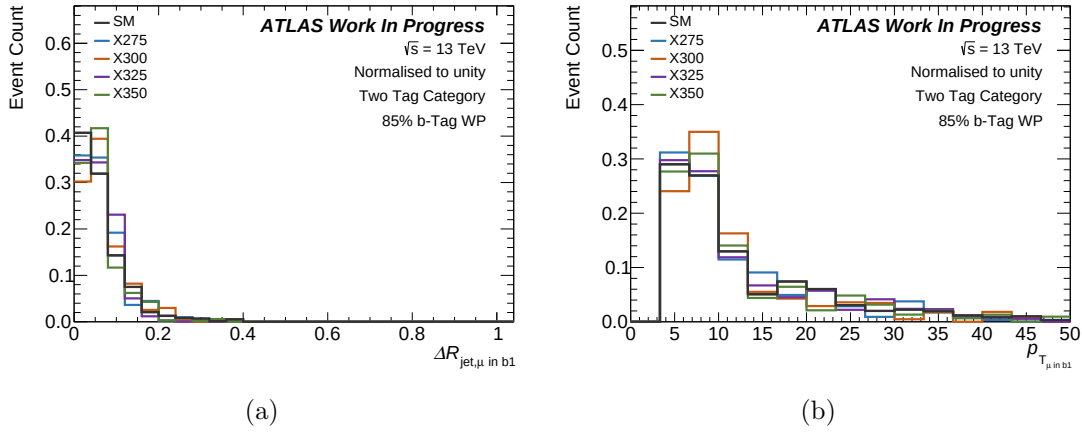


Figure 6.6: a) the ΔR between muons and the leading b -jet and b) the p_T of the muons overlapping the leading b -jet.

samples) and 3.2 fb^{-1} of data. The results in Table 6.6 show that the loosest working point of 85% provides the best significance. The 85% working point is chosen as the default.

6.6.2 Muon Corrections

Muons that are found overlapping with b -jets are added back into it. This step is performed before the overlap removal and before the kinematic selections are applied on the b -jets. There are two aspects to investigate: the size of the ΔR cone and how many or which muon to add back. Figure 6.6 shows the ΔR between muons and the leading b -jet in the 2-tag category for various signal samples. The total energy added back into the b -jet is small in the order of a few GeV and as a result the overall effect is rather small.

The size of the ΔR cone was studied and found that a cone of $\Delta R = 0.4$

6.6. OBJECT AND EVENT SELECTION OPTIMISATIONS

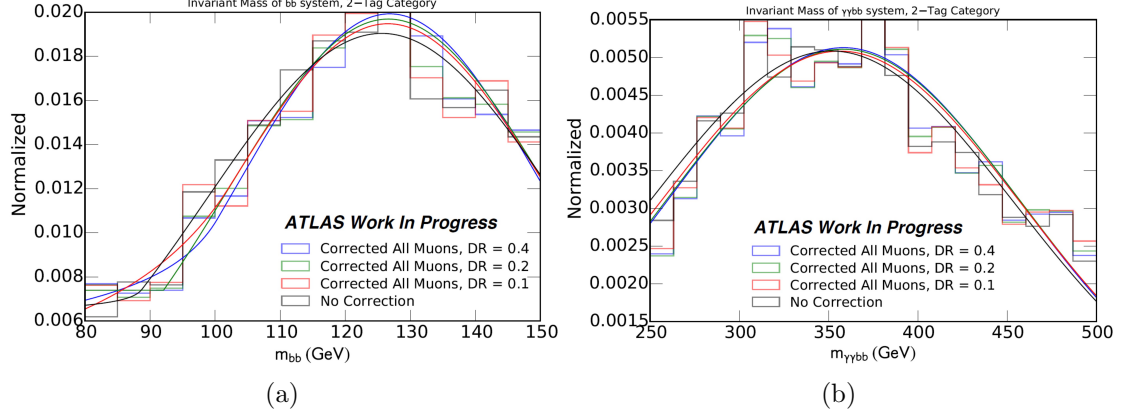


Figure 6.7: a) The effect of different ΔR cone sizes on the $m_{b\bar{b}}$ shape and subsequently b) the affect on the $m_{\gamma\gamma b\bar{b}}$ shape.

provided the best result. This confirms what was concluded in the Run I result. In addition to this it was found that all muons within the cone should be added back into the b -jet. Figure 6.7 shows the results for different ΔR muon corrections on the $m_{b\bar{b}}$ and $m_{\gamma\gamma b\bar{b}}$ objects. Although Gaussian fits show a relatively small improvement the correction is still included.

6.6.3 Dijet Mass Constraint

The $b\bar{b}$ pair that is selected to be consistent with a Higgs boson tend to have poor mass resolution. A simple scaling is applied to constrain the mass to that of the Higgs boson. This is done by scaling the $m_{b\bar{b}}$ by $m_h/m_{b\bar{b}}$ which is equivalent to keeping the η and ϕ of the four vector the same but changing the p_T and E of the dijet object.

The result of the $m_{b\bar{b}}$ scaling dramatically improves the mass resolution of $m_{\gamma\gamma b\bar{b}}$ for the different resonance signal samples, Figure 6.8a, and little affect on the control region, Figure 6.8b. The affect on the 95% window can be seen in Figure 6.8c. The mass constraint allows for a smaller 95% window and thus has a larger background rejection while maintaining the signal efficiency. The values of the windows in the 0-tag, 1-tag and 2-tag are provided in Table 6.7. The window size for the 1-tag category is significantly larger than the 2-tag and results in an increased acceptance of background events. This is one of the reasons why the improvement from this category is not optimal and was not used in the final result.

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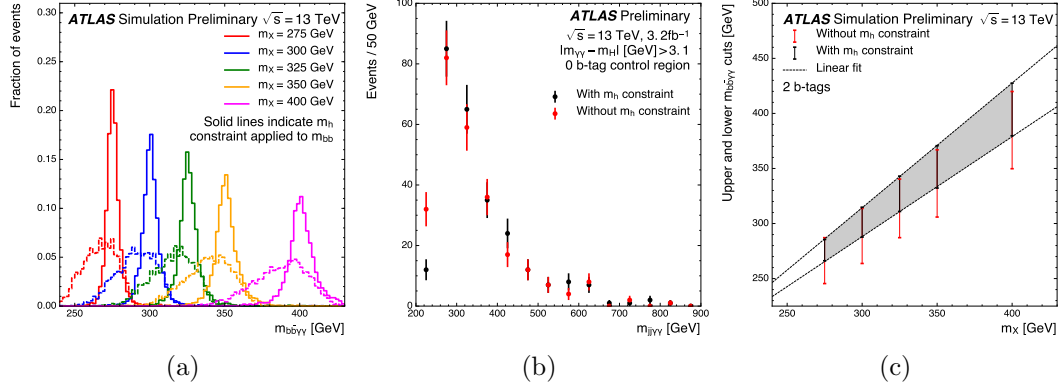


Figure 6.8: a) The affect of the $m_h/m_{b\bar{b}}$ scaling on the $m_{\gamma\gamma b\bar{b}}$ mass resolution for signal sample and b) background samples. c) Shows the window containing 95% of the signal as a function of resonance mass both with and without the mass constraint [162].

Table 6.7: The 95% window sizes of $m_{\gamma\gamma b\bar{b}}$ with the $m_{b\bar{b}}$ constraint for the resonant signal samples at masses of $m_X = 275, 300, 350$ and 400 GeV.

M_X [GeV]	Category	Low	High	Width
275	0-tag	255.3	511.8	256.5
	1-tag	251.8	383.6	131.7
	2-tag	266.2	285.5	19.4
300	0-tag	259.5	501.5	242.0
	1-tag	259.0	434.6	175.6
	2-tag	287.7	314.8	27.1
325	0-tag	251.8	691.3	439.6
	1-tag	260.0	449.9	190.0
	2-tag	310.9	343.0	32.1
350	0-tag	266.8	533.1	266.3
	1-tag	261.7	505.1	243.4
	2-tag	332.2	370.7	38.5
400	0-tag	303.0	759.9	456.9
	1-tag	284.4	591.1	306.8
	2-tag	379.7	427.5	47.8

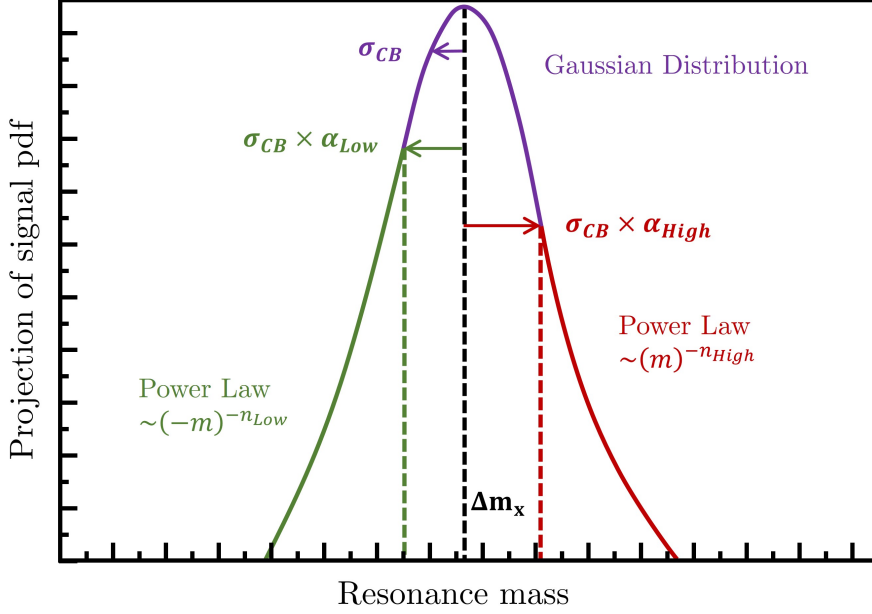


Figure 6.9: An illustration of the double-sided crystal ball function used to parametrise the $m_{\gamma\gamma}$ shape.

6.7 Signal and Background Modelling

Each production mechanism (resonant and non-resonant) requires a slightly different search procedure when modelling the signal and background contributions. In both cases the 0-tag category is considered the control region and the 2-tag category is used to test for the presence of a signal. The control region is primarily used for a data-driven estimate of the continuum background. Initially, the 1-tag category was combined with the 2-tag category to form the overall result. As mentioned before this category is not used in the final result.

6.7.1 Non-Resonant Di-Higgs Boson Production

A fit to the $m_{\gamma\gamma}$ distribution is performed simultaneously in the 0-tag and 2-tag categories. The shape of the distribution for the simulated non-resonant di-Higgs and single-Higgs boson samples are parametrised using a double-sided Crystal Ball (DSCB) function. The parameters in the DSCB are illustrated in Figure 6.9.

The shape of the diphoton continuum background is fitted using an exponential in the sidebands of the $m_{\gamma\gamma}$ distribution. The sidebands are defined as $105 \text{ GeV} < m_{\gamma\gamma} < 160 \text{ GeV}$ with the exclusion of the window $m_h \pm 2\sigma_{m_{\gamma\gamma}}$. The shape of the background is then fixed and used in the 2-tag category with the normalisation

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defined by the number of observed events in the 0-tag and 2-tag regions, respectively. The choice of the fit function and the associated uncertainties are described in Section 6.8.

6.7.2 Resonant Di-Higgs Boson Production

A counting technique is used to estimate the signal and background events in the resonant di-Higgs search because of the lack of statistics in this final state. The signal region in the 2-tag category is defined as events that have a $m_{\gamma\gamma}$ which fall inside $m_h \pm 2\sigma_{m_{\gamma\gamma}}$ and the four object, $m_{\gamma\gamma b\bar{b}}$, must be in the 95% window, which is resonant mass dependant. The number of background events is extrapolated using the following formula:

$$N_{SR}^B = N_{SB} \frac{\varepsilon_{m_{\gamma\gamma}}^B}{1 - \varepsilon_{m_{\gamma\gamma}}^B} \varepsilon_{m_{\gamma\gamma b\bar{b}}}^B \quad (6.2)$$

where N_{SB} is the number of observed events in the $m_{\gamma\gamma}$ sidebands, $\varepsilon_{m_{\gamma\gamma}}^B$ is the efficiency to pass the $m_{\gamma\gamma}$ window cuts and $\varepsilon_{m_{\gamma\gamma b\bar{b}}}^B$ is the efficiency to pass the $m_{\gamma\gamma b\bar{b}}$ window cuts. The denominator, $(1 - \varepsilon_{m_{\gamma\gamma}}^B)$, accounts for the fact that N_{SB} is the number of events in the $m_{\gamma\gamma}$ sidebands while $\varepsilon_{m_{\gamma\gamma}}^B$ is derived with respect to the full $m_{\gamma\gamma}$ range. A diagram representing this background estimation technique is shown in Figure 6.10.

To calculate $\varepsilon_{m_{\gamma\gamma}}^B$ an exponential function is fitted to the $m_{\gamma\gamma}$ distribution in the data 0-tag category, and then integrated in the full mass range and in the $m_{\gamma\gamma}$ window. It yields 0.126 ± 0.001 and the corresponding extrapolation factor $\varepsilon_{m_{\gamma\gamma}}^B / (1 - \varepsilon_{m_{\gamma\gamma}}^B)$ is 0.144 ± 0.001 . This is calculated before any $m_{\gamma\gamma b\bar{b}}$ cuts and is therefore common to all resonance masses. The error quoted is the statistical error and does not include the systematic uncertainty. The systematic uncertainty is discussed in Section 6.8.

The $\varepsilon_{m_{\gamma\gamma b\bar{b}}}^B$ efficiency is determined from the $m_{\gamma\gamma jj}$ spectrum in the data 0-tag category. The shape is used to model the continuum background in the 2-tag category. This data-driven approach assumes the kinematics are similar in the 0-tag and 2-tag category which introduces an uncertainty. This is discussed in Section 6.8. The $m_{\gamma\gamma jj}$ spectrum, after applying the $m_{\gamma\gamma}$ selection, is fitted with a Landau function. The contribution from the Single-Higgs production, approximately 6%, is removed from the distribution before fitting. The values of $\varepsilon_{m_{\gamma\gamma b\bar{b}}}^B$ are calculated for each resonance mass using the integral of the Landau function in the full mass range and in the 95% window. The values range from 0.09 ± 0.03 and 0.16 ± 0.03 for different resonance mass hypotheses.

The contributions from the SM single-Higgs boson and non-resonant di-Higgs

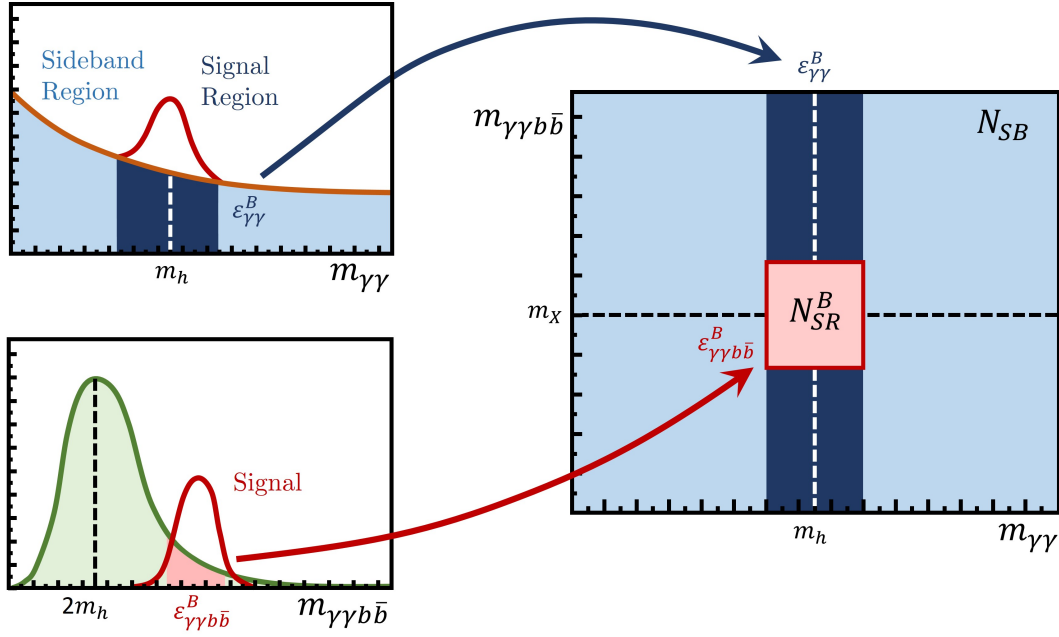


Figure 6.10: The search for the resonant di-Higgs production has a selection on the $m_{\gamma\gamma}$ and $m_{\gamma\gamma b\bar{b}}$ distributions. Two counting categories are defined: A background-dominated category from the $m_{\gamma\gamma}$ sidebands, and a signal region inside the $m_{\gamma\gamma}$ and $m_{\gamma\gamma b\bar{b}}$ windows. The efficiency is required in each dimension to extrapolate the background rate from the sidebands to the signal region. N_{SB} refers to the number of observed events in the sideband of the continuum background. N_{SR}^B is the number of expected continuum background events in the signal region. Figure adapted from Ref. [162].

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boson production in the SR are calculated in a similar fashion using:

$$N_{SR}^{SM} = N^{SM} \varepsilon_{m_{\gamma\gamma}}^{SM} \varepsilon_{m_{\gamma\gamma b\bar{b}}}^{SM} \quad (6.3)$$

where N^{SM} denotes the total number of single-Higgs boson and di-Higgs events in the inclusive $m_{\gamma\gamma}$ spectrum. The rates are normalised to the SM expectations. The number of expected $X \rightarrow hh \rightarrow \gamma\gamma b\bar{b}$ events is taken directly from MC and corrected for $\varepsilon_{m_{\gamma\gamma}}^X$ and $\varepsilon_{m_{\gamma\gamma b\bar{b}}}^X$. The efficiency of $\varepsilon_{m_{\gamma\gamma b\bar{b}}}^X$ is by construction 95% for the resonant samples. Table 6.8 shows the expected number of events from the di-Higgs and single-Higgs productions. It includes the estimated number of continuum background events in the $m_{\gamma\gamma}$ window for the non-resonant selection. The last row shows the number of observed events.

Process	0-tag	2-tag
Continuum Background	35.8 ± 2.1	1.63 ± 0.30
SM Single-Higgs	1.8 ± 1.5	0.14 ± 0.05
SM Di-Higgs	< 0.001	0.027 ± 0.006
Observed	27	0

Table 6.8: The observed and expected number of events in the $m_h \pm 2\sigma_{m_{\gamma\gamma}}$ mass window in the 0-tag and 2-tag categories in the non-resonant selection, in 3.2 fb^{-1} of Data collected in 2015.

6.8 Systematic Uncertainties

The small predicted and observed yields mean that the statistical uncertainties are dominant. This is especially true in the di-Higgs resonant production. The sources of systematics are in the modelling of the data, theory and experimental techniques. These are described below.

6.8.1 Background Modelling Uncertainties

The uncertainties from modelling the continuum background shape are calculated in a multi-stage process. Firstly, the statistical uncertainty is studied using a toy MC method. This involves fitting numerous toy distributions, generated with Poisson-fluctuations from the nominal exponential fit, and recalculating $\varepsilon_{m_{\gamma\gamma}}^B$ for each toy. The standard deviation among the toys is interpreted as the statistical uncertainty on the measured efficiency. This was calculated at less than 1%. Three

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control regions are defined for photons: no isolation, loose photon identification and a combination of both. These regions are not strictly orthogonal, but the overlap is minimal. Fits are performed on the three categories with three different functions: zero and first order polynomial and a modified second order exponential. The fits are made on the $m_{\gamma\gamma}$ distribution in the full range $105 < m_{\gamma\gamma} < 160$ GeV, while excluding the region $120 < m_{\gamma\gamma} < 130$ GeV to avoid contamination with the SM single-Higgs boson events. The extrapolated yield in each control region is calculated for each fit and compared to the nominal fit. The largest variation is 11% and is chosen as the uncertainty on the continuum diphoton background modelling. This is repeated for both 0-tag and 2-tag categories and little difference is observed. Therefore, no error is assigned when using the 0-tag exponential shape in the 2-tag signal region.

The uncertainty on $\varepsilon_{m_{\gamma\gamma b\bar{b}}}^B$, in the resonant di-Higgs production, has three components which are summed in quadrature: the heavy-flavour uncertainty, the statistical uncertainty from the fitting procedure, and the choice of function to fit the shape. The heavy-flavour uncertainty originates from the assumption that the shape of the 0-tag category (no b -tag events) can be used to estimate the $m_{\gamma\gamma b\bar{b}}$ shape in the signal region (with two b -jets). A Landau is fitted to the four object distribution ($m_{\gamma\gamma b\bar{b}}$ and $m_{\gamma\gamma jj}$) that falls in the $m_{\gamma\gamma}$ sidebands for both 2-tag and 0-tag categories. The relative difference between the two fits provides an estimate for the heavy-flavour uncertainty in the fit. This is repeated for each resonance mass resulting in an uncertainty ranging from 6% ($m_X = 275$ GeV) to 11% ($m_X = 350$ GeV). The largest error is used for all hypotheses.

A background sample with multiple jets and photons is used to assess the fit function. A Landau function is fitted to the 0-tag $m_{\gamma\gamma jj}$ distribution and integrated in each of the 95% signal windows. The number of events in the signal window are then counted and compared to the integrated Landau. The largest difference is found to be 20% and is chosen as a conservative uncertainty arising from the choice of using the Landau to fit the continuum background.

A toy MC approach, as in the $m_{\gamma\gamma}$ case, is used for the statistical uncertainty. Landau fits are used to calculate the window efficiency for each toy. The standard deviation gives the statistical uncertainty on the estimated efficiency, which is dependant on the mass hypothesis, and ranges from 15% to 30%. The uncertainty on $\varepsilon_{m_{\gamma\gamma b\bar{b}}}^{\text{SM}}$ also affects the SM single-Higgs boson and di-Higgs boson processes. These processes contribute to the background for the resonant analysis. The parametrised signal mass window efficiency for these samples are compared to simply counting the number of simulated events inside the window. Again, the largest difference is chosen which is found to be 25%.

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6.8.2 Uncertainties on Signal Samples

Theoretical uncertainties on single Higgs boson production are due mostly to scale and PDF uncertainties and their associated heavy-flavour production uncertainties. The uncertainties of the $h \rightarrow \gamma\gamma$ and $h \rightarrow b\bar{b}$ branching fractions are $\pm 5\%$ and $\pm 3\%$, respectively, with an additional systematic uncertainty caused by the limited statistical precision of each simulated sample. The scale uncertainties, $+14\%/-24\%$, and PDF uncertainties, $\pm 9\%$, are calculated by the LHC Higgs boson Cross Section Working Group [15]. A study on the associated heavy-flavour production in $t\bar{t}$ indicate that a 100% uncertainty should be applied to the ggF mode [163]. There is also a 100% uncertainty on the Wh and VBF processes based on the work in Ref. [164]. The dominant heavy-flavour contribution in the Zh channel comes from $Z \rightarrow b\bar{b}$ and does not arise from additional radiation. Similarly, in $t\bar{t}h$ the major b -jet production is from the top-quark decays. No heavy-flavour uncertainty is applied for either of these cases. In the resonant search, the scale and PDF uncertainties on the NNLO cross section for SM di-Higgs production are combined with an additional component from the simplifications used in the EFT approximations. The overall uncertainty on this cross section is $+11\%/-12\%$.

6.8.3 Experimental Uncertainties

The experimental uncertainties are taken, as far as possible, from the CP groups recommendations. The experimental uncertainties are:

- The uncertainty on the integrated luminosity was calculated, using a method described in Ref. [165], as $\pm 5\%$.
- The diphoton trigger uncertainties are measured using a bootstrap method [166], and is 99.4%, with a systematic uncertainty of 0.4%.
- The uncertainty on the efficiency of the neural network vertex selection is negligible.
- The photon identification procedure has correction factors to make simulation agree with data. The full difference, with and without the factors, is taken as the uncertainty and is measured to be 2.5%.
- Photon isolation has two uncertainties relating to the calorimeter or track-based isolation factors. These shifts are compared to the nominal value and the full difference of each is combined in quadrature to give 4%.
- The diphoton mass resolution has an uncertainty that is propagated by the energy scale and resolution of the photons which ranges from 15% to 30%.
- Systematic uncertainties from the jet energy scale (JES) and jet energy resolution (JER) are propagated to the $m_{b\bar{b}}$ spectra. The two uncertainties

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are combined in quadrature. The JER uncertainty varies between 1.7% and 9.8% for different mass hypotheses and is therefore parametrised as a function of the resonance mass [167, 168].

- Uncertainties from the muon calibration [169] are reflected in the muon corrected b -jet correction.
- The b -tagging uncertainties [159, 170] are reflected when tagging jets and identification of category.
- The pileup reweighting technique has associated systematic uncertainties that range from 1% to 2.5% depending on the sample.

A summary of the systematic uncertainties on signal and background samples (including the continuum background) is shown in Table 6.9. In the non-resonant case, the SM di-Higgs sample is considered as the signal process with the single-Higgs boson samples forming part of the background. In the resonant search both SM single-Higgs boson and non-resonant production are treated as backgrounds. The luminosity is fully correlated over all samples. The JES uncertainty includes multiple components such as the uncertainty on jets arising from b -quarks. The b -tagging uncertainties include sources from the efficiency to correctly tag b -jets and to miss-tag jets that arise from c -quarks or light-flavour quarks. In the $X \rightarrow hh$ search, the JER and $m_{\gamma\gamma b\bar{b}}$ modelling uncertainties are parametrised as a function of the resonance mass and the full range is quoted in Table 6.9.

In the non-resonant analysis we include all uncertainties by selecting events inside the $2\sigma m_{\gamma\gamma}$ window, which includes the shape distortion on photons. The resonant analysis has the same criteria with the additional 95% window cut on $m_{\gamma\gamma b\bar{b}}$ which is mass dependant.

Performing the selection on all samples totals 53 unique systematic sets.¹ Each tool used in the HH2yybb framework, the tools which perform object calibration, flavour tagging etc., provide a set of systematic shifts that affect it. In the $\gamma\gamma b\bar{b}$ analysis there is a sum of 108 systematics which need to be studied. For every systematic the full cutflow is performed and the final yield is compared to the nominal case to calculate the percentage difference. The total number of systematic shifts, after combining the sets and the number of object systematics, is $53 \times 108 = 5724$ unique systematic uncertainties. After calculating each shift, the values are combined by object type and added in quadrature. The tables with these combined numbers can be found in Tables C.7 to C.19.

¹This is calculated as follows: There are 8 single-Higgs boson samples. A run is performed on each sample for the one non-resonant window and five resonance windows totalling 48 runs. There are 5 resonance signal samples, one for each mass hypothesis. This totals 53 unique sets of systematics.

Table 6.9: Summary of systematic uncertainties, in percent, for 2-tag events in the signal region. Entries marked ‘-’ indicate that the systematic is not applicable in this category. See text for more detail.

Source of Systematic Uncertainty		Non-Resonant Mode			Resonant Mode		
		hh signal	Single- h bkg	Cont.	$X \rightarrow hh$ signal	SM $h+hh$ bkg	Cont.
Luminosity		± 5.0	± 5.0	-	± 5.0	± 5.0	-
Trigger		± 0.4	± 0.4	-	± 0.4	± 0.4	-
Pileup reweighting		± 1.6	+2.4 / -0.4	-	± 1.0	± 2.3	-
Generated event statistics		± 1.3	± 16.8	-	± 4.3	± 12.6	-
Photon	Energy resolution	+30 / -15	+30 / -15	-	+7.0 / -0.3	+0.0 / -3.8	-
	Energy scale	± 0.5	± 0.5	-	+1.9 / -3.5	+2.8 / -3.0	-
	Identification	± 2.5	± 2.5	-	± 2.5	± 2.5	-
	Isolation	± 3.4	± 3.4	-	± 3.9	± 3.9	-
Jet	Energy resolution	± 2.7	± 24	-	± 9.1	± 1.6 –9.8	-
	Energy scale	+1.3 / -1.1	± 12	-	± 12.1	± 10.6	-
b -tagging	b -jets	± 12.9	± 10.0	-	± 12.6	± 12.6	-
	c -jets	± 0.05	± 4.1	-	± 0.2	± 3.0	-
	Light-jets	± 0.5	+3.9 / -4.6	-	± 0.2	± 0.5	-
	Extrapolation	± 5.1	± 2.8	-	± 5.2	± 3.0	-
Shape	$m_{\gamma\gamma}$ modelling	-	-	± 11	-	-	± 11
	$m_{\gamma\gamma b\bar{b}}$ modelling	-	-	-	-	± 25.0	± 27 –40
Theory	PDF+ α_S	-	+6.8 / -6.6	-	-	+7.4 / -7.3	-
	Scale	-	+5.7 / -8.2	-	-	+6.9 / -10.9	-
	EFT	-	-	-	-	± 5.7	-
Total		+34 / -22	+43 / -35	± 11	+23 / -22	+36 / -35	± 29 –41

6.9 Statistical Analysis

The profile likelihood ratio used for the statistical analysis is given by:

$$\tilde{q}_\mu = \begin{cases} -2\ln \frac{L(\mu, \hat{\theta}(\mu))}{L(0, \hat{\theta}(0))} & \hat{\mu} < 0 \\ -2\ln \frac{L(\mu, \hat{\theta}(\mu))}{L(\hat{\mu}, \hat{\theta}(\mu))} & 0 \leq \hat{\mu} \leq \mu \\ 0 & \hat{\mu} > \mu \end{cases} \quad (6.4)$$

where θ represent the nuisance parameters (such as systematic uncertainties) and μ the parameter of interest which in our case is the BSM cross-section. Due to the lack of statistics, toy experiments are generated in order to calculate limits and quantify a significance [161]. The frequentist recommendation is followed for the toy generation and global observables are randomised. The nuisance parameters are fixed to their values when fitted on the data for the given signal hypothesis μ . The 95% exclusion limits are set using the recommended CL_S method [171]. The statistical approach is different for the resonant and non-resonant searches.

6.9.1 Non-resonant analysis

A single unbinned fit to the $m_{\gamma\gamma}$ distribution is performed simultaneously in the signal region (2-tag category) and the control region (0-tag category). The background, in the 0-tag category, is fitted with an exponential function and a double sided Crystal Ball is used to model the SM and BSM components.

6.9.2 Resonant analysis

The resonant search uses a counting technique due to the extreme lack of statistics. This is based on the $m_{\gamma\gamma}$ and $m_{\gamma\gamma b\bar{b}}$ windows discussed in Section 6.7.2. The number of events in the $m_{\gamma\gamma}$ sidebands remain the same for all hypotheses and the number of observed events in the different resonance mass windows changes. The number of events in the sideband and signal regions can be split into contributions from the background continuum, the SM and BSM as:

$$\begin{aligned} N^{Sideband} &= N_{Continuum}^{SB} + N_{SM}^{SB} + N_{BSM}^{SB} \\ N^{SR} &= N_{Continuum}^{SR} + N_{SM}^{SR} + N_{BSM}^{SR} \end{aligned} \quad (6.5)$$

6. HIGGS BOSON PAIR PRODUCTION IN $\gamma\gamma b\bar{b}$ EVENTS

where each of the terms are defined as:

$$\begin{aligned}
N_{\text{SR}}^{\text{Continuum}} &= N_{\text{SB}}^{\text{Continuum}} \times \frac{\varepsilon_{m_{\gamma\gamma}}^{\text{B}}}{1 - \varepsilon_{m_{\gamma\gamma}}^{\text{B}}} \varepsilon_{m_{\gamma\gamma}b\bar{b}}^{\text{B}} \\
N_{\text{SB}}^{\text{SM}} &= N^{\text{SM}} \times (1 - \varepsilon_{m_{\gamma\gamma}}^{\text{SR}}) \\
N_{\text{SR}}^{\text{SM}} &= N^{\text{SM}} \times \varepsilon_{m_{\gamma\gamma}}^{\text{SM}} \times \varepsilon_{m_{\gamma\gamma}b\bar{b}}^{\text{SM}} \\
N_{\text{SB}}^{\text{BSM}} &= N^{\text{BSM}} \times (1 - \varepsilon_{m_{\gamma\gamma}}^{\text{SR}}) \\
N_{\text{SR}}^{\text{BSM}} &= N^{\text{BSM}} \times \varepsilon_{m_{\gamma\gamma}}^{\text{SR}} \times \varepsilon_{m_{\gamma\gamma}b\bar{b}}^{\text{BSM}}
\end{aligned} \tag{6.6}$$

The number of BSM events is given by:

$$N^{\text{BSM}} = \mathcal{B}_{\gamma\gamma} \times \mathcal{B}_{b\bar{b}} \times 2 \times 1000 \times \mathcal{L} \times \text{sel. eff.} \times \text{npbBSM}. \tag{6.7}$$

where $\mathcal{L}$ is given in fb^{-1} . The fitted parameters, in addition to the systematic uncertainties, are $N_{\text{Continuum}}^{\text{SB}}$ and npbBSM in Equations (6.6) and (6.7).

The 1-tag category was found to have limited increase in the sensitivity and was removed. This choice will be revisited on future data when the single b -jet can be better selected.

6.10 Results

After performing the simultaneous unbinned likelihood fit on the signal and control regions for the non-resonant analysis we get the distributions shown in Figure 6.11 for the 0-tag and 2-tag categories. In the $\pm 2\sigma_{m_{\gamma\gamma}}$ window around m_h , 1.8 events are expected from the combination and the continuum and single-Higgs boson backgrounds while no events were observed in the 2015 dataset. The expected upper limit on the non-resonant di-Higgs production cross section is $5.4_{-1.0}^{+2.8}$ pb. Since there was a deficit of observed events in the signal region, the observed limit is 3.9 pb, as shown in Figure 6.12.

No events were observed in the 2015 data for the resonant analysis since no diphoton events were in the $m_{\gamma\gamma}$ signal window. The expected exclusion limits at 95% CL vary from 7.5 pb at $m_X = 275$ GeV to 4.4 pb at $m_X = 400$ GeV. The limits improve for higher resonance masses because of the improvement in the acceptance and selection efficiency. Figure 6.13a shows the 95% CL upper limits on the cross section times branching fraction for a narrow resonance with mass m_X . These limits are also presented in Figure 6.13b as the expected and observed limits on the number of events after the event selection. The present result excludes excesses above 3 events at 95% CL. The modest excess presented in Run I, shown in Figures 6.2a and 6.2b, would translate into about 2 events in the 2015 dataset. This is under the assumption that it was induced by gluon-initiated

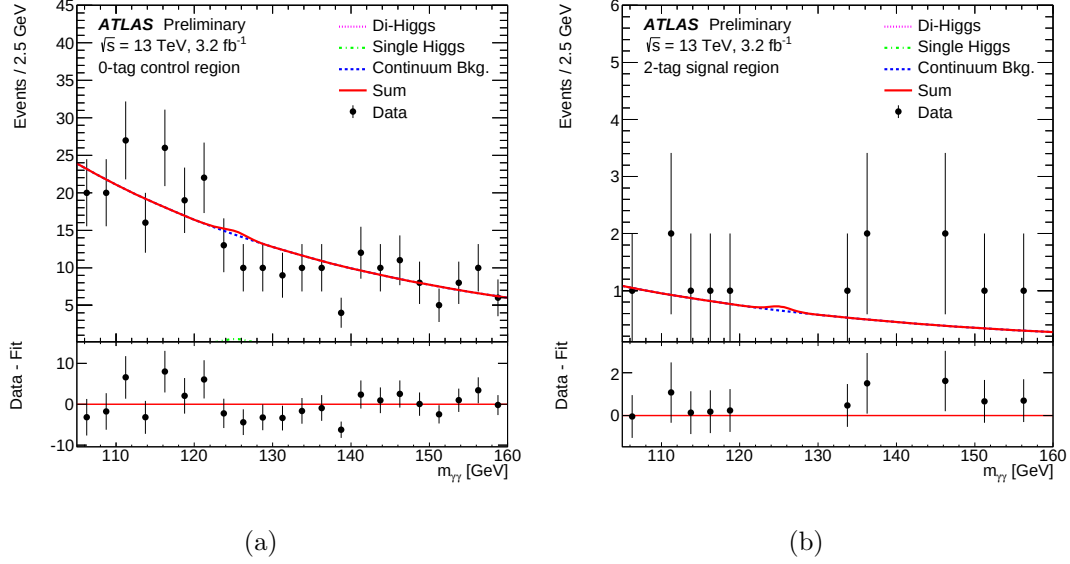


Figure 6.11: The signal and background fit to the observed diphoton invariant mass spectrum in the non-resonant search for the a) 0-tag category and b) 2-tag category. The individual contributions from single-Higgs boson production, di-Higgs production and continuum background are shown, together with their sum. The expected rates for single-Higgs boson and di-Higgs boson production are small. The bottom insert plots show the difference in number of events between the observed data and the signal-plus-background fit [162].

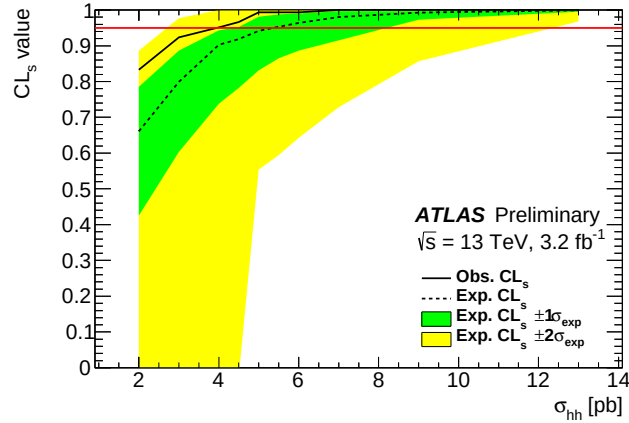


Figure 6.12: Scan of the observed (solid line) and expected (dashed line) CL_s values as a function of the production cross section σ_{hh} for the non-resonant search. The green (yellow) band represents the 1σ (2σ) intervals on the expected CL_s value [162].

6. HIGGS BOSON PAIR PRODUCTION IN $\gamma\gamma b\bar{b}$ EVENTS

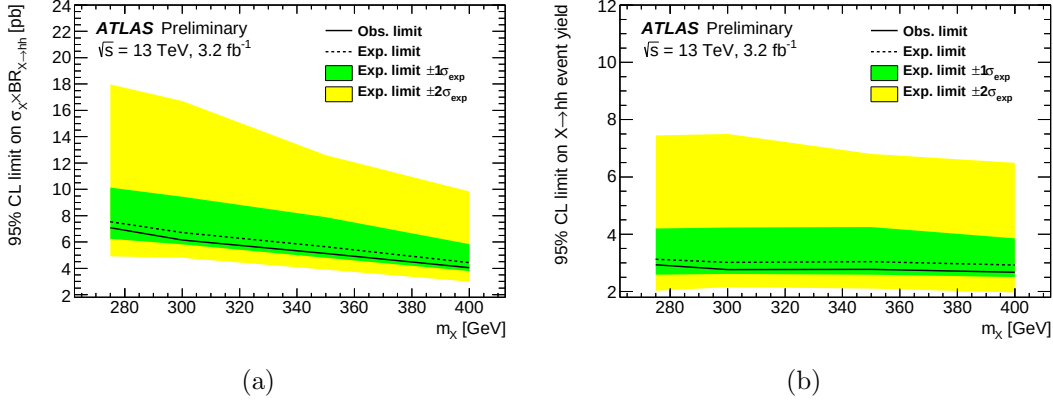


Figure 6.13: a) The 95% CL expected (dashed line) and observed (solid line) limits on the production cross section times $X \rightarrow hh$ branching fraction as a function of the resonance mass m_X and b) the corresponding 95% CL limits in terms of the expected and observed number of events after the full selection. The green (yellow) band represents the 1σ (2σ) intervals on the expected limit [162].

states and accounting for the change in acceptance and parton-luminosity ratio between 13 TeV and 8 TeV, which is approximately 3 [172].

6.11 Conclusions

Searches for the resonant and non-resonant Higgs boson pair production are performed in the $\gamma\gamma b\bar{b}$ final state using 3.2 fb^{-1} of proton-proton collision data collected at 13 TeV using the ATLAS detector at CERN. No excess was found with respect to the background-only hypothesis and, as a result, 95% upper limits were set. The upper limits for the non-resonant search is extracted to be 3.9 pb with the expected limit at 5.4 pb. In the search for a narrow width $X \rightarrow hh$ resonance, the observed limit ranges from 7.0 pb to 4.0 pb for resonance masses in the range 275 – 400 GeV. The expected limit varies according to the resonance mass from 7.5 pb to 4.4 pb. Although no excess was observed, we cannot rule out the Run I excess or Madala hypothesis until more data has been analysed. An updated search with the full 2015 and 2016 dataset is currently ongoing at the time of writing, which will have over 10 times more data.

A Search for Higgs Bosons with Missing Energy

Higgs bosons produced with missing transverse momentum ($E_{\text{T}}^{\text{miss}}$) in the final state can be indicative of scenarios involving dark matter (DM) candidates. This chapter details a search for new phenomena in events with missing transverse momentum and a Higgs boson decaying to two photons. The outlining theory is described by the Madala hypothesis in Section 1.6.

7. A SEARCH FOR HIGGS BOSONS WITH MISSING ENERGY

7.1 Introduction

The ATLAS Collaboration has previously searched for missing energy events at a centre-of-mass energy of $\sqrt{s} = 8$ TeV [173] and with 3.2 fb^{-1} of data at $\sqrt{s} = 13$ TeV [174]. This chapter expands on Ref. [174] by adding an additional 10.1 fb^{-1} of data, recorded at 13 TeV in 2016. Figure 7.1 shows limit plots as a function of the heavy scalar mass in the range between 270 GeV (260 GeV) and 350 GeV for a DM candidate mass of 50 GeV (60 GeV) [174]. These limits were measured with the Run II dataset in 2015 and are improved upon in this chapter.

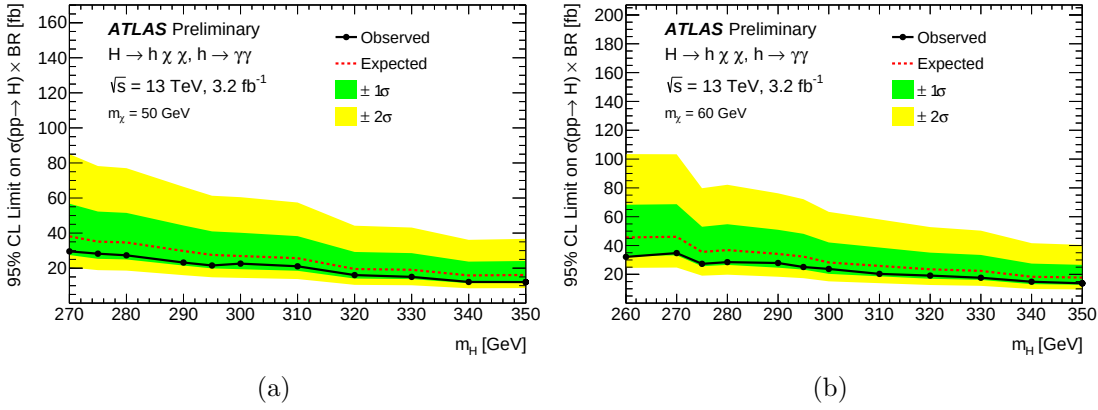


Figure 7.1: Early Run II expected and observed 95% CL exclusion limits on the product of the cross section and $\text{BR}(H \rightarrow h\chi\chi, h \rightarrow \gamma\gamma)$ for the Madala hypothesis, with a DM candidate mass of a) 50 GeV and b) 60 GeV. This was measured using 3.2 fb^{-1} of data. These results suggest the branching ratio to DM is lower than originally estimated.

7.2 Data and Simulated Samples

The $\gamma\gamma + E_T^{\text{miss}}$ analysis uses proton-proton collision data recorded in 2015 and the first half of 2016 at $\sqrt{s} = 13$ TeV. Data is required to satisfy the quality criteria specified in Section 5.3. The dataset corresponds to a total integrated luminosity of 13.3 fb^{-1} .

7.2.1 Signal Samples

The signal samples are generated using MADGRAPH5 at LO using the NNPDF3.0LO PDF set. The showering and hadronization are simulated using PYTHIA8 with the

7.3. OBJECT AND EVENT SELECTION

Table 7.1: Table of background processes, in addition to Tables 5.5 and 5.6 used in the $\gamma\gamma + E_T^{\text{miss}}$ analysis.

Process	Generator	PDF Set
$Z\gamma \rightarrow ll\gamma$ up to 3 jets	SHERPA	CT10
$W\gamma \rightarrow l\nu\gamma$ up to 3 jets	SHERPA	CT10
$Z\gamma\gamma \rightarrow ll\gamma\gamma$ up to 2 jets	SHERPA	CT10
$W\gamma\gamma \rightarrow l\nu\gamma\gamma$ up to 2 jets	SHERPA	CT10

where, $l = \mu, e, \text{ or } \tau$

A14 tune using the NNPDF2.3LO PDF set. The heavy scalar, H , is described in Section 1.6. The $pp \rightarrow H \rightarrow h\chi\chi$ events are produced with various masses of H in the range $260 \leq m_H \leq 350$ GeV in steps of 10 GeV. An additional mass point at $m_H = 275$ GeV is produced with two different DM masses of $m_\chi = 50$ and 60 GeV.

7.2.2 Background Samples

The background to the $h \rightarrow \gamma\gamma + E_T^{\text{miss}}$ process are the SM Higgs boson samples listed in Table 5.5 and the non-resonant $\gamma\gamma$, γj and jj backgrounds in Table 5.6. The SM Higgs boson is generated with a mass of 125 GeV in all production modes. Additional samples are included such as the $W\gamma$ and $W\gamma\gamma$. The full list of MC samples is summarised in Table 7.1. The MC samples are used to model the background and evaluate the uncertainties on its shape. The normalisation of the non-resonant backgrounds is data-driven. All samples are corrected for detector affects and reweighted for pileup conditions, as described in Section 5.4.

7.3 Object and Event Selection

The object identification and selection follows the nominal diphoton analysis. This has been summarised for each object, including the missing transverse energy, in Section 5.2. This is also true for the event selection which is described in Section 5.3. Two photons are chosen to satisfy the full event selection up to the mass window $105 \text{ GeV} < m_{\gamma\gamma} < 160 \text{ GeV}$. Once the nominal diphoton event selection is performed, events are categorised into four mutually exclusive categories to cover the sensitive regions for the different models in the analysis. There are two models that are tested in this analysis which are described in Ref. [174] and [175]. In order not to

7. A SEARCH FOR HIGGS BOSONS WITH MISSING ENERGY

Table 7.2: The optimised categories and the requirements on $S_{E_T^{\text{miss}}}$ and $p_T^{\gamma\gamma}$ in the $\gamma\gamma + E_T^{\text{miss}}$ study. A ‘-’ denotes no requirement on that observable in that category over and above the nominal selection. The $p_T^{\gamma\gamma} > 15$ GeV requirement in the ‘Rest’ category is driven by the large contribution of low $p_T^{\gamma\gamma}$ events in gluon induced SM Higgs boson production.

Category	Short Name	$S_{E_T^{\text{miss}}} \left[\sqrt{\text{GeV}} \right]$	$p_T^{\gamma\gamma} \left[\text{GeV} \right]$
High $S_{E_T^{\text{miss}}}$, high $p_T^{\gamma\gamma}$	HMHP	> 7	> 90
High $S_{E_T^{\text{miss}}}$, low $p_T^{\gamma\gamma}$	HMLP	> 7	≤ 90
Intermediate $S_{E_T^{\text{miss}}}$	IntMET	> 4 and ≤ 7	> 25
Rest	Rest	-	> 15

digress, only the heavy scalar model (the Madala hypothesis) is discussed for its direct relevance and the Z'_B and Z' -2HDM models will be mentioned where needed.

Events are categorised based on two properties. Firstly, the missing energy significance ($S_{E_T^{\text{miss}}}$) which was introduced in Section 5.2.5 and secondly, the transverse momentum of the diphoton pair. The Z'_B and Z' -2HDM models have a Higgs boson which recoils against a pair of DM particles. This introduces a large E_T^{miss} in the event and a large p_T of the diphoton candidate. The heavy scalar model, however, has a wide range of E_T^{miss} and $p_T^{\gamma\gamma}$.

The vector-mediator models have the largest significance in the high $S_{E_T^{\text{miss}}}$ categories while the lower $S_{E_T^{\text{miss}}}$ categories have significant sensitivity to the heavy scalar model. Therefore, the results for the heavy scalar model are extracted from a simultaneous likelihood fit over all four categories. Figure 7.2 shows the data and MC distributions for the inclusive $S_{E_T^{\text{miss}}}$ case. The bottom insert shows the statistical uncertainties from the MC samples added in quadrature with the systematic uncertainties. The $\gamma\gamma$ distribution is reweighted to describe the γj contribution using a data driven measurement of the diphoton mass. The total $\gamma\gamma$ and γj distribution is then built with a composition of 78% and 21%, respectively, which is measured with a data driven approach. The full difference between the MC and data is taken as an additional systematic uncertainty.

7.4 The Missing Energy Analysis Framework

The $\gamma\gamma + E_T^{\text{miss}}$ analysis followed after the $\gamma\gamma b\bar{b}$ search in mid-2016. There were many developments on the central `HGamTools` package which allowed for major

7.4. THE MISSING ENERGY ANALYSIS FRAMEWORK

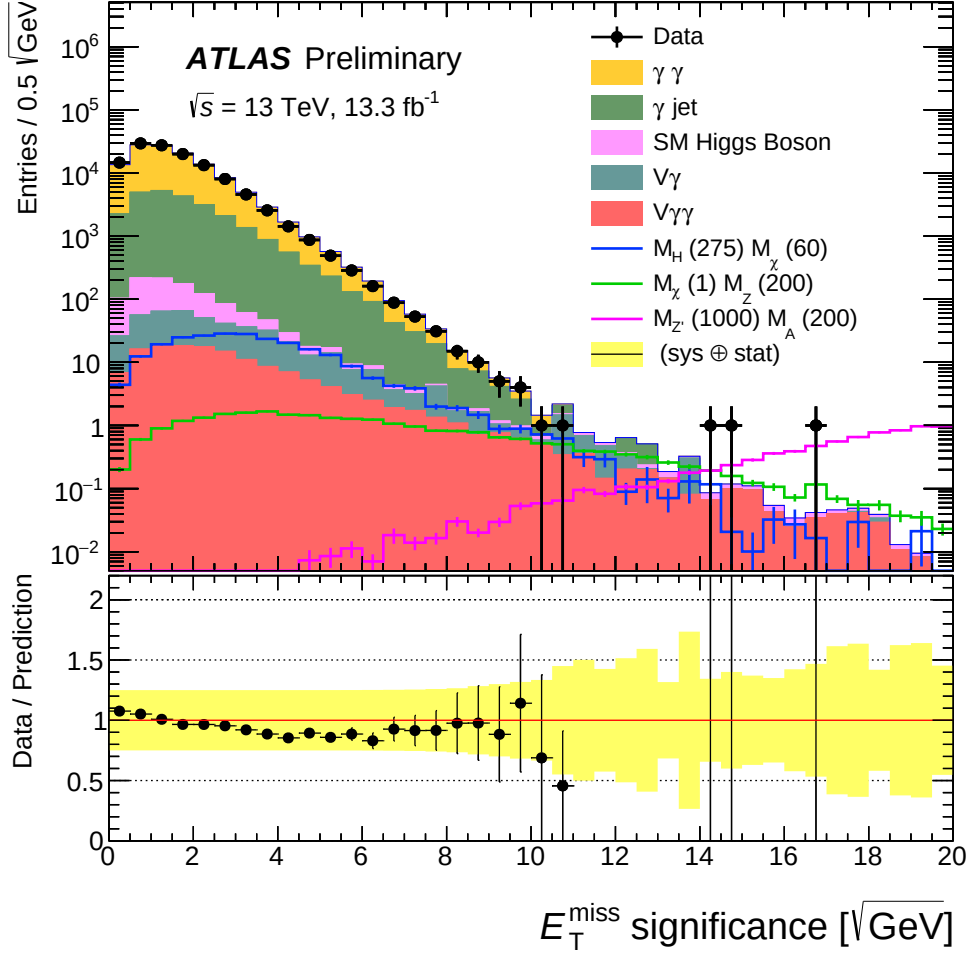


Figure 7.2: Inclusive $S_{E_T^{\text{miss}}}$ distribution comparing MC to data. The $\gamma\gamma$ sample shape is reweighted to the E_T^{miss} distribution in the data. The γj shape is obtained from reweighting the $\gamma\gamma$ sample using a data driven measurement. This method involves measuring the $\gamma j/\gamma\gamma$ ratio as a function of the diphoton mass. The $\gamma\gamma$ and γj are scaled to the data driven purities of 78% and 21%, of the total, respectively. The stacked backgrounds are normalised to the data. The scalar model with a mass of $m_H = 275 \text{ GeV}$ and $m_{\chi} = 60 \text{ GeV}$ is shown in blue and peaks around the lower $S_{E_T^{\text{miss}}}$ region [175].

7. A SEARCH FOR HIGGS BOSONS WITH MISSING ENERGY

simplifications in the code compared to the $\gamma\gamma b\bar{b}$ analysis. The techniques and experience gained from developing the **HH2yybb** framework made for a rapid deployment of the $\gamma\gamma + E_T^{\text{miss}}$ software, called the **Mad2s** framework.¹ Instead of processing DxAOD files, the **Mad2s** framework exclusively uses the centrally processed MxAOD made by the HGam community. This has numerous benefits which include:

- All objects are already calibrated and selected and therefore, the framework requires no additional tools.
- Large DxAODs are slimmed by excluding events without two loose identified photons. This means there are less events to loop over.
- Central MxAODs are used by the whole group. Any issues are identified and resolved promptly.
- MxAODs are faster to process allowing for quick re-runs if needed.

The inheritance of the **Mad2s** framework is similar to that of $\gamma\gamma b\bar{b}$ in Figure 6.4 but does not make use of all the object tools since all these corrections are already applied. An output file is produced in a very simple **ROOT** format called an ntuple. The framework was configured to run over all datasets and MC files with the output ntuple being available to the whole analysis team for all the studies that were required.

7.5 Signal and Background Modelling

The modelling strategy is similar to the non-resonant $\gamma\gamma b\bar{b}$ search, discussed in Section 6.7.1. The signal and SM Higgs samples are modelled with a DSCB, shown in Figure 6.9, by fitting the function to the $m_{\gamma\gamma}$ distribution in each of the four categories. The samples use a Higgs boson with a mass of 125 GeV. The shapes of both BSM and SM signals are similar, as expected.

The non-resonant background is modelled using a data-driven approach. The functional form is chosen by fitting a signal plus background model to the background distribution and testing for a spurious signal. Since no signal should be present the resulting signal yield can be interpreted as a measure of the bias. The bias is considered acceptable one of the following conditions are met: if the extracted spurious signal yield is less than 10% of the expected signal rate of Higgs bosons or if the yield is smaller than 20% of the statistical uncertainty on the number of background events in the fitted signal peak. The largest yield in the mass range is taken as a systematic uncertainty on the choice of the background

¹The name suggests the decay of the heavy scalar H, from the Madala hypothesis, to the intermediate scalar S. This theory is described in Section 1.6

shape. This spurious signal test is performed on the intermediate and rest categories because they have sufficient number of events. An exponential with a second order polynomial is chosen to model these categories. The intermediate and rest categories have a background shape uncertainty of 3% and 13%, respectively. The small number of events in the high $S_{E_T^{\text{miss}}}$ categories prevents this type of study and a simple exponential is used to model the background.

7.6 Systematic Uncertainties

Experimental and theoretical uncertainties affect the SM Higgs boson and signal MC samples. The techniques used to calculate object uncertainties are analogous to Section 6.8. The $\gamma\gamma b\bar{b}$ systematic code is modified for the $\gamma\gamma + E_T^{\text{miss}}$ categories and incorporates the new systematic shifts from the CP groups. The major sources of uncertainties are outlined in this section.

7.6.1 Theoretical Uncertainties

- The predicted cross sections of the SM Higgs boson and signal processes are due to missing higher-order terms in perturbative QCD. These are estimated by varying the factorisation and renormalisation up and down by a factor of two and recalculating the cross section each time. The values are taken from Ref. [11]. The selection on the Higgs boson p_T adds an uncertainty which is evaluated, again, by varying the factorisation and renormalisation by a factor of 2 and is found to be 9% to 20% for the Higgs boson p_T selection from 5 GeV to 120 GeV.
- The PDF uncertainties, $\pm 9\%$, are calculated by the LHC Higgs Cross Section Working Group [15].
- The $h \rightarrow \gamma\gamma$ branching ratio has an uncertainty of $\pm 5\%$ taken from Ref. [11].
- The effect of multi-parton interactions (MPI) was evaluated by switching it on and off in PYTHIA8 and comparing the difference. The resulting uncertainty on the number of events in this sample is 50% in the high $S_{E_T^{\text{miss}}}$, low $p_T^{\gamma\gamma}$ category.

7.6.2 Experimental Uncertainties

The object uncertainties are calculated by applying the CP group recommendations and shifting the objects values up and down. Each shift is compared to the nominal case and a percentage shift is calculated. The different systematics making up each group is shown in Table 7.3 where each term has an up and down component.

7. A SEARCH FOR HIGGS BOSONS WITH MISSING ENERGY

Table 7.3: List of systematics used in each sub-group.

Group	Systematic Shift
EG Res	EG_RESOLUTION_ALL
EG Scale	EG_SCALE_ALLCORR
	EG_SCALE_E4SCINTILLATOR
	EG_SCALE_LARCALIB_EXTRA2015PRE
	EG_SCALE_LARTEMPERATURE_EXTRA2015PRE
JER	EG_SCALE_LARTEMPERATURE_EXTRA2016PRE
	JET_JER_SINGLE_NP
JES	JET_EffectiveNP_3
	JET_EffectiveNP_4
	JET_EffectiveNP_5
	JET_EffectiveNP_6restTerm
	JET_EtaIntercalibration_Modelling
	JET_EtaIntercalibration_NonClosure
	JET_EtaIntercalibration_TotalStat
	JET_Flavor_Composition
	JET_Flavor_Response
	JET_Pileup_OffsetMu
	JET_Pileup_OffsetNPV
	JET_Pileup_PtTerm
	JET_Pileup_RhoTopology
	JET_PunchThrough_MC15
	JET_SingleParticle_HighPt
	JET_BJES_Response
	JET_EffectiveNP_1
	JET_EffectiveNP_2
JVT	JvtEfficiency
MET	MET_JetTrk_Scale
	MET_SoftTrk_ResoPara
	MET_SoftTrk_ResoPerp
	MET_SoftTrk_Scale
PH Eff	PH_EFF_ID_Uncertainty
	PH_EFF_TRKISO_Uncertainty
PH Iso	PH_Iso_DDonoff
PRW	PRW_DATASF

7.6. SYSTEMATIC UNCERTAINTIES

Table 7.4 shows the combined systematic uncertainties for the seven single Higgs boson samples. Table 7.5 shows the systematic uncertainties for the heavy scalar sample with $m_H = 275$ GeV and $m_\chi = 60$ GeV. The largest uncertainty for the SM samples is the photon efficiency at 5% while for the heavy scalar is it the jet energy scale at up to 13%. The other experimental systematics include:

- The uncertainty on the integrated luminosity for 2015 and 2016 was calculated, using a method described in Ref. [165], as 2.9%. This was derived from a preliminary calibration of the luminosity scale using x - y beam-separation scans performed in August 2015 and May 2016.
- The diphoton trigger uncertainties are measured using a bootstrap method [166], and is 99.4%, with a systematic uncertainty of 0.4%.
- The uncertainty on the efficiency of the neural network vertex selection is negligible.
- The photon identification procedure has correction factors to make simulation agree with data. The full difference, with and without the factors, is taken as the uncertainty and is measured to be $\pm 2.8\%$.
- Photon isolation has two uncertainties relating to the calorimeter or track-based isolation factors. These shifts are compared to the nominal value and the full difference of each is combined in quadrature to give $\pm 4\%$.
- The uncertainty on photon energy scale is less than 1% in the p_T range of the photons used in this analysis, and less than 2% for the resolution.
- The $S_{E_T^{\text{miss}}}$ reconstruction is affected by the jet energy scale, JES, and jet energy resolution, JER. The impact of the uncertainties are measured by changing each systematic shift and recalculating the $S_{E_T^{\text{miss}}}$. There are over 20 uncorrelated uncertainties for JES and JER and 3 for the E_T^{miss} soft term. The soft term is the missing energy component from low energy track terms [141]. The largest uncertainty is for the SM Higgs boson in the intermediate category of 15% and 10% in the high E_T^{miss} category. The uncertainties are smaller than 1% for the rest category.
- The pileup reweighting has a $\pm 1.0\%$ uncertainty on the event yield of the signal and SM Higgs boson samples.
- Mismodelling the $S_{E_T^{\text{miss}}}$ for SM gluon fusion Higgs boson production is derived by comparing the difference between data sidebands and the background model. The systematic uncertainty is 25% for the High $S_{E_T^{\text{miss}}}$, high $p_T^{\gamma\gamma}$ and 60% for High $S_{E_T^{\text{miss}}}$, low $p_T^{\gamma\gamma}$ categories.

7. A SEARCH FOR HIGGS BOSONS WITH MISSING ENERGY

Table 7.4: Combined symmetric systematic uncertainties for SM Higgs boson production. Uncertainties are in percent.

Syst. Name	HMHP	HMLP	IntMET	Rest
EG Res	0.21	0.40	0.12	0.15
EG Scale	0.90	1.86	0.08	0.08
JER	0.85	3.87	3.60	0.24
JES	0.90	4.97	3.34	0.23
JVT	0.56	1.11	0.99	1.16
MET	0.44	1.90	3.67	0.23
PH Eff	5.37	5.85	5.65	5.74
PH Iso	0.19	0.28	0.37	0.37
PRW	1.28	0.15	0.64	0.67

Table 7.5: Combined symmetric systematic uncertainties for the heavy scalar sample with $m_H = 275$ GeV and $m_\chi = 60$ GeV. Uncertainties are in percent.

Syst. Name	HMHP	HMLP	IntMET	Rest
EG Res	1.13	0.26	0.34	0.08
EG Scale	1.18	1.44	0.23	0.09
JER	0.40	4.25	2.53	0.81
JES	5.43	13.68	2.19	1.48
JVT	0.56	1.11	0.99	1.16
MET	0.88	2.97	1.40	0.62
PH Eff	5.35	5.86	5.83	5.83
PH Iso	0.73	0.39	0.28	0.30
PRW	0.70	1.43	1.04	0.25

A summary of the experimental and theoretical uncertainties is given in Table 7.6 in terms of the fractional impact on the number of events from SM Higgs boson production processes.

7.7 Results

The final event yields in 13.3 fb^{-1} of data, two heavy scalar models and the backgrounds is shown in Table 7.7. The efficiencies for the signal models is also provided. Figure 7.3 shows the diphoton distributions in all four categories with their respective fits using the heavy scalar model. No significant excess is observed in any category, so exclusion limits are set on the production cross sections of the theoretical models.

The statistical results of the analysis are derived from a likelihood fit, using a similar technique to Section 6.9. The systematic uncertainties are modelled as nuisance parameters and the fit is in the range $105 \leq m_{\gamma\gamma} < 160 \text{ GeV}$. The upper limits at the 95% CL_s confidence level are calculated using a one-sided profile-likelihood ratio using the asymptotic approximation. The 95% CL upper limits are calculated for the $pp \rightarrow H$ cross section times branching ratio. The BR is the process $H \rightarrow h\chi\chi \rightarrow \gamma\gamma\chi\chi$. The CL upper limits are shown in Figure 7.4 as a function of m_H in the range $260 < m_H < 350 \text{ GeV}$. The limits are better at $m_H = 275 \text{ GeV}$ with $m_\chi = 60 \text{ GeV}$ compared to other masses largely due to statistical fluctuations in the signal MC selection efficiency.

7.8 Improvements and Future Work

The intermediate missing energy region is dominated by fake missing energy which is difficult to take into consideration. Following the two missing energy analyses in Run II the analysis group has dedicated significant efforts to understanding the intricacies that make up the missing energy variable.

Figure 7.5 shows an illustration of a signal process (left) resulting in real MET. In this case there is only a physics vertex with a real MET component. The right diagram shows a diphoton background process but includes a secondary pileup vertex. The physics vertex contains no real MET. The secondary vertex will normally have jets associated to it which may be rejected by the JVT algorithm or kept because they are outside the JVT region, but in either case they will contribute to the MET calculation. These jets tend to create a pileup vertex that is harder than the background physics vertex. A significant number of background events can be rejected by requiring the distance between the physics and pileup vertices to be very small.

7. A SEARCH FOR HIGGS BOSONS WITH MISSING ENERGY

Table 7.6: Summary of the dominant systematics on the yield of the SM Higgs boson with missing energy. All production modes of the SM Higgs boson are considered together. These values represent the systematic values for all four categories unless they are very different.

Source	Maximum Uncertainty (%)
Experimental	
Luminosity	2.9
Trigger efficiency	0.4
Vertex selection	3.6 (IntMET) 20 (HMLP and HMHP)
Photon identification efficiency	2.8
Photon energy scale	1.0
Photon energy resolution	2.0
Photon isolation efficiency	4.0
$S_{E_T^{\text{miss}}}$ reconstruction	1.0 (Rest) 20.0 (Others)
Pile-up reweighting	1.0
Theoretical	
QCD scale ggF p_T spectrum	9.0 - 20.0
Modelling of ggH E_T^{miss} spectrum	25.0
PDF	9.0
MPI	1.0 (IntMET) 50.0 (HMLP and HMHP)
$\text{BR}(h \rightarrow \gamma\gamma)$	4.9

7.8. IMPROVEMENTS AND FUTURE WORK

Table 7.7: Final event yields in the $m_{\gamma\gamma}$ distribution for 13.3 fb^{-1} of data, signal models, SM Higgs boson and non-resonant background. The signal samples shown correspond to a heavy scalar model with $m_H = 275 \text{ GeV}$ and $m_\chi = 50$ or 60 GeV . The errors on the signal yields consist of statistical and systematic uncertainties added in quadrature.

Category	IntMET	HMHP	HMLP	Rest
Data	1862	25	98	85551
Heavy scalar, $m_H = 275 \text{ GeV}$, $m_\chi = 50 \text{ GeV}$				
Yields	54.9 ± 1.2	5.41 ± 0.39	6.93 ± 0.41	102.1 ± 1.6
Selection Eff(%)	12.32 ± 0.26	1.21 ± 0.09	1.55 ± 0.09	22.89 ± 0.35
Heavy scalar, $m_H = 275 \text{ GeV}$, $m_\chi = 60 \text{ GeV}$				
Yields	57.8 ± 1.3	7.65 ± 0.45	6.01 ± 0.40	159.3 ± 2.1
Selection Eff(%)	9.52 ± 0.21	1.26 ± 0.07	0.99 ± 0.07	26.22 ± 0.34
Backgrounds				
SM Higgs boson	13.21 ± 0.13	1.26 ± 0.02	0.51 ± 0.02	527 ± 0.92
Non-resonant	1845 ± 48	24.9 ± 5.6	97 ± 11	85210 ± 330

7. A SEARCH FOR HIGGS BOSONS WITH MISSING ENERGY

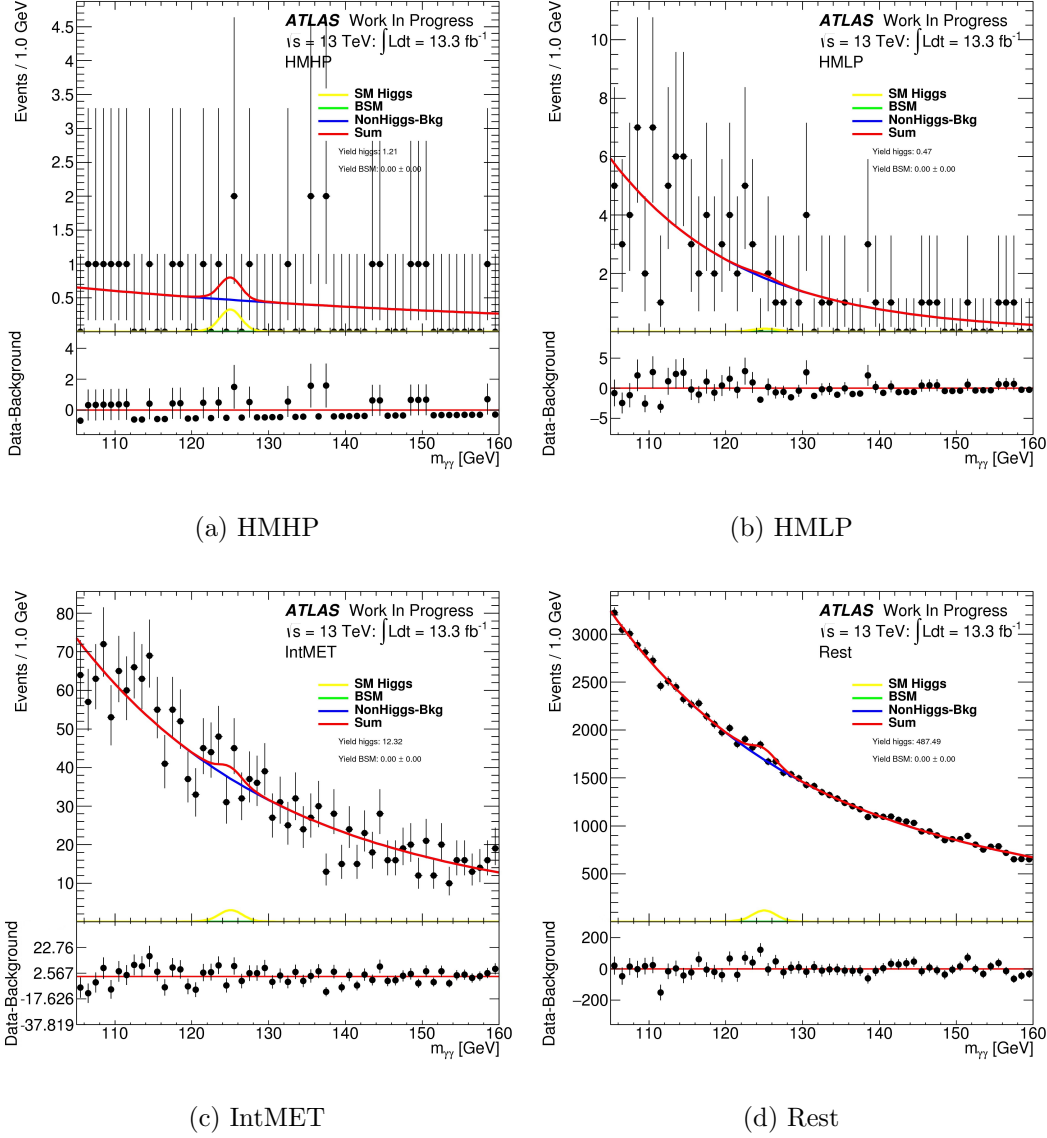


Figure 7.3: The final diphoton invariant mass distribution for data in the four categories. Each distribution is fitted simultaneously. The non-resonant background and the predicted SM Higgs boson contributions are also shown. The red curve shows the contribution from the SM Higgs boson, heavy scalar H and non-resonant backgrounds added together. The best fit value has zero BSM events.

7.8. IMPROVEMENTS AND FUTURE WORK

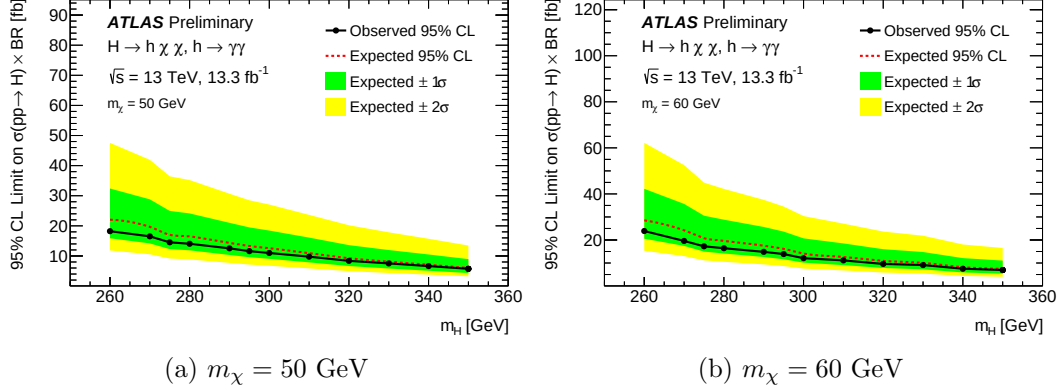


Figure 7.4: The expected and observed 95% CL exclusion upper limits on the cross section times branching ratio ($H \rightarrow h\chi\chi$, $h \rightarrow \gamma\gamma$) for the heavy scalar model with a mass of $m_H = 275$ GeV and $m_\chi = 50$ GeV shown in a) and $m_\chi = 60$ GeV shown in b). The limits are represented as a function of the heavy scalar mass from 260 to 350 GeV.

The method described above is detailed in the supporting documentation for the $\gamma\gamma + E_T^{\text{miss}}$ analysis in Ref. [176] and is called the “Same Vertex Method”. Preliminary calculations show the background can be reduced by as much as 90% while maintaining a considerable proportion of signal events. Using the heavy scalar sample and the diphoton background it was observed that the sensitivity can be improved by as much as 70%. The underlying principle behind this “Same Vertex Method” is attributed to the sum of the transverse momentum squared, Σp_T^2 , of all objects related to the vertex. This is illustrated in Figure 7.6 where it can be seen the background diphoton process has a softer Σp_T^2 for the physics vertex and a harder Σp_T^2 for the pileup vertex. The two signal processes shown remain flat for the physics vertex and drop off for the pileup vertex. The difference between Σp_T^2 for the two vertices is shown in Figure 7.6c. A large proportion of the background sample has a negative difference meaning the pileup Σp_T^2 is generally larger than the physics Σp_T^2 . The same vertex method is equivalent to the condition $\Sigma p_{T\text{Physics}}^2 - \Sigma p_{T\text{Pileup}}^2 \geq 0$. This method can be used for all MET related physics analyses provided that the leading contribution is the fake MET background process. It can also be used for other processes such as $ZZ \rightarrow \ell\ell\nu\nu$ or $Z + \text{jets}$. The method can validate data and check if any observed excess has real or fake missing energy. This powerful new feature unlocks the intermediate missing energy and improves the overall discovery sensitivity for MET related searches possibly providing a portal to dark matter.

7. A SEARCH FOR HIGGS BOSONS WITH MISSING ENERGY

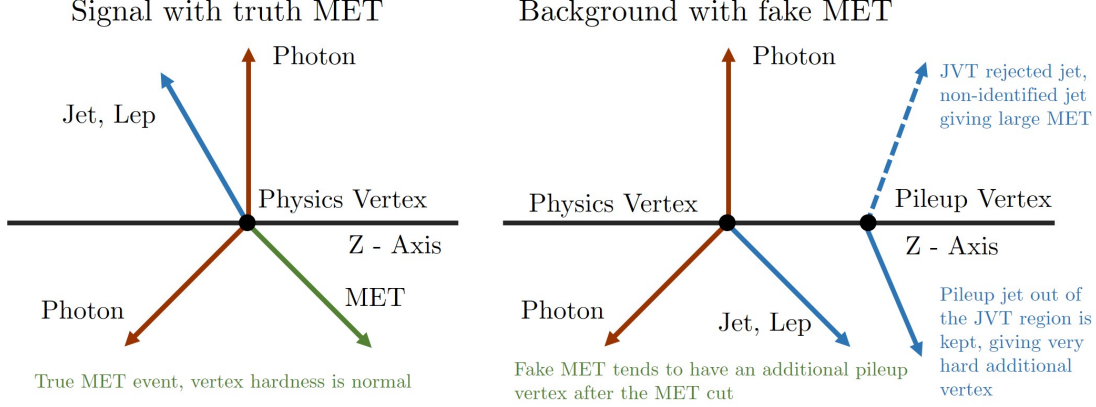


Figure 7.5: An illustration of real MET with a physics vertex (left) and fake missing energy caused by an additional pileup vertex. Figure adapted from Ref. [176].

Future work will involve integrating the method into the nominal analysis. An investigation into the usage of the Same Vertex Method in other channels will be undertaken. The first place to study will be the high mass diphoton region as it has already been shown to benefit from the fake MET in the diphoton backgrounds. In particular, the region $250 < m_{\gamma\gamma} < 295$ GeV around the predicted mass of the Madala boson of 270 GeV would be a good place to start.

7.9 Conclusions

Searches for new physics in diphoton events with missing energy are performed using 13.3 fb^{-1} of proton-proton collision data collected at 13 TeV using the ATLAS detector at CERN. No significant excess over the background expectation is observed. A 95% CL upper limit of 18.2 fb is set on the cross section times branching ratio for a DM particle with mass $m_\chi = 50$ GeV and 23.9 fb for a DM mass of $m_\chi = 60$ GeV. Due to the larger dataset and improvements in categorisation these limits are a betterment from the previous study by almost a factor of two. These results set limits on a large branching ratio of $S \rightarrow \chi\chi$ which is consistent with the excess of leptons discussed in Ref. [47] and the recent excesses observed by both ATLAS [177] and CMS [178] in the production of a Higgs boson in association with top quarks in the multilepton final state.

A new method has been developed to reduce the fake MET contribution by up to 90%. This new method, called the Same Vertex Method, opens the intermediate missing energy region and enhances the overall discovery sensitivity for MET related searches and can be used in different final state analyses. The Same Vertex Method may just be the sought after technique to peer into the dark matter sector.

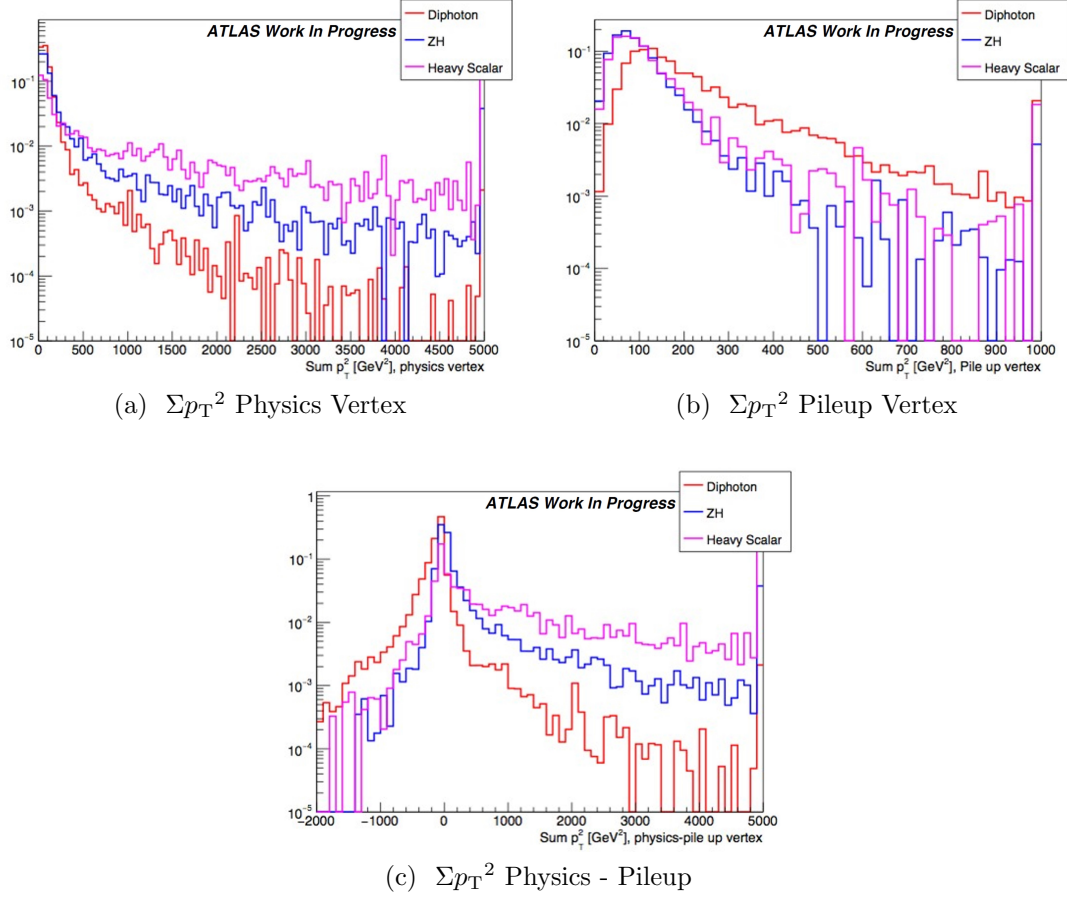


Figure 7.6: The principle behind the Same Vertex Method is directly related to the evolution of the sum of the transverse momentum squared for the physics and pileup vertices. Three samples are shown: a background $\gamma\gamma$ process (red), a ZH signal sample (blue), and a heavy scalar (magenta). Figure 7.6a shows the distribution of the Σp_T^2 for the physics vertex where the diphoton background drops off faster than the signal samples. Figure 7.6b shows the Σp_T^2 for the pileup vertex with the diphoton background dropping off slower than the signal samples. The difference of sum p_T^2 between the two vertices is shown in Figure 7.6c where it is noticed that a large proportion of the background has a negative value which indicates the pileup vertex tends to be harder than the physics vertex. This means the difference in the Σp_T^2 for the two vertices can be used as a discriminating variable [176].

A Search for Resonances in High Mass Diphoton Events

In December 2015, ATLAS measured an excess of events at 750 GeV in the search for high mass diphoton resonances [64]. This chapter will outline the 750 GeV excess and investigate the jet properties using 3.2 fb^{-1} of data. An updated measurement, using 2015 and 2016 data, is also provided which shows that the 750 GeV excess was a statistical fluctuation [179]. The Madala boson can decay into two photons and would be measured in the region $250 < m_{\gamma\gamma} < 295 \text{ GeV}$, providing another reason to study this channel.

8. HIGH MASS DIPHOTON ANALYSIS

8.1 Introduction

In late 2015 the high mass diphoton search reported an excess at $m_X = 750$ GeV with a significance of 3.9σ for a large width approximation [64]. Taking the look-elsewhere effect into consideration the excess is reduced to 2.3σ . This generated a lot of attention as it was the first hint of physics beyond the SM. Following the announcement, over 250 theoretical papers were published between the 15th December 2015 and 12th April 2016 [180]. The jet differential distribution of the excess is an interesting property to investigate as it can hint at what production mechanism is driving the physical process (if it is indeed real). This chapter will briefly discuss the analysis and provide a set of differential measurements on jets, something that was not discussed in Ref. [64]. In addition, the Madala boson may decay into two photons which would fall within the mass range of this study and will, therefore, also be studied.

8.2 Data and Simulated Samples

The high mass $\gamma\gamma$ analysis uses proton-proton collision data recorded in 2015 and the first half of 2016 at $\sqrt{s} = 13$ TeV. The dataset corresponds to a total integrated luminosity of 3.2 fb^{-1} for the first analysis performed in December 2015 and 12.2 fb^{-1} for the updated analysis in September 2016. The differential studies were performed just before the final data collection and only uses 11.3 fb^{-1} for 2016 data but the conclusions are the same.

Simulated high mass diphoton events are used to determine the shapes of the diphoton mass spectra for signal processes and to study the background parametrization. MC samples are passed through full detector simulation and undergo similar pileup reweighting as is done in Section 5.4. The signal samples are assumed to be SM Higgs-like and are generated at $\sqrt{s} = 13$ TeV via ggh , VBF, Wh , Zh and $t\bar{t}h$ using PYTHIA8 and in some cases in combination with POWHEG. A list of the signal samples are provided in Table 8.1. The width of the boson is set to 4 MeV for all samples and is referred as the Narrow Width Approximation (NWA).

Additionally, large natural width samples for gluon fusion are produced¹ using the DSCB as a model, pictured in Figure 6.9 in Section 6.7. Large width samples are produced in a similar range as the NWA from 200 to 2000 GeV for a range of widths from $\alpha = \Gamma/m_X$ from 1% to 10%. Here, m_X represents the mass of the resonance. Γ is the natural width.

¹This was driven by the observation of a wide structured excess and the width could be comparable to the experimental diphoton mass resolution.

8.3. OBJECT AND EVENT SELECTION

Table 8.1: MC samples of the different production modes with various Higgs masses for the high mass $\gamma\gamma$ study.

Process	Generator	Mass [GeV]	$N_{\text{Events}} (\times 10^3)$
ggh	POWHEG + PYTHIA8	150,200,250,300,350	30
		400,450,500,600,700	
		800	100
VBF	POWHEG + PYTHIA8	900,1000,1500,2000	30
		200,300,400,500,600	30
Wh	PYTHIA8	800,1000,1500,2000	
		200,300,400,500,600	30
Zh	PYTHIA8	800,1000,1500,2000	
		200,300,400,500,600	30
$t\bar{t}h$	PYTHIA8	800,1000,1500,2000	
		200,300,400,500,600	30

The background samples are listed in Table 5.6 which range in mass from $m_{\gamma\gamma} = 160$ to 5000 GeV.

8.3 Object and Event Selection

The object selection follows closely with that of the nominal diphoton definitions in Section 5.2. The only differences arise from the relative p_T cuts on the photons, the isolation and the mass range. This is largely due to the higher energies of the diphoton pair. Photons are required to pass the tight identification criteria and the leading and subleading photons are required to satisfy $p_T^{\gamma_1}/m_{\gamma\gamma} > 0.4$ and $p_T^{\gamma_2}/m_{\gamma\gamma} > 0.3$. These relative p_T cuts are optimised by maximising the ratio of the expected significance¹ using a tighter set of cuts compared to the photon trigger. The optimised relative p_T cuts improve the significance by over 10% for low resonance masses (200 GeV) and more than 20% for masses larger than 600 GeV.

¹The significance is calculated as the ratio between the signal efficiency and the square root of the background efficiency. A ratio of the significances is used which is independent of the signal yield and hence model independent.

8. HIGH MASS DIPHOTON ANALYSIS

The diphoton mass is required to be greater than 150 GeV.

The photon isolation is optimised in a similar way. The different isolation requirements largely affects the $\gamma\gamma$ and jj reducible components of the background. The requirements are a tighter selection on the calorimetric isolation with $E_T^{\text{iso}} < 0.022 \times E_T^\gamma + 2.45 \text{ GeV}$ and a track isolation with $p_T^{\text{iso}} < 0.05 \times E_T^\gamma$. The new isolation criteria has an improvement of over 20% for masses over 600 GeV. The efficiency is more than 80% for gluon fusion Higgs boson processes with masses of 200 GeV and over 90% for masses over 800 GeV. The total signal selection efficiency for high mass diphoton events ranges from 30% to 40% for masses from 200 to 600 GeV. This value varies with approximately $\pm 5\%$ based on the production mechanism which is largely driven by the jet activity and different kinematic properties.

If no signal is observed, the analysis sets limits on the fiducial production cross section times the branching ratio to two photons. This is set as a function of the resonance mass, m_X . In order to compute the fiducial cross section the measured events must be corrected for reconstruction, identification and selection efficiencies. This is done through correction factors, C_X , and is calculated as the ratio between the reconstructed event yields and particle level simulated samples.

8.4 Modelling and Statistical Analysis

The high mass $m_{\gamma\gamma}$ distributions are fitted with a signal-plus-background model to determine the signal and background yields. The signal is modelled using a DSCB, shown in Figure 6.9, for ggF resonance masses ranging from 200 to 2000 GeV. The parameters of the DSCB are then parametrised, using polynomials, as a function of the generated mass m_X . The bias from modelling to ggF and not a different production mechanism is found to be negligible. The large width approximation is parametrised as a function of α from 1% to 10%. In 2015 the largest significance of the observed excess occurs as $\alpha = 6\%$ which corresponds to a natural width of approximately $\Gamma = 45 \text{ GeV}$. The signal parametrisation, for a width of $\alpha = 6\%$, can be seen in Table 8.2.

The background is modelled using a data-driven approach. The model is a smooth function form which describes the entire $m_{\gamma\gamma}$ spectrum. A family of functions, used in a search for new physics in the multi-jet final state [181] are chosen. The form is:

$$f_{(k)}(x; b, \{a_k\}) = (1 - x^{1/3})^b x^{\sum_{j=0}^k a_j (\log x)^j}, \quad (8.1)$$

where $x = \frac{m_{\gamma\gamma}}{\sqrt{s}}$. The analytical function was determined using the methods detailed in Ref. [44]. The bias on the choice of function is measured by studying the spurious signal which is required to be smaller than one fifth of the statistical uncertainty on the fitted signal yield. The functional form is tested for $k = 0, 1, 2$ and satisfies the

8.4. MODELLING AND STATISTICAL ANALYSIS

Table 8.2: Parametrisation of the DSCB parameters describing the large width signal shape, as a function of $m_{nX} = \frac{m_X - 100}{100}$. The result are extracted by fitting multiple ggF large width samples with $\alpha = 6\%$.

Parameter	Parametrisation	a	b	c
Δm_X	$a + bm_{nX} + cm_{nX}^2$	-0.00637	-0.222	-0.02
σ_{CB}	$a + bm_{nX}$	3.64	2.73	
α_{Low}	$a + b/(m_{nX} + c)$	-0.022	30.6	24.8
n_{Low}	a	2.5		
α_{High}	$a + b/(m_{nX} + c)$	1.26	-0.0141	-0.803
n_{High}	a	2.1		

criterion for resonance masses ranging from 200 GeV to 3 TeV. It was shown that the simplest form, corresponding to $k = 0$, is suitable to describe the background shape. This is written as:

$$f_0(x; b, a) = (1 - x^{1/3})^b x^a. \quad (8.2)$$

where a and b are free parameters that are allowed to float in the fitting procedure.

The signal and background yields are obtained from an unbinned maximum likelihood fit of the $m_{\gamma\gamma}$ spectrum. A local significance, p -value, for the background only hypothesis is calculated as before in previous chapters using the asymptotic approximation [161]. An uncapped p -value is used such that the $p_0 = 0.5$ corresponds to no signal, $p_0 < 0.5$ to a positive signal, and $p_0 > 0.5$ to a negative signal. A global significance is calculated by calculating the look-elsewhere-effect (LEE) using methods described in Ref. [182]. The local p -value is measured by scanning the $q_0(m_X, \alpha)$ test statistic [161], which is dependant on the resonant mass and natural width:

$$q_0(m_X, \alpha) = -2 \log \frac{L(0, m_X, \alpha, \hat{\nu})}{L(\hat{\sigma}, m_X, \alpha, \hat{\nu})}, \quad (8.3)$$

where the values of the parameters marked with the hat superscript are chosen to maximize the likelihood and the parameters with the double hat are chosen to maximise the likelihood with the cross-section σ fixed to 0.

Systematic uncertainties are accounted for by nuisance parameters in the likelihood fits of the background-only and signal-plus-background fits. Systematic uncertainties are not included in the differential measurements and will be briefly discussed. The effects on the fitted signal yield from pileup modelling, photon

8. HIGH MASS DIPHOTON ANALYSIS

Table 8.3: Summary of the systematic uncertainties in the signal-plus-background likelihood fit when considering the narrow width signal model. Adapted from Ref. [64].

Source	Uncertainty
Background Modelling	
Spurious signal	$2 - 10^{-3}$ events, mass-dependent
Background fit	$\leq 50\% - \leq 20\%$ of the total signal yield uncertainty, mass- and signal-dependent
Signal Modelling	
Photon energy resolution	$^{+[55-110]\%}_{-[20-40]\%}$, mass-dependent
Signal Yield	
Luminosity	$\pm 5\%$
Trigger	$\pm 0.63\%$
C_X Factors	
Photon identification	$\pm(3-2)\%$, mass-dependent
Photon isolation	$\pm(4.1-1)\%$, mass-dependent
Production process	$\pm 3.1\%$

energy scale uncertainties, photon identification and isolation uncertainties, and from the modelling with different signal production mechanisms were all found to be negligible. The statistical uncertainty on the background components of the fits has a mass dependence on the fitted signal yields. It is maximum when there is no signal with a value of about 50% of the total uncertainty for a probed resonance mass of 200 GeV and reduces to 20% for a mass of 2 TeV. Object systematic uncertainties affect the correction factors, C_X , by shifting events in and out the fiducial volumes. The most important uncertainties are summarised in Table 8.3.

8.5 Results with 2015 Data

Figure 8.1 shows the diphoton mass spectrum observed in data. An unbinned background-only fit is superimposed. The p -value for the background-only fit is shown in Figure 8.2a. The largest deviation is for a mass of around 750 GeV with a local significance of 3.6σ and a global significance of 2.0σ after taking into account

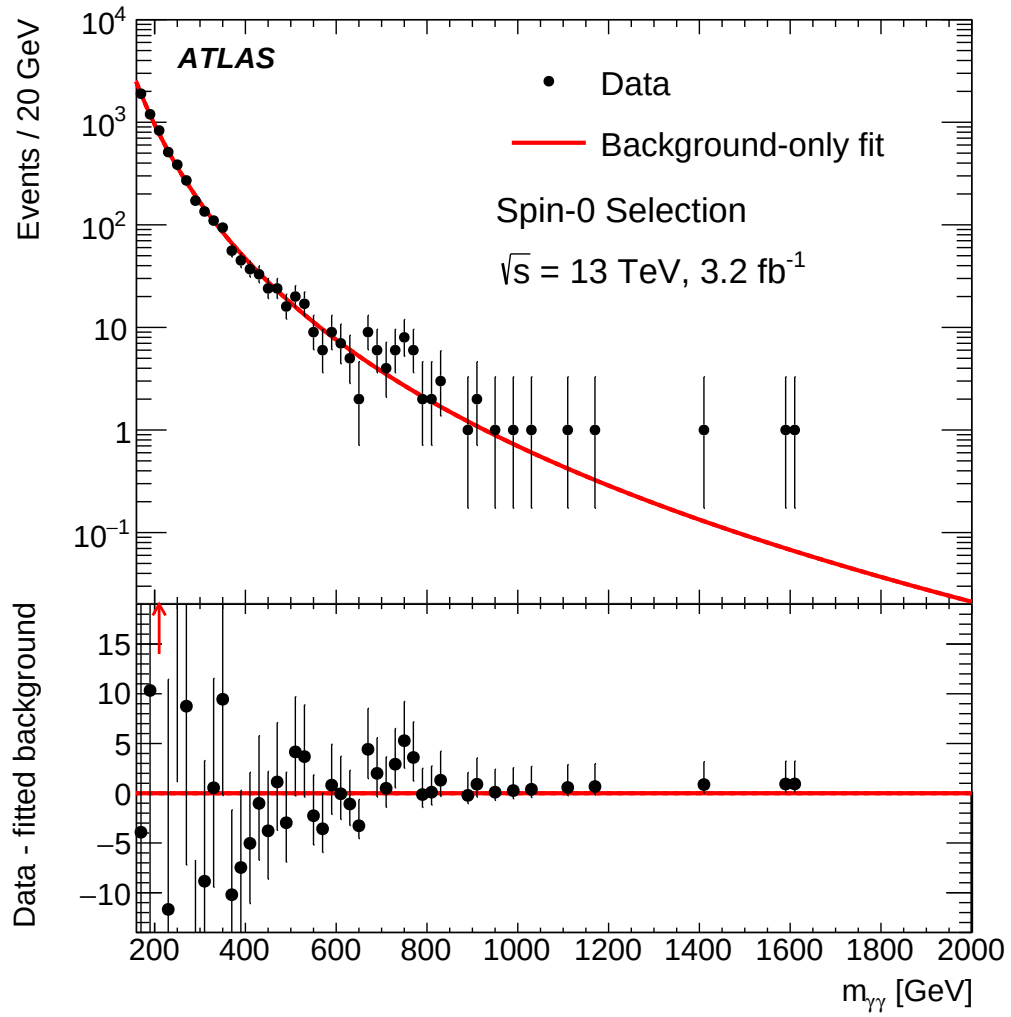


Figure 8.1: The background-only fit to the diphoton invariant mass distribution for 2015 data [64].

8. HIGH MASS DIPHOTON ANALYSIS

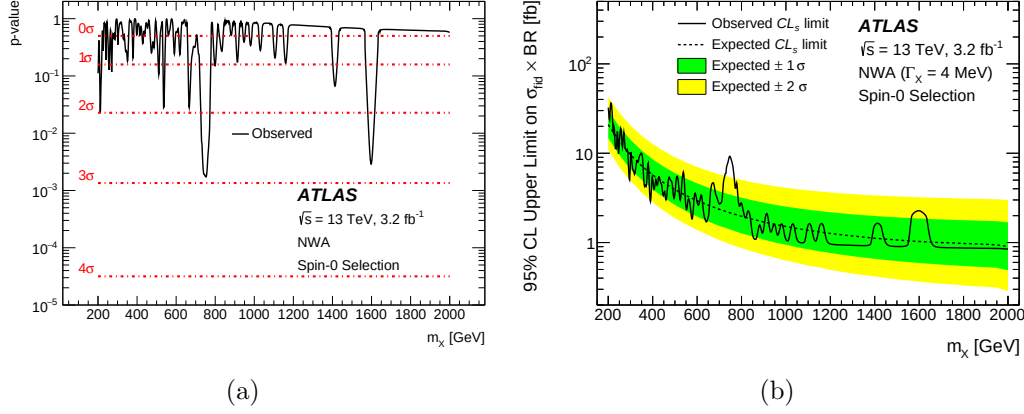


Figure 8.2: a) p -value for the background-only hypothesis as a function of the mass m_X for the NWA signal and b) the expected and observed upper limits, on the fiducial volume times branching ratio to diphotons, expressed at 95% CL, as a function of the assumed value of the narrow-width scalar resonance mass for 2015 data [64].

the LEE. Figure 8.2b shows the 95% CL expected and observed upper limits on the fiducial cross section times branching ratio into diphotons for a narrow width approximation signal. The sudden rise and fall of the limit at the boundaries of the 750 GeV region are a result of the fits pulling the nuisance parameter associated to the photon energy resolution. The large pull indicates that the excess is larger than the experimental $m_{\gamma\gamma}$ invariant mass resolution. This is largely what lead to the large width approximation study. The largest deviation for the LWA occurs at the same mass of 750 GeV with $\alpha \simeq 6\%$ which is a natural width of approximately $\Gamma = 45 \text{ GeV}$. The local significance corresponds to 3.9σ and reduces to 2.3σ after taking the LEE into consideration. Looking at the local significance in the window around the Madala boson mass from $250 < m_{\gamma\gamma} < 295 \text{ GeV}$ there are smaller peaks at $m_{\gamma\gamma} = 255$ and 269 GeV with a significance of around 1.2σ .

8.6 Jet Differential Distributions with 2015 Data

The jet content in the observed excess provides an insight into the possible production mechanism of a new particle at $m_X = 750 \text{ GeV}$. Before any jet differential measurements are made, the sidebands of the data are compared to a background MC sample to better understand the region around the 750 GeV excess. The sidebands (SB) are defined as the regions 600 to 700 GeV and greater than 800 GeV. Events are counted in the SB for different exclusive jet selections $N_j = 0$, $N_j = 1$

8.6. JET DIFFERENTIAL DISTRIBUTIONS WITH 2015 DATA

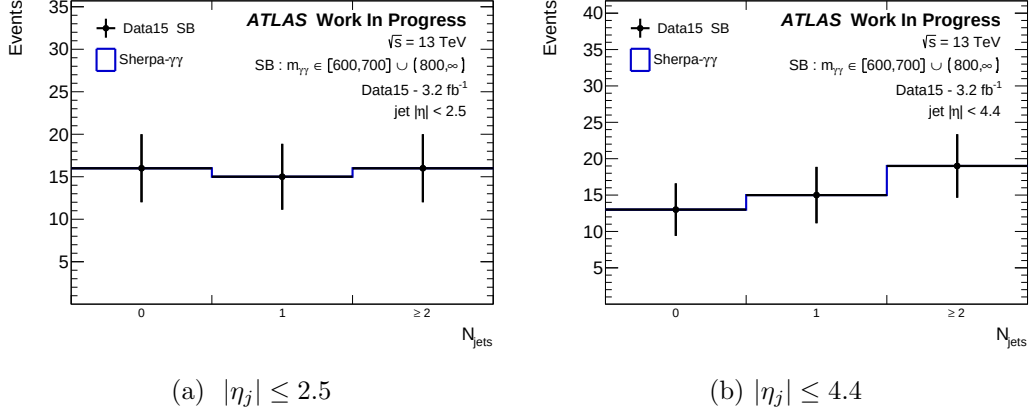


Figure 8.3: A jet multiplicity comparison between the 2015 data sidebands and SHERPA diphoton background MC. The bins are exactly zero jets, exactly one jet and at least two jets for a) central jets and b) all jets. There is very little discrepancy.

and $N_j \geq 2$. Figure 8.3 shows the comparison between the data SB and the SHERPA $\gamma\gamma$ MC, where the MC is normalised to the data SB. This is performed for jets in the central region, defined by $|\eta_j| \leq 2.5$, and for all jets, with $|\eta_j| \leq 4.4$. There is very good agreement in both cases.

In order to make a differential measurement the spectrum is required to be fitted with a signal-plus-background function which enables the signal yield to be extracted from the peak. This yield and its error are used to make a differential measurement for each jet category. To simplify the study no systematics have been included into the fitting procedure. The functional forms used for the signal and background are described in Section 8.4. The parameters for the signal shape are chosen for a resonance mass of $m_X = 750 \text{ GeV}$ and a width defined by $\alpha = 6\%$. The signal parameters are fixed for each category fit meaning only the signal yield can vary. The shapes of the signal and background are used to produce PDFs (PDF_{sig} and PDF_{bkg}) which can be combined into a signal-plus-background model. The combined model is defined as:

$$\text{Model}(S + B) = N_{\text{sig}} \times \text{PDF}_{\text{sig}} + N_{\text{bkg}} \times \text{PDF}_{\text{bkg}} \quad (8.4)$$

where N_{sig} and N_{bkg} extend the PDF models and provide the extracted yield for the fit. A combined fit to the nominal high mass diphoton selection can be seen in Figure 8.4. The extracted signal yield is 19.0 ± 7.1 . The dashed green line shows the signal model and the dashed red line shows the background model. The combined model is shown in blue. The parameters a and b are the floating parameters in the background function.

8. HIGH MASS DIPHOTON ANALYSIS

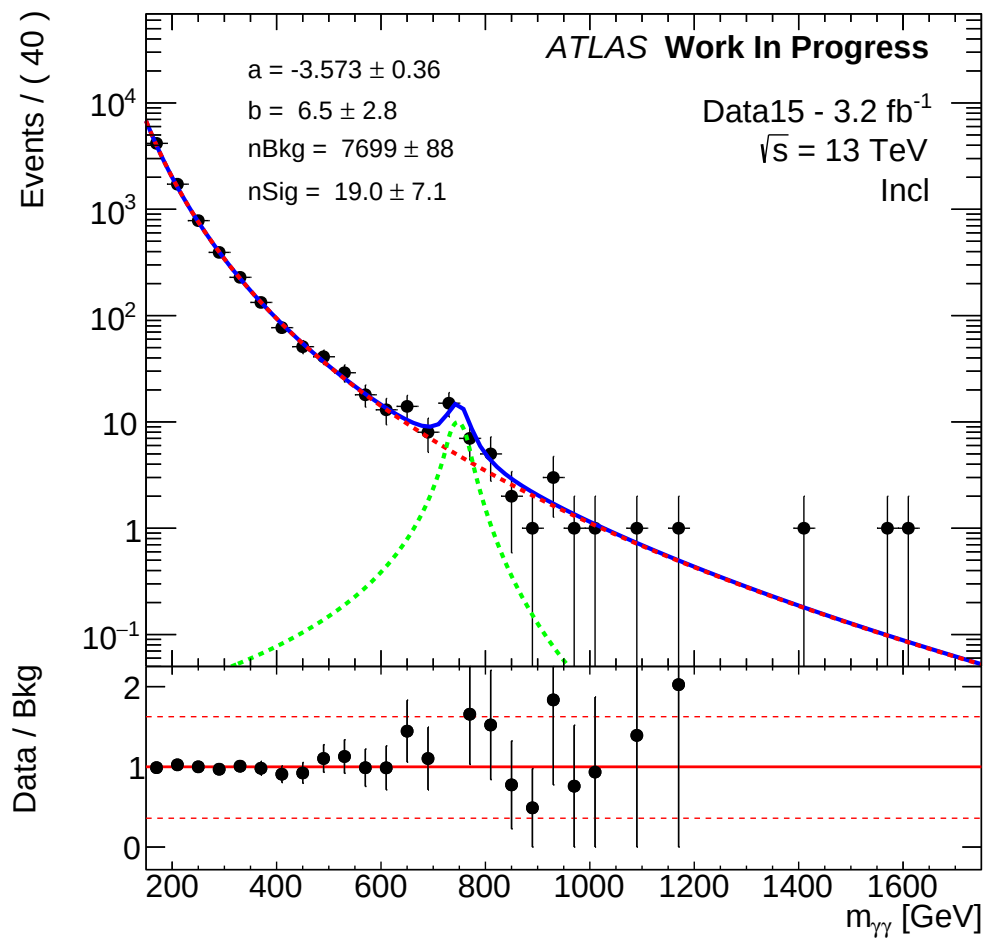


Figure 8.4: The inclusive fit to the diphoton invariant mass spectrum of 2015 data with a signal-plus-background model. The values a and b are the free floating parameters in the background function and the yields for the background and signal are given.

8.6. JET DIFFERENTIAL DISTRIBUTIONS WITH 2015 DATA

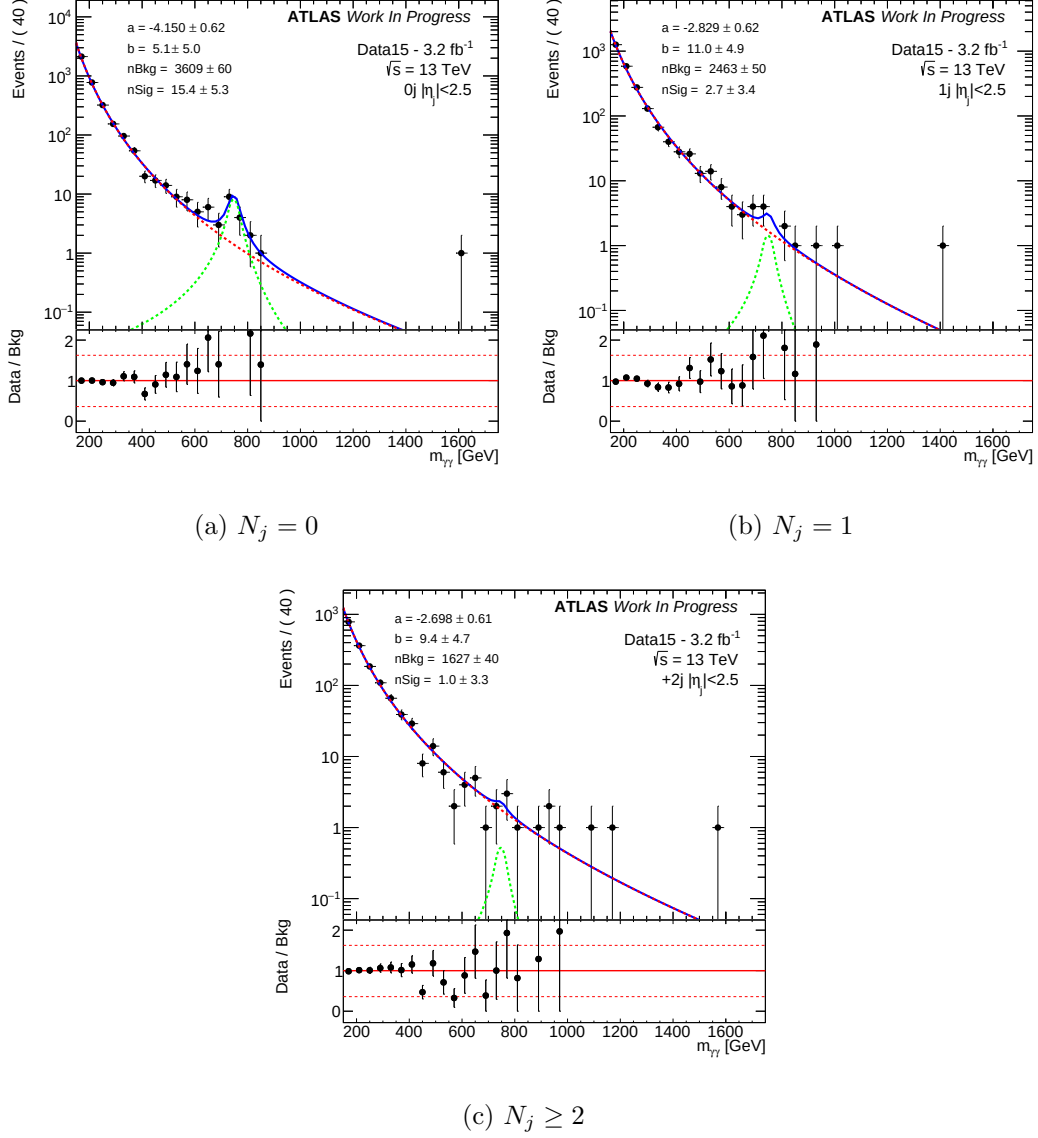


Figure 8.5: Fits on the diphoton invariant mass for various cuts on jet multiplicity in 2015 data. The extracted signal yield and statistical error are used to produce the differential plots. Three fits are performed corresponding to $N_j = 0$, $N_j = 1$ and $N_j \geq 2$ which are repeated for the two jet regions. Individual fits on all jets with $|\eta_j| \leq 4.4$ can be found in Figure D.1.

8. HIGH MASS DIPHOTON ANALYSIS

The dataset is separated into the exclusive jet categories and fitted with the signal-plus-background model described in Equation (8.4). The fits to three jet categories, for central jets, can be seen in Figure 8.5. The largest yield occurs for zero jets with a value of 15.4 ± 5.3 events. This is repeated for all jets, with $|\eta_j| \leq 4.4$, which can be seen in Figure D.1. The production of a heavy object, such as one at $m_X = 750$ GeV, would usually radiate jets making this result rather surprising. It must be noted that although the fits show a well structured excess there is still a high statistical error on the yield which is approximately 37% and is further enhanced when comparing different categories.

To better understand the jet properties, the yields from the individual category fits are used to create a differential distribution. The differential distributions, shown in Figure 8.6, are compared to a gluon produced heavy scalar at $m_X = 750$ GeV and a SHERPA $\gamma\gamma$ background sample. The signal and background are normalised to the inclusive yield of the data. It is observed that the differential distribution is not adequately described by the MC models, which is more prominent when looking at all jets with $|\eta_j| \leq 4.4$ in Figure 8.6b. A comparison to scalar produced via VBF with $m_X = 800$ GeV appears have better agreement for central jets, shown in Figure 8.7a, but when including all jets, Figure 8.7b, we see a complete disagreement. This is expected since a scalar produced via VBF generally has forward jets as a result of the forward quarks in the hard scattering process, as can be seen in Figure 1.5b. In these figures, an older signal shape and a larger signal region is used but, both of which, have a small effect on the final results. Even processes such as photon-photon fusion will predict some jet activity due to inelastic scattering and cannot fully explain the differential shape [183, 184]. Although photon-photon fusion still doesn't fully describe the shape it does predict a lot more events with little jet activity. No concrete conclusions can be made from the differential distributions due to the limited statistics in the 2015 data but it is revisited with a larger dataset collected in 2016.

8.7 Updated Results With 2016 Data

The 2016 analysis, of the high mass diphoton channel, follows closely to the previous year. The samples used in 2015 are reprocessed using the same reconstruction software used for the 2016 data. There are small improvements in the object calibration and reconstruction. Figure 8.8 shows the diphoton invariant mass distribution with the background-only fit for 12.2 fb^{-1} of 2016 data. No significant deviation from the background-only hypothesis is observed for the corresponding 2015 excess at 750 GeV.

The 2015 data was reprocessed using the improved object recommendations which causes changes to the excess from events migrating in and out the signal

8.7. UPDATED RESULTS WITH 2016 DATA

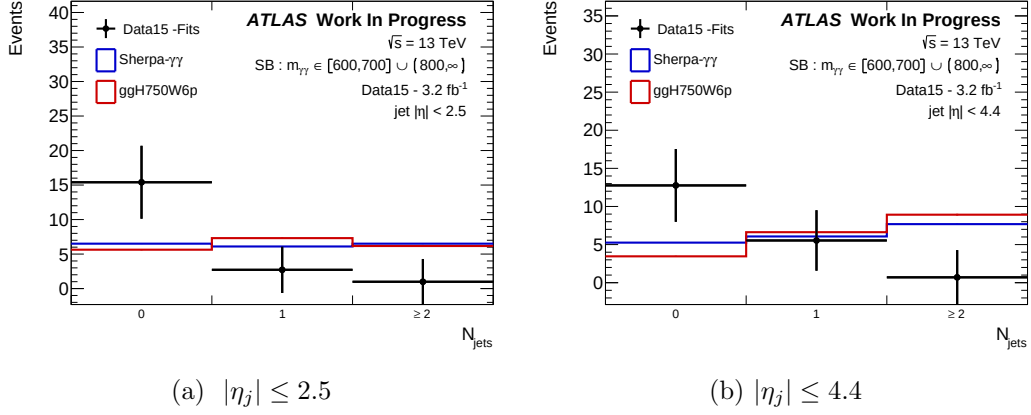


Figure 8.6: The extracted signal yields for various jet requirements. The SHERPA $\gamma\gamma$ MC background and a gluon fusion signal with resonance mass of $m_X = 750$ GeV and $\alpha = 6\%$ are normalised to the inclusive extracted signal yield shown in Figure 8.4. Two jet regions are used a) central jets with $|\eta_j| \leq 2.5$ and all jets with $|\eta_j| \leq 4.4$

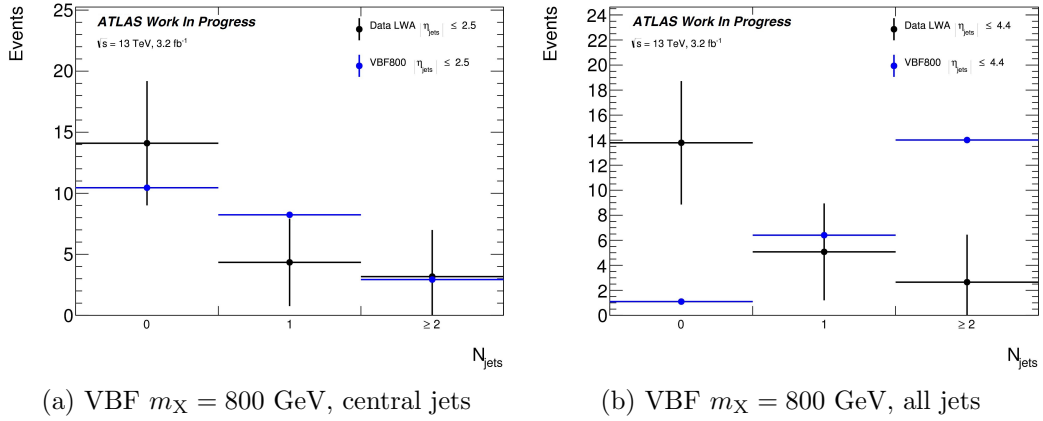


Figure 8.7: The extracted signal yields for different jet requirements on 2015 data compared to a VBF signal process for a) central jets and b) all jets. In these plots an older signal shape was used resulting in slightly smaller yields and the signal region definition is 40 GeV wider which has a small effect on the sideband yields. However, the conclusions that can be drawn are unchanged.

8. HIGH MASS DIPHOTON ANALYSIS

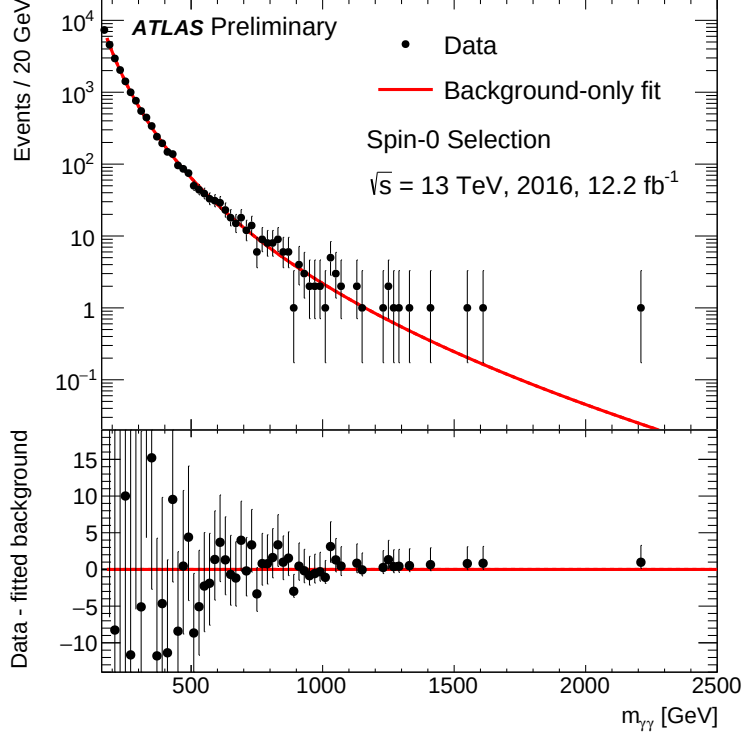


Figure 8.8: The background-only fit to the diphoton invariant mass distribution for 2016 data [179].

region. This has the effect of reducing the excess from 3.9σ in Ref. Section 8.5 to 3.4σ . The location also shifts from $m_X = 750$ GeV to 730 GeV with a wider relative width of $\alpha = 8\%$. After combining the 2015 and 2016 datasets, the local significance in the 700 to 800 GeV region decreases to 2.3σ which equates to a global significance of less than one standard deviation. The p -value as a function of the resonance mass for the NWA is shown in Figure 8.9a and the associated limit on the fiducial cross section times branching ratio is shown in Figure 8.9b. Although no signal is observed in the inclusive distribution at 750 GeV, the jet differential distributions are still checked. Figure 8.8 shows the comparison of the 2016 data sidebands to the SHERPA $m_{\gamma\gamma}$ MC and we observe good agreement as before in Figure 8.3.

The dataset is separated into the exclusive jet categories and each spectrum is fitted with the signal-plus-background model described in Equation (8.4). The fits to three jet categories for central jets can be seen in Figure 8.11. There is no signal near 750 GeV in any category. The small signal in the $N_j \geq 2$ is just a fluctuation of the fit and is evident by the error of approximately 300%. Fits to the jet categories for all jets, with $|\eta_j| \leq 4.4$, can be seen in Figure D.2, which

8.7. UPDATED RESULTS WITH 2016 DATA

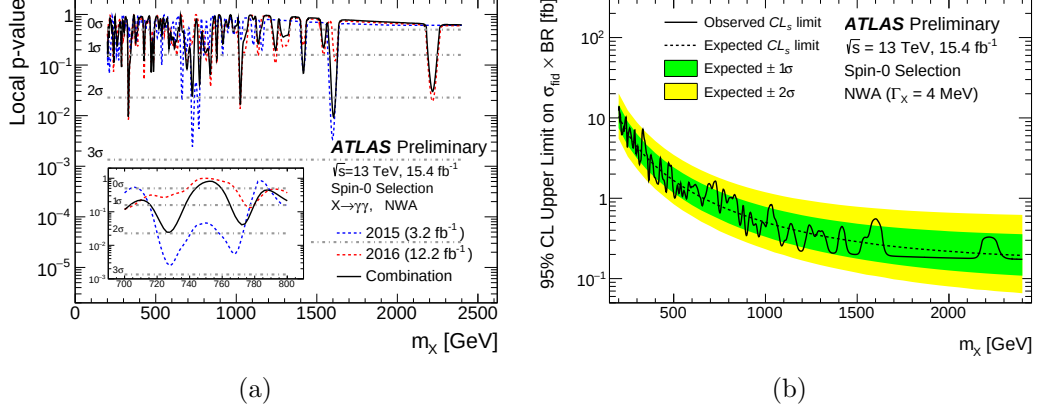


Figure 8.9: a) The p -value for the background-only hypothesis as a function of the mass m_X for the NWA signal and b) the expected and observed upper limits, on the fiducial volume times branching ratio to diphotons, expressed at 95% CL, as a function of the assumed value of the narrow-width scalar resonance mass for 2016 data [179].

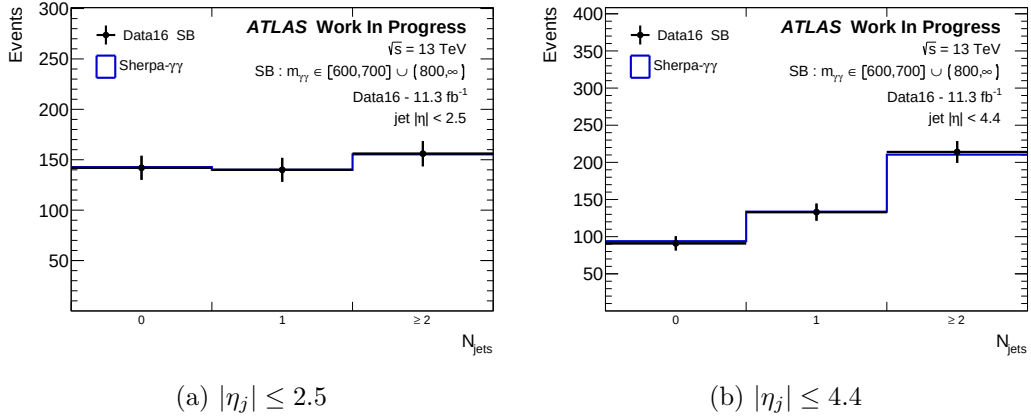


Figure 8.10: A jet multiplicity comparison between the 2016 data sidebands and SHERPA diphoton background MC. The bins are exactly zero jets, exactly one jet and at least two jets for a) central jets and b) all jets. There is very little discrepancy which confirms what is seen in the 2015 data.

8. HIGH MASS DIPHOTON ANALYSIS

also show no presence of a signal. Looking at the local significance in the window around the Madala boson mass from $250 < m_{\gamma\gamma} < 295$ GeV there is one smaller peak at $m_{\gamma\gamma} = 289$ GeV with a significance of about 1.4σ .

8.8 Conclusions

A search into high mass diphoton resonances is presented. In 2015 a deviation from the background-only hypothesis was observed for a diphoton mass of $m_X = 750$ GeV with a global significance of two standard deviations. A jet differential measurement was performed to better understand the properties of the 750 GeV excess. It was observed that a majority of the excess consisted of zero jet events which, with limited statistics, appeared to be inconsistent with a scalar produced by gluon-gluon fusion and other production modes such as vector boson fusion or photon-photon fusion. In the region around the Madala boson mass, the most significant deviation occurs at $m_{\gamma\gamma} = 269$ GeV with just over 1.0σ .

An updated measurement, using 15.4 fb^{-1} of proton-proton collision data, is made with a combination of 2015 and 2016 data. The data is consistent with the background-only hypothesis and no excess is observed in the 700 to 800 GeV region, for both the inclusive distribution or any jet category. The jet differential distribution, observed for the 750 GeV excess, in 2015 is attributed to a background fluctuation which falls within the large statistical errors observed on the extracted yields. The largest global significance observed in the combined dataset is less than one standard deviation.

The most significant deviation around the Madala boson mass occurs at $m_{\gamma\gamma} = 289$ GeV with a local significance of 1.4σ . The expected and observed limit on the cross section times branching ratio, for the Madala boson at $m_H = 270$ GeV, is approximately 5.5 fb .

8.8. CONCLUSIONS

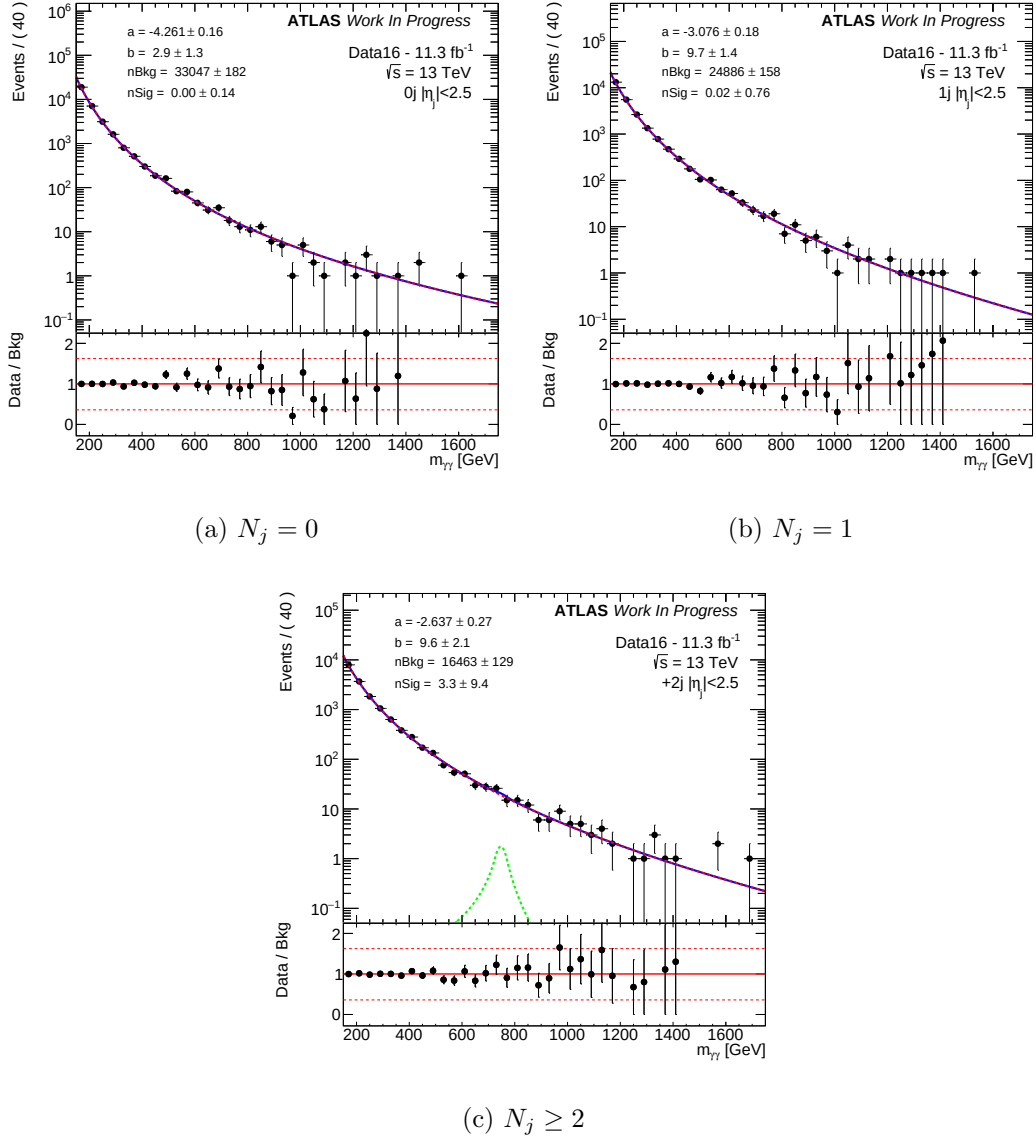


Figure 8.11: Fits on the diphoton invariant mass for various cuts on jet multiplicity in 2016 data. Three fits are performed corresponding to $N_j = 0$, $N_j = 1$ and $N_j \geq 2$ which are repeated for the two jet regions. Individual fits on all jets with $|\eta_j| \leq 4.4$ can be found in Figure D.2.

Concluding Statements

This thesis is composed in two parts consisting of work related to the ATLAS detector and searches for new physics using data collected in 2015 and 2016.

A high voltage (HV) board was designed and implemented into a portable test-bench used on the Tile Calorimeter front-end electronics. Four additional MobiDICK units, using the HV board, were manufactured to aid the validation efforts of the front-end electronics. This work contributed to the consolidation process that ensured the successful operation of the Tile Calorimeter during the 2015 and 2016 data taking periods, making the analyses presented in this work possible. During the first long shutdown, additional efforts were directed towards the Phase-II upgrade of the Tile Calorimeter front-end electronics, scheduled for completion in 2024. The proposed front-end upgrade includes the relocation of key components off the detector and into numerous ATCA chassis. A new software tool, called the fwATCA framework, was designed to integrate the ATCA chassis into the existing Detector Control System (DCS). The fwATCA framework became an ATLAS wide common framework used by numerous subsystems and forms the foundation for any ATCA related upgrades and its integration into the DCS.

Three different searches for new phenomena, linked by the underlying phenomenology of the Madala hypothesis, are presented. The di-Higgs search is performed with a limited dataset and, although no excess is observed, does not exclude the excess seen in Run I. The di-Higgs results are compatible with the $H \rightarrow hh$ and $H \rightarrow Sh$ processes discussed in Ref. [47] and require more data to make any conclusive statements. At the time of submitting this thesis, new results with

CONCLUDING STATEMENTS

the combined 2015 and 2016 datasets, which totals over ten times more data, is being prepared and will offer valuable insights into the model. The limit set on $\gamma\gamma + E_{\text{T}}^{\text{miss}}$ indicate the branching ratio $S \rightarrow \chi\chi$ is not 100%, which is consistent with a large branching ratio of S to charged particles. This is compatible with the excesses observed in the $t\bar{t}h$ searches with leptonic final states for both ATLAS and CMS in Run I, shown in Table 1.1, and Run II [177, 178]. A new technique, called the Same Vertex Method, has been developed to reduce background events with fake missing energy. This method improves the discovery significance considerably and opens the intermediate missing energy region, which may open the portal for dark matter searches. A search into high mass diphoton events was performed following the observation of an excess of events at 750 GeV in 2015 but with the increased dataset collected in 2016, it was shown to be a background fluctuation. No excess was observed with the di-diphoton decay around the Madala boson mass of 270 GeV, and a limit of 5.5 fb is set on the cross section times branching ratio.

High Voltage Board Design Information

This appendix serves to provide engineering information such as schematic designs and component properties. The design of the HV board can be entirely replicated with this information combined with the layouts seen in Chapter 3. The Bill Of Material (BOM), shown in Tables A.1 and A.2 show each component with an unique reference designator which can be mapped to the schematics. For interest, the relative size of the components can be seen in Figure A.1. Each component also has a part number from a local supplier, either Mantech or RS Online, in South Africa. The schematics, shown in Figures A.2 to A.4, contain all the logical connections between components.

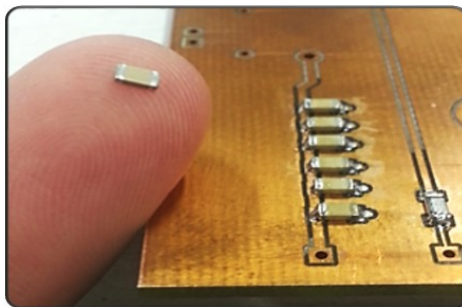


Figure A.1: Relative size of components to an index finger.

Table A.1: Bill of Materials - Part 1

Comp. Name	QTY	REFDES	Local Source	Part No.
Antelec_A60C2G	1	B5	Mantech Part	14M5074
Mate-n-lok-2p	1	U12	RS Part	514-855P
SN74LS07ND	1	U10	Mantech Part	35M2689
RELAY DPDT	1	LS1	Mantech Part	72M1623
1A_FuseHolder	2	F1;F2	Mantech Part	72M4287
MOC8204	1	U6	Mantech Part	35M1462
50K	3	R16;R24;R32	Mantech Part	35M4500
10K	1	R47	Mantech Part	35M1094
10U	2	C1;C17	Mantech Part	35M1885
100N	5	C2;C13;C14;C15;C18	Mantech Part	35M1812
10N	8	C3;C4;C5;C6;C7;C8;C11;C12	Mantech Part	35M2886
82K	4	R12;R20;R28;R29	Mantech Part	35M2642
1K	7	R14;R15;R22;R23;R30;R31;R50	Mantech Part	65M2919-H
1M	5	R17;R18;R19;R21;R48	Mantech Part	35M1659

Table A.2: Bill of Materials - Part 2

Comp. Name	QTY	REFDES	Local Source	Part No.
24K	1	R25	Mantech Part	35M1797
47K	1	R27	Mantech Part	35M1478
169K	10	R33;R34;R35;R36;R37;R38;R39;R40;R41;R42	Mantech Part	1206R1693F
2.2K	3	R43;R45;R46	Mantech Part	35M1308
120	2	R44;R51	Mantech Part	35M2110
10	1	R49	Mantech Part	35M1621
487	1	R52	Mantech Part	35M1510
0	4	R53;R54;R55;R56	Mantech Part	35M4011
100k	1	R57	Mantech Part	35M4182
100U	2	L1;L2	Mantech Part	83M0010
SIP2PIN	3	B2;B3;B4	Mantech Part	72M0358
CMS_C	5	D2;D3;D4;D7;D8	Mantech Part	72M0358
IQ2405SA	1	U11	Mantech Part	35M5132
LM311	3	U3;U4;U5	Mantech Part	35M1384
HVPins	2		Mantech Part	14M1498

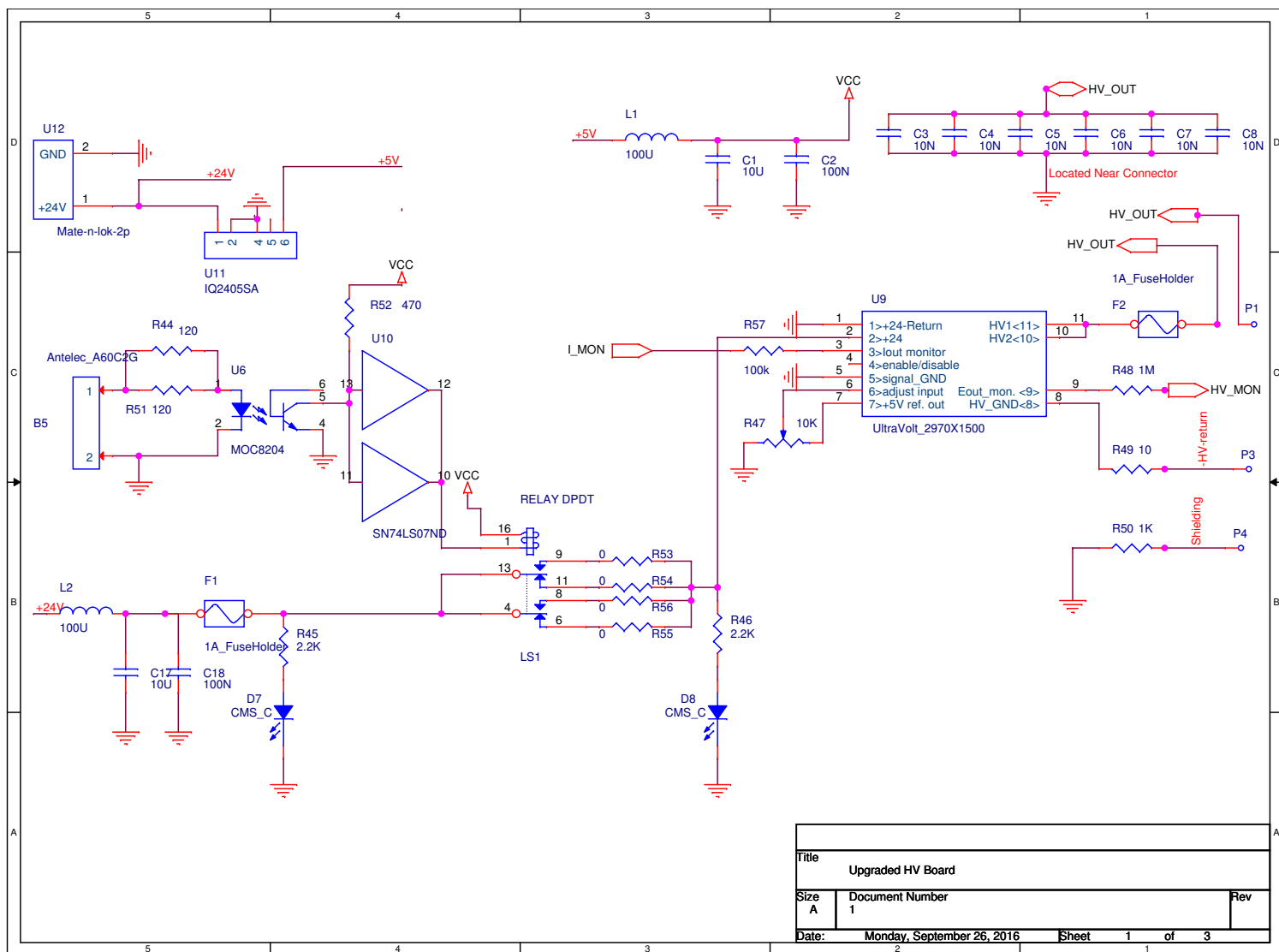


Figure A.2: First page of the HV Board schematic.

Figure A.3: Second page of the HV Board schematic.

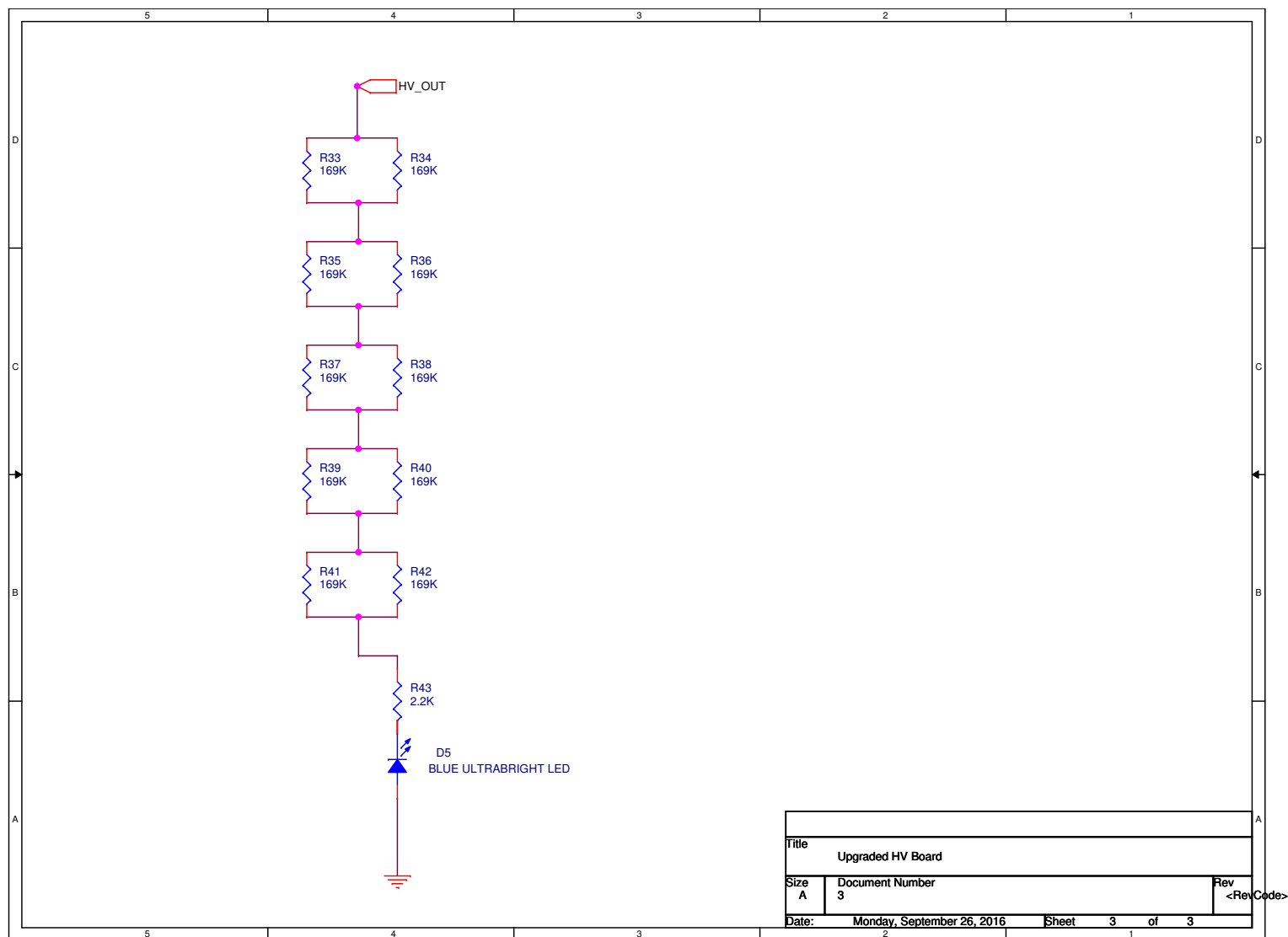


Figure A.4: Third page of the HV Board schematic.

fwATCA Supplementary Material

Figure B.1 shows the first proof of concept regarding ATCA monitoring using an SNMP OID approach. All the datapoints required were manually created in WinCC and connected to the corresponding OID by hand. Using some conditional formatting one can change the colour of the boxes depending on the values. This is in essence a primitive control system. The Activate/Deactivate buttons issues a hotswap command through the SNMP Set command and showed that the DCS could read and write to the ATCA chassis.

Figure B.2 shows the required software setup to work remotely with an ATCA system. Working remotely is a necessity when living in South Africa. The technical challenges faced with working on a remote ATCA chassis proved formidable. A secure TCP SSH connection is required to connect to the CERN network. WinCC on the other hand uses UDP which means a relay is required to forward UDP to the waiting TCP SSH tunnel. This setup is required on both ends of the network to allow dual traffic (send to the shelf manager and receive from the shelf manager).

Figure B.3 shows the custom sensor datapoint creation for an early version. The split progress bar shows individual sub-components (bottom) and overall status.

B. FWATCA SUPPLEMENTARY MATERIAL

QuickTest : testScript/createContentActivate.pnl (_ _ x)

Module Panel Scale Help

Board #	Name	HotSwap	SetState
Board-1	ATCA-2210	Inactive	Activate
Board-2	N/A	Not Installed	Activate
Board-3	ATCA-4550	Active	Deactivate
Board-3	ATCA-5400-RTM	Active	Deactivate
Board-4	ATCA-1200	Active	Deactivate
Board-4	CERN-AMC-GLIB	Active	Deactivate
Board-4	ATCA-1200-RTM	Active	Deactivate
Board-5	N/A	Not Installed	Activate
Board-6	AT8404	Active	Deactivate

Figure B.1: First working example of fwATCA concept.

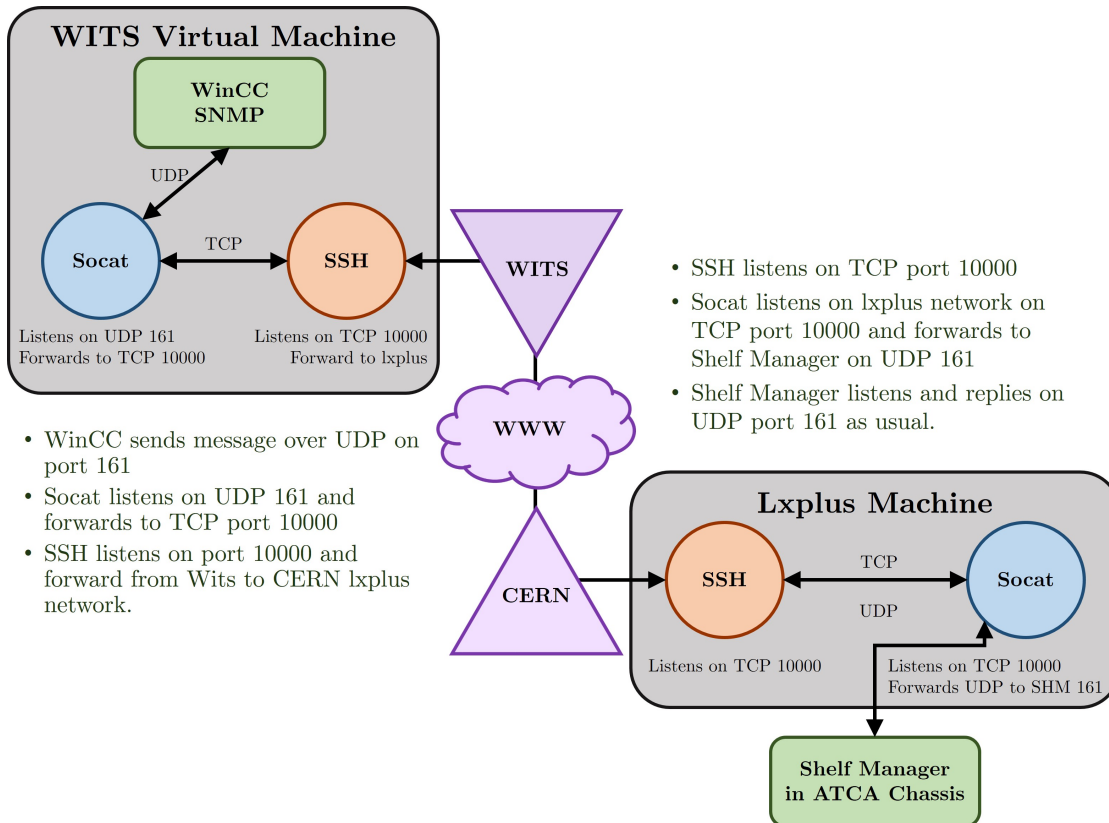


Figure B.2: Setup to work from South Africa with an ATCA chassis at CERN.

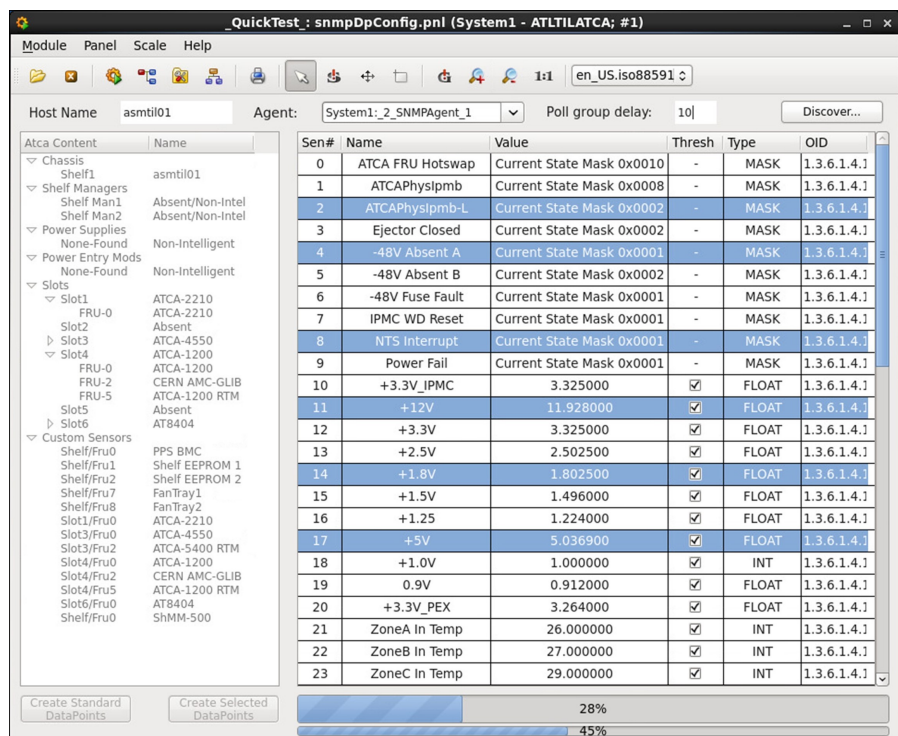


Figure B.3: Creating selected custom datapoints using fwATCA.

Di-Higgs Supplementary Material

Figure C.1 shows the efficiency of the full selection in the 1-tag category as a function of generated mass fitted with two different polynomials. Figures C.2 to C.4 show various kinematic properties of the particles making up the four object in the two tagged category in five di-Higgs signal samples. Tables C.1 to C.6 show cutflow tables for various MC samples. Tables C.7 to C.19 show combined systematic uncertainties for various MC samples.

C. DI-HIGGS SUPPLEMENTARY MATERIAL

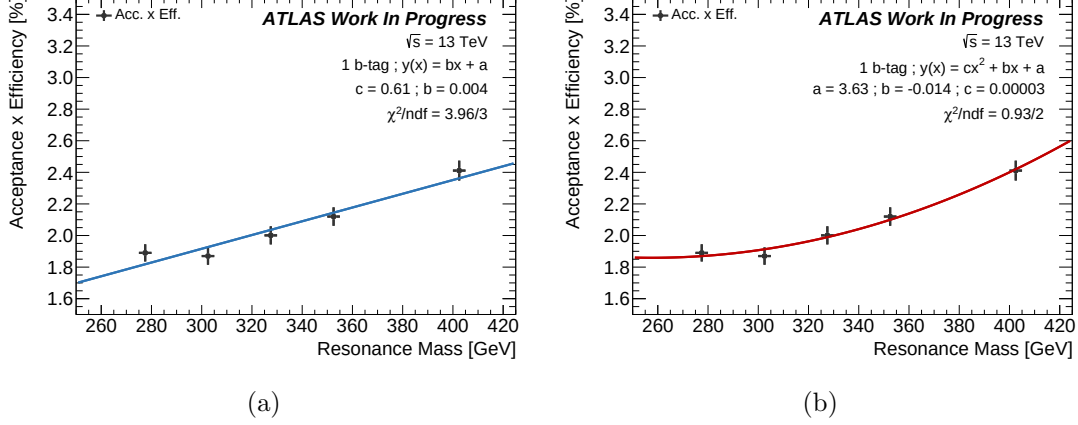


Figure C.1: Efficiency of the full selection as a function of the generated resonance mass for 1-tag category. The efficiency is fitted with a 1st order (a) and 2nd order (b) polynomial allowing interpolation for missing generated resonance masses.

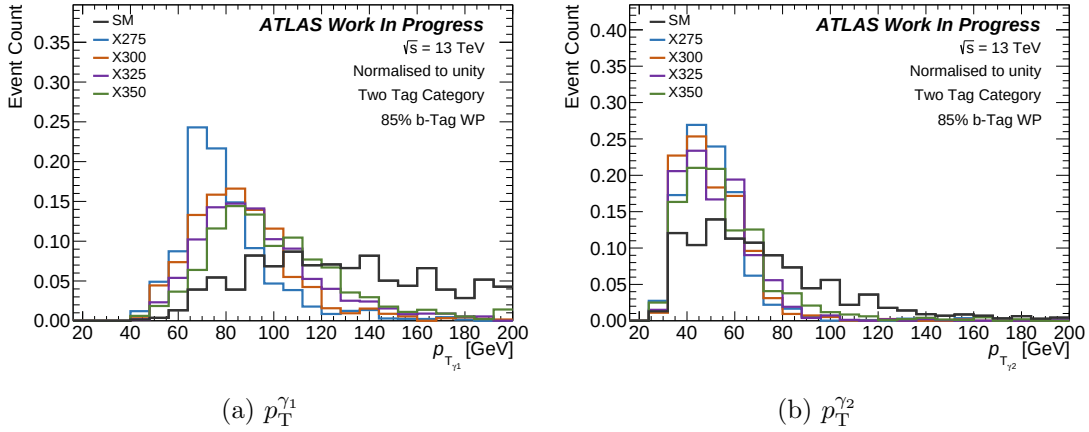


Figure C.2: Basic kinematic properties produced by the HH2yybb framework. Five signal sample are shown: Four resonance samples with masses of 275, 300, 325, 350 GeV and a SM non-resonant production model shown (black).

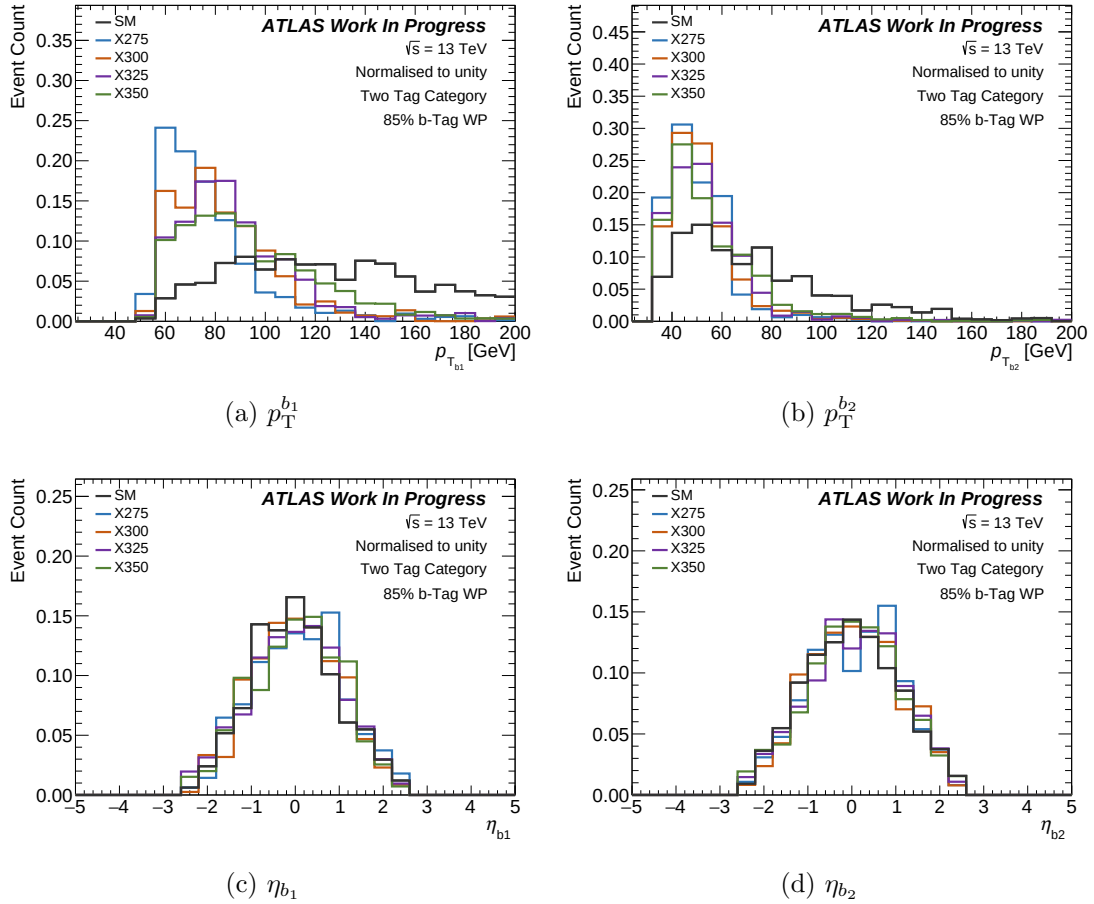


Figure C.3: Basic kinematic properties produced by the HH2yybb framework. Five signal sample are shown: Four resonance samples with masses of 275, 300, 325, 350 GeV and a SM non-resonant production model shown (black).

C. DI-HIGGS SUPPLEMENTARY MATERIAL

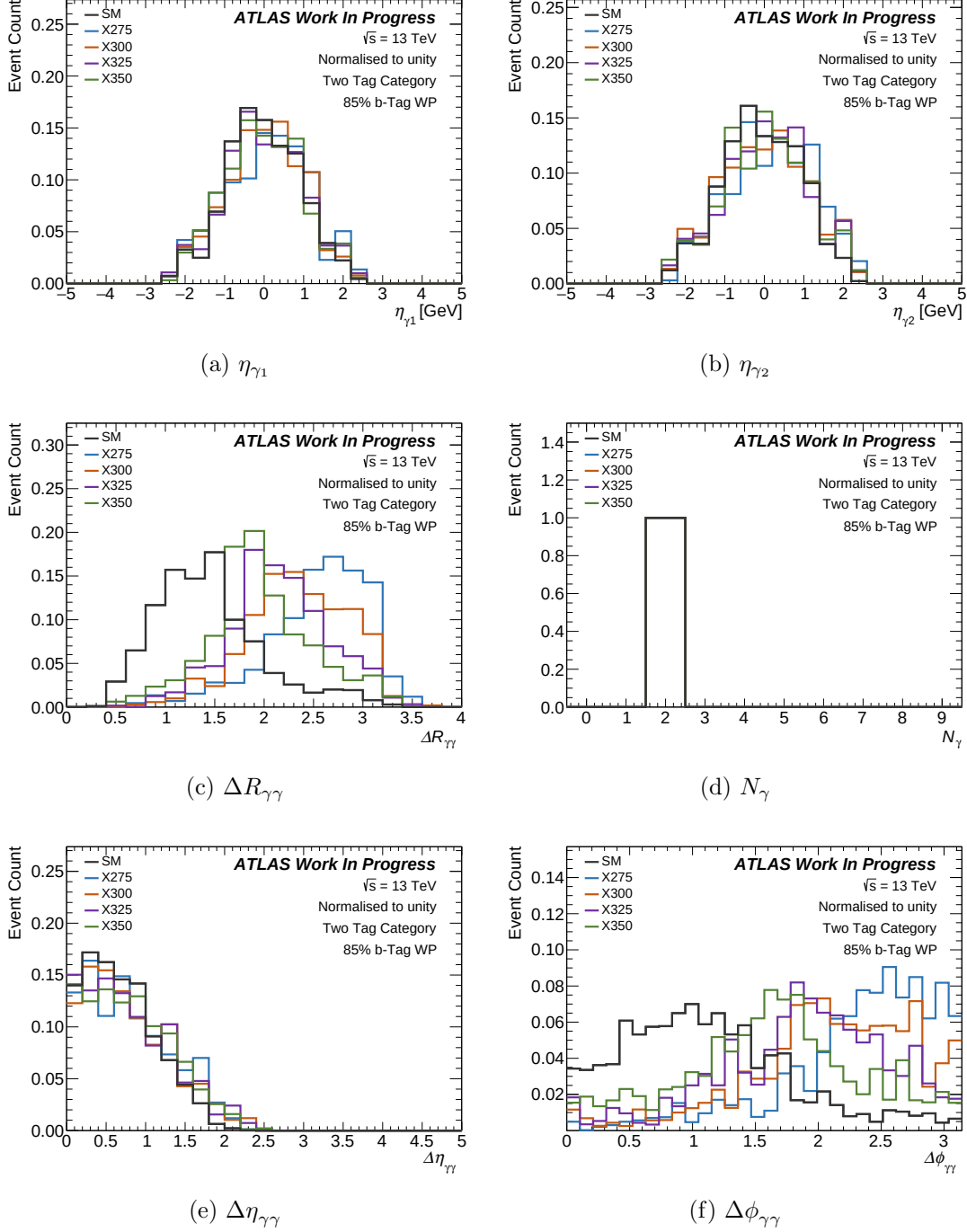


Figure C.4: Basic kinematic properties produced by the HH2yybb framework. Five signal sample are shown: Four resonance samples with masses of 275, 300, 325, 350 GeV and a SM non-resonant production model shown (black).

Table C.1: Cutflow for 275 GeV resonance sample for the 2-tag category with 85% b -tagging working point

Cuts	2-tag			1-tag			0-tag		
	Weighted	Error	Eff.	Weighted	Error	Eff.	Weighted	Error	Eff.
N_{xAOD}	100000	348	-	100000	348	inf	100000	348	-
N_{DxAOD}	100000	316	-	100000	316	inf	100000	316	-
All Events	32	0.128	100	32	0.128	100	32	0.128	100.0
No Duplicates	32	0.128	100	32	0.128	100	32	0.128	100.0
Pass Trigger	20.359	0.102	63.6	20.359	0.102	63.6	20.359	0.102	63.6
GRL	20.359	0.102	63.6	20.359	0.102	63.6	20.359	0.102	63.6
Detector DQ	20.359	0.102	63.6	20.359	0.102	63.6	20.359	0.102	63.6
Has PV	20.359	0.102	63.6	20.359	0.102	63.6	20.359	0.102	63.6
2 Loose Photons	17.226	0.094	53.8	17.226	0.094	53.8	17.226	0.094	53.8
$e - \gamma$ Ambiguity	17.082	0.094	53.4	17.082	0.094	53.4	17.082	0.094	53.4
Trigger Match	16.962	0.093	53	16.962	0.093	53	16.962	0.093	53.0
Tight ID	14.547	0.087	45.5	14.547	0.087	45.5	14.547	0.087	45.5
Isolation	12.138	0.079	37.9	12.138	0.079	37.9	12.138	0.079	37.9
Rel. p_{T} Cuts	11.114	0.076	34.7	11.114	0.076	34.7	11.114	0.076	34.7
$m_{\gamma\gamma} \in [105, 160]$ GeV	11.1	0.076	34.7	11.1	0.076	34.7	11.1	0.076	34.7
2 Cen. Jets	7.68	0.063	24	7.68	0.063	24	7.68	0.063	24.0
b -tagging	3.564	0.043	11.1	3.154	0.041	9.9	0.807	0.021	2.5
Jet p_{T} Cuts	2.186	0.033	6.8	2.086	0.034	6.5	0.482	0.016	1.5
$m_{b\bar{b}}$ Cut	1.577	0.028	4.9	0.607	0.019	1.9	0.115	0.009	0.4

Table C.2: Cutflow for 300 GeV resonance sample for the 2-tag category with 85% b -tagging working point

Cuts	2-tag			1-tag			0-tag		
	Weighted	Error	Eff.	Weighted	Error	Eff.	Weighted	Error	Eff.
N_{xAOD}	100000	375	-	100000	375	inf	100000	375	-
N_{DxAOD}	100000	316	-	100000	316	inf	100000	316	-
All Events	32	0.128	100	32	0.128	100	32	0.128	100.0
No Duplicates	32	0.128	100	32	0.128	100	32	0.128	100.0
Pass Trigger	20.484	0.103	64	20.484	0.103	64	20.484	0.103	64.0
GRL	20.484	0.103	64	20.484	0.103	64	20.484	0.103	64.0
Detector DQ	20.484	0.103	64	20.484	0.103	64	20.484	0.103	64.0
Has PV	20.484	0.103	64	20.484	0.103	64	20.484	0.103	64.0
2 Loose Photons	17.456	0.095	54.5	17.456	0.095	54.5	17.456	0.095	54.5
$e - \gamma$ Ambiguity	17.325	0.094	54.1	17.325	0.094	54.1	17.325	0.094	54.1
Trigger Match	17.199	0.094	53.7	17.199	0.094	53.7	17.199	0.094	53.7
Tight ID	14.822	0.087	46.3	14.822	0.087	46.3	14.822	0.087	46.3
Isolation	12.551	0.08	39.2	12.551	0.08	39.2	12.551	0.08	39.2
Rel. p_{T} Cuts	11.292	0.076	35.3	11.292	0.076	35.3	11.292	0.076	35.3
$m_{\gamma\gamma} \in [105, 160]$ GeV	11.28	0.076	35.2	11.28	0.076	35.2	11.28	0.076	35.2
2 Cen. Jets	7.96	0.064	24.9	7.96	0.064	24.9	7.96	0.064	24.9
b -tagging	3.711	0.044	11.6	3.285	0.042	10.3	0.774	0.02	2.4
Jet p_{T} Cuts	2.41	0.035	7.5	2.315	0.035	7.2	0.523	0.017	1.6
$m_{b\bar{b}}$ Cut	1.715	0.03	5.4	0.601	0.019	1.9	0.137	0.009	0.4

Table C.3: Cutflow for 325 GeV resonance sample for the 2-tag category with 85% b -tagging working point

Cuts	2-tag			1-tag			0-tag		
	Weighted	Error	Eff.	Weighted	Error	Eff.	Weighted	Error	Eff.
N_{xAOD}	100000	346	-	100000	346	inf	100000	346	-
N_{DxAOD}	100000	316	-	100000	316	inf	100000	316	-
All Events	32	0.128	100	32	0.128	100	32	0.128	100.0
No Duplicates	32	0.128	100	32	0.128	100	32	0.128	100.0
Pass Trigger	20.671	0.103	64.6	20.671	0.103	64.6	20.671	0.103	64.6
GRL	20.671	0.103	64.6	20.671	0.103	64.6	20.671	0.103	64.6
Detector DQ	20.671	0.103	64.6	20.671	0.103	64.6	20.671	0.103	64.6
Has PV	20.671	0.103	64.6	20.671	0.103	64.6	20.671	0.103	64.6
2 Loose Photons	17.571	0.095	54.9	17.571	0.095	54.9	17.571	0.095	54.9
$e - \gamma$ Ambiguity	17.443	0.095	54.5	17.443	0.095	54.5	17.443	0.095	54.5
Trigger Match	17.316	0.094	54.1	17.316	0.094	54.1	17.316	0.094	54.1
Tight ID	14.936	0.088	46.7	14.936	0.088	46.7	14.936	0.088	46.7
Isolation	12.865	0.081	40.2	12.865	0.081	40.2	12.865	0.081	40.2
Rel. p_{T} Cuts	11.515	0.077	36	11.515	0.077	36	11.515	0.077	36.0
$m_{\gamma\gamma} \in [105, 160]$ GeV	11.498	0.077	35.9	11.498	0.077	35.9	11.498	0.077	35.9
2 Cen. Jets	8.299	0.065	25.9	8.299	0.065	25.9	8.299	0.065	25.9
b -tagging	3.921	0.045	12.3	3.39	0.042	10.6	0.756	0.02	2.4
Jet p_{T} Cuts	2.66	0.037	8.3	2.528	0.037	7.9	0.536	0.017	1.7
$m_{b\bar{b}}$ Cut	1.884	0.031	5.9	0.641	0.019	2	0.12	0.009	0.4

Table C.4: Cutflow for 350 GeV resonance sample for the 2-tag category with 85% b -tagging working point

Cuts	2-tag			1-tag			0-tag		
	Weighted	Error	Eff.	Weighted	Error	Eff.	Weighted	Error	Eff.
N_{xAOD}	100000	349	-	100000	349	inf	100000	349	-
N_{DxAOD}	100000	316	-	100000	316	inf	100000	316	-
All Events	32	0.128	100	32	0.128	100	32	0.128	100.0
No Duplicates	32	0.128	100	32	0.128	100	32	0.128	100.0
Pass Trigger	20.682	0.103	64.6	20.682	0.103	64.6	20.682	0.103	64.6
GRL	20.682	0.103	64.6	20.682	0.103	64.6	20.682	0.103	64.6
Detector DQ	20.682	0.103	64.6	20.682	0.103	64.6	20.682	0.103	64.6
Has PV	20.682	0.103	64.6	20.682	0.103	64.6	20.682	0.103	64.6
2 Loose Photons	17.619	0.095	55.1	17.619	0.095	55.1	17.619	0.095	55.1
$e - \gamma$ Ambiguity	17.485	0.095	54.6	17.485	0.095	54.6	17.485	0.095	54.6
Trigger Match	17.348	0.094	54.2	17.348	0.094	54.2	17.348	0.094	54.2
Tight ID	14.97	0.088	46.8	14.97	0.088	46.8	14.97	0.088	46.8
Isolation	12.992	0.082	40.6	12.992	0.082	40.6	12.992	0.082	40.6
Rel. p_{T} Cuts	11.636	0.077	36.4	11.636	0.077	36.4	11.636	0.077	36.4
$m_{\gamma\gamma} \in [105, 160]$ GeV	11.622	0.077	36.3	11.622	0.077	36.3	11.622	0.077	36.3
2 Cen. Jets	8.593	0.066	26.9	8.593	0.066	26.9	8.593	0.066	26.9
b -tagging	4.029	0.045	12.6	3.57	0.043	11.2	0.704	0.019	2.2
Jet p_{T} Cuts	2.91	0.039	9.1	2.742	0.038	8.6	0.536	0.017	1.7
$m_{b\bar{b}}$ Cut	2.041	0.032	6.4	0.678	0.02	2.1	0.123	0.009	0.4

Table C.5: Cutflow for 400 GeV resonance sample for the 2-tag category with 85% b -tagging working point

Cuts	2-tag			1-tag			0-tag		
	Weighted	Error	Eff.	Weighted	Error	Eff.	Weighted	Error	Eff.
N_{xAOD}	100000	351	-	100000	351	inf	100000	351	-
N_{DxAOD}	100000	316	-	100000	316	inf	100000	316	-
All Events	32	0.129	100	32	0.129	100	32	0.129	100.0
No Duplicates	32	0.129	100	32	0.129	100	32	0.129	100.0
Pass Trigger	21.008	0.104	65.6	21.008	0.104	65.6	21.008	0.104	65.6
GRL	21.008	0.104	65.6	21.008	0.104	65.6	21.008	0.104	65.6
Detector DQ	21.008	0.104	65.6	21.008	0.104	65.6	21.008	0.104	65.6
Has PV	21.008	0.104	65.6	21.008	0.104	65.6	21.008	0.104	65.6
2 Loose Photons	17.937	0.096	56.1	17.937	0.096	56.1	17.937	0.096	56.1
$e - \gamma$ Ambiguity	17.801	0.096	55.6	17.801	0.096	55.6	17.801	0.096	55.6
Trigger Match	17.673	0.096	55.2	17.673	0.096	55.2	17.673	0.096	55.2
Tight ID	15.387	0.089	48.1	15.387	0.089	48.1	15.387	0.089	48.1
Isolation	13.597	0.084	42.5	13.597	0.084	42.5	13.597	0.084	42.5
Rel. p_{T} Cuts	12.351	0.08	38.6	12.351	0.08	38.6	12.351	0.08	38.6
$m_{\gamma\gamma} \in [105, 160]$ GeV	12.335	0.08	38.5	12.335	0.08	38.5	12.335	0.08	38.5
2 Cen. Jets	9.342	0.069	29.2	9.342	0.069	29.2	9.342	0.069	29.2
b -tagging	4.57	0.048	14.3	3.767	0.045	11.8	0.653	0.019	2.0
Jet p_{T} Cuts	3.581	0.043	11.2	3.089	0.041	9.7	0.527	0.017	1.6
$m_{b\bar{b}}$ Cut	2.526	0.036	7.9	0.772	0.021	2.4	0.106	0.008	0.3

Table C.6: Cutflow for SM non-resonant hh sample for the 2-tag category with 85% b -tagging working point

Cuts	2-tag			1-tag			0-tag		
	Weighted	Error	Eff.	Weighted	Error	Eff.	Weighted	Error	Eff.
N_{xAOD}	100000	346	-	100000	346	inf	100000	346	-
N_{DxAOD}	100000	316	-	100000	316	inf	100000	316	-
All Events	0.317	0.00131	100	0.317	0.00131	100	0.317	0.00131	100.0
No Duplicates	0.317	0.00131	100	0.317	0.00131	100	0.317	0.00131	100.0
Pass Trigger	0.221	0.00109	69.8	0.221	0.00109	69.7759	0.221	0.00109	69.8
GRL	0.221	0.00109	69.8	0.221	0.00109	69.7759	0.221	0.00109	69.8
Detector DQ	0.221	0.00109	69.8	0.221	0.00109	69.7759	0.221	0.00109	69.8
Has PV	0.221	0.00109	69.8	0.221	0.00109	69.7759	0.221	0.00109	69.8
2 Loose Photons	0.191	0.00102	60.4	0.191	0.00102	60.4206	0.191	0.00102	60.4
$e - \gamma$ Ambiguity	0.19	0.00101	60.1	0.19	0.00101	60.0688	0.19	0.00101	60.1
Trigger Match	0.189	0.00101	59.6	0.189	0.00101	59.6112	0.189	0.00101	59.6
Tight ID	0.167	0.000949	52.6	0.167	0.000949	52.6088	0.167	0.000949	52.6
Isolation	0.149	0.000896	47	0.149	0.000896	46.9624	0.149	0.000896	47.0
Rel. p_{T} Cuts	0.137	0.00086	43.2	0.137	0.00086	43.2356	0.137	0.00086	43.2
$m_{\gamma\gamma}$ window	0.137	0.00086	43.2	0.137	0.00086	43.168	0.137	0.00086	43.2
2 Cen. Jets	0.108	0.000763	34	0.108	0.000763	34.0165	0.108	0.000763	34.0
b -tagging	0.056	0.00055	17.6	0.041	0.000473	12.8542	0.007	0.000192	2.1
Jet p_{T} Cuts	0.046	0.000497	14.4	0.034	0.000435	10.8049	0.006	0.000179	1.8
$m_{b\bar{b}}$ Cut	0.032	0.000414	10	0.009	0.000236	2.9371	0.001	0.0000853	0.3

Table C.7: Combined object systematic uncertainties for 275 GeV signal resonance analysis. In percentages.

Systematic Name	0-tag	1-tag	2-tag
Flavor tag (B) up	6.2	8.75	12.28
Flavor tag (B) down	6.41	9.04	13
Flavor tag (C) up	0.43	0.21	0.01
Flavor tag (C) down	0.43	0.21	0.01
Flavor tag (LF) up	34.6	23.52	0.15
Flavor tag (LF) down	44.48	23.67	0.15
Muon up	0	0.38	0.22
Muon down	0	0.4	0.2
EGRes up	8.11	8.51	6.57
EGRes down	6.97	4.02	3.19
JES up	3.81	6.36	6.37
JES down	7.67	12.11	12.39
JER	5.8	6.58	7.86
Photon up	4.8	4.67	4.68
Photon down	4.72	4.92	4.76
Photon DD iso	0	1.1	0.57
Pileup RW up	1.02	3.41	0.42
Pileup RW down	1.94	2.83	0.11

Table C.8: Combined object systematic uncertainties for 300 GeV signal resonance analysis. In percentages.

Systematic Name	0-tag	1-tag	2-tag
Flavor tag (B) up	6.27	8.94	12.26
Flavor tag (B) down	6.49	9.25	12.98
Flavor tag (C) up	0.55	0.16	0.02
Flavor tag (C) down	0.55	0.16	0.02
Flavor tag (LF) up	33.93	22.26	0.19
Flavor tag (LF) down	43.17	22.47	0.19
Muon up	0	0.03	0.18
Muon down	0	0.03	0.16
EGRes up	6.32	8.24	7.14
EGRes down	4.22	2.64	2.66
JES up	8.77	5.29	8.28
JES down	2.08	7.78	13.28
JER	4.89	4.49	9.84
Photon up	4.86	4.82	4.7
Photon down	4.78	4.72	4.75
Photon DD iso	0.82	0.47	0.45
Pileup RW up	3.85	0.75	1
Pileup RW down	2.39	0.81	1.07

Table C.9: Combined object systematic uncertainties for 325 GeV signal resonance analysis. In percentages.

Systematic Name	0-tag	1-tag	2-tag
Flavor tag (B) up	6.66	9.1	12.26
Flavor tag (B) down	6.9	9.43	12.98
Flavor tag (C) up	0.21	0.18	0.02
Flavor tag (C) down	0.21	0.18	0.02
Flavor tag (LF) up	32.99	21.11	0.18
Flavor tag (LF) down	41.34	21.2	0.18
Muon up	0	0.07	0.01
Muon down	0	0.03	0.06
EGRes up	12.9	7.64	6.92
EGRes down	3.79	2.95	2.57
JES up	6.12	5.29	8.9
JES down	8.57	10.61	12.81
JER	5.66	7.4	9.93
Photon up	4.81	4.84	4.72
Photon down	4.73	4.73	4.65
Photon DD iso	0	0.48	0.25
Pileup RW up	1.5	0.29	0.38
Pileup RW down	5.21	0.44	0.52

Table C.10: Combined object systematic uncertainties for 350 GeV signal resonance analysis. In percentages.

Systematic Name	0-tag	1-tag	2-tag
Flavor tag (B) up	6.64	9.26	12.24
Flavor tag (B) down	6.89	9.61	12.96
Flavor tag (C) up	0.29	0.18	0.04
Flavor tag (C) down	0.3	0.18	0.04
Flavor tag (LF) up	32.67	19.97	0.28
Flavor tag (LF) down	41.24	20	0.28
Muon up	0	0.24	0.03
Muon down	0	0	0.03
EGRes up	5	6.25	7.84
EGRes down	6.54	2.56	2.95
JES up	5.4	5.85	8.17
JES down	5.96	8.1	11.48
JER	2.89	3.97	8.81
Photon up	4.73	4.74	4.68
Photon down	4.64	4.65	4.6
Photon DD iso	1.17	0.17	0.24
Pileup RW up	5.94	1.67	1.86
Pileup RW down	4.4	1.08	1.71

Table C.11: Combined object systematic uncertainties for 400 GeV signal resonance analysis. In percentages.

Systematic Name	0-tag	1-tag	2-tag
Flavor tag (B) up	7.62	9.38	12.28
Flavor tag (B) down	7.93	9.75	13.02
Flavor tag (C) up	0.19	0.19	0.02
Flavor tag (C) down	0.19	0.19	0.02
Flavor tag (LF) up	27.51	19.18	0.3
Flavor tag (LF) down	34.03	19.25	0.3
Muon up	0	0.02	0
Muon down	0	0.03	0.05
EGRes up	1.49	8.75	7.49
EGRes down	0.22	4.38	3.8
JES up	11.18	6.3	9.13
JES down	2.95	8.2	10.1
JER	2.36	8.21	8.1
Photon up	4.55	4.64	4.56
Photon down	4.47	4.56	4.49
Photon DD iso	0	0.07	0.28
Pileup RW up	0.29	0.65	0.7
Pileup RW down	4.16	1.21	1.1

Table C.12: Combined object systematic uncertainties for SM hh signal. In percentages.

Systematic Name	0-tag	1-tag	2-tag
Flavor tag (B) up	7.44	10.12	12.5
Flavor tag (B) down	7.75	10.61	13.3
Flavor tag (C) up	0.24	0.2	0.05
Flavor tag (C) down	0.24	0.2	0.05
Flavor tag (LF) up	29.32	16	0.48
Flavor tag (LF) down	36.11	16.05	0.49
Muon up	0	0	0.03
Muon down	0	0	0.04
EGRes up	0.06	0.15	0.08
EGRes down	0	0.41	0.09
JES up	7.61	8.22	9.97
JES down	7.95	7.85	8.5
JER	3.23	5.09	7.65
Photon up	4.25	4.2	4.15
Photon down	4.19	4.13	4.06
Photon DD iso	0	0.6	0.21
Pileup RW up	1.77	0.54	1.79
Pileup RW down	2.47	0.76	1.37

Table C.13: Combined object systematic uncertainties for ggh non resonant analysis. In percentages.

Systematic Name	0-tag	1-tag	2-tag
Flavor tag (B) up	0.08	0.96	12.39
Flavor tag (B) down	0.08	0.96	13.15
Flavor tag (C) up	0.52	16.68	0
Flavor tag (C) down	0.52	18.74	0
Flavor tag (LF) up	64.16	13.02	0
Flavor tag (LF) down	96.26	16.32	0
Muon up	0	0	0
Muon down	0	0	0
EGRes up	0.01	0	0
EGRes down	0.53	0	0
JES up	12.31	52.04	9.16
JES down	28.03	28.78	9.21
JER	36.37	98.68	97.04
Photon up	4.6	4.53	2.26
Photon down	4.53	4.45	2.25
Photon DD iso	0	0	0
Pileup RW up	1.27	32.11	248.98
Pileup RW down	3.98	5.05	82.23

Table C.14: Combined object systematic uncertainties for VBF Higgs boson non resonant analysis. In percentages.

Systematic Name	0-tag	1-tag	2-tag
Flavor tag (B) up	0	2.18	0.34
Flavor tag (B) down	0	2.18	0.36
Flavor tag (C) up	3.82	5.4	0
Flavor tag (C) down	3.93	5.4	0
Flavor tag (LF) up	56.67	46.02	64.05
Flavor tag (LF) down	80.86	52.97	97.16
Muon up	0	0	0
Muon down	0	0	0
EGRes up	0	0	0
EGRes down	0	0	0
JES up	15.47	32.26	20.94
JES down	7.48	34.69	2.76
JER	21.15	18.44	2.75
Photon up	4.61	4.27	7.22
Photon down	4.53	4.21	7.02
Photon DD iso	0	0	0
Pileup RW up	10.47	17.57	99.23
Pileup RW down	7	12.97	98.33

Table C.15: Combined object systematic uncertainties for WH Higgs boson non resonant analysis. In percentages.

Systematic Name	0-tag	1-tag	2-tag
Flavor tag (B) up	0	0.07	0
Flavor tag (B) down	0	0.07	0
Flavor tag (C) up	3.37	9.81	10.89
Flavor tag (C) down	3.42	9.89	10.89
Flavor tag (LF) up	59.31	45.52	43.7
Flavor tag (LF) down	85.21	53.24	46.94
Muon up	0	0	0
Muon down	0	0	0
EGRes up	0	10.68	0
EGRes down	0	0	0
JES up	16.27	39.1	88.99
JES down	9.55	45.15	18.04
JER	13.98	12.78	62.98
Photon up	4.63	4.82	4.51
Photon down	4.56	4.74	4.43
Photon DD iso	0	10.68	0
Pileup RW up	0.13	4.78	39.94
Pileup RW down	4.17	3.83	26.4

Table C.16: Combined object systematic uncertainties for ZH Higgs boson non resonant analysis. In percentages.

Systematic Name	0-tag	1-tag	2-tag
Flavor tag (B) up	0.25	2.49	8.16
Flavor tag (B) down	0.26	2.57	8.69
Flavor tag (C) up	1.38	3.71	7.53
Flavor tag (C) down	1.5	4.09	8.44
Flavor tag (LF) up	60.67	43.86	1.22
Flavor tag (LF) down	90.58	61.21	1.22
Muon up	0	0	5.78
Muon down	0	0	0
EGRes up	2.26	0.06	0
EGRes down	0	0	0
JES up	22.69	46.73	43.49
JES down	13.31	11.15	36.2
JER	2.36	26.7	27.31
Photon up	4.64	4.66	4.17
Photon down	4.56	4.58	4.1
Photon DD iso	0.03	0	0
Pileup RW up	5.7	4.31	5.03
Pileup RW down	1.76	10.07	3.37

Table C.17: Combined object systematic uncertainties for ttH Higgs boson non resonant analysis. In percentages.

Systematic Name	0-tag	1-tag	2-tag
Flavor tag (B) up	3.63	6.78	10.26
Flavor tag (B) down	3.63	6.83	10.74
Flavor tag (C) up	1.82	1.36	3.63
Flavor tag (C) down	1.82	1.36	3.64
Flavor tag (LF) up	46.61	35.51	2.52
Flavor tag (LF) down	58.8	35.55	2.56
Muon up	0	0	0
Muon down	0	0	0
EGRes up	0	0	0.01
EGRes down	0	0.04	0.06
JES up	17.29	6.39	4.72
JES down	25.6	8.65	6.25
JER	7.02	0.1	3.07
Photon up	4.76	4.44	4.51
Photon down	4.67	4.37	4.44
Photon DD iso	0	0.02	0.01
Pileup RW up	3.9	2.63	1.33
Pileup RW down	0.68	2.62	1.59

Table C.18: Combined object systematic uncertainties for bbH-yb2 Higgs boson non resonant analysis. In percentages.

Systematic Name	0-tag	1-tag	2-tag
Flavor tag (B) up	4.74	6.53	11.59
Flavor tag (B) down	4.59	6.53	12.23
Flavor tag (C) up	3.29	0.28	0.01
Flavor tag (C) down	3.29	0.28	0.01
Flavor tag (LF) up	42.19	39.65	5.19
Flavor tag (LF) down	40.4	38.9	5.19
Muon up	0	0	0
Muon down	0	0	0
EGRes up	0	0.01	0
EGRes down	0	0	0
JES up	84.07	46.35	29.47
JES down	104.11	22.03	11.34
JER	36.09	17.46	96.88
Photon up	4.6	4.69	6.72
Photon down	4.52	4.61	6.59
Photon DD iso	0	0	0.09
Pileup RW up	0.63	6.34	36.27
Pileup RW down	43.54	20.67	25.11

Table C.19: Combined object systematic uncertainties for bbH-ybyt Higgs boson non resonant analysis. In percentages.

Systematic Name	0-tag	1-tag	2-tag
Flavor tag (B) up	6.22	6.32	12.32
Flavor tag (B) down	6.27	6.34	13.04
Flavor tag (C) up	0	0	0.15
Flavor tag (C) down	0	0	0.15
Flavor tag (LF) up	40.23	40.87	0.14
Flavor tag (LF) down	42.67	41.22	0.14
Muon up	0	0	0
Muon down	0	0	0
EGRes up	0	5.9	0
EGRes down	16.75	0.03	0
JES up	15.25	36.35	9.35
JES down	6.18	45.78	21.3
JER	18.21	30.28	2.01
Photon up	5.06	4.69	4.3
Photon down	4.97	4.6	4.22
Photon DD iso	0.02	0	0
Pileup RW up	0.75	16.88	13.05
Pileup RW down	6.15	14.46	0.42

— *Appendix* **D** —

High Mass Diphoton Supplementary Material

Figure D.1 shows the individual fits to each differential jet category for all jets in the range $|\eta| \leq 4.4$, using 2015 data. Figure D.2 shows the individual fits to each differential jet category for all jets in the range $|\eta| \leq 4.4$, using 2016 data.

D. HIGH MASS DIPHOTON SUPPLEMENTARY MATERIAL

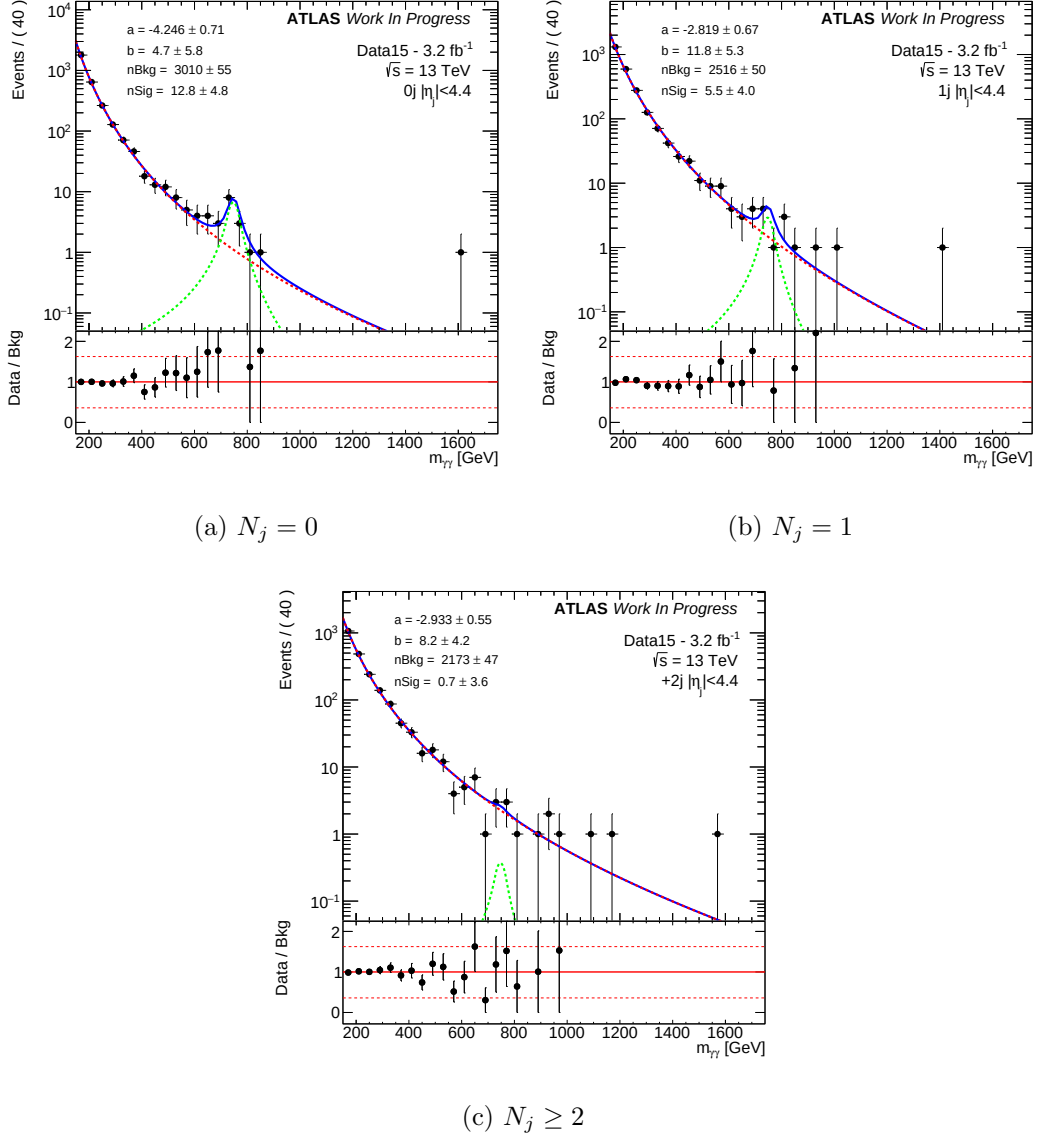
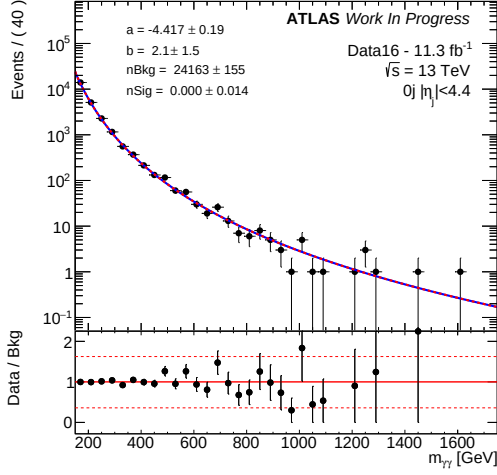
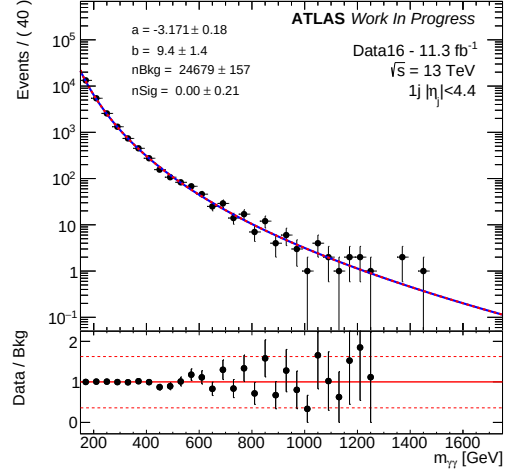


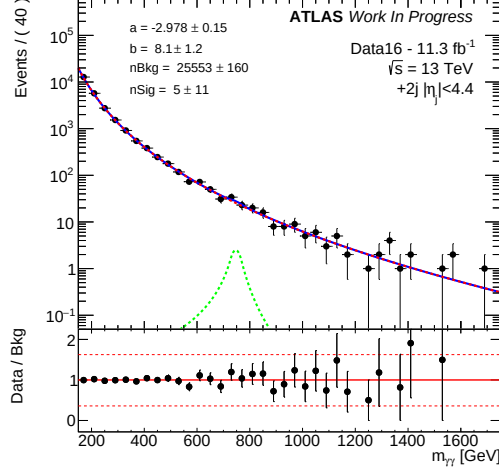
Figure D.1: Fits on the diphoton invariant mass for various cuts on jet multiplicity in 2015 data. The extracted signal yield and statistical error are used to produce the differential plots. Three fits are performed corresponding to $N_j = 0$, $N_j = 1$ and $N_j \geq 2$ for all jets with $|\eta_j| \leq 4.4$.



(a) $N_j = 0$



(b) $N_j = 1$



(c) $N_j \geq 2$

Figure D.2: Fits on the diphoton invariant mass for various cuts on jet multiplicity in 2016 data. The extracted signal yield and statistical error are used to produce the differential plots. Three fits are performed corresponding to $N_j = 0$, $N_j = 1$ and $N_j \geq 2$ for all jets with $|\eta_j| \leq 4.4$.

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