

OBSERVATION OF THE HIGGS BOSON DECAYING TO $WW^* \rightarrow \ell\nu\ell\nu$

by

Nikolina Ilic

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Abstract

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The search for the Higgs boson produced through gluon fusion and vector boson fusion and decaying to WW bosons is performed. The WW bosons subsequently decay to combinations of electrons, muons and neutrinos. The final states are accompanied by up to two jets. The search is performed using 25 fb^{-1} of data collected by the ATLAS detector in $\sqrt{s} = 7 \text{ TeV}$ and $\sqrt{s} = 8 \text{ TeV}$ proton-proton collisions at the LHC. Comparing the collected data to Standard Model expectations, in which the Higgs boson is assumed to not exist, yields a 6.1σ excess at around $m_H = 130 \text{ GeV}$ and over a wide mass range. The significance is the same for $m_H = 125.36 \text{ GeV}$, which is the Higgs mass determined by the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$ searches. The vector boson fusion production process is observed with a significance of 3.2σ at $m_H = 125.36 \text{ GeV}$. The ratio of the expected to the observed values of the total production cross section times branching ratio is $1.08^{+0.22}_{-0.20}$ at a Higgs boson mass of $m_H = 125.36 \text{ GeV}$. When separated by Higgs production modes, this value is $1.01^{+0.27}_{-0.25}$ for gluon fusion, and $1.27^{+0.53}_{-0.45}$ for vector boson fusion. The total cross sections for the gluon fusion and vector boson fusion processes are measured. The fiducial cross section for the gluon fusion process is measured in final states containing zero and one associated jets.

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Author's Contribution to ATLAS

Research

$H \rightarrow WW^*$ Analysis

- Co-convened $H \rightarrow WW^*$ statistics subgroup
- Maintained statistics code and provided corresponding results for 0- and 1-jet channels
- Found a missing background in VBF channel ($WW + 2$ jet: is 30% of total background)
- Generated $WW + 2$ jet background and calculated theory uncertainties
- Made visual displays of individual events

Vector Boson Scattering Analysis

- Calculated theory uncertainties for WZ and WW backgrounds

Jet & MET Calibration and Performance

- Analyzed hadronic recoil in $Z \rightarrow ee/\mu\mu$ events to test most optimal MET calibrations
- Validated jet performance for new Athena releases

Liquid Argon Calorimeter Operations

- As Run Coordinator for 2011-2012, coordinated all hardware and software operations
- As hardware expert for 2010-2012, ensured operation of high voltage system, assisted in exchange of power supplies and high voltage lines
- Organized hardware and software training sessions for on-call experts and shifters

Conferences and Workshops

ATLAS Physics Prospects at the High-Luminosity LHC (Talk)

3rd International Conference on New Frontiers in Physics, Kolymbari, Greece, July 2014

Statistics Fit Model in $H \rightarrow WW^*$ (Talk)

ATLAS Higgs Workshop, Rome, Italy, Apr. 2014

Performance of the ATLAS Liquid Argon Calorimeter (Talk)

13 Topical Seminar on Innovative Particle and Radiation Detectors, Sienna, Italy, Oct. 2013

Review of $H \rightarrow WW^*$ Results with 25 fb⁻¹ of Data (Talk)

The XXI International Conference on HEP and QFT, St. Petersburg, Russia, June 2013

Data Quality in the LAr ATLAS Detector (Talk)

ATLAS Electron and Photon Calibration Workshop, Mainz, Germany, June 2013

ATLAS Detector Performance in 2012: Calorimeters (Poster)

113th LHCC Meeting, CERN, Geneva, Switzerland, Mar. 2013

WW background for Vector Boson Fusion Processes (Talk)

ATLAS Higgs to WW^* Workshop, Sesimbra, Portugal, Nov. 2012

Summary of Recent Work on MET (Talk)

CERN ATLAS Week, Geneva, Switzerland, Oct. 2011

Selected Publications

As Member of Editorial Board

ATLAS Collaboration, *Search for a Supersymmetric Partner to the Top Quark in Final States with Jets and Missing Transverse Momentum at $\sqrt{s} = 7$ TeV with the ATLAS Detector*, Phys. Rev. Lett. 109 (2012) 211802.

As Author or Analyst

N.Ilic, *ATLAS Physics Prospects for the Upgraded LHC*, Eur. Phys. J. Web of Conferences is an open access journal: <http://www.epj-conferences.org>, 2015.

ATLAS Collaboration, *Observation and Measurement of Higgs Boson Decays to WW^* with the ATLAS Detector*, CERN-PH-EP-2014-270, submitted to Physical Review D, 2014.

ATLAS Collaboration, *Evidence of Electroweak Production of $W^\pm W^\pm jj$ in pp Collisions at $\sqrt{s} = 8$ TeV with the ATLAS Detector*, Phys. Rev. Lett. 113, 141803, 2014.

N.Ilic. *Performance of the ATLAS Liquid Argon Calorimeter After Three Years of LHC Operations and Plans for a Future Upgrade*, JINST 9 C03049, 2014.

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ATLAS Collaboration, *Measurements of Higgs Boson Production and Couplings in Di-boson Final States with the ATLAS Detector at the LHC*, Phys. Lett. B 726 88, 2012.

N.Ilic, K.Lie, *Performance of the Liquid Argon and the Tile Calorimeters During the 2012 Data Taking Period*, ATL-PHYS-SLIDE-2013-168, 2013.

ATLAS Collaboration, *Particle Consistent with the Higgs Boson Observed with the ATLAS Detector at the Large Hadron Collider*, Science, Vol. 388 no.6114 pp.1576-1582, 2012.

ATLAS Collaboration, *Search for the Standard Model Higgs Boson in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ Decay Mode with 4.7 fb^{-1} of ATLAS Data at $\sqrt{s} = 7 \text{ TeV}$* , Phys.Lett. B716 62-81, 2012.

ATLAS Collaboration, *Observation of an Excess of Events in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC*, ATLAS-CONF-2012-093, 2012.

ATLAS Collaboration, *An Update to the Combined Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC Using up to 4.9 fb^{-1} of pp collision data at $\sqrt{s} = 7 \text{ TeV}$* , ATLAS-CONF-2012-019, 2012.

ATLAS Collaboration, *Performance of Missing Transverse Momentum Reconstruction in Proton-Proton Collisions at 7 TeV with ATLAS*, Eur. Phys. J. C 72 1844, 2012.

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Chapter 1

Introduction

Curiosity is one of the most defining traits of humanity. Curiosity fosters the only thing strong enough to survive all threats to human progress: knowledge. Throughout history, the advancement of knowledge has persisted despite obstacles such as war, poverty, and collapse of civilizations. This time transcendent property of collective knowledge makes it the best measure of progress.

The current understanding of the universe is based on thousands of years of accumulated knowledge. The development of modern theories owes its existence to discoveries dating back to the invention of written record keeping (6th millennium BC) [1] and the foundation of modern mathematics (6th century BC) [2]. The current approach to the development of scientific theories is based on identifying elementary constituents of visible matter, an idea that dates back to 7th century BC [3]. Elementary constituents, along with the concept of forces, is the foundation of the current theory used to describe the universe. This theory, called the *Standard Model* (SM), describes how elementary particles and fundamental forces interact with each other. The SM was developed in the second half of the 20th century, and is the most accurate description of fundamental interactions thus far. The SM rests on a mathematical foundation called *Quantum Field Theory* (QFT). In QFT, the interactions between particles and forces are modelled by fluctuating quantum fields. These fields are described by a single equation, called the *Lagrangian*.

There are four fundamental forces: the electromagnetic, weak, strong and gravitational forces. The SM accounts for three of them, and the SM Lagrangian models how the electromagnetic, weak and strong forces are mediated by spin-1 particles called gauge bosons. Photons (denoted by γ) mediate the electromagnetic force. W and Z bosons mediate the weak force, and gluons (g) mediate strong interactions. Fundamental fermions are spin- $\frac{1}{2}$ particles that interact with these mediators. Fermions can be sub-categorized into two types of particles: leptons and quarks. Leptons interact exclusively with the electromagnetic and weak force mediators, while quarks interact with the strong, electromagnetic and weak force mediators. All fermions exist in three generations, where each successive generation carries different quantum numbers and has different masses. The three generations of charged leptons are the electron (e), the muon (μ), and the tau (τ). The charged leptons have three associated neutral leptons, called neutrinos. In the SM, the neutrinos are massless particles denoted by ν_e , ν_μ and ν_τ . The three generations of quarks contain up-type and down-type fermions. The up-type quarks are the up (u), charm (c) and top (t), and the associated down-type quarks are down (d), strange (s) and bottom (b). The gauge boson and fermion masses, alongside their charges, are summarized in Figure 1.

During the formulation of the Standard Model, scientists realized that this theory failed to incorpo-

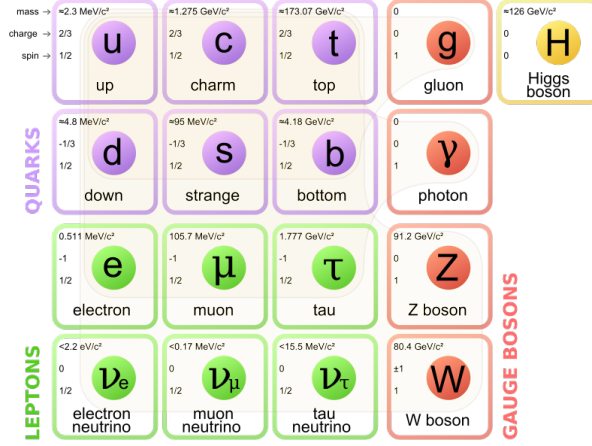


Figure 1.1: The gauge boson and fermions in the Standard Model with their masses, charges, and spins shown. The shaded areas represent the gauge boson and fermion interactions. The Higgs boson is shown on the upper right of the figure [4].

rate the fact that elementary particles had mass. It was not possible to add terms to the Lagrangian that would account for mass without breaking the gauge invariance of the Lagrangian. This problem was resolved in 1964 when a mechanism allowing particles to acquire mass was proposed [5, 6, 7], and adapted to the SM three years later [8]. Referred to as the Englert-Brout-Higgs mechanism, it predicted the existence of a spin zero particle, called the Higgs boson. The Higgs boson was the last particle predicted whose discovery was required in order to validate the SM.

The Higgs boson can be produced through gluon fusion ($gg \rightarrow H$), vector boson fusion ($q\bar{q} \rightarrow WW/ZZ \rightarrow H$), in association with W/Z bosons ($q\bar{q} \rightarrow WH/ZH$), and in association with a top and anti-top quark pair ($gg \rightarrow Ht\bar{t}$). The main channels through which the Higgs boson can decay include $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^*$, $H \rightarrow WW^*$, $H \rightarrow b\bar{b}$, and $H \rightarrow \tau\tau$. The star denotes the fact that the Higgs boson decays to virtual W and Z particles that can be of any mass. This ensures that the Higgs particle can decay to two heavy gauge bosons without the requirement that it weigh at least twice the boson's mass.

Searches for the Higgs boson have been performed by various experiments at the Large Electron-Positron (LEP) Collider, the Tevatron and the Large Hadron Collider (LHC). Searches at LEP and the Tevatron excluded the existence of a Higgs boson, at a 95% confidence level, for masses below 114.5 GeV and between 147 GeV and 179 GeV [9].

Using proton-proton collisions at the LHC, the ATLAS and CMS experiments reported the discovery of a Higgs-like particle on July 4, 2012. The particle was observed at a mass around 126 GeV, with ATLAS reporting a local significance of 5.0σ [10], and CMS observing 4.9σ [11]. The addition of the $H \rightarrow WW^*$ analysis to the ATLAS results at the end of July resulted in the overall discovery significance growing to 5.9σ . For the discoveries, the ATLAS experiment used $4.8 (5.8) \text{ fb}^{-1}$ of data, while the CMS experiment used $5.1 (5.3) \text{ fb}^{-1}$ of data in 2011 (2012) collisions. Since the discovery was announced, approximately 15 fb^{-1} more of data has been collected.

Despite its success, the SM contains many shortcomings. The SM does not take into account the fourth fundamental force: gravity. The theory does not address the abundance of matter with respect to anti-matter in today's universe. This conflicts with the prediction that matter and anti-matter should have been created in equal amounts at the beginning of the universe. The Higgs mechanism does not

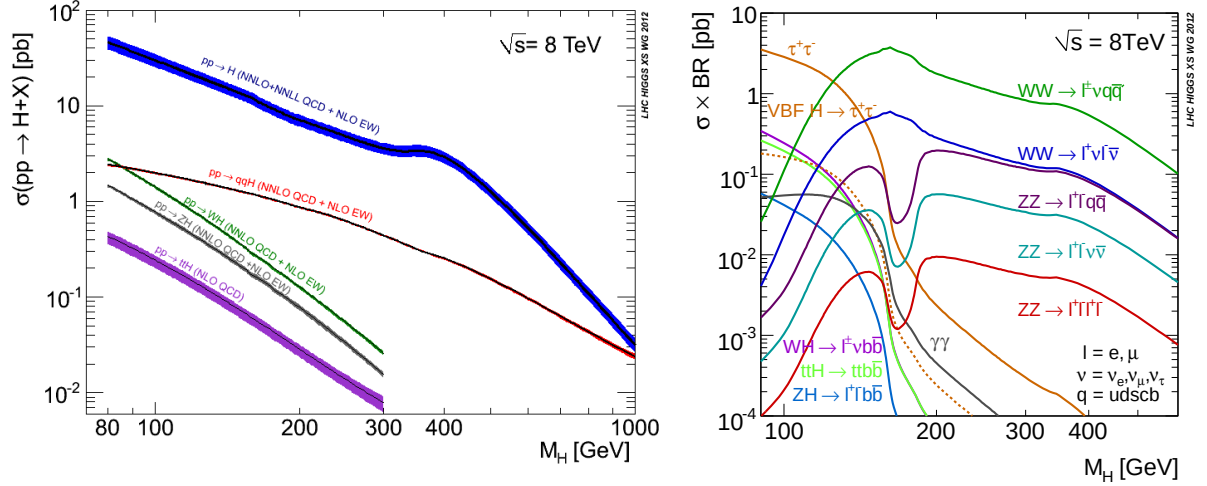


Figure 1.2: The relative cross sections of the Higgs production process: ggF, denoted by $pp \rightarrow H$, VBF, denoted by $pp \rightarrow qqH$, and production in association with $W/Z/t\bar{t}$ (left). The cross section multiplied by the branching ratio for all Higgs production modes and decays (right) [13].

account for the experimental observation that neutrinos have mass. Additionally, the SM cannot explain the fact that the universe consists of 24% Dark Matter and 71% Dark Energy, as demonstrated by cosmological observations of cosmic background radiation, gravitational lensing, and red shifts of galaxies [12]. The Hierarchy problem is one of the main outstanding issues within the SM. This problem is concerned with the question of why the weak force is much stronger than gravity. An additional shortcoming of the SM is that despite being theoretically possible, experimentally it is observed that quantum chromodynamics does not break CP symmetry. Another inconvenience is that the electromagnetic, weak and strong coupling constants do not unify when extrapolated to higher energies.

Many theories including, Supersymmetry (SUSY), composite-Higgs models, vector-like quarks, axion models, baryogenesis models, grand unified theories and string theories, offer solutions to the problems within the SM. Thus far, no evidence of these theories has been uncovered. Analysing the full 25 fb^{-1} dataset can further validate the Standard Model and can reveal deviations from it. Deviations from the Standard Model would be an indication of exotic theories that can account for the SM's shortcomings. The Higgs boson and its properties are the last remaining unexplored sectors of the Standard Model. Exploring the Higgs sector is a vital component in validating the SM and detecting deviations from it.

This thesis describes the search for the Higgs boson which decays to WW^* bosons, which subsequently decay to leptons and neutrinos, using the full 25 fb^{-1} dataset. For this analysis, The Higgs boson is produced via gluon fusion (ggF) and vector boson fusion (VBF). The ggF and VBF production processes have the largest cross section when compared to Higgs production in association with a W/Z boson, or a $t\bar{t}$ pair. This can be seen in Figure 1.2, which shows the relative Higgs production cross sections simulated for 8 TeV data. The Higgs decays to WW^* bosons, with an expected branching ratio of 22% [13]. The WW^* bosons decay to two leptons and two neutrinos in 11% of all WW^* decays. Since the Higgs has zero charge, its leptonic decay products must be oppositely charged in order to satisfy the conservation of charge. The right of Figure 1.2 shows that the relative production cross section (σ) multiplied by the branching ratio (BR) of the Higgs decaying to WW^* bosons that decay leptonically is relatively high compared to some other decay modes. The presence of neutrinos in the final decay states means the Higgs boson mass cannot be fully reconstructed, leading to a poor mass resolution.

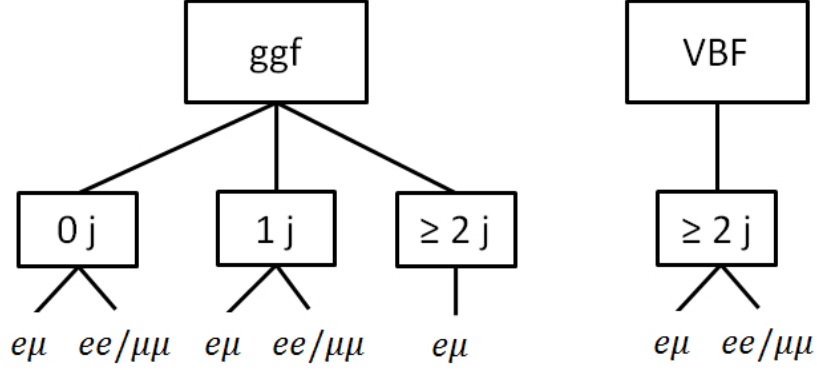


Figure 1.3: The representation of the different channels in which the $H \rightarrow WW^*$ search is performed. The ggF production process is searched for in the $e\mu$ (DF) and $ee/\mu\mu$ (SF) 0- and 1-jet channels and the $e\mu$ (DF) ≥ 2 -jet channel. The VBF production process is searched for in the $e\mu$ (DF) and $ee/\mu\mu$ (SF) ≥ 2 -jet channels.

Despite the high cross section times branching ratio, extracting the $H \rightarrow WW^*$ process is challenging since there exist many background processes that resemble the signal process. These backgrounds include WW , top ($t\bar{t}$, Wt), Drell-Yan ($Z/\gamma^* + \text{jets}$), $W + \text{jets}$, multi-jet (QCD), and non- WW di-boson (WZ , ZZ , $W\gamma$, $W\gamma^*$) production. The non- WW di-boson backgrounds are denoted by VV , and the $W + \text{jets}$ and multi-jet backgrounds are referred to as *Misid*, since they contain misidentified leptons.

The analysis is performed by searching for final states containing different-flavour (DF) leptons, $e\mu$, and same-flavour leptons (SF), ee and $\mu\mu$. The different-flavour channel is split into an $e\mu$ and μe channel, depending on whether the e or μ has the higher transverse momentum. In addition to the leptons and neutrinos produced, the final states are also accompanied by 0, 1 or ≥ 2 jets, which originate from quark/gluon radiation in ggF production, and initial quarks in VBF production. The search in the ggF production mode is performed in the same-flavour and different-flavour channels with 0 or 1 jets, and in the different-flavour channel with ≥ 2 jets. The ggF same-flavour channel with ≥ 2 jets is not used since it contains lower statistics. The same-flavour channel has less statistics since it is more difficult to separate this signal from its backgrounds. The VBF search is performed in the same-flavour and different-flavour channels in association with ≥ 2 jets. A visual summary of the different search channels is shown in Figure 1.3.

In this thesis, the historical development and theoretical basis of the SM are presented in Chapter 2. The LHC and ATLAS experiments are described in Chapter 3. Chapter 4 describes the simulation of physics processes which are largely motivated by theory-based calculations. The reconstruction of physics processes from the collected data is explained in Chapter 5. A detailed summary of the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis is presented in Chapter 6. The statistical analysis techniques used to quantify the compatibility of the collected data with simulations is presented in Chapter 7. The results of the statistical analysis are shown in Chapter 8. Finally, the conclusions and future outlook are presented in Chapter 9.

Chapter 2

Theory of the Standard Model

This chapter summarizes the evolution of the Standard Model. The theory of electromagnetism is described in Section 2.1, followed by the discovery of the weak force in Section 2.2. These two forces are unified into the electroweak force in Section 2.3. Within the unified electroweak theory, the Higgs mechanism, as described in Section 2.4, is developed in order to explain the massive nature of particles. The strong interaction is detailed in Section 2.5, and the concept of renormalization is discussed in Section 2.6. Finally Section 2.7 consolidates the previous sections and presents the full Standard Model.

2.1 Electromagnetic Interactions: Quantum Electrodynamics

In 1864 James Clerk Maxwell modified Ampere's law and combined it with Gauss's law and Faraday's law to form four equations that explain the relationship between electricity and magnetism [14]. Maxwell's four equations are shown below:

$$\begin{aligned}\nabla \cdot \mathbf{E} &= \frac{\rho}{\epsilon_0} \\ \nabla \cdot \mathbf{B} &= 0 \\ \nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t} \\ \nabla \times \mathbf{B} &= \mu_0 \mathbf{J} + \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}.\end{aligned}\tag{2.1}$$

In equation 2.1, $\mathbf{E}$ is the electric field, $\mathbf{B}$ is the magnetic field, $\mathbf{J}$ is the total current density, ρ is the total charge density, μ_0 is the permeability of free space, ϵ_0 is the permittivity of free space, and the speed of light in free space, c , is $\frac{1}{\sqrt{\mu_0 \epsilon_0}}$.

Maxwell's equations are incompatible with Newtonian mechanics. The equations imply that the speed of light in a vacuum is a universal constant and thus the same in every inertial reference frame. The fact that the speed of light is independent of the movement of its source contradicts the Newtonian notion that vector velocities can be added. To rectify this, Einstein proposed the special theory of relativity in 1905 [15].

Unfortunately, special relativity and Maxwell's view of light as an electromagnetic wave were not consistent with the quantum mechanical picture suggested by Max Planck in 1900. His description,

along with subsequent work by Albert Einstein, Werner Heisenberg, Wolfgang Pauli, Pascual Jordan, Erwin Schrödinger, and Paul Dirac, led to the development of Quantum Mechanics, which describes light as consisting of discrete quanta, called photons.

In 1927 Dirac reconciled special relativity with Quantum Mechanics by describing the path of a relativistic moving electron [16]. Dirac's equation of motion can be used to describe all spin $\frac{1}{2}$ massive particles with vector interactions and is given by

$$(i\gamma^\mu \partial_\mu - m)\psi(x) = 0. \quad (2.2)$$

In equation 2.2, $\psi(x)$ are fields describing fermions, γ^μ are the gamma matrices [17] and $x = x_\mu$. The corresponding Dirac Lagrangian is given by

$$\mathcal{L} = \bar{\psi}(x)(i\gamma^\mu \partial_\mu - m)\psi(x). \quad (2.3)$$

When constructing the equation of motion, Dirac required it to be relativistically, or *Lorentz*, invariant. This means that if a rotation or boost is performed on a field, taking it to a new reference frame, the equations of motion remains the same. A consequence of Dirac's theory is the prediction of negative energy states, which can be interpreted as particles with the same mass as SM particles, but opposite charge. Such particles, called *antiparticles*, were confirmed to exist with the discovery of the positron in 1931 by Carl Anderson [18], and the antiproton and antineutron in 1955 and 1956, respectively, at the Berkeley Bevatron [19, 20].

Field transformations, such as rotations and boosts, can be expressed using in group theory. The fields can be transformed to other coordinate systems using a *complex* phase, $i\alpha$. These transformations form groups of symmetries, in this case referred to as the U(1) group. The physical system then corresponds to a class of mathematical configurations, expressed in different reference frames, and related to one another by this symmetry transformation. This ensures that physical observables are calculable and finite, regardless of what reference frame is used to describe them. The Dirac equation is invariant under *global* U(1) transformation, in which the complex phase, α , does not depend on space-time coordinate x . The fields transform from $\psi(x)$ to $\psi'(x)$ under this transformation as

$$\begin{aligned} \psi(x) &\rightarrow \psi'(x) = e^{-ieQ\alpha}\psi(x) \\ \partial_\mu\psi(x) &\rightarrow e^{-ieQ\alpha}\partial_\mu\psi(x). \end{aligned} \quad (2.4)$$

In equation 2.4, e is the fundamental unit of electric charge and Q represents the charge operator ($Q\psi(x) = -\psi(x)$ for electrons).

In order for a theory to be *renormalizable* (see Section 2.6), it is necessary for the equation of motion and the Lagrangian to be invariant under *local* transformations, in which the phase is dependent on space-time coordinates, $\alpha(x)$. Making the Dirac fields and their partial derivatives invariant under local U(1) transformations yields

$$\begin{aligned} \psi(x) &\rightarrow \psi'(x) = e^{-ieQ\alpha(x)}\psi(x) \\ \partial_\mu\psi(x) &\rightarrow e^{i\alpha(x)}\partial_\mu\psi(x) - ieQ(\partial_\mu\alpha(x))e^{-ieQ\alpha(x)}\psi(x). \end{aligned} \quad (2.5)$$

Since the partial derivative is not invariant under this transformation, a new invariant derivative, referred to as the *covariant derivative*, must also be defined. The covariant derivative is defined as

$$D_\mu \equiv \partial_\mu + ieQA_\mu(x). \quad (2.6)$$

In order to make the derivative term invariant under local U(1) transformation, a new type of field, $A_\mu(x)$, is necessarily introduced. The new field and covariant derivative transform under the local U(1) symmetry as

$$\begin{aligned} A_\mu(x) &\rightarrow A_\mu(x) - \frac{1}{e}\partial_\mu\alpha(x) \\ D_\mu\psi(x) &\rightarrow e^{-ieQ\alpha(x)}D_\mu\psi(x). \end{aligned} \quad (2.7)$$

Using these definitions it is possible to obtain a Lagrangian of the theory. The individual terms of the Lagrangian must obey symmetries that are observed in nature. *Parity*, denoted by P, is a symmetry that reverses the handedness of space, meaning $(t, x) \rightarrow (t, -x)$, where t represents time, and x represents three dimensional space. Parity is a transformation that tests a property called *chirality*. A chiral object, such as a human hand, is distinguishable from its mirror image, while an achiral object, such as a sphere, is not. Time reversal, denoted by T, is a symmetry that interchanges forward and backward time, sending $(t, x) \rightarrow (-t, x)$. Charge conjugation is a symmetry, denoted by C, under which particles and anti-particles are interchanged. The theory of electromagnetic interactions is symmetric with respect to P, C and T. The Lagrangian describing electrodynamics (QED) satisfies this criterion and is invariant under the U(1) group of transformations:

$$\mathcal{L}_{QED} = \bar{\psi}(x)(i\gamma^\mu D_\mu - m)\psi(x) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}. \quad (2.8)$$

In equation 2.3, $\bar{\psi}(x) = \psi^\dagger(x)\gamma^0$ is the adjoint of the $\psi(x)$ field. The term, $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$, is the electromagnetic field tensor. When the Lagrangian is expanded, the first term, $\bar{\psi}i\gamma^\mu D_\mu\psi$, corresponds to the kinetic energy of the system. The second term, $m\bar{\psi}\psi$, corresponds to the mass term, where m is the mass of the particle represented by the ψ field. The last term, $F_{\mu\nu}F^{\mu\nu}$, represents the propagation of the A_μ fields. A mass term for the A_μ field of the form $mA_\mu A^\mu$ is not gauge invariant and is excluded from the Lagrangian. The A_μ field is a spin-1 massless gauge boson, which represents the photon.

By applying the Euler-Lagrange equation [21] to the Lagrangian in 2.8, it is possible to obtain Maxwell's equations. To achieve this, it is necessary to define the electric and magnetic fields in terms of the fundamental fields: $\mathbf{E} = \frac{\partial \mathbf{A}}{\partial t} - \nabla\phi$, $\mathbf{B} = \nabla \times \mathbf{A}$. These equations contain in them the conservation of electromagnetic current, which also implies conservation of charge. This is an illustration of Emmy Noether's theorem which states that if a system is invariant under a differentiable symmetry, there exist corresponding quantities whose values are conserved in time [22].

QED is an elegant theory that provides a framework for calculating cross sections of processes involving charged fundamental particles. However, in the early versions of QED, these cross sections diverged when they were calculated beyond leading order in perturbation theory. In particular, during the 1940's it was shown that discrepancies existed between QED and experimentally measured shifts of the levels of hydrogen, known as the Lamb Shift [23]. It is possible to explain the Lamb Shift by redefining the mass and charge of QED to absorb the divergences. This procedure, known as renormalization, allowed

for finite cross section calculations beyond leading-order perturbations. The concept of renormalization gave QED a strong foundation and is discussed in Section 2.6, in the context of electroweak and strong interactions.

2.2 Weak Interactions

Quantum electrodynamics explains how charged particles interact with the electromagnetic field. It is unable to explain processes such as β decay in which a proton or neutron can change into one another with the emission of an electron or positron. In 1930, Wolfgang Pauli proposed the existence of the neutrino in order to preserve energy, momentum and angular momentum (spin) conservation in β decays [24]. Two years later James Chadwick discovered the neutron by analyzing scattering data [25]. Armed with the proton, neutron, and neutrino, Enrico Fermi, in 1934, proposed that β decay can be explained by a four-fermion interaction, referred to as the *weak* interaction [26]. He suggested that the weak interaction was a contact force with no range. This theory provided accurate results at low energies but failed at higher energies and was not renormalizable.

Additional properties of weak interactions were discovered that required more complex theories to explain them. Helicity is the projection of the direction of the spin of a particle along its momentum. Helicity is defined as positive (right-handed) if the momentum and spin are in the same direction, and negative (left-handed) if they are in opposite directions. It was observed that Parity was not a symmetry of the weak interactions [27]; neutrinos have left-handed helicity, while anti-neutrinos are always right-handed [28]. Electrons have negative chirality (left-handed), while positrons have positive chirality (right-handed).

These observations suggested that the weak interaction does not behave the same way for a particle and its mirror particle. Thus Fermi's theory was modified to include the fact that weak interactions treat left- and right-handed particles differently. The fields in Fermi's theory were replaced with right- and left-handed fields, which were defined by transformations under chiral projection operators P_L and P_R :

$$\begin{aligned}\psi_R &= P_R \psi = \frac{1}{2}(1 + \gamma_5) \\ \psi_L &= P_L \psi = \frac{1}{2}(1 - \gamma_5).\end{aligned}\tag{2.9}$$

Equation 2.9 implies that charged weak interactions have a vector minus axial vector (V-A) nature, in which vectors are objects whose Lorentz structure of interactions is given by γ_μ , while axial vectors have a $\gamma_5 \gamma_\mu$ structure. The modified Fermi theory was useful in describing the observed leptonic weak decays.

It defined left-handed leptonic doublets, $\Psi_\ell = \begin{pmatrix} \ell \\ \nu_\ell \end{pmatrix}$, and right-handed singlets, $\psi_R = \ell_R$.

It is necessary to explain the role that weak interactions play in hadronic decays. The current theory of weak interactions is explained with the help of the quark model, whose development is described in Section 2.5. Weak interactions allow for mixing between quark generations. Up-type quarks are able to change into down-type quarks of different generations. In addition, it was observed that the weak interaction breaks the combined charge-parity (CP) symmetry [29]. These facts are accounted for by the proposal that weak interactions mediate mixtures of three generations of quark states, defined by the

Cabibbo-Kobayashi-Maskawa (CKM) matrix [30]. The CKM matrix accommodated the small amount of CP violation by including a complex phase factor. The CKM matrix in its current form is given by

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}. \quad (2.10)$$

The physical quarks in hadrons, denoted by d', s', b' , are mixtures of the d, s, b quarks characterized by their mixing angles, θ_{ij} for quarks i, j [31]. The V_{ij} terms for i, j quarks are combinations of the quark mixing angles. These values are determined from various experiments.

Despite the many modifications made to weak theory to include all the observed properties, a complete theory of weak interactions was not developed until electroweak unification, as described in Section 2.3.

2.3 Electroweak Unification

In 1954, Chen Ning Yang and Robert Mills extended the gauge theory for abelian groups (QED) to nonabelian groups. The Yang-Mills theory includes fields that are invariant under SU(2) gauge transformations [32]. This theory is used to explain the weak force component in the unified electroweak theory developed by Sheldon Glashow, Abdus Salam and Steven Weinberg (and others) in 1962 and 1967 [33, 8].

Since the SU(2) model alone cannot take into account electromagnetism, the unified theory was proposed to be invariant under SU(2) $\times$ U(1) transformations, as shown below:

$$\psi(x) \rightarrow e^{\frac{i}{2}\alpha(x)Y + \frac{i}{2}\beta_a(x)\tau^a} \psi(x). \quad (2.11)$$

In equation 2.11, the $e^{\frac{i}{2}\beta_a(x)\tau^a}$ term represents SU(2) transformations. The τ^a are Pauli matrices, τ^1, τ^2, τ^3 . The generators of the SU(2) group are given by $T^a = \frac{1}{2}\tau^a$.

These generators satisfy the commutation relations $[T_a, T_b] = i\epsilon_{abc}T_c$, where ϵ_{abc} are the structure constants of the group. The invariance under the SU(2) group leads to conservation of a quantity called *weak isospin*. The $e^{\frac{i}{2}\alpha(x)Y}$ term represents the U(1) transformation. The Y terms are the generators of the U(1) group, and satisfy $[Y_a, Y_b] = 0$. Invariance of terms under the U(1) group leads to conservation of hypercharge, Y .

In order to construct a Lagrangian invariant under this symmetry the partial derivative must be replaced by the covariant derivative:

$$D_\mu \equiv (\partial_\mu - \frac{i}{2}g_1 Y B_\mu - \frac{i}{2}g_2 \tau_a W_\mu^a). \quad (2.12)$$

To obtain this covariant derivative, it was necessary to introduce a spin-1 field triplet, $W_\mu^a = (W_\mu^1, W_\mu^2, W_\mu^3)$, as the SU(2) gauge field, and a spin one field singlet, B_μ , as a U(1) gauge field. The dependence of the fields on x is dropped in the notation, but is implied. The fields transform under the

Leptons	$\Psi_L = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$
	$\psi_R = e_R$	μ_R	τ_R
Quarks	$\Psi_L = \begin{pmatrix} u \\ d' \end{pmatrix}_L$	$\begin{pmatrix} c \\ s' \end{pmatrix}_L$	$\begin{pmatrix} t \\ b' \end{pmatrix}_L$
	$\psi_R = u_R$	c_R	t_R
	d_R	s_R	b_R

Table 2.1: The lepton and fermion doublets and singlets in electroweak theory. The primed quark states are mixtures of quark fields given by the CKM matrix.

SU(2) $\times$ U(1) operations as

$$\begin{aligned}
 B_\mu &\rightarrow B'_\mu = B_\mu - \frac{1}{g_1} \partial_\mu \alpha(x) \\
 W_\mu^a &\rightarrow W'^a_\mu = W_\mu^a - \frac{1}{g_2} \partial_\mu \beta^a + \epsilon_{abc} \beta^b W_\mu^c.
 \end{aligned}
 \tag{2.13}$$

The unified electroweak theory must take into account the left-handed nature of charged weak interactions. Thus lepton fields are defined as doublets containing left-handed electrons, muons, taus and neutrinos, Ψ_L , and right-handed singlets, ψ_R , containing right-handed electrons, muons and taus. The quarks are also placed into left-handed doublets, and right-handed singlets. This is summarized in Table 2.1.

The left-handed doublets transform under the SU(2) group, denoted as SU(2)_L, while the right-handed singlets transform under the U(1) group, denoted as U(1)_Y. The Lagrangian of the unified electroweak theory is then given by

$$\mathcal{L}_{EW} = \bar{\Psi}_L i \gamma^\mu D_\mu \Psi_L + \bar{\psi}_R i \gamma^\mu D_\mu \psi_R - \frac{1}{4} W_a^{\mu\nu} W_{\mu\nu}^a - \frac{1}{4} B^{\mu\nu} B_{\mu\nu}.
 \tag{2.14}$$

In equation 2.14, the a indices represent the three components of the τ^a matrices and the W_μ^a field. The covariant derivative transforming ψ_R does not have a $\frac{i}{2} g_2 \tau_a W_\mu^a$ term. The field tensors are given by

$$\begin{aligned}
 W_{\mu\nu}^a &= \partial_\mu W_\nu^a - \partial_\nu W_\mu^a + g_2 \epsilon_{abc} W_\mu^b W_\nu^c \\
 B_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu.
 \end{aligned}
 \tag{2.15}$$

In equation 2.13, the B_μ terms do not have a cross product term since the generators of the U(1)_Y group (Y) commute.

The electroweak Lagrangian describes massless fermions and massless gauge boson fields (W_μ^1 , W_μ^2 , W_μ^3 and B_μ). However, fermions have mass. A mass term of the form $m \bar{\Psi} \Psi$ cannot simply be added since it would not be invariant under a SU(2)_L $\times$ U(1)_Y transformation. Thus another mechanism is needed to describe how fermions obtain their mass.

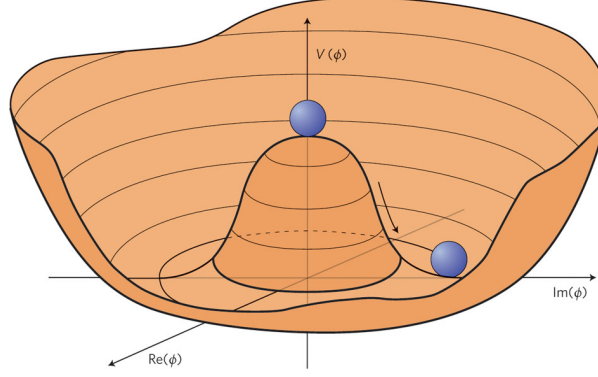


Figure 2.1: The potential, $V(\Phi)$, in the Higgs Lagrangian, for $\lambda > 0$, and $\mu^2 < 0$. The potential is drawn along its real and imaginary axes [36].

2.4 The Englert-Brout-Higgs Mechanism

2.4.1 Higgs and Gauge Boson Masses

A mechanism by which particles obtain mass was first proposed by Philip Warren in 1963 [34]. The relativistic version was developed in 1964 by three groups independently: Peter Higgs; Robert Brout and Francois Englert; and Gerald Guralnik, Carl Hagen, and Tom Kibble [5, 6, 35]. When trying to add a term to the Lagrangian that will lead to mass terms, two conditions must be met:

1. The potential, V , of the Lagrangian must be at most fourth order in the fields in order to ensure a renormalizable theory.
2. The potential, V , of the Lagrangian, must be bounded from below so that the theory has a stable ground state.

Following these criteria, a term can be added to the electroweak Lagrangian that is of the form

$$\mathcal{L}_{Higgs} = (D_\mu \Phi)^\dagger (D_\mu \Phi) - (\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2). \quad (2.16)$$

In equation 2.16, $\lambda > 0$ is required in order to ensure the stability of the vacuum. The last two terms in equation 2.16 represent the potential term, $V(\Phi)$, in its most general renormalizable form. The Higgs field, Φ , consists of complex fields arranged in an isodoublet:

$$= \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}. \quad (2.17)$$

The minimum value of the potential corresponds to the vacuum state and is obtained by solving $V'(\Phi) = 0$. For $\mu^2 > 0$, the minima occur at $\phi_i = 0$. For $\mu^2 < 0$ the potential resembles a Mexican hat shown in Figure 2.1. The minima occur along a circle of the Mexican hat radius at values of

$$\Phi^\dagger \Phi = \phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2 = -\frac{\mu^2}{\lambda}. \quad (2.18)$$

It is possible to choose a certain minimum, defined by $\phi_1 = \phi_2 = \phi_4 = 0$, $\phi_3 = v = -\frac{\mu^2}{\lambda}$, where v is referred to as the *vacuum expectation value*. Choosing a minimum is called spontaneously breaking the

symmetry. There is no loss of generality in choosing this minimum, since the original form of the fields can be obtained by a $SU(2) \times U(1)$ rotation. Although the original generators T and Y are broken, the operator $Q = T^3 - Y/2$ remains unbroken. This means that the remaining symmetry of the theory is $U(1)_{em}$. This allows the photon to remain massless, while the W_μ, B_μ fields mix and acquire mass. After choosing a minimum, the Higgs field can be expressed as

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}. \quad (2.19)$$

Quantized fluctuations of a field about its lowest energy state, v , correspond to particle excitations. Thus expanding the field around a vacuum by a perturbation $H(x)$, the field becomes

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}. \quad (2.20)$$

The field can be parametrized by another $SU(2)$ transformation:

$$\Phi = e^{i\vec{\tau} \cdot \vec{\xi}/2v} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}. \quad (2.21)$$

In equation 2.21 $\vec{\xi} = (\xi^1, \xi^2, \xi^3)$, where the ξ^i terms are called Goldstone bosons. Under this transformation, the new Lagrangian contains Goldstone bosons that do not have mass. There are no physical particles that corresponds to these Goldstone bosons. For this reason, fields and their derivatives are transformed to another basis which has a physical interpretation. A gauge called the *unitary* gauge is used in which the Goldstone bosons disappear and the remaining fields can be interpreted in a physical sense. The unitary gauge is a $SU(2)$ transformation given by $U(\vec{\xi}) = e^{-i\vec{\tau} \cdot \vec{\xi}/2v}$. Under this transformation the fields transform as

$$\begin{aligned} \Phi' &= U(\xi)\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix} = \frac{1}{\sqrt{2}}(v + H)\chi \\ \Psi'_L &= U(\xi)\Psi_L \\ \vec{W}'_\mu &= U(\xi)\vec{W}'_\mu U(\xi)^{-1} - \frac{i}{g_2}(\partial_\mu U(\xi)U^\dagger(\xi)). \end{aligned} \quad (2.22)$$

In equation 2.22, $\chi = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$ and $\vec{W}'_\mu = \vec{W}_\mu \cdot \frac{\vec{\tau}}{2}$. The B_μ and ψ_R fields remain unchanged under this transformation ($\psi'_R = \psi_R, B'_\mu = B_\mu$). Under the unitary gauge transformation the potential term, $V(\Phi)$ of $\mathcal{L}_{Higgs}$ becomes

$$V(\Phi') = -\frac{\mu^2 v^2}{4} + \frac{1}{2}(2\mu^2)H^2 + \lambda v H^3 + \frac{\lambda}{4}H^4. \quad (2.23)$$

Equation 2.23 suggests the existence of a massive gauge field of spin 0, referred to as the Higgs boson. The mass of this field can be read off from the H^2 terms, as $M_H = \sqrt{2\mu^2}$. The H^3 and H^4 terms demonstrate that the Higgs boson couples to itself via 3-point and 4-point vertices.

Under the unitary transformations the $(D_\mu \Phi)^\dagger D_\mu \Phi$ component of $\mathcal{L}_{Higgs}$ becomes

$$(D_\mu \Phi)^\dagger D'_\mu \Phi = \partial_\mu H \partial^\mu H - \frac{1}{8}(v + H)^2 g_2^2 |W_\mu'^1 - iW_\mu'^2|^2 - \frac{1}{8}(v + H)^2 (g_2 W_\mu'^3 - g_1 B'_\mu)^2. \quad (2.24)$$

From equation 2.24, the terms that can be interpreted as the mass of the gauge boson fields are given by

$$\frac{v^2}{8} (g_2^2 W_\mu'^1 W^{1\mu'} + g_2^2 W_\mu'^2 W^{2\mu'} + (g_2 W_\mu'^3 - g_1 B'_\mu)^2). \quad (2.25)$$

Equation 2.25 highlights the fact that the $W_\mu'^1$ and $W_\mu'^2$ terms do not mix with any other fields and only appear in the combination $W_\mu'^1 W^{1\mu'} + W_\mu'^2 W^{2\mu'}$. Their masses can therefore be directly read off as $\frac{g_2 v}{2}$.

It is convenient to write the fields as two degrees of freedom belonging to a particle and its antiparticle:

$$W^\pm = \frac{W_\mu'^1 \mp iW_\mu'^2}{\sqrt{2}}. \quad (2.26)$$

With this definition of charged bosons the sum of the first two terms in equation 2.25 can be rewritten as $\frac{1}{4} g^2 v^2 W_\mu^+ W_\mu^-$. This allows the constants to be interpreted as the mass of the charged bosons: $M_{W^\pm} = \frac{1}{2} g v$.

The third term in equation 2.25, $(g_2 W_\mu'^3 - g_1 B'_\mu)^2$, consists of neutral fields and can be written as

$$\frac{v^2}{8} \begin{pmatrix} W_\mu'^3 & B'_\mu \end{pmatrix} \begin{pmatrix} g_2^2 & -g_2 g_1 \\ -g_2 g_1 & g_1^2 \end{pmatrix} \begin{pmatrix} W_\mu'^3 \\ B'_\mu \end{pmatrix}. \quad (2.27)$$

The above term can be diagonalized by the orthogonal transformation:

$$\begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix} = \begin{pmatrix} \cos \theta_W & -\sin \theta_W \\ \sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} W_\mu'^3 \\ B'_\mu \end{pmatrix}, \quad (2.28)$$

where θ_W is called the Weinberg angle, or weak mixing angle. This angle is not theoretically predicted and is obtained from experiment. With this orthogonal transformation the third term of $\mathcal{L}_{Higgs}$ becomes

$$\frac{v^2}{8} \begin{pmatrix} Z_\mu & A_\mu \end{pmatrix} \begin{pmatrix} g_2^2 + g_1^2 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix} = \frac{v^2}{8} (g_2^2 + g_1^2) Z_\mu Z^\mu + 0 \cdot A_\mu A^\mu. \quad (2.29)$$

The diagonalization led to the introduction of two other fields: Z_μ and A_μ . Equation 2.29 shows that the A_μ field is massless, and can thus be interpreted as the photon field. The Z_μ field represents a massive gauge boson, whose mass can be read from equation 2.29 as $M_Z = \frac{1}{2} v \sqrt{g_2^2 + g_1^2}$. The diagonalization leads to defining the Weinberg angle as $\tan \theta_W = \frac{g_1}{g_2}$, or equivalently $\sin \theta_W = \frac{g_1}{\sqrt{g_2^2 + g_1^2}}$ or $\cos \theta_W = \frac{g_2}{\sqrt{g_2^2 + g_1^2}}$. The $W^\pm$ and Z boson masses are proportional to $1/\sin \theta_W$ and $1/\cos \theta_W$, respectively, and their values can be predicted from the experimentally obtained value of θ_W . The masses were predicted and the bosons were experimentally confirmed in 1983 [37, 38].

Thus after the unitary gauge transformation and with definitions of the $W^\pm$ and Z_μ fields, the final Higgs Lagrangian is

$$\begin{aligned}
\mathcal{L}_{Higgs} = & \frac{1}{2}(\partial_\mu H)^2 - \frac{1}{2}M_H^2 - \lambda v H^3 - \frac{\lambda}{4}H^4 \\
& + \frac{g^2}{8}(H^2 + 2Hv)\left[\frac{1}{\cos^2\theta_W Z_\mu Z^\mu} + 2W_\mu^+ W^{-\mu}\right] \\
& + M_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2}M_Z^2 Z_\mu Z^\mu.
\end{aligned} \tag{2.30}$$

2.4.2 Fermion Masses

The previous section shows how the Higgs mechanism leads to the prediction of the Higgs, $W^\pm$ and Z gauge boson fields and how their masses are obtained. In order to ensure that fermions obtain a mass, it is necessary to add an additional term that couples fermions to scalars. This term is called the Yukawa term and is given by

$$\mathcal{L}_{Yukawa} = -(\Gamma_{i,j}^\ell \bar{\Psi}_L^\ell \Phi \psi_R^\ell + \Gamma_{i,j}^D \bar{\Psi}_L^Q \Phi \psi_R^D + \Gamma_{i,j}^U \bar{\Psi}_L^Q \Phi^\dagger \psi_R^U) + h.c. \tag{2.31}$$

In equation 2.31, the field doublets and singlets are split into their lepton and quark components. The lepton doublet and singlet are represented by Ψ_L^ℓ and ψ_R^ℓ , the left-handed up- and down-type quark doublets are represented by Ψ_L^Q , and the right-handed up- and down-type quark singlets are represented by ψ_R^U and ψ_R^D respectively. The $\Gamma_{i,j}$ terms are Yukawa coupling matrices for leptons and up and down quarks. These matrices contain terms of the Yukawa couplings $y_{i,j}$ for each fermion flavour i, j . The Yukawa couplings are not predicted by theory and must be obtained by experiment. In equation 2.31 the sum of lepton and quark flavours is implied. After symmetry breaking in the unitary gauge the Yukawa term takes the form

$$\begin{aligned}
\mathcal{L}'_{Yukawa} = & -\Gamma_{i,j}^\ell \Psi_L'^\ell \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix} \psi_R'^\ell - \Gamma_{i,j}^D \Psi_L'^Q \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix} \psi_R'^D - \Gamma_{i,j}^U \bar{\Psi}_L'^Q \frac{1}{\sqrt{2}} \begin{pmatrix} v + H \\ 0 \end{pmatrix} \psi_R'^U \\
= & -\frac{v}{\sqrt{2}} \Gamma_{ij}^\ell \bar{\Psi}_L'^\ell \psi_R'^\ell - \frac{1}{\sqrt{2}} \Gamma_{ij}^\ell \bar{\Psi}_L'^\ell \psi_R'^\ell H - \frac{v}{\sqrt{2}} \Gamma_{ij}^D \bar{\Psi}_L'^Q \psi_R'^D - \frac{1}{\sqrt{2}} \Gamma_{ij}^D \bar{\Psi}_L'^Q \psi_R'^D H \\
& - \frac{v}{\sqrt{2}} \Gamma_{ij}^U \bar{\Psi}_L'^Q \psi_R'^U - \frac{1}{\sqrt{2}} \Gamma_{ij}^U \bar{\Psi}_L'^Q \psi_R'^U H + h.c.
\end{aligned} \tag{2.32}$$

The fermion mass terms can be read off as $m = \frac{y_{ij}v}{\sqrt{2}}$. The primed fields represent the fermion fields in the unitary gauge. The terms containing H represent the fermion couplings to the Higgs boson.

2.5 Strong Interactions: Quantum Chromodynamics

Strong interactions were hypothesized in order to explain why the nucleus does not fly apart due to the repulsion of positive protons. The invention of bubble chambers and spark chambers in the 1950's led to many discoveries of new heavy hadrons [39]. The hadrons were produced fast and decayed slowly, which provided evidence that their production and decay mechanisms were governed by different forces. To explain why these particles decayed more slowly than they were produced, it was suggested that some particles carried *strangeness* [40]. Strangeness was conserved in strong interactions that mediated the particle production, but not in weak interactions that mediated their decay. Strangeness did not apply

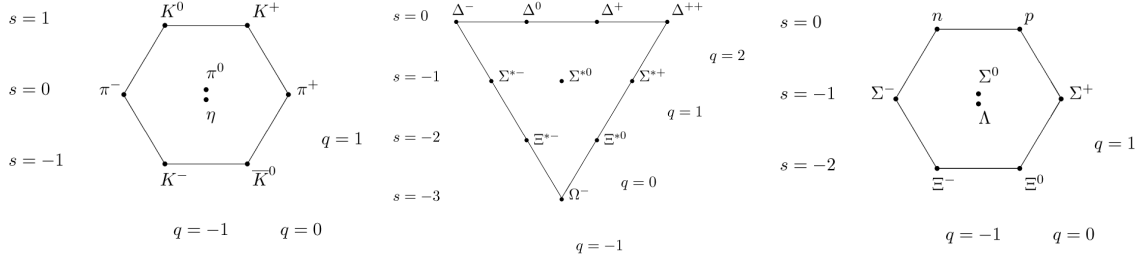


Figure 2.2: Hadrons arranged in the hexagonal and triangular shapes based on their mass, charge and strangeness [42].

to leptons and photons since they do not experience the strong force.

In 1962, Murray Gell-Mann arranged all the newly discovered hadrons in geometrical patterns according to their mass, charge and strangeness [41]. These patterns, referred to as the *eightfold way*, are shown in Figure 2.2. The eight lightest hadrons fit into a hexagonal array with two particles at the centre. The ten heavier hadrons were fit into a triangular shape. Antiparticles fit into the same patterns.

To explain the patterns hadrons fit into, it was proposed that hadrons are made of three different quarks: the up (u), down (d), and strange (s) quarks. The quarks have charge and strangeness numbers associated to them that explain the patterns the hadrons fit into. Despite the fact that deep inelastic experiments confirmed this theory [43], individual quarks were not observed.

To account for this fact, in 1964 it was suggested that there exist three colour charges (red, green, blue) and that all naturally occurring particles are colourless [44]. This meant that quarks combined in quark-anti-quark pairs (colour+anti-colour), called *mesons* or triplets of each colour (red+green+blue), called *baryons*. The fact that quarks are confined in hadrons is an experimentally observed phenomenon, referred to as *confinement*, that has not been theoretically proven.

In subsequent decades, the charm, c , bottom, b and top, t quarks were discovered. The original hadron multiplets were extended into 3 dimensional supermultiplets.

The SU(3) symmetry best describes all of the observed properties of strong interactions. In its current form, it accounts for all the quarks, and predicts the existence of the strong force carrier, the gluon. The quark fields, $\psi_{q,c}$, are given by

$$\psi_{q,r} = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}, \psi_{q,b} = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}, \psi_{q,g} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}, \quad (2.33)$$

where the q indices represent quark flavour, and the $c = r, b, g$ indices represent the red, blue and green quark colours. The colour fields transform under the SU(3) colour group, denoted as SU(3) $_C$, as shown below:

$$\psi_{q,c}(x) \rightarrow \psi'_{q,c}(x) = e^{\frac{i}{2}\gamma_i(x)\lambda^i} \psi_{q,c}(x). \quad (2.34)$$

The SU(3) $_C$ group is generated by eight Gell-Mann matrices, $\lambda^{i,8}$, which are generalizations of the isospin matrices. The matrices satisfy the commutation relations $\left[\frac{\lambda^i}{2}, \frac{\lambda^j}{2}\right] = if_{ijk}\frac{\lambda^k}{2}$, where f_{ijk} are the structure constants of the group.

In order to preserve gauge invariance of the Lagrangian terms under the SU(3) $_C$ group, the covariant

derivative is defined as

$$D_\mu \equiv \partial_\mu - \frac{i}{2} g_3 \lambda^i G_\mu^i, \quad (2.35)$$

where g_3 is the strong coupling constant. The definition of the covariant derivative required the introduction of a G_μ^i term, corresponding to eight gluon fields. Each of these i gluon fields transforms as

$$G_\mu^i \rightarrow G_\mu^{i'} = G_\mu^i - \frac{1}{g_3} \partial_\mu \gamma^i(x) - f_{ijk} \gamma^j G_\mu^k. \quad (2.36)$$

The $SU(3)_C$ Lagrangian is then given by

$$\mathcal{L}_{QCD} = \bar{\psi}_{q,c} (i \gamma^\mu D_\mu - m_q) \psi_{q,c} - \frac{1}{4} G_{\mu\nu}^i G^{i\mu\nu}, \quad (2.37)$$

where m_q are the quark masses. The field strength tensor is given by

$$G_{\mu\nu}^i = \partial_\mu G_\nu^i - \partial_\nu G_\mu^i + g_3 f_{ijk} G_\mu^j G_\nu^k. \quad (2.38)$$

Like photons in QED that carry the EM force, gluons are massless spin-1 bosons that carry the strong force. However, unlike photons, which do not carry electric charge, gluons also carry colour charge. As a result gluons also interact with themselves, while photons do not. The gluon-gluon self interaction is responsible for the different behaviour of QCD and QED, and in particular the QCD feature of confinement. The self-coupling is also responsible for the *asymptotic freedom* of QCD, described in Section 2.6.

2.6 Renormalization

Physical observables, such as charge or mass, must be computed beyond leading order perturbations in order to obtain an accurate representation of all paths through which a physics process can occur. Calculations beyond leading order involve Feynman diagrams that contain closed loops of virtual particles. Since the particles in the loop are virtual, they can have any momenta, and thus the loop contribution must be integrated over all possible momenta from zero to infinity. This integration leads to divergent contributions to the cross section calculations. In order to resolve this, the terms that appear in the Lagrangian that represent particle characteristics such as mass and charge can be re-interpreted. These terms do not correspond to physical quantities that are measured in the laboratory. Instead, they represent *bare* values, which do not include the virtual loop corrections that are present in the physical quantities. The Lagrangian can be re-written by redefining physical quantities that absorb the infinities. Renormalization is the process of absorbing loop corrections by redefining measurable quantities and introducing a renormalization energy scale μ_R , up to which the observables are calculated. Observable quantities are then quantifiable, but dependent on the cutoff scale, μ_R . Renormalization is a way to hide the dependence of an observable on a large energy scale by looking at the observable on a longer-distance scale.

The fact that physical quantities are finite implies that the bare quantities are also divergent and cancel the divergent corrections. A theory is renormalizable when the number of terms in the Lagrangian (which are associated to bare quantities) that is needed to cancel the loop divergences is finite. These terms must also be dependant on the cutoff scale.

When calculating observable quantities, the renormalization scale is usually chosen to be close to the energy that is exchanged in an interaction. This is done in order to minimize the contribution from loop diagrams, since increasing the renormalization scale corresponds to including more loop diagrams. The phenomenon of physical constants changing with the renormalization scale is referred to as *running*. The amount by which physical quantities change with the renormalization scale can be represented by beta-functions, β . Calculating the β functions of the coupling constants in QED and QCD can reveal underlying differences between the two theories, as demonstrated below.

If a theory is renormalizable, physical observables, R , should not depend on the cutoff scale, implying that the equation

$$\left(\mu_R^2 \frac{\partial}{\partial \mu_R^2} + \beta(g) \frac{\partial}{\partial g} \right) R = 0 \quad (2.39)$$

should be satisfied. Equation 2.39 is called a Renormalization Group Equation (RGE), in which g is the charge of the theory (electric charge in QED, colour in QCD).

The β function contains the dependence of the coupling parameter, g , on the energy scale μ . It can be written as $\beta(\alpha) = -\beta_0 \alpha^2 - \beta_1 \alpha^3 - \dots$, where $\alpha \propto g$. The α parameter can be expressed as

$$\alpha(Q^2) = \frac{\alpha(\mu_R^2)}{1 + \alpha(\mu_R^2) \beta_0 \ln \frac{Q^2}{\mu_R^2}}, \quad (2.40)$$

where Q^2 is the four-momentum-squared, transferred in an interaction between particles. The β is obtained by considering Feynman diagrams containing one loop corrections to the propagator and using the RGE. After evaluating the β function for QED, it is possible to obtain the α for QED:

$$\alpha_{EM}(\mu_R^2) = \frac{\alpha_{EM}(\mu_R^2)}{1 - \frac{\alpha_{EM}(\mu_R^2)}{3\pi} \ln \frac{Q^2}{\mu_R^2}}. \quad (2.41)$$

Equation 2.41 shows that the electromagnetic coupling strength increases for larger Q^2 , or as two charges get closer together. However this increase is very slow for currently accessible energies, and thus QED observables such as electron charge and mass appear stable.

Evaluating the β function for QCD gives the α for QCD:

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu_R^2)}{1 + \frac{\alpha_s(\mu_R^2)}{12\pi} (33 - 2n_f) \ln \frac{Q^2}{\mu_R^2}}. \quad (2.42)$$

In the above equation n_f is the number of quark flavours, which is six in the Standard Model. This equation shows that the behaviour of α_s is very different from that of α_{EW} . The α_s term decreases with increasing momenta transfer (or decreasing distance). In fact α_s goes to 0 as $Q^2 \rightarrow \infty$. This behaviour is referred to as *asymptotic freedom* and is the result of the contribution of gluon self interaction loops in the calculation of the β function.

Unlike α_{EW} , α_s varies substantially over the accessible energy scale. Since α_s grows quickly, the perturbative expansion of the β function in terms of powers of α quickly breaks down.

The energy scale at which this occurs, Λ , is experimentally found to be approximately 200 MeV. Below 200 MeV (at long distances) the perturbative regime breaks down, and numerical methods such as lattice QCD are used [45]. The Λ scale can be defined as

$$\Lambda = \mu_R^2 \exp \left(\frac{-12\pi}{(33 - 2n_f)\alpha_s(\mu_R^2)} \right). \quad (2.43)$$

2.7 The Standard Model

The Standard Model is a theory that unifies the electroweak and strong interactions. The fields in this theory are invariant under the local $SU(3)_C \times SU(2)_L \times U(1)_Y$ transformations. The fields transform as

$$\psi \rightarrow \psi' = e^{\frac{i}{2}\alpha(x)Y + \frac{i}{2}\beta_a(x)\tau^a + \frac{i}{2}\gamma_i(x)\lambda^i} \psi \quad (2.44)$$

The covariant derivative is given by

$$D_\mu \equiv \partial_\mu + \frac{i}{2}g_1 Y B_\mu + \frac{i}{2}g_2 \tau_a W_\mu^a + \frac{i}{2}g_3 \lambda_i G_\mu^i. \quad (2.45)$$

The Standard Model Lagrangian then consists of three terms:

$$\mathcal{L}_{SM} = \mathcal{L}_{fg} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa} \quad (2.46)$$

The $\mathcal{L}_{fg}$ term describes the free propagation of fermion and gauge fields, the couplings of fermions and gauge fields to each other, and the self coupling of gauge fields. The $\mathcal{L}_{Higgs}$ and $\mathcal{L}_{Yukawa}$ couplings before symmetry breaking are given by equations 2.16 and 2.31, respectively.

After spontaneous symmetry breaking the $SU(2)_L \times U(1)_Y$ symmetry is broken to a $U(1)_{em}$ symmetry. After symmetry breaking in the unitary gauge the $\mathcal{L}_{Higgs}$ and $\mathcal{L}_{Yukawa}$ terms are given by equations 2.30 and 2.32, respectively.

Chapter 3

The LHC and the ATLAS Detector

This chapter describes how the Large Hadron Collider and ATLAS detector function. Section 3.1 describes the LHC and explains a particle's trajectory through it. Section 3.2 focuses on describing all of the components of the ATLAS detector, and concludes by explaining how they relate to the $H \rightarrow WW^*$ analysis.

3.1 The Large Hadron Collider

The Large Hadron Collider (LHC) is the world's largest particle accelerator, constructed at the European Organization for Nuclear Research (CERN). It is a hadron-hadron collider, 26.7 km in circumference, situated on the French-Swiss border near Geneva. It is located underground at depths ranging from 50 m, near the Lac Léman side, to 175 m underneath the Jura mountain. The LHC guides two beams of either protons or heavy ions (Pb^{82+}) in opposite directions. The particles interact at experiments located at four points around the LHC. The two experiments built for general searches for a wide range of physics processes are ATLAS (A Toroidal LHC Apparatus) and CMS (Compact Muon Solenoid). The LHCb (LHC beauty) experiment is designed to investigate CP violation in interactions involving b -hadrons. The ALICE (A Large Ion Collider Experiment) experiment is designed to study quark-gluon plasma, which existed shortly after the Big Bang and is created in heavy ion collisions. Three other smaller experiments, TOTEM (Total Cross Section, Elastic Scattering and Diffraction Dissociation at the LHC), MoEDAL (Monopole and Exotics Detector at the LHC) and LHCf (LHC forward), have more specific roles. The locations of the main experiments around the ring are shown in Figure 3.1.

Over 10 000 scientists from more than 100 countries were involved in the design and construction of the LHC and its experiments. The machine was built in a tunnel previously occupied by the Large Electron-Positron (LEP) collider. The construction of the LHC lasted from 1998 until 2008. Nine days after the collider's startup on September 10, 2008, a faulty electrical connection caused magnet quenches and the rupture of a liquid helium enclosure. The collider was shut down for 14 months to repair the damaged superconducting magnets, clean the liquid helium and restore the vacuum. The experiment was restarted on November 20, 2009, and three days later successfully collided two beams of protons at an energy of 450 GeV per beam. The LHC collided protons at an energy of 3.5 TeV per beam in 2010, and 2011, and 4 TeV in 2012. The heavy-ion collisions were carried out at a nucleon-nucleon centre-of-mass energy of 2.76 TeV. The LHC is currently being upgraded for proton-proton collisions at

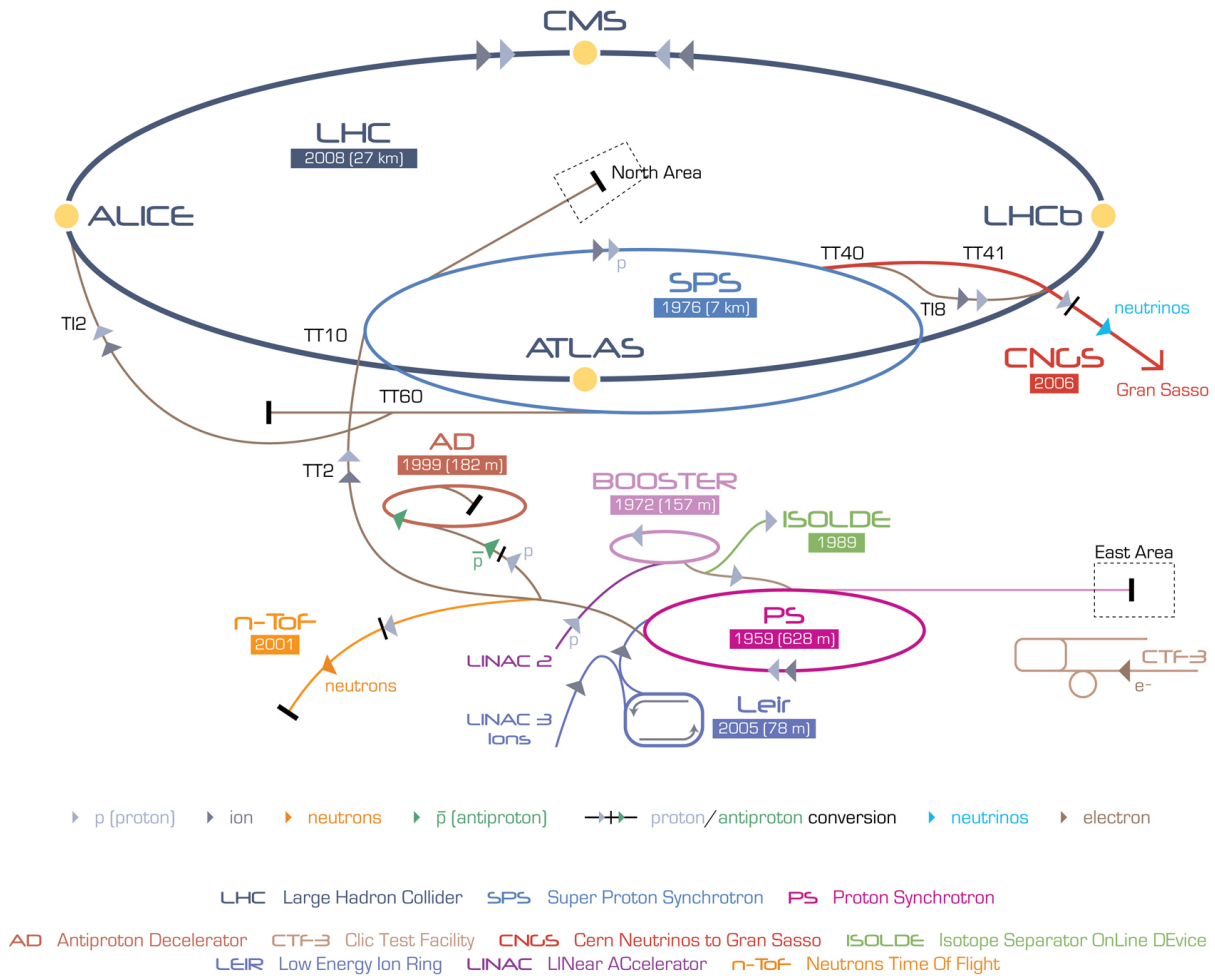


Figure 3.1: The LHC injector complex [46].

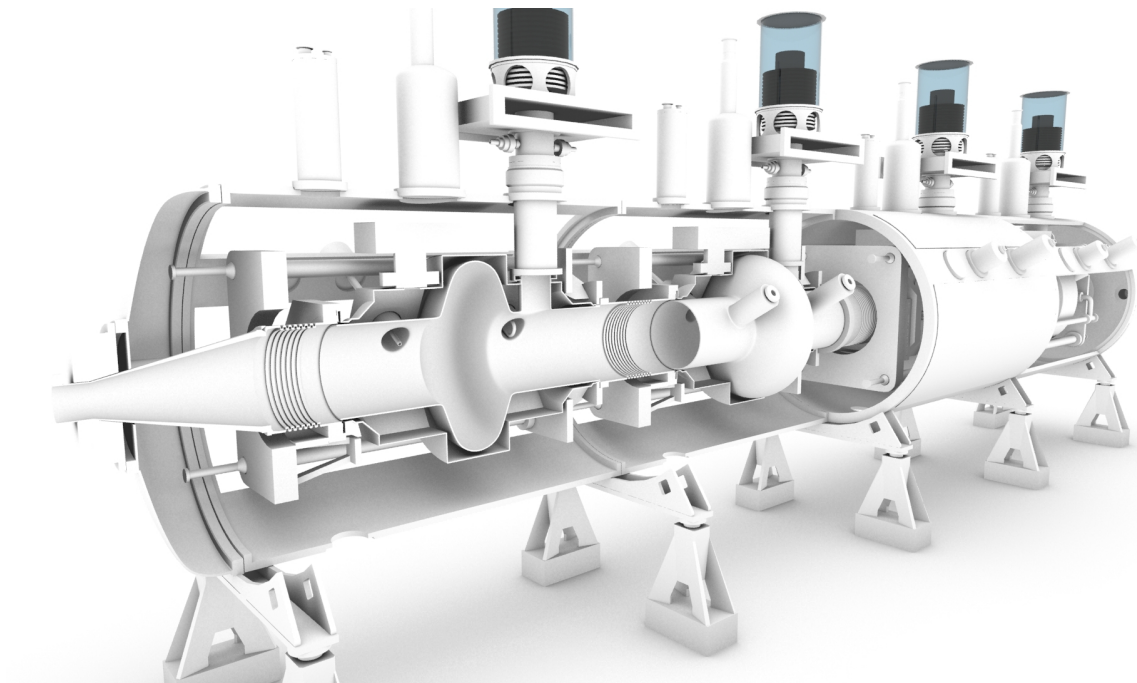


Figure 3.2: The LHC radio frequency cavities used for particle acceleration [47].

6.5 TeV per beam when it restarts in 2015.

3.1.1 Particle Injection Chain

The LHC injector complex is shown in Figure 3.1. The protons are accelerated incrementally by a combination of linear and circular colliders and transferred from one to the next via transfer lines (TT). The protons accelerated by the LHC are obtained by stripping electrons from hydrogen atoms contained in a bottle. After the protons are stripped, they are accelerated by Radio Frequency Quadrupoles to an energy of 750 KeV per beam. A linear accelerator, called LINAC2, then accelerates the protons to an energy of 50 MeV. The protons are then guided into a circular accelerator called the PS Booster (PSB), which increases the beam energy to 1.4 GeV in 530 ms. The PSB also separates the proton beam into discrete packets, called *bunches*. The protons are accelerated to 25 GeV in 1025 ms by the Proton Synchrotron (PS). If the protons are a part of the first batch arriving from the PSB, they are stored for 1.2 s before being accelerated. The PS also further decreases the size of the bunches using radiofrequency pulses. It provides 81 bunches with a 25 ns spacing between them. The PS also provides protons for other experiments, such as ALPHA (Antihydrogen Laser Physics Apparatus), which studies the properties of antihydrogen, or nTOF (neutron time-of-flight facility), which studies neutron-nucleus interactions. After the PS, the protons enter the SPS where they are accelerated to 450 GeV in 4.3 s. The protons arriving at the SPS can be stored for up to 10.8 s, depending on which bunch they arrive in, before being accelerated. The SPS injects the proton bunches into the LHC clockwise and counter-clockwise in two separate beam-pipes enclosed in the same cooling vessel. Particles with slightly lower momentum are accelerated by the RF cavities. In this way the particles oscillate around the ideal particle's trajectory, forming tight bunches.

The bunches travel around the LHC in two vacuum pipes situated beside each other. The pipes are



Figure 3.3: Dipole magnet in the LHC beam pipe (left) and quadrupole magnet (right) [47].

surrounded by magnets, which are enclosed in a superfluid-helium-cooled cryostat. The magnet system contains 1232 dipole and 392 quadrupole magnets used to bend and correct the beam's path. The 14.3 m-long, 35 ton, dipole magnets provide the main magnetic bending force used to keep the beams in circular motion. These dipoles are made of superconducting Nb-Ti (niobium-titanium) cables cooled down to 1.9 K, and carrying a maximum current of 11 700 A. The magnet system is also equipped with sextapole, octupole and decapole magnets used to correct imperfections in the magnetic field at the ends of the dipoles. Alternating 5-7 m-long quadrupole magnets are used to focus the beam's width and height. Quadrupole magnets are also used in series of threes to create the *inner triplet*, which is used to direct the beams into each other at the interaction points. The dipole and quadrupole magnets and the beam pipe are shown in Figure 3.3.

Particles oscillate harmonically as they travel around the LHC. The size and quality of the beam are characterized by the emittance, ϵ , which is the width of the beam. A smaller emittance means the particles are constrained to a smaller space and have higher momenta. The amplitude function, denoted by β , is also used to characterize the beam quality and is dependent on the configuration of the magnets. It is defined as: $\beta = \pi\sigma^2/\epsilon$, where σ is the cross sectional size of the bunch. Smaller β values correspond to a more narrow and squeezed beam. The amplitude function at the interaction point is denoted as β^* [48].

Using the emittance and amplitude function it is possible to define the number of collisions produced per cm^2 each second. This quantity, referred to as the *luminosity*, is defined as

$$L = \frac{f_{rev}n_1n_2N_1N_2\gamma F}{4\pi\epsilon\beta^*}. \quad (3.1)$$

In equation 3.1, n_i is the number of bunches in beam i , N , is the number of protons in each bunch, f_{rev} is the revolution frequency, γ is the Lorentz factor, and F is the geometric luminosity reduction factor which characterizes the loss in luminosity due the crossing angle at the interaction point. Equation 3.1 describes the instantaneous luminosity. The total luminosity can be obtained by integrating over the running time of the LHC $\mathcal{L} = \int L dt$. The integrated luminosity is given in units of inverse barns (b), where $1b = 1 \times 10^{-28} \text{ m}^2$.

Since a typical bunch contains 1.6×10^{11} protons, more than two protons can interact at each crossing. The number of interactions per bunch crossing, μ , is defined as

$$\mu = \frac{L\sigma_{inel}}{nf_{rev}}. \quad (3.2)$$

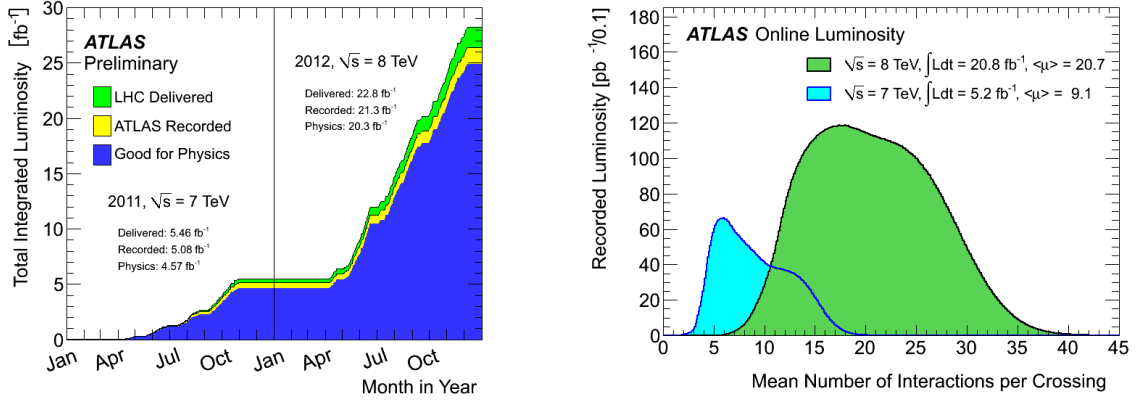


Figure 3.4: The integrated luminosity as a function of time delivered by the LHC (green), collected by ATLAS (yellow), and used for physics analyses (blue) in proton-proton collisions (left)[49]. The mean number of interactions per LHC bunch crossing in 2011 (blue) and 2012 (green) (right)[49].

In equation 3.2, σ_{inel} is the inelastic pp cross section (71.5 (73) mb for a proton beam energy of 3.5 (4) TeV).

3.1.2 LHC Performance

The amount of integrated luminosity delivered by the LHC, recorded by ATLAS, and considered suitable for physics analyses is shown on the left in Figure 3.4. The energy of the collision, measured in the centre-of-mass frame, is called the centre of mass energy, $\sqrt{s}$. In proton-proton collisions, ATLAS recorded 45 pb^{-1} at a centre of mass energy of 7 TeV in 2010, 5.25 fb^{-1} at $\sqrt{s} = 7$ TeV in 2011, and 21.7 fb^{-1} at $\sqrt{s} = 8$ TeV in 2012. The high particle multiplicities at unprecedented energies created a challenging environment for ATLAS. The right plot of Figure 3.4 shows the distribution of the mean number of interactions per LHC bunch crossing in 2011 and 2012.

3.2 The ATLAS Detector

The ATLAS detector, shown in Figure 3.5, is one of two multi-purpose detectors at CERN. The innermost part of the detector is used for gathering information about the momentum and the sign of the charge of charged particles. The Inner Detector (ID) consists of a silicon Pixel detector, a silicon-strip Semi-Conductor Tracker (SCT), and a straw-tube Transition Radiation Tracker (TRT). A thin solenoid magnet surrounds the Inner Detector, providing it with the magnetic field used to curve charged particles left or right in the transverse plane, depending on their charge.

The Inner Detector is surrounded by electromagnetic and hadronic calorimeters. The electromagnetic calorimeter, consisting of lead and liquid argon (LAr), measures the energy of electrons and photons. It consists of a barrel component in the centre of the detector and two electromagnetic end-caps beside the barrel. In addition, copper-LAr hadronic end-caps are placed behind the electromagnetic end-caps to capture hadronic energy in this region. The electromagnetic calorimeter is surrounded by the steel and scintillating hadronic Tile calorimeter (TileCal), which measures the energy of hadrons. The Tile calorimeter consists of a central barrel, and two extended barrels in the forward regions. The regions closest to the beam pipe are covered by forward calorimeters (FCal), which consist of three modules

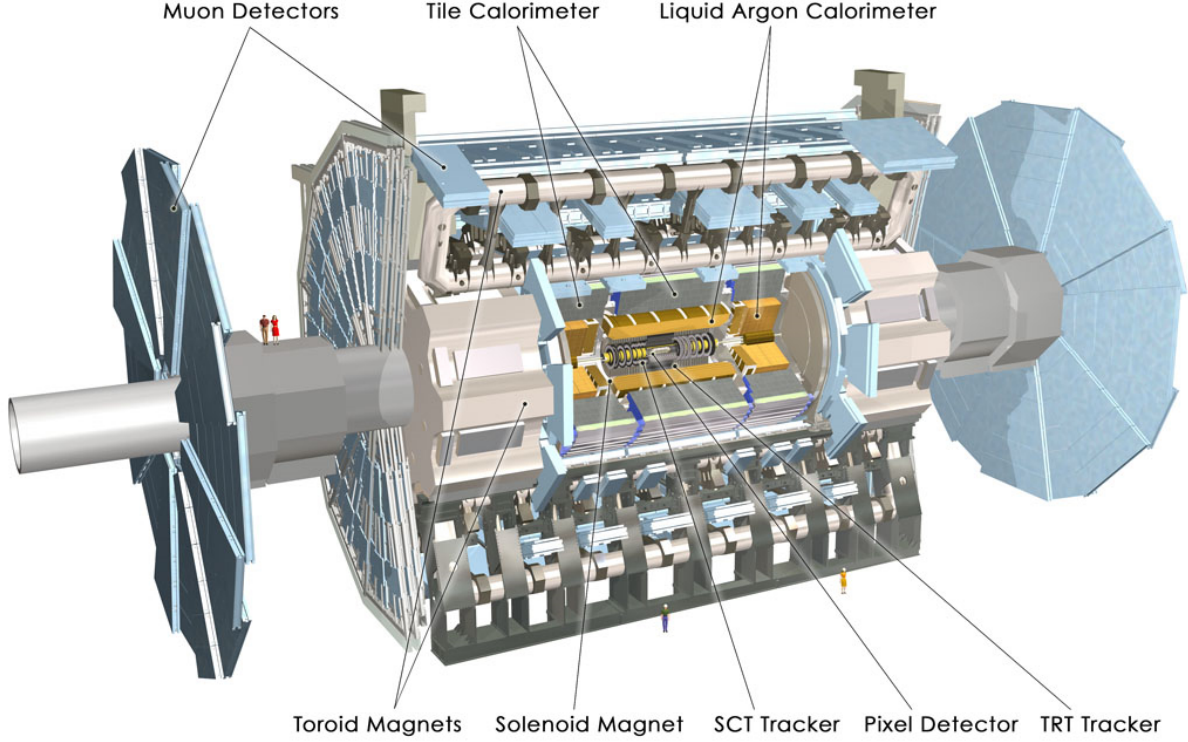


Figure 3.5: The ATLAS detector [50].

that measure scattering at very small angles. The first module is made of copper-LAr and used for electromagnetic measurements. The other two modules consist of tungsten and LAr and are used for hadronic measurements.

The calorimeters are surrounded by superconducting toroidal magnets made of eight air-core superconducting barrel loops and two end-caps. The toroid magnets have non-uniform magnetic fields, which bend charged particles that are measured by the Muon Spectrometer. The Muon Spectrometer (MS) system consists of two high-precision tracking chambers: the Monitored Drift Tubes (MDT) and Cathode Strip Chambers (CSC), as well as two tracking chambers used for triggering and providing the coordinates in the non-bending plane: Resistive Plate Chambers (RPC) and Thin Gap Chambers (TGC).

3.2.1 Coordinate System

The coordinate system in ATLAS is defined such that the z -axis is aligned with the direction of the beam. The positive z direction is defined counter-clockwise when viewing the LHC tunnel from above. The $x-y$ plane is the plane which is transverse to the beam. The positive y -axis is defined to point from the interaction point upwards, while the positive x -axis is defined to point from the interaction point to the centre of the LHC ring. The r, θ, ϕ coordinate system can also be used, in which $r = \sqrt{x^2 + y^2}$, $\cos\theta = \frac{z}{\sqrt{x^2 + z^2}}$, and $\cos\phi = \frac{x}{\sqrt{x^2 + y^2}}$. Since particles leave the interaction point and travel outwards, it is convenient to express their path relative to the beam axis. The pseudorapidity, η , describing the particle's path relative to the beam axis, is defined as $\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$. The pseudorapidity can

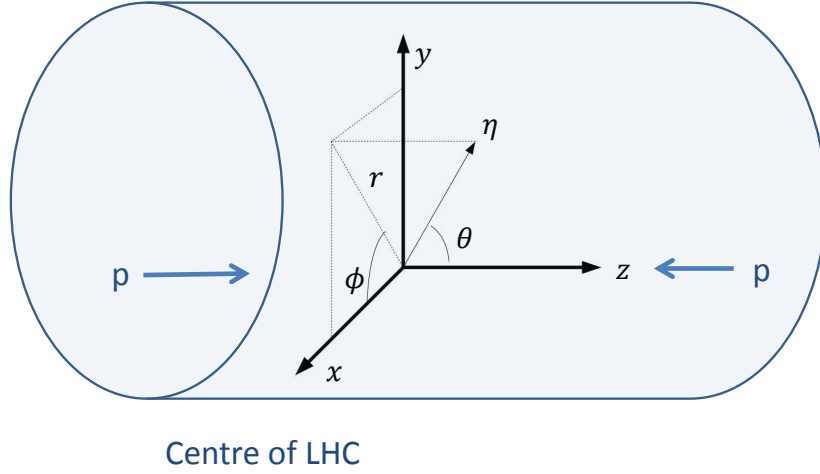


Figure 3.6: The coordinate system used by the ATLAS detector. The ATLAS detector is represented by the blue cylinder. The blue arrows and letters p indicate the direction of the colliding particles. The η direction is located at an angle θ in the $y - z$ plane.

be written in terms of the particle three-momentum, $\mathbf{p}$, as $\eta = \frac{1}{2} \ln \left(\frac{|\mathbf{p}| + p_L}{|\mathbf{p}| - p_L} \right)$, where p_L is the particle momentum along the beam axis. When the particle is travelling close to the speed of light, or when its mass is nearly zero, the pseudorapidity converges to the rapidity: $y = \frac{1}{2} \ln \left(\frac{E + p_L}{E - p_L} \right)$, where E is the energy of the particle. The separation between two particles in η and ϕ can be characterized by $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$. The ATLAS coordinate system is graphically represented in Figure 3.6. The forward regions of the detector that are close to the beam line have high η values.

3.2.2 Magnets

The ATLAS magnet system, shown in Figure 3.7 consists of a central solenoid (CS), generating a magnetic field that bends particles in the Inner Detector, and three toroid magnets providing the magnetic field needed to bend muons in the Muon Spectrometers. The thin CS is located in front of the electromagnetic calorimeter and shares the same vacuum vessel in order to minimize material. It generates a 2 T magnetic field parallel to the beam line in the Inner Detector.

The toroid magnet system consist of a barrel toroid (BT) and two end-cap toroids (ECT) located at each end of the solenoid. In the $|\eta| < 1$ range, the barrel toroid provides the magnetic field to bend the muons, while in the $1.4 < |\eta| < 2$ range the magnetic field is provided by the end-cap magnets. In the $1.0 \leq |\eta| \leq 1.4$ transition region, the muon trajectories are bent by a magnetic field generated by both magnets. The BT and ECT each consist of eight coils around the beam axis. The ECT is rotated at an angle of 22.5° with respect to the BT in order to optimize the magnetic field in the regions where the two overlap. The superconducting BT coils are placed inside an aluminium alloy casing for stability. The BT coils sit inside their own individual cryostats which are linked together for mechanical stability. The ECT coils are made of the same material, but housed in a single cryostat on each side. The cooling

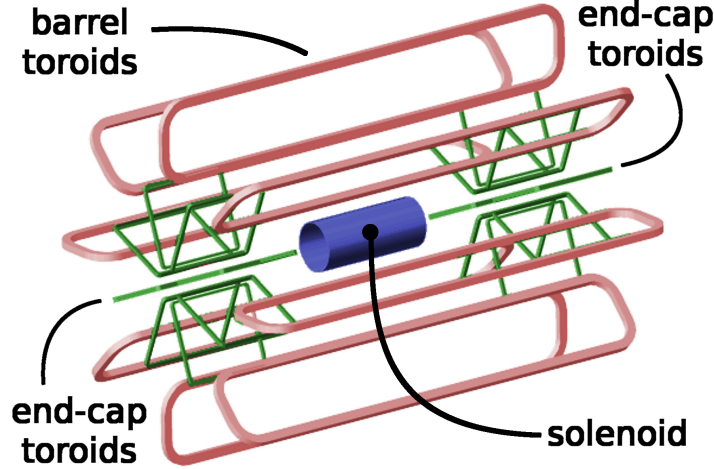


Figure 3.7: The ATLAS Magnet system [51].

is provided by helium of 4.5 K flowing through tubes that are welded onto the magnet casings.

3.2.3 Inner Detector

The Inner Detector, shown in Figure 3.8, measures the position and momenta of particles at and near the interaction point. The high precision measurements needed due to the large particle fluxes require the need for a fine-granularity detector, especially near the beam line. The Inner Detector extends to the $|\eta| = 2.5$ region, and consists of a barrel component and two end-caps.

The innermost ID layer, the Pixel detector, is made of instrumented pixels and exhibits the highest granularity. The Pixel detector provides the interaction location, measures the *impact parameter* of particle trajectories and identifies short-lived particles such as b -hadrons and τ leptons. The impact parameter, $d_0(z_0)$, is the transverse (longitudinal) position relative to the beam axis at the point of closest approach.

The pixels are segmented in r, ϕ , and η . There are over 80 million pixels of size $50 \times 400 \mu\text{m}$ in the $r\phi - z$ directions. The pixels are mounted onto 1744 modules, each containing 16 electronic readout chips. The number of pixels used is limited due to the high cost of the pixels and large amount of cabling required for the many readout channels. There are three concentric pixel layers mounted parallel to the beam line in the barrel section, and five disks perpendicular to the beam line in the end-cap sections. The resolution of the Pixel detector is $12 \mu\text{m}$ in the $r\phi$ direction and $66 \mu\text{m}$ in the z direction for the barrel, and $77 \mu\text{m}$ in $r\phi$ direction for the end-caps. The η coverage and resolution of the Pixel barrel and end-caps are shown in Table 3.1.

The middle section of the ID is the SCT, which provides additional information on the interaction point and the particle's trajectory. The silicon detectors are $6.36 \times 6.40 \text{ cm}^2$ rectangles containing 780 readout strips of $80 \mu\text{m}$ pitch. A single module consists of four p-on-n silicon detectors. On each module two detectors are mounted onto each other back-to-back, at a 40 mrad angle in order to obtain a measurement in z . The modules are 12.8 cm long strips, which are mounted onto eight concentric barrel layers, providing four space-point measurements. On the end-caps, modules are tapered at the edges and mounted in up to three rings. The design resolution of the SCT is $16 \mu\text{m}$ in the $r\phi$ direction and $580 \mu\text{m}$ in the z direction for the barrel and $r\phi$ direction for the end-caps. The η coverage and

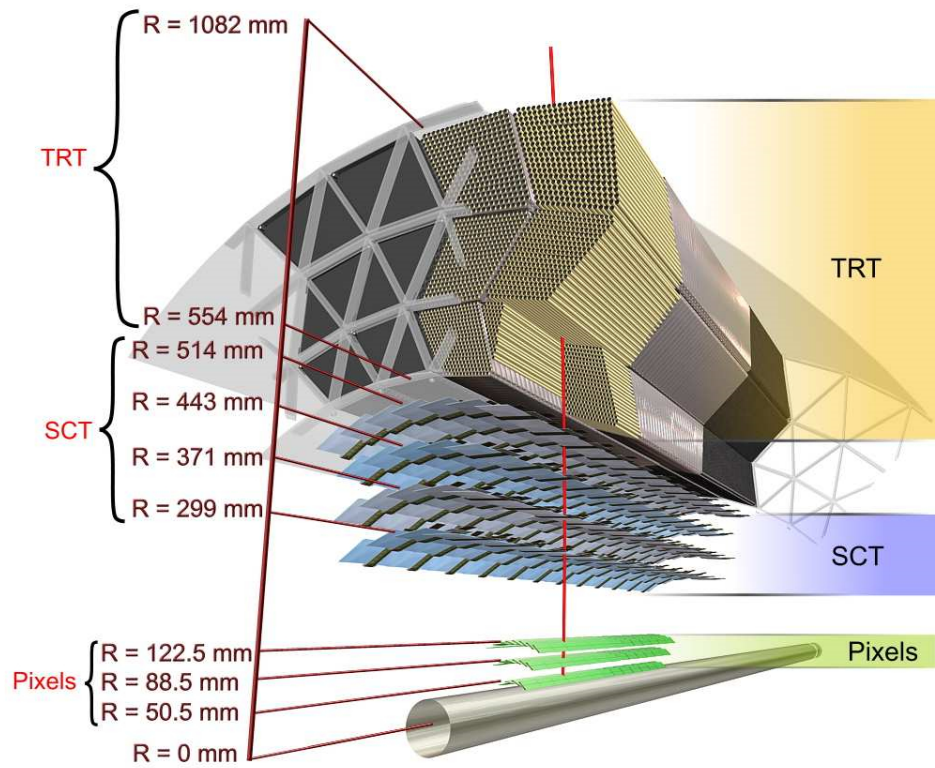


Figure 3.8: The Inner Detector, showing the radial position (R in this figure) of the different layers of the Pixel, SCT and TRT detectors [52].

System	Position	$ \eta $ coverage	Resolution (μm)
Pixel	1 removable barrel layer	< 2.5	$r\phi = 12, z = 66$
	2 barrel layer	< 1.7	$r\phi = 12, z = 66$
	10 end-cap disks	$1.7 - 2.5$	$r\phi = 12, z = 77$
SCT	4 Barrel layers	< 1.4	$r\phi = 16, z = 580$
	18 end-cap wheels	$1.4 - 2.5$	$r\phi = 16, z = 580$
TRT	Axial barrel straws	< 0.7	170/straw
	Radial end-cap straws	$0.7 - 2.5$	170/straw

Table 3.1: The η coverage and resolution of the Pixel, SCT and TRT detectors.

resolution of the SCT are shown in Table 3.1.

The outermost segment of the ID is the TRT, which provides additional trajectory coordinates and particle identification. The 4 mm tubes are parallel (perpendicular) to the beam pipe in the barrel (end-cap), and filled with a gas mixture of 70% Xe 27%, CO₂ and 2% O₂. A particle traversing the tubes ionizes the gas, and the freed electrons are collected onto a 31 μm thick wire inside the tube (*anode*). The outer coating of the tube is a 25 μm polyimide film and 0.2 μm aluminium tube coating, which acts as the cathode. The TRT consists of 50 000 barrel, and 420 radial end-cap straws mounted on 18 wheels, and comprises 420 000 electronic channels. The design resolution of the TRT is 170 μm per straw. The η coverage and resolution of the TRT are summarized in Table 3.1.

Accurate particle identification is achieved by exploiting the fact that ultra-relativistic particles emit transition radiation when moving between media of different dielectric constants. The total emitted radiation is proportional to the Lorentz factor, γ . Thus when a particle crosses the border between the xenon gas filled straws and radiator in the TRT, the amount of emitted radiation is used to distinguish between electrons and charged hadrons. The xenon gas efficiently absorbs transition radiation since its energy levels are well matched to the wavelength of transition radiation X-rays. The xenon gas ionizes and the freed electrons are collected as additional hits. The front-end electronics of the TRT discriminate between adjustable high- and low-energy threshold hits. The low threshold is set at approximately 300 eV and is intended to identify minimum ionizing particles, while the high-threshold level is set to 6-7 KeV and is intended to identify particles with high ionization or large energy deposition due to absorption of transition radiation by the xenon gas [53].

3.2.4 Liquid Argon Calorimeter

The LAr calorimeter, shown in Figure 3.9, is a sampling calorimeter consisting of four subsystems: the electromagnetic barrel (EMB) covering a pseudorapidity range of $|\eta| < 1.475$, the electromagnetic end-cap (EMEC), covering a range of $1.375 < |\eta| < 3.2$, the hadronic end-cap (HEC), covering the region of $1.5 < |\eta| < 3.2$ and forward calorimeters (FCal) covering the region $3.1 < |\eta| < 4.9$. The EMB is enclosed in the barrel cryostat, while the end-cap cryostats contain the EMEC, HEC and FCal. The LAr calorimeter is also divided into longitudinal layers, with layers closer to the beam line containing higher granularity segments. The signals from the LAr calorimeter are read out in longitudinal, η and ϕ partitions of varying sizes, referred to as *cells*. The granularity of each LAr layer, or size of cell, is shown in Table 3.2.

The EMB and EMEC were constructed using an accordion geometry, with copper and kapton electrodes and lead as the absorber material. The electrodes are flexible and therefore held in place between the absorber plates by honeycomb spacers. This design allows for good hermeticity, azimuthal unifor-

Subsystem	Barrel	End-cap
EMB/EMEC		
Layer 1	0.003×0.1	0.025×0.1 for $1.375 < \eta < 1.5$ 0.003×0.1 for $1.5 < \eta < 1.8$ 0.004×0.1 for $1.8 < \eta < 2.0$ 0.006×0.1 for $2.0 < \eta < 2.5$ 0.1×0.1 for $2.5 < \eta < 3.2$
Layer 2	0.025×0.025	0.025×0.025 for $1.375 < \eta < 2.5$ 0.1×0.1 for $2.5 < \eta < 2.5$
Layer 3	0.05×0.025	0.05×0.025 for $1.5 < \eta < 2.5$
Presampler	0.021×0.1	0.021×0.1
HEC		0.1×0.1 for $1.5 < \eta < 2.5$ 0.2×0.2 for $2.5 < \eta < 3.2$
FCal		$\sim 0.2 \times 0.2$

Table 3.2: The granularity of the LAr calorimeter in $\Delta\eta \times \Delta\phi$ sized cells [54] ufzaq.

mity and fast response. The calorimeter is segmented into three longitudinal layers for $|\eta| < 2.5$ and two coarser-granularity layers for $|\eta| > 2.5$. The layer closest to the beam line is segmented into fine-granularity strips in η and is referred to as the strip layer. A finer granularity presampler, covering the range $|\eta| < 1.8$, provides an estimate of the energy loss in front of the calorimeter.

The HEC is segmented into four layers constructed in a parallel-plate geometry. It has copper absorbers and copper and kapton electrodes. The FCal consists of three modules constructed of electrode rods parallel to the beam pipe, sitting in a metal matrix absorber (Figure 3.9). The LAr gap between the rods and matrix is smaller than in the rest of the LAr detector in order to endure the high particle fluxes in the forward regions. The first module of the FCal, consisting of a copper matrix, is used for electromagnetic measurements. The two latter modules, consisting of tungsten matrices, are used for hadronic measurements.

3.2.4.1 Requirements of the Liquid Argon Calorimeter

The design for the LAr calorimeter was largely motivated by requirements on searches for the Higgs boson which can decay to photons, electrons, jets and energy missing in the transverse plane. The reconstruction of these objects is detailed in Chapter 5. These particles must be accurately identified, necessitating fine lateral and longitudinal segmentation in the calorimeter. The energy resolution of the calorimeter is given by

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c. \quad (3.3)$$

In equation 3.3, a is the coefficient of the sampling term, representing the statistical shower development, b is the noise term, and c is the constant term. To meet the mass resolution required for the Higgs searches the sampling term is required to be 10% for electrons and photons in the electromagnetic calorimeter, 50% for jets in the hadronic calorimeter and 100% for jets in the forward calorimeters. The constant term, which dominates the calorimeter resolution at high energy, is required to be 0.7% for the electromagnetic calorimeter, 3% for the hadronic calorimeter, and 10% for the forward calorimeters. Measurements performed in test beam studies show that these resolution requirements have been met [56, 57].

The LAr calorimeter must also have a fast shaping time and minimal dead time in order to cope

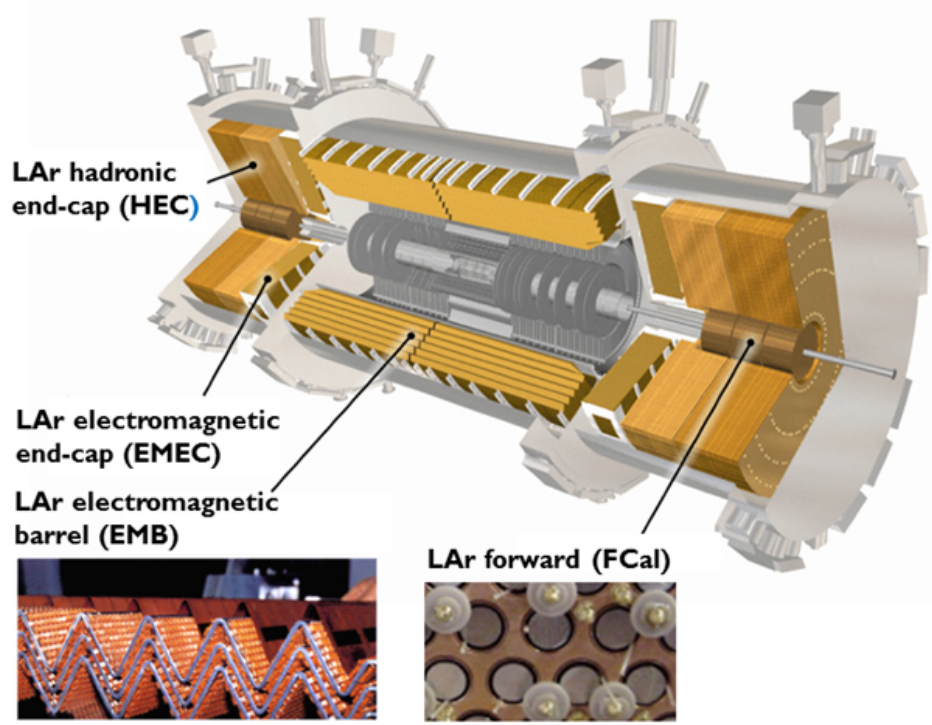


Figure 3.9: The liquid argon subsystems: the hadronic end-cap, the electromagnetic end-caps and barrels with their accordion geometry design, and the forward calorimeter with its rod-matrix geometry [55].

with the 40 MHz bunch crossing rate at the LHC. Minimal coherent noise ($<5\%$ of the incoherent noise) and a linearity of 0.1% is required. Finally, the calorimeter must be capable of sustaining high radiation doses. In order to satisfy the linearity, stability and radiation hardness requirements, liquid argon was chosen as the active material.

3.2.4.2 The Liquid Argon Readout Chain and Energy Reconstruction

The high voltage system generates an electric field across the liquid argon gap between the absorbers and readout electrodes. The left part of Figure 3.10 shows the layout of the electrodes and absorbers in the barrel. When a charged particle crosses the liquid argon gap, it ionizes the argon along its trajectory. The freed electrons are guided by an electric field applied to the electrodes. The resulting ionization signal has a triangular shape and a drift time of $\sim 450\text{--}600$ ns in the barrel. Since this drift time spans 18-24 LHC bunch crossings, the signal must be shaped and shortened in order to mitigate the effects of overlapping interactions. The 1524 front end boards (FEBs), located concentrically around the LAr calorimeter, shape the signal such that the summed area of the positive and negative lobes of the pulse shape is zero. This is done in order to minimize the effect of pileup from overlaying events. The LAr pulse shape is shown at the right of Figure 3.10 before and after shaping. The shaping is performed in three different gains in order to meet the large dynamic energy range expected for physics signals. The readout chain is schematically represented on the right of Figure 3.11.

After the signal is shaped, it is transmitted through two paths: an analog path, which leads to the Level 1 (LVL1) calorimeter trigger system, and a digitized path. In the analog path a sum is performed over approximately 60 readout cells creating energy collections called *trigger towers*. The summed analog

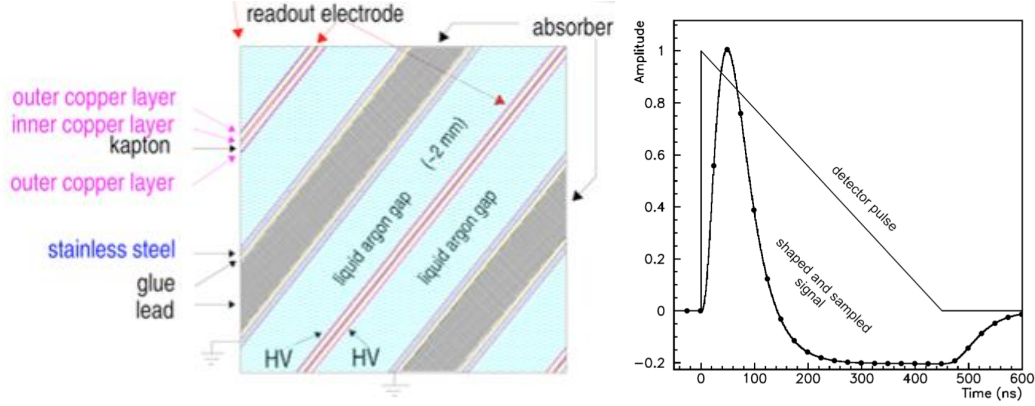


Figure 3.10: Section of the EMB showing the position of the electrodes and absorbers (left). The LAr calorimeter pulse shape before and after shaping (right) [54].

pulses are then analyzed by the hardware-based LVL1 electronics, which take $2 \mu\text{s}$ to decide whether to retain or discard a particular event.

In the digitized path, shaped analog signals are stored in a switched capacitor array (SCA) and digitized in five samples once the decision from the LVL1 trigger arrives, indicating that an event should be retained. The five samples are then sent via optical transmitters to back-end electronics located in a room beside the detector. The back-end electronics consist of digital signal processing (DSP) chips, which compute the amplitude and *quality factor* of the pulse shapes and energy of cells. The quality factor quantifies how well the pulse shape obtained matches the expected pulse shape from a physics signal. The energy is obtained from the amplitude of the pulse shape, A , which is given by:

$$A = \sum_{j=1}^5 a_j (s_j - p). \quad (3.4)$$

Using the amplitude, the timing offset, τ , is computed as

$$A\tau = \sum_{j=1}^5 b_j (s_j - p). \quad (3.5)$$

In equations 3.4 and 3.5, s_j represents the signal pulses obtained. The a_j, b_j and p factors are obtained from electronics calibrations carried out by injecting well-known exponential pulses at the beginning of the readout chain near where the physics pulse is produced in the EMB/EMEC and HEC, and later in the readout path for the FCal. The injection is performed by calibration boards located in the same crates as the FEBs. The a_j and b_j factors are Optimal Filter Coefficients (OFCs) derived from the pulse shape and the noise autocorrelation [58]. They are obtained from *Delay* calibration runs in which the amplitude of the pulses is kept fixed but the timing of injection is varied. The OFC calculation also includes electronics noise, as well as noise that originates from lower energy interactions between quarks and gluons within colliding proton bunches [59]. The pedestal, p , is an electronics baseline describing the mean value of the signal per cell in the absence of an energy deposit. It is calculated from *Pedestal* calibration runs, in which there is no signal injected into the detector and the amount of electronics noise is measured. The value of the pedestal, p is the average sample value over approximately 3000 events

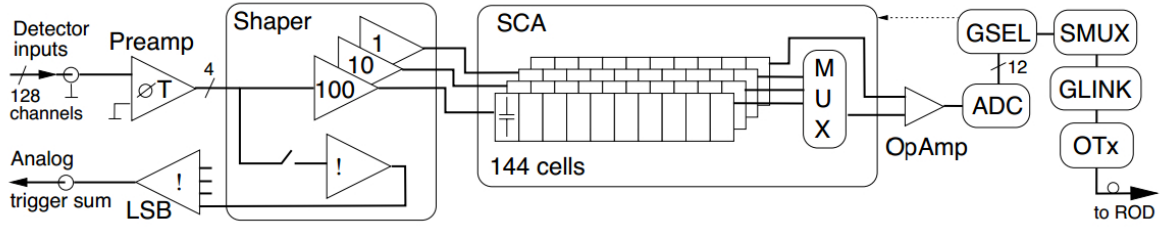


Figure 3.11: The LAr readout chain showing the amplifiers and bi-polar shapers that shape the triangular ionization pulse on the FEBs [59].

that are recorded with 32 samples. The noise is measured as the root-mean-square of the value of the pedestal. The amplitude, A , is then used in the calculation of cell energies using the equation

$$E_{cell} = F_{\mu A \rightarrow MeV} \cdot D_{DAC \rightarrow \mu A} \cdot \frac{M_{calibration}}{M_{physics}} \cdot R \cdot A. \quad (3.6)$$

The $F_{\mu A \rightarrow MeV}$ factor is obtained from test beam data and describes the amplitude of the current pulse, obtained per MeV of deposited energy in the detector. The $D_{DAC \rightarrow \mu A}$ factor represents the amount of current obtained from a calibration board for a given digital-to-analog (DAC) setting. The ratio $\frac{M_{calibration}}{M_{physics}}$ is a factor applied to compensate for the difference in shapes between calibration and physics pulses. This difference would otherwise introduce biases into the energy reconstruction. The factor is calculated by comparing the maximum amplitudes of the calibration and physics pulses. The R factor quantifies the gain of each cell and is obtained from *Ramp* calibration runs in which the timing of the pulses is kept constant and the amplitude is varied.

3.2.4.3 Performance of the Liquid Argon Calorimeter

The LAr calorimeter performed very well during LHC operation. It exhibited stable running conditions and had few operational problems [60].

Liquid Argon Monitoring During operation the liquid argon temperature and purity were constantly monitored in order to ensure accurate energy measurements. A change in temperature on the order of 1 K induces a 2% change in the energy measurement due to the changes in the drift time and the liquid argon density. For this reason, there are 508 PT100 probes in the LAr calorimeter that monitor the temperature which remains at approximately 88.5 K. The temperature uniformity between different probes is on the order of 50-60 mK, well below the design requirement of ≤ 100 mK.

Electronegative impurities, such as O_2 , that can capture drifting electrons within the liquid argon, can also degrade the signal. For this reason, 30 purity monitors, immersed in the liquid argon, are read out every 10 to 15 minutes. The measured impurities are approximately 140-200 ppb, well below the design specification of ≤ 1000 ppb.

Operational Performance During its operation the LAr calorimeter performed exceptionally well, with only a small percentage of data rejected due to malfunctioning channels. A small number of non-operational readout channels were permanently excluded from the energy reconstruction. Some channels were also temporarily excluded since they were temporarily affected by large electronics noise. When

	EM Calorimeter	HEC	FCAL	Total
Total Channels	173312	5632	3524	182468
Permanent	76 (0.04%)	22 (0.39%)	8 (0.23%)	106 (0.06%)
Temporary	8 (0.005 %)	5 (0.09%)	0	13 (0.007%)

Table 3.3: The total number of channels permanently and temporarily excluded from the energy reconstruction [60].

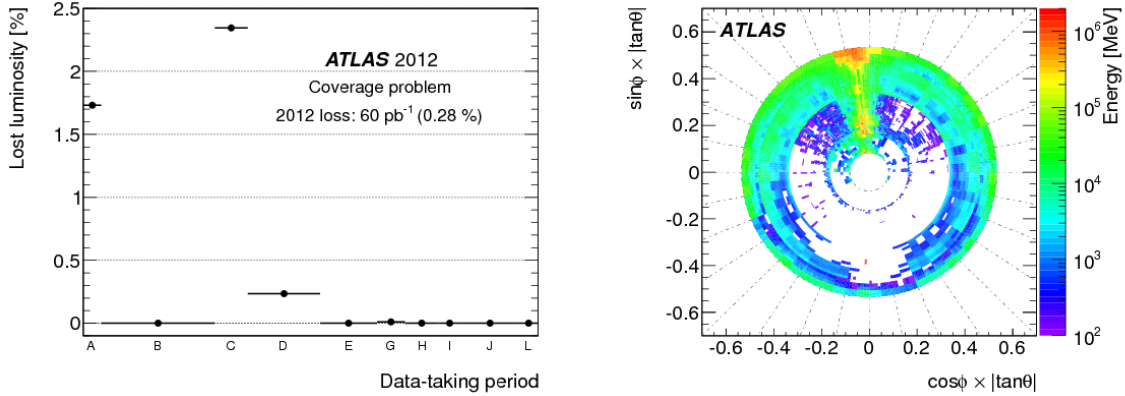


Figure 3.12: The percentage of luminosity lost due to high-voltage trips as a function of the data period (left) [61]. The data period is a period of several weeks into which the LHC running is divided. An example of an event affected by a noise burst during empty LHC bunches in the EMEC (right) [61].

channels were excluded from the reconstruction, their energy was estimated from the neighbouring cells. Table 3.3 shows the percentage of permanently and temporarily excluded channels.

In addition to non-operational channels, there were minor hardware problems, which typically persisted for several weeks. In 2010, 30 FEBs lost connection to the data acquisition system due to broken optical transmitters. The broken and suspicious transmitters were replaced in 2010 and 2011 and have functioned properly since then. In 2011, 6 FEBs and a calibration board in the EMB lost their connection due to a burnt fuse on one of the electronics boards. After the replacement of the burnt fuse such problems did not reappear. Finally in November of 2012, a leak in part of the front-end cooling developed. The result was the shutdown of 4 FEBs, affecting 4.5% of the HEC channels and 1.2% of the EMEC channels. The leak was attributed to a loose connector, which was fixed a few weeks later. The loss in detector coverage due to each problem was simulated in the Monte Carlo.

Data Quality During the LHC’s three years of operation the percentage of LAr data considered to be of good quality for physics analyses increased, despite the increase in instantaneous luminosity that led to more challenging operating conditions. In 2012 proton-proton collisions, more than 99% of the recorded data were suitable for physics, compared with 97% in 2011 and 90% in 2010. The improved efficiency is attributed to the improved treatment of *high-voltage* (HV) trips and *noise bursts*, which were responsible for data losses of 0.46% and 0.28% (in 2012), respectively. High voltage trips and noise bursts are described below.

- **High voltage trips:** The power supplies providing high voltage to the detector electrodes trip when too much current is drawn. Most modules ramp the voltage back up automatically. During the ramping stage the data are recoverable after HV energy scale corrections are applied [62]. The

only data lost are those taken between the near-instantaneous voltage drops and the start of the ramp. In order to minimize the losses, sensitive channels that trip regularly usually have their voltages lowered by a few hundred volts from their nominal operating point (1 kV - 2 kV). In order to decrease the rate of HV trips in sensitive detector areas, more robust HV power supplies were installed at the beginning of 2012. These modules are able to tolerate short current spikes without tripping. The left of Figure 3.12 shows the percentage of luminosity lost due to HV trips as a function of the integrated luminosity in 2012. The drastic decrease in data lost after the first data point is a result of the new module installation. The smaller increase near 12 fb^{-1} is attributed to the hardware failure of a module that caused six HV trips in one LHC data taking period. Following the replacement of the problematic module, the rate of HV trips returned to its baseline value. Higher rates of HV trips are correlated with large increases in instantaneous luminosity. Based on this observed behaviour, when running resumes in 2015, the rate of HV trips is expected to stabilize after the initial increase in luminosity at the beginning of the data taking period.

- Noise bursts: Noise bursts occur when a large fraction of cells in a partition of the calorimeter are simultaneously affected by noise. They are observed only during collisions and usually last less than $5 \mu\text{s}$. An example of such an event is shown on the right of Figure 3.12 in the EMEC. Noise bursts are suspected to be induced by the unshielded HV cables inside the cryostat. They are identified by using the quality factor, which distinguishes between pulse shapes from physics events and distorted ones due to noise. The quality factor is defined as $Q = \sum_{i=1}^5 (s_i - p - A(g_i - \tau g'_i))^2$, where g_i is the normalized ionization pulse shape and g'_i is its derivative with respect to time. Events in which more than five FEBs contain more than 30 channels with a high Q (> 4000) are identified as originating from noise bursts. An improved definition of the quality factor, which takes into account its observed energy dependence, is discussed in [63], but is not used in this analysis. Events that lie within a conservative 200 ms time window around the burst are vetoed. The frequency of noise bursts increases with the instantaneous luminosity, but their duration in time remains constant. Although more bursts are expected after the shutdown in 2015, the conservative time window used for the event veto can be shortened to reduce data loss.

3.2.5 Tile Calorimeter

The Tile calorimeter consists of layers of steel and plastic scintillating tiles. Incoming hadrons initiate hadronic showers in the steel. The showers cause the scintillating tiles to emit photons, which are collected by wavelength shifting fibres and directed to photomultiplier tubes (PMTs). A digitized signal measurement is obtained from the PMTs. The current pulse is obtained quickly due to the low dark current of the PMT, and is shaped into a quasi-Gaussian pulse [64].

The Tile calorimeter consists of a barrel covering the $|\eta| < 1$ region, and two extended barrels covering the $0.8 < |\eta| < 1.7$ regions. The barrel and extended barrel are azimuthally divided into 64 modules, one of which is shown in Figure 3.13. The Tile calorimeter is also longitudinally divided into three layers. The granularity of the layers is shown in Table 3.4. The tiles are 3 mm thick and are placed vertically and staggered in depth. The hadronic calorimeter is 11 interaction lengths (λ) in depth at $\eta = 0$, in order to contain all particles, except muons and neutrinos, before they enter the Muon Spectrometer.

Between the barrel and end-cap components there exists a 68 cm gap used to house cables, cooling pipes, and electronics for several detectors. In order to estimate the energy lost in this gap, a vertical

Detector	Barrel	Extended Barrel
TileCal		
Layers 1 & 2	0.1×0.1	0.1×0.1
Layer 3	0.2×0.1	0.2×0.1

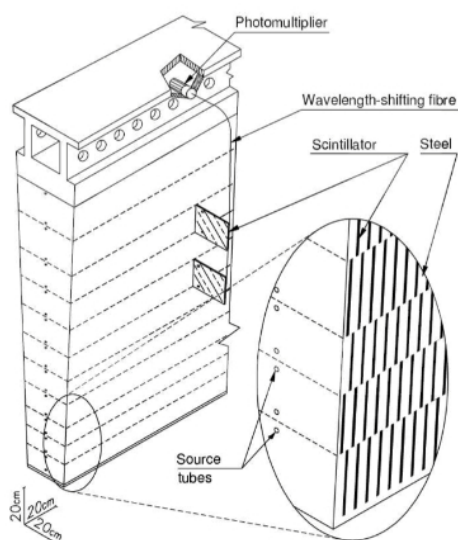
Table 3.4: The granularity of the Tile calorimeter in $\Delta\eta \times \Delta\phi$ segments.

Figure 3.13: A module of the Tile calorimeter, showing the staggered plastic scintillating tiles and lead absorber. Also shown is the wavelength shifting fibre which collects the light released in the scintillators and guides it to the photomultiplier tubes [50].

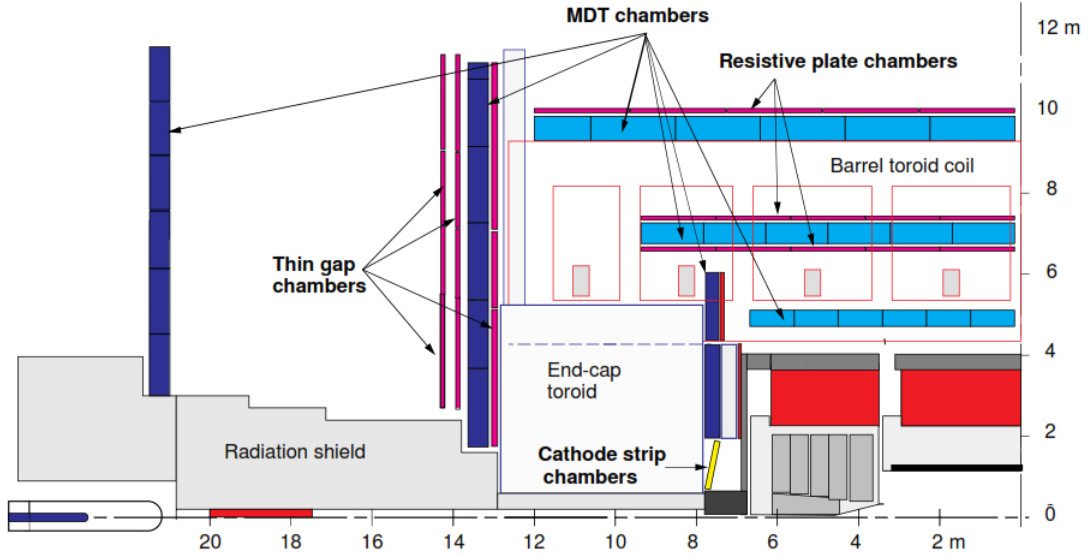


Figure 3.14: The Muon Spectrometer showing the position of the Monitored Drift Tubes, Cathode Strip Chambers, Resistive Plate Chambers and Thin Gap Chambers [66].

intermediate-tile calorimeter (ITC) composed of two radial slices is installed.

The Tile calorimeter is required to measure jets with an energy resolution of

$$\frac{\sigma}{E} = \frac{50\%}{\sqrt{E(\text{GeV})}} \oplus 3\%. \quad (3.7)$$

Measurements performed in test beam studies show that these resolution requirements have been met [65].

3.2.6 Muon Spectrometer

The Muon Spectrometer consists of two kinds of precision tracking chambers and two kinds of triggering chambers. The precision chambers are used to provide precise muon trajectory coordinates, while the triggering chambers are used to trigger on muons, provide bunch-crossing identification, and provide a measurement of the muon trajectory in a direction perpendicular to the one measured by the precision chambers. The precision chambers used are the MDTs and CSCs, while the triggering chambers consist of the RPCs and TGCs. The layout of the different chambers is shown in Figure 3.14. The $|\eta| < 1$ range consists of rectangular-shaped barrel chambers. These chambers are located on three concentric cylinders parallel to the beam axis. The end-cap muon system consists of trapezoidal-shaped chambers, arranged on four disks in the $1 < |\eta| < 2.7$ range. At $\eta = 0$, there is a coverage gap needed to provide space for the cables and cooling services of the other detectors. The z coordinate of the muon momenta is measured by the barrel chambers, while the r coordinate is measured by chambers in the transition and end-cap regions. The η coverage and resolution of the Muon Spectrometer is summarized in Table 3.5.

The measurement of the muon's trajectory in most of the η range is made using the MDT chambers. The MDTs are monitored for their position, internal deformations and external conditions such as temperature and magnetic field [67]. The monitoring is performed by a laser-scanning system [67]. The MDTs are 30-mm diameter tubes containing a non-flammable gas mixture of 93% Ar and 7% CO₂ at a

System	Function	$ \eta $ coverage	Resolution (mm)
MDT	tracking	< 2.7	$z = 0.035$
CSC	tracking	$2.0 - 2.7$	$r = 0.04, \phi = 5$
RPC	trigger	< 1.05	$z = 10, \phi = 10$
TGC	trigger	$1.05 - 2.4$	$r = 2 - 6, \phi = 3 - 7$

Table 3.5: The η coverage and resolution of MDT, CSC, RPC and TGC.

pressure of 3 bar. A 50 μm W-Re wire in the centre of the tubes is held at 3080 V with respect to the grounded, 400- μm -thick, tube walls. The voltage difference generates an electric field such that when muons cross the MDTs and ionize the gas, the resulting freed electrons drift onto the central wire, or anode. The drift time of the freed electrons (< 700 ns) is used to infer the muon's position in the drift tube. The resolution of the MDTs is 80 μm per wire. The MDT chambers are mounted onto three layers in the barrel and three wheels on the end-caps, covering the range $|\eta| < 2.7$.

In areas of the detector with higher particle fluxes, such as at large pseudorapidity ($2 < |\eta| < 2.7$), the precision CSCs measure the muon's position instead of the MDTs. The CSCs consist of positively charged anode wires crossing negatively charged cathode strips at perpendicular angles. The strips and wires are immersed in a gas mixture of 30% Ar, 50% CO_2 and 20% CF_4 . A muon transversing the CSC's ionizes the gas, and the resulting avalanche of electrons is collected onto the anode wire, creating a signal pulse. Positive ions move towards the negatively charged strips, inducing another signal pulse at an angle perpendicular to the wire. Thus for each passing particle a measurement in z and R coordinates can be made. The anode wire pitch is 2.54 mm, while the cathode readout pitch is 5.08 mm, leading to a resolution of 40 μm in the bending plane and 5 mm in the transverse plane. This design allows for a short electron collection time of 30 ns, and good timing resolution of 7 ns. These features make the CSCs more suitable for dealing with higher particle fluxes.

While the MDTs and CSCs provide precise muon position measurements, additional muon chambers are used for triggering on muons. These are RPCs in the barrel region, and TGCs in the end-cap region. These chambers also measure the muon position in the direction orthogonal to the one made by the precision tracking chambers. These chambers have a resolution of 5-10 mm.

The RPCs are placed above or below the MDT chambers, as shown in Figure 3.14, and provide muon triggering in the barrel section at $|\eta| < 1.05$. They consist of parallel plates separated by 2 mm insulating polycarbonate spacers and are maintained at a voltage of 9.8 kV. The space between the plates is filled with a non-flammable gas mixture of 94.7% $\text{C}_2\text{H}_2\text{F}_4$, 5% Iso- C_4H_{10} and 0.3% SF_6 . The Tetrafluoroethane ($\text{C}_2\text{H}_2\text{F}_4$) gas has a high primary ionization production but a low free path for electron capture [68]. When a muon transverses the plates, ionizing the gas, the freed electrons are collected onto the positively charged anode plate. The muon position is inferred from the collection time.

The TGCs provide muon triggering in the end-caps at $1.04 < |\eta| < 2.7$. They operate on the same principle as the CSCs, but have an anode wire pitch larger than the anode-cathode distance, allowing for a low drift time. The low drift time makes them suitable for handling higher particle fluxes. The TGCs are filled with a 55% CO_2 , 45% n-pentane gas and are maintained at a voltage of 2.9 kV.

3.2.7 Trigger System

The LHC design luminosity of $10^{34}\text{cm}^{-2}\text{s}^{-1}$ and bunch crossing of 25 ns leads to a 40 MHz collision rate. Since it is not possible to record and analyze all the collisions, the ATLAS trigger system is used

to reject uninteresting background events. The trigger system consists of three levels. At each level uninteresting events are rejected in order to efficiently reduce the amount of data in the final storage. The trigger system consists of a hardware-based Level 1 (L1) and software-based Higher Level trigger (HLT). The HLT is further divided into the Level 2 (L2) and Event Filter (EF) triggers. These three levels of triggers were designed to reduce the 40 MHz collision rate down to 200 Hz.

The L1 trigger is designed to receive data at a LHC bunch-crossing rate of 40 MHz and reduce it to 75 kHz by making decisions, in less than $2.5 \mu\text{s}$, on whether to discard events. In order to identify interesting events it uses information from muons, electromagnetic clusters and hadronic clusters. Information on muon momentum, η , and ϕ is passed to the L1 trigger from the RPC and TGC trigger chambers. The electromagnetic and hadronic clusters and missing transverse energy are obtained from coarse sums of transverse energy in calorimeter towers. The size of these towers range from $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ in the central regions to $\Delta\eta \times \Delta\phi = 0.4 \times 0.4$ elsewhere. The energy deposited in the electromagnetic and hadronic calorimeters is summed separately and in parallel. The L1 algorithm uses information from the detectors to define regions of interest (RoI) around the identified high-momentum objects. During the L1 processing, information from the different detectors is stored in pipeline memories. After a decision is made by the L1 trigger to accept an event, the information is stored in readout buffers (ROBs), which are later read out by the HLT.

The L2 trigger is designed to reduce the rate from 75 kHz to 1 kHz by deciding whether to discard an event in 40 ms. The L2 trigger uses the momentum, η and ϕ of objects provided by the L1 trigger in the RoI. The L2 uses the full granularity and precision of these objects and uses information from the ID. The Pixel and SCT detectors are used to reconstruct the particle trajectories, and the TRT is used to improve the momentum resolution and electron identification.

The EF is designed to reduce the output rate from 1 kHz to 200 Hz and has a few seconds to make a decision on whether to transmit the event to permanent storage. The EF trigger provides the final event selection based on full granularity information about the entire event. The full event data used by the EF trigger allows it to identify γ conversions and calculate the amount of missing transverse energy. The EF trigger is able to perform vertex reconstruction, track fitting, and includes bremsstrahlung of electrons. The access to complete data allows the EF trigger to perform monitoring, calibration and apply alignment corrections during detector operation. The calibration and alignment performed by the EF trigger is not the final one, but provides reliable intermediate values.

3.2.8 Detecting the $H \rightarrow WW^*$ Process with ATLAS

The efficient functioning of all of the detector's components is essential in the identification of final states that result from the Higgs decay. The electrons, muons and jets that make up the final state must be accurately measured. The LAr calorimeter must efficiently determine the energy that the electrons deposit. The Tile calorimeter is responsible for accurately measuring hadrons from which jets are built. The Muon Spectrometer needs to correctly measure the momenta of muons.

The triggers used in the $H \rightarrow WW^*$ analysis require either one or two leptons. Di-lepton triggers that select two leptons have looser requirements on lepton identification and p_T . The p_T thresholds required by the triggers are different for the Level-1 and High Level triggers, as shown in Table 3.6.

The efficiencies of the triggers are measured using *tag-and-probe* methods in which events with pairs of leptons are used to measure the trigger performance. The lepton that has triggered an event is called the *tag* lepton, while the other lepton is called the *probe* lepton. The trigger efficiency is obtained

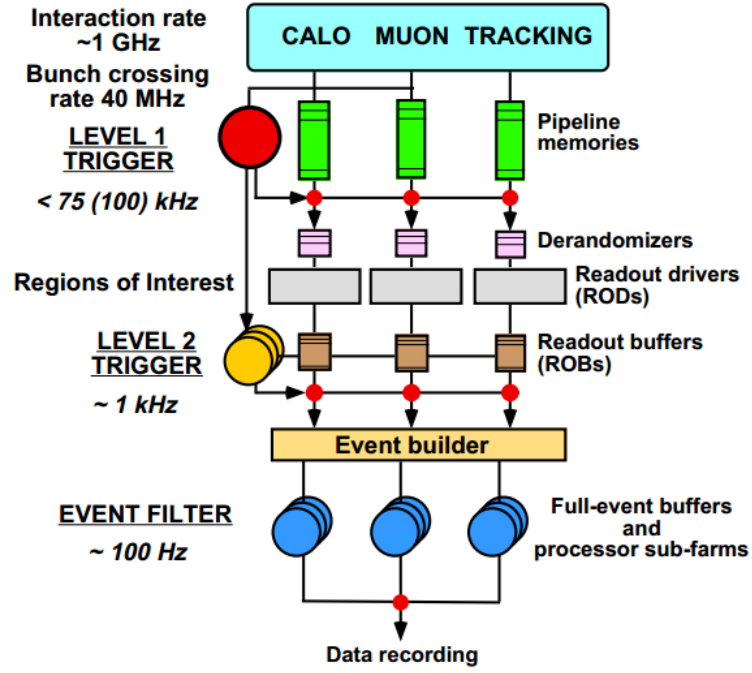


Figure 3.15: The ATLAS trigger system [69].

Trigger	Level-1 trigger	Higher-level trigger
Single Lepton		
e	18 or 30	24i or 60
μ	15	24i or 36
Di-lepton		
e, e	10 and 10	12 and 12
μ, μ	15 and 0	18 and 8
e, μ	10 and 6	12 and 8

Table 3.6: The hardware and software p_T thresholds, in GeV, required by the Level 1 and Higher Level triggers. The i denotes that the isolation required by the trigger is looser than what is required when reconstructing objects for the analysis.

by measuring the fraction of reconstructed probe leptons that pass the trigger [70, 71]. The trigger efficiencies are calculated using $Z/\gamma^* \rightarrow ee/\mu\mu$ events. The trigger efficiency of the muons used in the analysis varies with η and is $\sim 70\%$ for $|\eta| < 1.05$ and $\sim 90\%$ for $|\eta| > 1.05$. The trigger efficiency for electrons used in the analysis is approximately 90%, and varies with p_T . The di-lepton trigger efficiencies are calculated as the sum of the single lepton trigger efficiencies minus their product. Scale factors that quantify the difference between trigger efficiencies in data and MC are calculated and applied to each event.

Chapter 4

Event Simulation

The physics events that are obtained in data are compared to events that are simulated. Simulating physics processes in Monte Carlo (MC) simulation consists of three steps. The first step is *event generation*, described in Section 4.1, which consists of simulating proton collisions. The second step is *detector simulation*, described in Section 4.2, which consists of simulating the detector and its response to the particles traversing it. The final step is the *digitization* process, described in Section 4.3, in which energy deposited in the detector is turned into signals. Finally, Section 4.4 describes the simulation of processes in the $H \rightarrow WW^*$ analysis.

4.1 Event Generation

An *event* contains all of the particles involved in an interaction. Events are produced by simulating several separate steps, including the *hard scatter* of the collision, the *parton shower* (PS), the *hadronization* and the *underlying event* (UE). These processes are described in this section.

When two protons collide there is sometimes a high-energy parton-parton interaction, referred to as the hard scatter. The hard scatter of the collision is calculated from perturbation theory. Within a hard scatter event, the quarks and gluons in the initial and final states radiate other quarks and gluons in processes known as *initial- and final-state radiation* (ISR/FSR). The radiated partons can radiate secondary partons or produce $g\bar{q}$ pairs. This cascade process is called parton showering. Due to confinement, the radiated partons cannot exist freely, and quickly recombine to form hadrons in a process called hadronization. Hadrons can then decay to other lighter particles. Partons that do not participate in the hard scatter process can also interact in processes known as *spectator interactions*. These processes that do not include the hard scatter and parton showers are referred to as underlying events. A schematic representation of the different processes described above is shown in Figure 4.1.

4.1.1 Description of the Proton

As described in Chapter 2, α_s becomes very strong at longer distances and perturbation theory breaks down. For this reason, a description of the proton derived from first principles does not exist. Deep inelastic scattering experiments have shown that at low probing 4 momentum, Q^2 , three quarks, referred to as *valence* quarks, make up the proton. However as the probing four-momentum increases, it becomes apparent that there are many quark and anti-quark pairs within the proton, referred to as *sea* quarks,

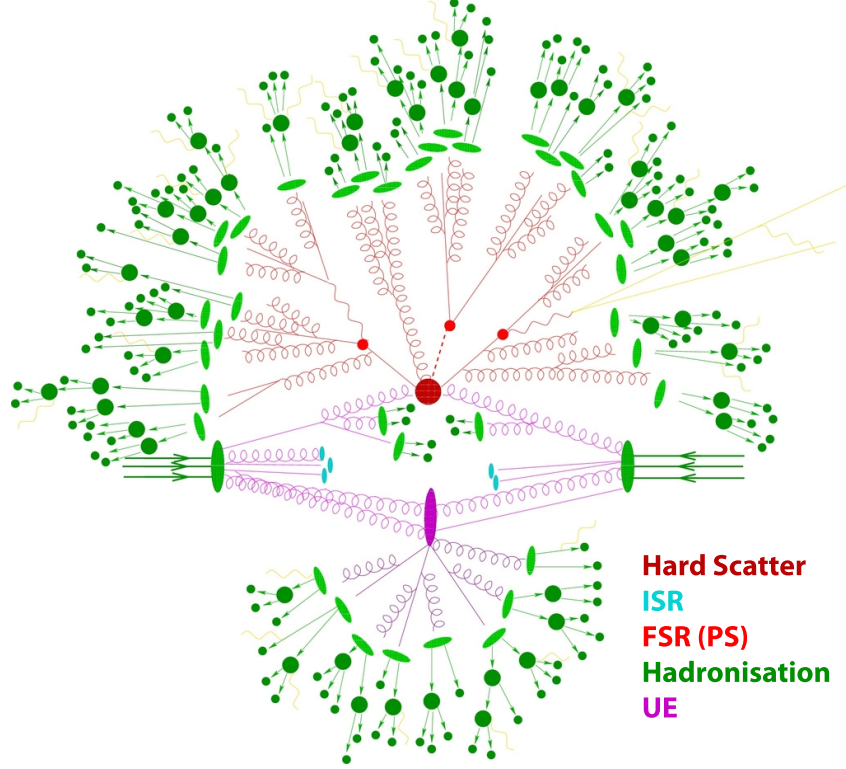


Figure 4.1: A visual representation of event generation, including the hard scatter, initial-state radiation, parton showering from final-state radiation, hadronization and underlying event [72].

which carry some of the proton's momentum. Thus the proton consists of gluons, valence and sea quarks sharing its momentum. The Parton Model uses Parton Distribution Functions (PDFs) to describe the probability of finding a parton carrying a fraction of the proton's momentum, x , at a scale Q^2 . PDFs are extracted from data since they are non-perturbative and difficult to calculate. They are measured in deep inelastic scattering experiments, at a particular Q^2 , and then extrapolated to all values of Q^2 using the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution equations [73, 74, 75]. There are different schemes used for fitting PDF sets. A few common schemes include MSTW [76], CTEQ [77] and NNPDF [78]. The MSTW PDFs are shown in Figure 4.2 for two different values of Q^2 . When obtaining PDFs there are many free parameters that are used as inputs. The nominal input parameters correspond to a nominal PDF set. Variations of the parameters correspond to different PDF sets, called *eigenvector* sets.

4.1.2 The Parton-Parton Hard Scatter

At large values of four-momentum transfer, α_S is small, making it possible to model quarks and gluons as approximately free particles. Since large Q^2 is exchanged in a hard scatter, this process can be modelled by perturbation theory.

In addition to the hard scatter, there are many other interactions between the proton's partons, referred to as *soft* interactions. Soft interactions exchange lower Q^2 and cannot be described by perturbation theory. The boundary between hard and soft interactions is the scale at which perturbation theory breaks down, called the *factorization scale*, μ_F . The choice of factorization scale is arbitrary and

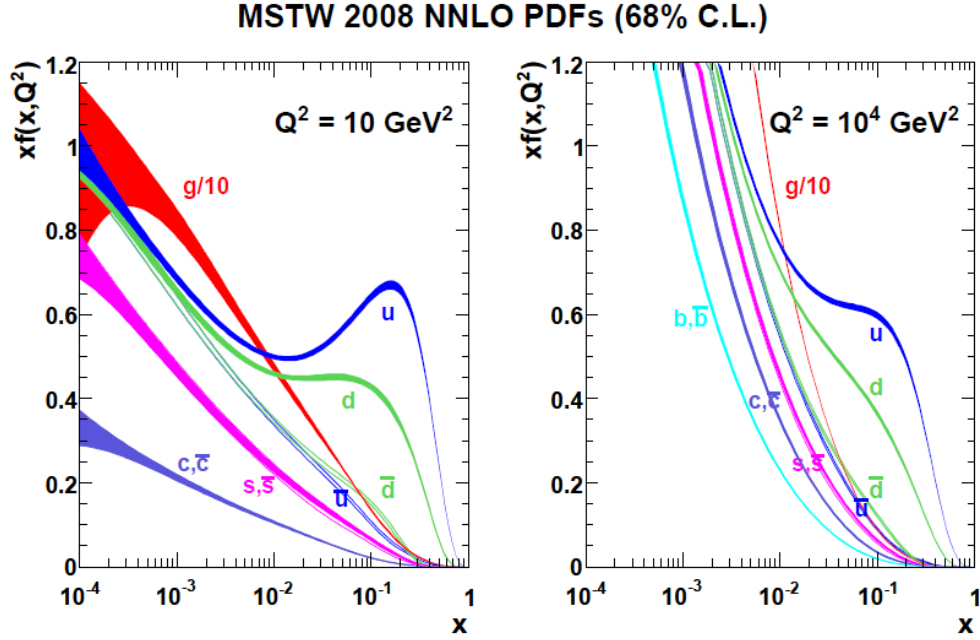


Figure 4.2: The MSTW PDF set obtained from deep inelastic scattering experiments for a probing energy of 10 GeV (left) and 1 TeV (right). The u, d valence quarks are denoted by the blue and green distributions, and the rest are sea quarks. The dominance of the sea quarks at higher Q^2 is apparent when the left and right figures are compared. The bands denote the uncertainties [79].

is usually set to equal the renormalization scale, which is set equal to Q : $\mu_F = \mu_R = Q$.

The cross section of a given process is then calculated from the cross sections of the hard scatter obtained from perturbative QCD, and from soft interactions modelled by PDFs. If a and b are the partons found in protons A and B , the interaction can be modelled as

$$A + B \rightarrow c + X. \quad (4.1)$$

The hard scatter component can be written as $a + b \rightarrow c + X$, where $c + X$ are the final state particles. The cross section for the collision can be written as

$$\sigma_{A+B \rightarrow c+X} = \sum_{a,b} \int dx_a dx_b [f_{a/A}(x_a, \mu_F) f_{b/B}(x_b, \mu_F)] \hat{\sigma}_{a+b \rightarrow c+X}. \quad (4.2)$$

In equation 4.2, the sum is taken over all the possible partonic interactions that can give the final products $c + X$. The $f_{a/A}$ and $f_{b/B}$ terms denote the PDFs that provide the probability that parton $a(b)$ carries the fraction $x_a = \mathbf{p}_a / \mathbf{p}_A$ ($x_b = \mathbf{p}_b / \mathbf{p}_B$), of the proton's total momentum, $\mathbf{p}_A$ ($\mathbf{p}_B$). The $\hat{\sigma}_{a+b \rightarrow c+X}$ term represents the hard-scatter cross section of the partons calculated from perturbative QCD. This cross section is given by

$$\hat{\sigma}_{a+b \rightarrow c+X} = \int \frac{1}{2x_a x_b s} |\mathcal{M}_{a+b \rightarrow c+X}|^2 d\Omega. \quad (4.3)$$

In equation 4.3, s is the square of the centre-of-mass energy of the parton-parton collision. $|\mathcal{M}_{a+b \rightarrow c+X}|^2$ is the perturbative matrix-element-level calculation of the partonic processes, squared and averaged

over the colour and spin states. The processes are integrated over the phase space, which allows for $a + b \rightarrow c + X$ interactions, denoted by $d\Omega$.

4.1.3 Parton Showers

Parton showers are models of QCD processes. Since these processes are not perturbative, it is not possible to calculate them exactly, and an approximation method is used. This method is based on approximating the cross sections of radiated partons based on the angle they are radiated at, and the fraction of energy they carry. For example, if $d\sigma_n$ is the n -parton differential cross section before the radiation, the cross section after particle i splits into particles $j + k$ is given by

$$d\sigma_{n+1} \approx d\sigma_n \frac{\alpha_s}{2\pi} \frac{d\theta^2}{\theta^2} dz d\phi P_{ji}(z, \phi). \quad (4.4)$$

In equation 4.4, θ and ϕ are the opening angles at which the particles are radiated. The P_{jk} term describes the probability that the radiated particle, j , carries a momentum, z , of the original momentum particle i had. This calculation is repeated for all radiated particles in the shower until the virtual mass squared of each particle is higher than the hadronization scale.

The parton shower approximation takes into account not only the particles that are radiated collinearly, but also quantum loop effects. These are taken into account by *Sudakov form factors* [80], which describe the probability that a particle does not split in going from its initial state, q_i , to its final state, q_f . The Sudakov form factors are given by

$$\Delta_i(q_i^2, q_f^2) = \exp \left\{ - \int_{q_f^2}^{q_i^2} \frac{dq^2}{q^2} \frac{\alpha_s}{2\pi} \int_{Q_0^2/q^2}^{1-Q_0^2/q^2} dz \int_0^{2\pi} d\phi P_{ji}(z, \phi) \right\}. \quad (4.5)$$

The processes described above work for FSR. For ISR, the angles of radiated particles are found through backwards evolution after the hard scattering processes. In this case, the Sudakov form factors also include PDF terms.

4.1.4 Hadronization

There are two different types of methods used for modelling the hadronization of particles: The *Lund String Model* [81] and the *Cluster Model* [82]. The Lund model is largely inspired by the observation that the potential energy of a colour field between $q\bar{q}$ pairs increases linearly with the distance between the $q\bar{q}$ pair. This means that the colour field can be modelled as a string stretching between $q\bar{q}$ pairs. The string breaks once its potential energy exceeds the energy required to produce a $q\bar{q}$ pair. Once the string breaks a new $q\bar{q}$ pair is formed and strings of lower potential energy bind the newly formed parton pairs to the original partons. This process continues until the energy of the hadrons is smaller than the energy required for them to escape confinement. In this model, gluons make a kink in the string. A graphical representation of the model is shown on the left in Figure 4.3.

The Cluster Model is based on a pre-confinement property of QCD [83]. A feature of this property is that at energies much less than that of the hard-scatter scale, partons cluster in colourless groups and have invariant mass distributions that are independent of the hard-scatter scale. In this model, gluons break into $q\bar{q}$ pairs in order to form these clusters, which are called *proto-hadrons*. Larger proto-hadrons then decay into the final-state hadrons. A graphical representation of this model is shown in the right of Figure 4.3.

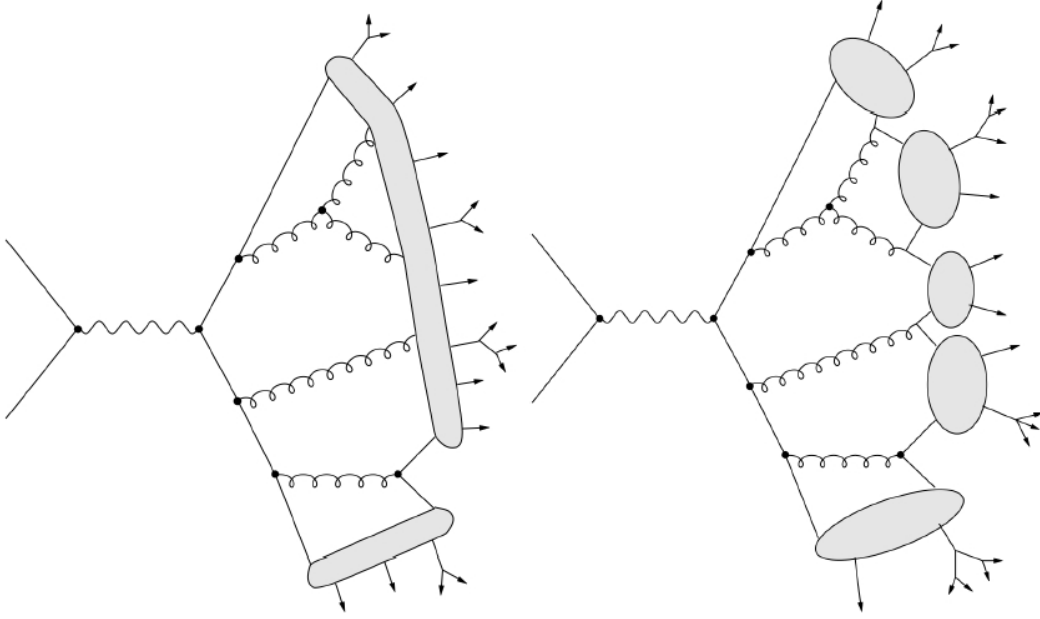


Figure 4.3: A visual representation of the Lund String Model (left) and Cluster Model (right) [82].

4.1.5 Underlying Event

The underlying event results from interactions of partons not involved in the hard scatter. Underlying event processes include *multiple parton* interactions, *beam remnants*, and *pileup*. These processes are non-perturbative and thus approximation methods are used to describe them.

Multiple parton interactions include semi-hard collisions between different combinations of partons. At the LHC the most common of these interactions is gluon scattering ($gg \rightarrow gg$). These processes are modelled by distributing the partons in each incoming hadron over a transverse area of approximately 1 fm^2 , which is approximately the area of a proton. The impact parameter of the collision is defined as the distance between the centres of these two defined areas. The collisions are then modelled as a function of the size of the impact parameter, where larger impact parameters correspond to a small overlap between the areas and thus fewer multiple interactions.

Pileup is modelled as interactions that overlap with the hard scatter. Out-of-time pileup consists of the collisions from past bunch crossings and is characterized by the expected average number of interactions, μ . In-time pileup consists of additional proton collisions in an event, which are characterized by the number of identified hard-scatter interaction points, referred to as *primary vertices* (N_{PV}).

Beam remnants are what is left over when partons are knocked out of beam hadrons that do not participate in the hard scatter or the multiple parton interactions. The remnants are colour connected to the other particles in the event. Momentum is conserved between the beam remnants and the rest of the event.

4.1.6 Generators

There exist many event generators used to simulate physics processes. Generators can be used to model all aspects of event generation, or can be specialized for certain physics processes or certain generation

steps. The generators used in the $H \rightarrow WW^*$ analysis are described below.

- PYTHIA [84] is a general-purpose generator capable of simulating all collision processes involving e^+e^- , ep , and $pp/p\bar{p}$ initial states. This generator uses the Lund string hadronization model. PYTHIA can model the underlying event and is often used to simulate in-time pileup. There are two versions of PYTHIA: PYTHIA 6 is the original generator and its successor is PYTHIA 8.
- SHERPA [85] is a general-purpose generator that models processes at leading order (LO). It matches matrix-element calculations to parton showers and removes overlapping diagrams. SHERPA produces complete events by using an interface to PYTHIA for hadronization and underlying event modelling. This generator provides better approximations for events containing multiple jets than PYTHIA or HERWIG, which are based on pure QCD showering.
- HERWIG [86] contains built-in processes generated at LO. HERWIG uses a cluster hadronization model and is tuned to agree with Tevatron data. In order to model multiple parton interactions and the underlying events, HERWIGF is used with the JIMMY [87] package. JIMMY calculates the multiple parton cross sections as a function of the PDFs and the area overlap between colliding protons.
- POWHEG [88] generates hard scattering at next-to-leading order (NLO). It is usually used with PYTHIA or HERWIG for showering and hadronization.
- ALPGEN [89] generates multiple parton hard processes at LO. It is usually used with POWHEG or PYTHIA for hadronization. ALPGEN is usually used for multi-jet final states since its fixed-order matrix-element calculations give a better approximation than the showering used in PYTHIA or HERWIG. ALPGEN is also often used to produce W/Z bosons with many jets.
- ACERMC [90] generates hard scatter processes at LO, and is usually interfaced with PYTHIA or HERWIG for parton showering and event hadronization. ACERMC is usually used to generate events containing W/Z bosons with jets.
- GG2VV [91] is a generator that generates gluon induced processes that decay to WW and ZZ final states. This generator includes box diagram calculations for these processes.
- MC@NLO [92] generates hard scatter processes at NLO and matches them to parton showers. NLO calculations include loop-level diagrams, which lead to negative weights for some events. The negative weights result from the subtraction between real and virtual corrections. Despite this, physical kinematic distributions are obtained if enough events are generated. MC@NLO is used with HERWIG or JIMMY, which simulate the parton shower and hadronization. This generator is often used for top events since it models the momenta of top quarks better than PYTHIA or HERWIG. This generator is also often used for W and Z production.
- MCFM [93] is a generator used to calculate cross sections of different processes at NLO. The cross sections of LO generators are often normalized to cross sections calculated in MCFM.

4.2 Detector Simulation

GEANT4 (GEometry ANd Tracking) [94], is a tool for simulating how particles interact with matter. It is used to model the ATLAS detector geometry using parameters that are variable throughout operation, such as information about disabled parts, temperatures and high-voltage settings.

The full detector simulation, referred to as FullSim, contains all the information about the different detectors. The energy, position and time associated with each energy deposit are recorded as data-points called *hits* and later digitized. The full detector simulation precisely models Inner Detector hits and shower development. FullSim is very accurate, but time consuming.

The ATLFAS-II simulation algorithm contains condensed detector geometry information. This algorithm uses the Fast ATLAS Tracking Simulation (FATRAS) [95] for simulating particle trajectories in the ID and MS, and Fast Calorimeter Simulation (FastCaloSim) [96] for simulating calorimeter deposits. FATRAS reconstructs particle trajectories based on a detailed detector geometry in sensitive detector areas, and a more coarse grained geometry in other regions. The FastCaloSim does not model shower development, but approximates the size and shape of a shower based on the information of the input particle.

4.3 Digitization

Digitization is the process of converting the detector hits from simulation into signals that represent the response of the detector, called *digits*. The software used for this purpose is GEANT4. Digits are signal shapes that are obtained when charges from ionization or photons from scintillation are collected in the detector. The different light and charge collection techniques in each detector are also modelled using digitization software specific to each detector. The digits of the detector are then converted to Raw Data Objects (RDO), which is the same format as the data that is written out from the detector's readout drivers. The RDOs are passed through the same trigger chain as the data.

4.4 Event Simulation for the $H \rightarrow WW^*$ Analysis

A summary of the different generators used to model the signal and background processes in the $H \rightarrow WW^*$ analysis is shown in Table 4.1. The same table also shows the cross section times branching ratio of each process. Cross sections are often normalized to higher-order corrections obtained from different generators. This is done by normalizing samples with a k -factor, which is defined as the higher-order cross section calculation divided by the lower-order cross section calculation.

Separate generators are usually used to model the hard scatter and parton shower/hadronization. POWHEG is usually used to generate the hard processes since it includes NLO corrections in α_S . When higher parton multiplicities are required, ALPGEN and SHERPA are used since they can generate these events at LO. There are a few processes for which only LO generators such as ACERMC and GG2VV are available. PYTHIA 6, PYTHIA 8, HERWIG and SHERPA are used for parton shower and hadronization. The older PYTHIA 6 is sometimes used instead of the newer PYTHIA 8 since its modelling of jets better matches other generators. JIMMY is often used for modelling the underlying event, and PYTHIA 8 is used to model pileup interactions. The CT10 [97] PDF set is used for the POWHEG and SHERPA samples, CTEQ6L1 [77] is used for ALPGEN+HERWIG and ACERMC, while MRSTMCAL [98] is used by SHERPA to

model the $Z\gamma^*$ background.

The processes included in the signal are ggF, VBF and WH/ZH production followed by a decay to WW^* bosons. The contribution of the $H \rightarrow \tau\tau$ process is very small and simulated using the same generator as the $H \rightarrow WW^*$ process. The processes in which a Higgs boson is produced in association with a $t\bar{t}$ or $b\bar{b}$ pair are negligible in this analysis.

The ggF signal cross sections are computed at next-to-next-to-leading-order (NNLO) in QCD, with EW corrections applied at NLO. These calculations assume that the EW and QCD corrections can be factorized [99, 100, 101]. QCD soft-gluon resummations are also applied at next-to-next-to-leading-log [102]. The VBF signal processes are computed up to NLO QCD and EW corrections. Approximate NNLO QCD [103] corrections are also used in the calculation of the cross section. The WH/ZH processes are calculated up to NNLO QCD corrections [104, 105] and NLO EW corrections [106].

The signal cross sections are modelled in generators that do not adequately model the distribution of the Higgs p_T . For this reason the Higgs p_T distribution is re-weighted to a NNLO calculation performed by HQT [107].

For the 0- and 1-jet channels the WW background is simulated by POWHEG+PYTHIA 6 for $q\bar{q} \rightarrow WW$ processes, and GG2VV+HERWIG for $gg \rightarrow WW$ processes. The cross section is normalized to a NLO cross section calculated in MCFM.

The generators used for the 0- and 1-jet channels do not include multiple partons at matrix element level and can thus omit some processes that can contribute to backgrounds in the ≥ 2 -jet channels. For this reason, the WW background in the ≥ 2 -jet channels is generated with SHERPA. SHERPA simulates events in which two protons collide to produce WW bosons and up to three jets in the final state with no restrictions on intermediate-state particles. The SHERPA simulation is generated in two samples, called $WW+2$ jets EW and $WW+2$ jets QCD. The $WW+2$ jets EW background is defined as having no QCD vertices, while the $WW+2$ jets QCD background has no EW vertices other than what is needed for the WW boson decay. A third sample called $WW+2$ jets QCD+EW, not shown in the table, is also generated in order to calculate the theoretical uncertainty on the interference between the two samples. The double parton interactions producing W bosons denoted by $(q\bar{q} \rightarrow W) + (q\bar{q} \rightarrow W)$ are also included, as shown in Table 4.1.

The top quark processes are simulated separately for events containing $t\bar{t}$ and single top quarks, such as Wt , $tq\bar{b}$, and $t\bar{b}$. The $t\bar{t}$ processes are simulated in POWHEG+PYTHIA 6 and normalized to NLO cross sections with resummation of higher-order terms to next-to-next-to-leading-log evaluated with TOP++ 2.0 [108]. The single top processes are simulated in POWHEG+PYTHIA 6 for Wt and $t\bar{b}$ production, and ACERMC for $tq\bar{b}$ production. The cross section of single top processes is normalized, as described in Refs. [109, 110, 111].

The $W\gamma^*$ and WZ processes have the same final state and are thus considered together. It is difficult for MC generators to produce di-leptons at NLO at very low masses. Thus the $W\gamma^*$ and WZ samples are separated into low-mass samples ($m_Z < 7$ GeV) containing mostly $W\gamma^*$ processes and high-mass samples ($m_Z > 7$ GeV) containing mostly WZ processes. The high-mass WZ samples are simulated by POWHEG+PYTHIA 8, and normalized to the POWHEG cross section. The low-mass $W\gamma^*$ samples are simulated with SHERPA with ≤ 1 partons included in the matrix element calculation. The SHERPA samples are normalized to the NLO cross section obtained with MCFM. The WZ processes for the ≥ 2 -jet case are generated with multiple partons in SHERPA, and denoted by $WZ+2$ jets in Table 4.1.

The ZZ and $Z\gamma^*$ processes lead to the same final state and must be considered together. The same

Process	MC Generator	$\sigma \cdot BR$ (pb)
Signal		
ggF $H \rightarrow WW^*$	POWHEG+PYTHIA 8	0.435
VBF $H \rightarrow WW^*$	POWHEG+PYTHIA 8	0.0356
VH $H \rightarrow WW^*$	PYTHIA 8	0.0253
WW		
$q\bar{q}/qg \rightarrow WW$	POWHEG+PYTHIA 6	5.68
$gg \rightarrow WW$	GG2VV+HERWIG	0.196
$(q\bar{q} \rightarrow W) + (q\bar{q} \rightarrow W)$	PYTHIA 8	0.480
$q\bar{q} \rightarrow WW + 2 \text{ jets QCD}$	SHERPA	0.568
$q\bar{q} \rightarrow WW + 2 \text{ jets EW}$	SHERPA	0.0397
Top quarks		
$t\bar{t}$	POWHEG+PYTHIA 6	26.6
Wt	POWHEG+PYTHIA 6	2.35
$tq\bar{b}$	ACERMC+PYTHIA 6	28.4
$t\bar{b}$	POWHEG+PYTHIA 6	1.82
Other dibosons (VV)		
$W\gamma$	ALPGEN+HERWIG	369
$W\gamma^*$	SHERPA	12.2
WZ	POWHEG+PYTHIA 8	12.7
$WZ + 2 \text{ jets EW}$	SHERPA	0.0126
$Z\gamma$	SHERPA	163
$Z\gamma^*$	SHERPA	7.31
ZZ	POWHEG+PYTHIA 8	0.733
$ZZ \rightarrow \ell\ell\nu\nu$	POWHEG+PYTHIA 8	0.504
Drell-Yan		
$Z \rightarrow \ell\ell$	ALPGEN+HERWIG	16500
$Z \rightarrow \ell\ell + 2 \text{ jets}$	SHERPA	5.36

Table 4.1: The Monte Carlo samples used for modelling the background and signal processes and their cross sections times branching ratios. The ℓ denotes final states consisting of electrons, muons and tau leptons.

procedure is used for $Z\gamma^*$ and ZZ events, as is used for $W\gamma^*$ and WZ events, but the mass cutoff is applied at 4 GeV instead of 7 GeV. The cross section of the $Z\gamma^*$ sample is normalized to NLO processes calculated in DYNNLO [112].

The $W\gamma$ sample is simulated in ALPGEN+HERWIG and its cross section is normalized to the NLO cross sections calculated with MCFM. The $Z\gamma$ background is simulated in SHERPA and its cross section is normalized to MCFM. The Drell-Yan backgrounds are simulated in ALPGEN+HERWIG and SHERPA in the ≥ 2 -jet channels where greater parton multiplicities are required.

Chapter 5

Event Reconstruction

Particles traversing the detector interact with the material and deposit energy through various processes. Depending on the detector, this can be measured as ionisation charge or scintillation light. These signals are used to reconstruct objects in the detector that correspond to the particles they originate from. Reconstructed objects are often calibrated from Monte Carlo and data in order to obtain accurate measurements of their true energy. The identified objects are then used to reconstruct an event or part of an event that contains the decay products from a certain physics process.

Colliding protons traverse ATLAS, depositing energy in each detector layer. A graphical representation of this is shown in Figure 5.1. The ID reconstructs the paths of charged particles at and beyond the interaction point, as described in Section 5.1. Electrons and photons interact electromagnetically, initiating showers in the electromagnetic calorimeters and depositing most of their energy there, as described in Sections 5.2 and 5.3. Hadrons such as protons and neutrons interact strongly, initiating showers in the hadronic calorimeters and leaving most of their energy there, as described in Sections 5.4. Section 5.5 describes the reconstruction of hadronically decaying tau leptons, which also deposit most of their energy in the hadronic calorimeters. Muons pass through most of the ATLAS layers and are tracked in the MS, where their momentum is reconstructed, as described in Section 5.6. Neutrinos do not interact with material in the ATLAS detector and pass through undetected. Their presence is inferred by analyzing the amount of missing transverse energy, as described in Section 5.7. Finally, Section 5.8 describes the identification and calibration of the electrons, muons, jets and missing transverse energy which are searched for in the final state in order to identify the $H \rightarrow WW^*$ signal.

5.1 Track and Vertex Reconstruction

A *track* is the trajectory followed by a charged particle originating from the interaction point. The interaction point, referred to as a *vertex*, can originate from the hard scatter, or from underlying events and long lived decaying particles. The tracks are identified by using ID hits. Two different types of algorithms exist for reconstructing tracks: *inside-out* algorithms and *outside-in* algorithms.

Inside-out algorithms first identify the hits in the Pixel and first layer of the SCT. These hits are referred to as *seeds*. The seeds are then extended to the remaining layers of the SCT to reconstruct the entire track. A hit in the remaining SCT layers that deviates from the expected position of the track is called an *outlier*. The absence of a hit where one is expected along a track trajectory is called a *hole*.

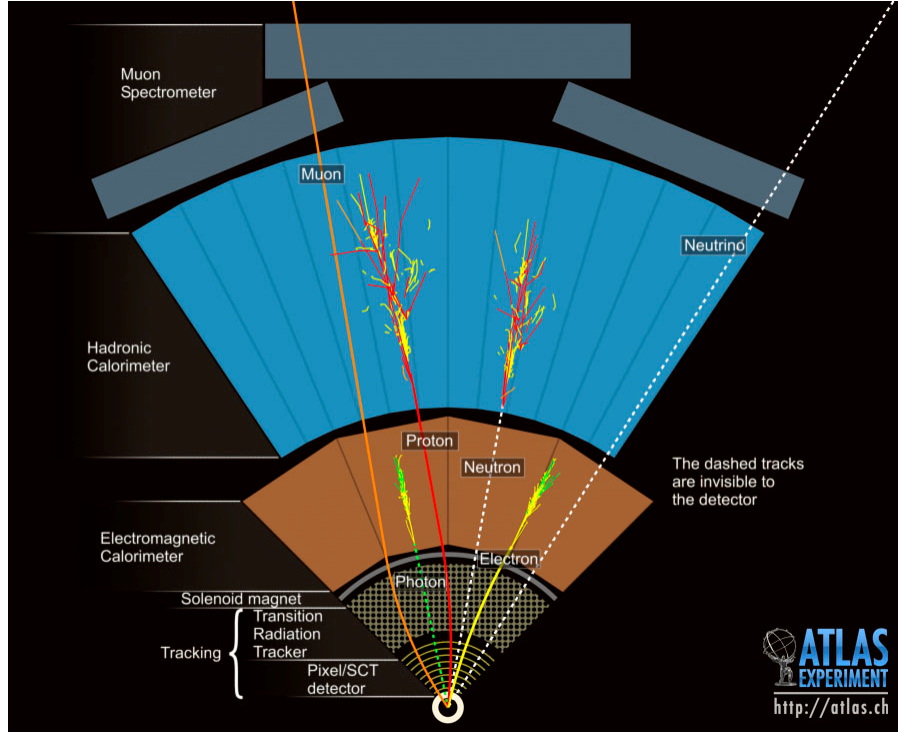


Figure 5.1: Different types of particles depositing their energy in different layers of the ATLAS detector [113].

To obtain the track's position, the hits that satisfy certain quality criteria are fitted in three dimensions using a global- χ^2 procedure [114]. The track is then extended to include hits identified in the TRT.

By contrast the outside-in algorithm starts with hits in the TRT detector and extends tracks back into the SCT and Pixel detectors. This algorithm is mainly used for tracks that do not originate from the primary hard scatter vertex. Once the tracks are reconstructed, the points at which they cross along the z axis is extrapolated. These crossings are then identified as either primary vertices originating from the hard scatter, or secondary vertices originating from the underlying event. Track crossings are also extrapolated in the $r\phi$ direction and associated to secondary vertices originating from long-lived particle decays. The primary vertex is chosen as the vertex whose tracks contain the highest sum of transverse momenta, squared, $\sum p_T^2$. Here, p_T denotes the magnitude of the particle's momentum, $\mathbf{p}_T$, which is a vector quantity.

The tracks are characterized by five parameters shown in Figure 5.2, and defined as:

- d_0 : The transverse impact parameter, defined as the distance of closest approach of a particle to the centre of the detector in the transverse plane ($x = 0, y = 0$).
- z_0 : The longitudinal impact parameter defined as the z location of the distance of closest approach of a particle to the centre of the detector in the transverse plane.
- q/p : The curvature describes the charge, q , of the track divided by the track momentum, p .
- ϕ_0 : The ϕ coordinate of the track at the particle's point of closest approach to the centre of the detector.

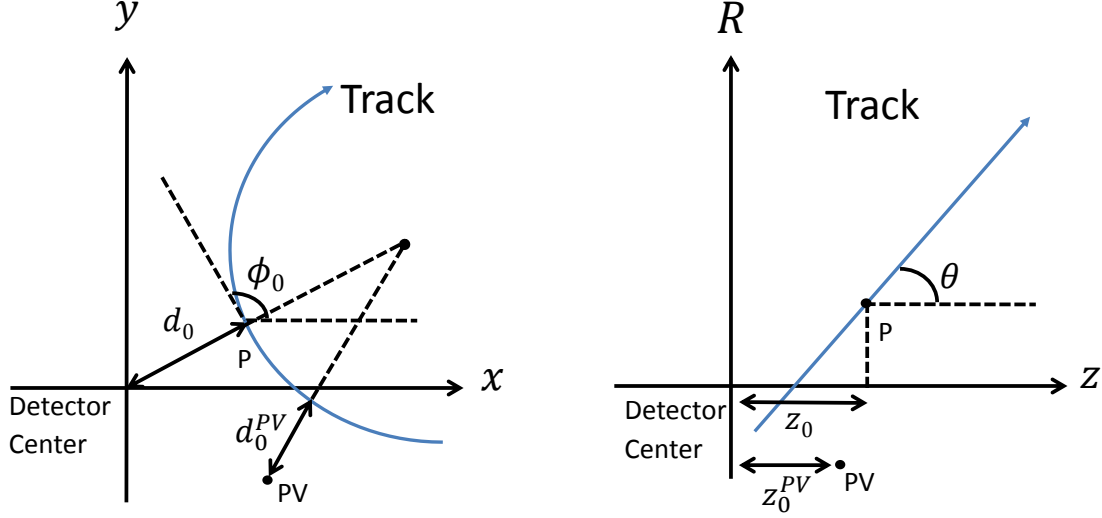


Figure 5.2: The track parameters in the transverse (xy) plane (left) and longitudinal (rz) plane (right). The location of the primary vertex is denoted by PV, and the closest point of the particle's approach to the detector centre is denoted by P. Made by N.Ilic.

- $\cot \theta$: The cotangent of the θ coordinate of the track at the particle's point of closest approach to the centre of the detector.

The impact parameters are sometimes defined with respect to the primary vertex instead of the centre of the detector. These definitions are denoted by z_0^{PV} and d_0^{PV} and are shown in Figure 5.2.

The number of reconstructed vertices in an event increases with the number of interactions per bunch crossing, as shown in Ref. [115]. This is likely due to the poor MC modelling of low-energy events. In order to correct for this mis-modelling, a scaling factor of 1.11 ± 0.03 is applied to the value of μ .

5.2 Electrons

5.2.1 Reconstruction

Electrons traversing the detector leave tracks in the ID and produce narrow showers of particles that are mainly contained in the electromagnetic calorimeter. The electromagnetic showers are narrow since electrons interact with the detector material through ionization and radiation which tends to be collimated, while hadrons interact strongly with detector nuclei and scatter off of them at larger angles. The electromagnetic showers are mostly contained in the electromagnetic calorimeters since the distance that they can travel, which is characterized by radiation length (X_0), is proportional to $1/Z^2$, where Z is the atomic number. Since the electromagnetic calorimeter is made of materials with high Z , most of the electromagnetic showers are contained.

The main algorithm used to reconstruct electrons is the outside-in algorithm, which identifies clusters of energy in the electromagnetic calorimeter and matches them to ID tracks. The electromagnetic clusters are identified by using a sliding window algorithm [116]. This algorithm sums electromagnetic energy deposits within a fixed rectangular window of 3×5 cells in $\eta \times \phi$. This window slides around the detector, performing iterative sums of energy in cells, until it centres itself on the maximum energy deposit, referred to as a seed. A cluster is then defined as the seed plus the sum of energies deposited

in the cells around the seed. When selecting cells to form a cluster it is important to include most of the electron energy while trying to exclude the detector noise. Which cells are selected depends on the object being reconstructed and its position in the detector [116].

When matching electromagnetic clusters to ID tracks, it is important to take into account the fact that an electron's trajectory can change due to the energy it loses via bremsstrahlung radiation. Approximately 20% of electrons will lose half of their energy in the ID before they enter the electromagnetic calorimeter. Thus, a Gaussian Sum Filter (GSF) technique is used to correct for changes in the electron track due to bremsstrahlung losses [117]. The GSF technique corrects for the fact that the true electron momentum, p_{true} , divided by the reconstructed momentum, p_{reco} , is non-Gaussian due to bremsstrahlung radiation. The GSF technique models this non-Gaussian behaviour by weighing the sum of different Gaussian components. The tracks are refitted using the GSF correction and the improved track is then matched to calorimeter clusters.

The inside-out algorithm starts with ID tracks and matches them to electromagnetic clusters in order to identify electrons. This algorithm is used for finding low energy electrons that might not be efficiently reconstructed with the outside-in algorithm.

5.2.2 Identification

Electrons can be grouped into different categories depending on which selection criteria they satisfy. The selection criteria are based on discriminating variables that have different distributions for electrons and other particles. The discriminating variables consider the leakage of the particle shower into the hadronic calorimeters, the size and shape of the showers in each layer of the electromagnetic calorimeters, the quality of tracks, the matching between tracks and clusters and additional output variables from the GSF algorithm. The discriminating variables are described below [118].

- Hadronic leakage variables: the ratio of the energy in the first layer of the hadronic calorimeter to that of the electromagnetic cluster (R_{HAD1}); the ratio of the energy in the hadronic calorimeter to that of the electromagnetic cluster (R_{HAD}).
- Amount of energy in Layer 3: the ratio of the energy in the third layer of the electromagnetic calorimeter to the total energy in the electromagnetic calorimeter (f_3).
- Shower size and shape in Layer 2: the ratio of the energy in 3×3 cells in $\eta \times \phi$ to that of the energy in 3×7 cells whose centre is defined at the electron cluster position (R_ϕ); the ratio of the energy in 3×7 cells to that of the energy in 7×7 cells whose centre is defined at the electron cluster position (R_η); the lateral width of the shower defined by $\sqrt{(\sum E_i \eta_i^2)/(\sum E_i) - ((\sum E_i \eta_i)/(\sum E_i))^2}$, where $E(\eta)$ are the energy (pseudorapidity) of a cell and the sum is performed in a window of 3×5 cells ($W_{\eta 2}$).
- Shower shape and size in Layer 1: the total shower width defined by $\sqrt{(\sum E_i (i - i_{max})^2)/(\sum E_i)}$, where the sum is performed over strips in a window of $\Delta\eta \times \Delta\phi \approx 0.0625 \times 0.2$ and i_{max} represents the highest-energy strip (W_{tot}); the ratio of the difference in energies between the largest and second largest energy deposits divided by the sum of these two energies (E_{ratio}); the ratio of the energy in the first layer of the electromagnetic calorimeter to the total energy in the electromagnetic calorimeter (f_1).

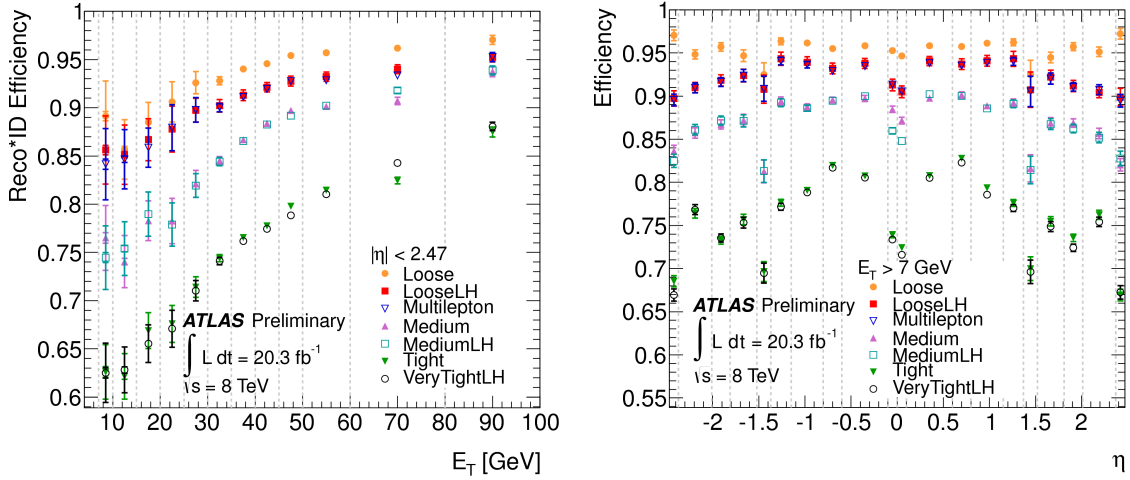


Figure 5.3: The measured combined electron identification and reconstruction efficiencies for different electron classifications as a function of electron energy in the transverse plane, E_T , (left) and η (right). The cut-based method identifies leptons as Loose, Multi-lepton, Medium, Tight. The Multi-lepton identification has more stringent requirements than the Loose, but less stringent requirements than the Medium selection. The likelihood method identifies electrons as LooseLH, MediumLH, Very-TightLH. The inner error bars show the statistical uncertainty, while the outer error bars show the statistical+systematic uncertainties. Dashed lines correspond to the bins in which the efficiencies were calculated [118].

- Track variables: the number of pixel hits (nPixHits); the number of hits in the first pixel layer (NBlayerHits); the number of SCT hits (nSiHits); the number of TRT hits (nTRTHits); the transverse impact parameter (d_0); the significance of the transverse impact parameter, defined as the transverse impact parameter divided by its estimated uncertainty (d_0/σ_{d_0}); the ratio of the number of high threshold hits to the total number of hits in the TRT (F_{HT}).
- Track-cluster matching: the $\Delta\eta$ between the cluster location in the first electromagnetic layer and the associated track ($\Delta\eta_1$); the $\Delta\phi$ between the cluster location in the middle electromagnetic layer and the associated track ($\Delta\phi_2$); the ratio of the cluster energy to the track momentum (E/p).
- GSF variables: the momentum the track loses while travelling from the perigee to the last point at which the track is measured divided by the total momentum ($\Delta p/p$); the $\Delta\phi$ between the cluster location in the middle electromagnetic layer and the associated track where the track momentum is scaled to the cluster energy ($\Delta\phi_{Res}$).

There are two methods for classifying electrons into their different categories. The first method is the *cut-based* method and identifies electrons by making selections on the discriminating variables [119, 120]. The cut-based method categorizes electrons into four different types: *loose*, *multi-lepton*, *medium* and *tight*. The selection on the discriminating variables becomes more strict in going from the loose to the tight definition.

The second method for classifying electrons into their categories is the *likelihood* method. This method classifies electrons into *loose LH*, *medium LH* and *very tight LH* classes. The method identifies electrons by inputting the discriminating variables into a multi-variate algorithm [121]. Using the variables, the algorithm analyzes electron and non-electron objects in MC simulation to create probability

distribution functions that describe the probability of an object being an electron. The five electron types are identified based on how efficiently the algorithm selects electrons and rejects backgrounds.

Figure 5.3 shows the measured electron identification and reconstruction efficiencies for the different electron classifications with the cut-based and likelihood methods. The efficiency is derived by analysing $Z \rightarrow ee$ and $J/\Psi \rightarrow ee$ events using the *tag-and-probe* method. One of the two electrons is required to satisfy strict selection criteria and is referred to as the *tag* electron. The remaining electron, called the *probe*, is not required to satisfy strict selection requirements and is used to measure the efficiency of electron reconstruction and identification. The efficiency is defined as the fraction of probe electrons that also pass the required strict criteria. The identification efficiency is the ratio of the number of probe electrons passing the required identification criteria to the number of probe electrons with a matching track that pass the track quality requirements. The reconstruction efficiency is the ratio of the number of probe electrons that are reconstructed as a cluster with a matching track to the number of clusters with or without a matching track. The efficiencies measured in data match the ones simulated in MC [118].

The energy of the electron is required to be isolated from other deposits in the calorimeter. The criteria applied to isolate the electrons depend on the analysis, and are thus described in Chapter 6.

5.2.3 Calibration

The first calibration applied to electrons is the energy correction to individual calorimeter cells described in Section 3.2.4. This base calibration is called the electromagnetic scale calibration. The remaining steps of the electron calibration for MC and data events are shown in Figure 5.4.

The first step in the calibration of electrons in data involves the longitudinal layer inter-calibration. The scales in the different longitudinal layers of the calorimeter must be properly calibrated, to model minimum ionizing particles, in each layer before the overall energy scale is determined. The first and second layers are calibrated using $Z \rightarrow \mu\mu$ events since muons do not lose energy upstream of the calorimeter. The muons behave as minimum ionizing particles and usually deposit 60 (210) MeV in the first (second) calorimeter layers. The third layer is not calibrated since its contribution is negligible [122].

In the second step the energy clusters in data are calibrated using corrections derived from $Z \rightarrow ee$, $W \rightarrow e\nu$ and $J/\Psi \rightarrow ee$ MC events. This calibration corrects for longitudinal/lateral shower leakage as well as energy loss in front of the calorimeters. The calibration constants are derived by feeding discriminating variables into a multivariate algorithm [122]. The discriminating variables include the total energy measured in the calorimeter, the ratio of the energy in the presampler to the calorimeter energy, and the shower depth [122].

In the third step, uniformity corrections are applied to account for variations in the energy response that are not in the detector simulation. These include non-optimal HV settings due to HV trips, energy lost between barrel calorimeter modules or biases in the LAr electronics calibration [122].

The fourth calibration applied is called an *in-situ* calibration. In-situ calibration refers to using data in well understood physics processes to calibrate detector objects. In this case, the calibration is derived from $Z \rightarrow ee$ events. This in-situ calibration accounts for any other differences in the modelling of material, leakage and shower development between the MC simulation and data. The corrections are derived by comparing the invariant mass of the di-lepton pair and its resolution in data and MC.

Finally, the energy scale calibration is validated by comparing the di-lepton invariant mass of $J/\Psi \rightarrow ee$ events in data and MC.

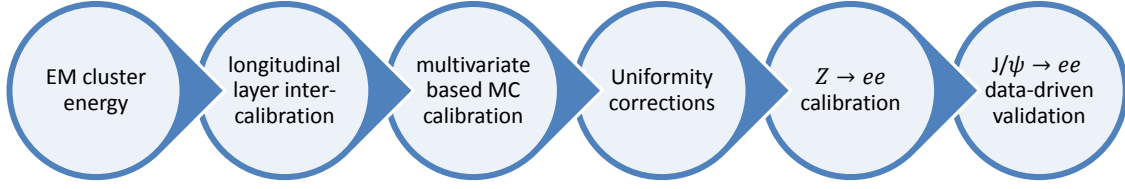


Figure 5.4: The electron calibration steps. Made by N.Ilic.

5.3 Photons

Photons traversing the detector interact electromagnetically and thus deposit most of their energy in the electromagnetic calorimeters. Photons interact with the detector material by producing e^+e^- pairs, undergoing Compton scattering and through photoelectric effects, which all tend to result in shower shapes more narrow than the ones produced by hadrons. Since photons are neutral particles they do not leave tracks in the ID. In approximately 40% of cases the photons convert into an e^+e^- pair before reaching the calorimeters. The uncovered photons are identified by searching for electromagnetic showers without matching ID tracks. Photons that have converted in the ID are reconstructed by searching for oppositely charged electrons near each other, whose tracks do not originate from the interaction point.

Photons are categorized into loose and tight categories using cut-based selections [123]. Loose photons are identified by making selections on the R_{HAD} , R_{HAD1} , R_η and $W_{\eta2}$ variables. Tight photons are identified by additional selections on the R_ϕ , W_{tot} , E_{ratio} , W_{S3} (the shower width in Layer 1 defined by three strips around the strip containing the maximum energy deposit), and F_{side} (the energy deposited in Layer 1 defined as the energy outside the three central strips but within seven strips divided by the energy within the three central strips) [123].

The calibration scheme for photons is the same as the one described for electrons, but using MC simulation containing photons ($Z \rightarrow \ell\ell\gamma$, $Z \rightarrow \mu\mu\gamma$, $\gamma + X$) to derive and validate the calibration factors. The additional calibration applied to photons from $Z \rightarrow ee$ events corrects for imperfections that do not apply to photons. These extra corrections on the photons are accounted for in the uncertainties on the photon calibration.

5.4 Jets

5.4.1 Reconstruction

Jets are objects formed from hadrons that initiate particle showers. Algorithms are employed to identify hadronic and electromagnetic energy deposits from which jets are reconstructed. The jet-finding algorithms that are employed should be *infrared* and *collinear* safe. Infrared safety refers to the fact that the same number of jets should be reconstructed by the algorithm regardless of whether there exist other soft particles in the event that do not originate from the fragmentation of a hard-scattered parton. Collinear safety means that an algorithm should reconstruct the same jet even if the particle that seeds the jet decays into two collinear particles.

In ATLAS, jet-finding algorithms are based on three-dimensional clusters of energy defined in the

calorimeters, called *topological* clusters [116]. These topological clusters are identified by scanning the $\sim 200\,000$ calorimeter cells to identify ones whose energy deposits are 4σ above the electronics and pileup noise level. These cells are referred to as seed cells and serve as the centre of the cluster. Cells neighbouring the seed that contain energy deposits above 2σ of the noise level are then iteratively added to the growing energy cluster. Finally, neighbouring cells that are not above the noise level are added. Cells containing the maximum energy are defined as cells whose energy is above 500 MeV, whose energy is greater than that of any neighbouring cell, and which have at least four neighbouring cells above a specified threshold. If there are multiple maxima, the cluster is split into two.

Older jet finding algorithms, referred to as a *fixed-cone* algorithms, involve identifying higher energy clusters and summing the four vectors of particles found in a cone ΔR around the cluster. These algorithms then adjust the centre of the jet to match the maximum energy deposits in the cone. Cone algorithms are not infrared safe since soft radiation between jets leads to merging of jets.

Newer algorithms join objects together based on the distance between the objects defined as

$$d_{ij} = \min(p_{T,i}^{2p}, p_{T,j}^{2p}) \frac{\Delta R_{ij}^2}{R^2}. \quad (5.1)$$

In equation 5.1, $p_{T,i(j)}$ are the transverse momenta of objects $i(j)$, and ΔR_{ij} is the distance between them. The distance between each object and the beam axis is denoted as $d_i = p_{T,i}^{2p}$. The objects with the smallest d_{ij} values are merged into a single object. This process is repeated until the distance between the beam and object, d_i , is smaller than the distance between objects, d_{ij} . The merged objects are then defined as a jet. A value of $p = 1$ corresponds to the k_T algorithm [124, 125, 125], in which the lowest p_T objects that are farthest from the interaction point are merged first. The jet is built backwards towards the high p_T objects. This algorithm has the disadvantage that low- p_T objects can change the shape of a jet. A value of $p = -1$ corresponds to the anti- k_T algorithm [126], in which jets are built starting with the highest p_T objects, located near the interaction point, outwards. In this algorithm, soft objects cannot greatly change how the jet is built. The k_T and anti- k_T algorithms usually use $\Delta R = 0.4$ or $\Delta R = 0.6$ sizes and are both infrared and collinear safe. A value of $p = 0$ corresponds to the Cambridge/Aachen algorithm [127, 128], in which the transverse momentum is ignored and the distance between the objects is the only information relevant in jet reconstruction.

5.4.2 Identification

Jets are categorized into four types depending on which selection criteria they satisfy. The selection criteria are defined in order to avoid biases from detector defects, cosmic rays and interactions of the beam that are unrelated to collisions. Jets are identified as *looser*, *loose*, *medium* or *tight* jets depending on the criteria they satisfy, which are based on the variables listed below [129].

- f_{EM} , $f_{quality}$ are variables used to eliminate coherent noise contributions from the electromagnetic calorimeters, in which a low amount of energy is deposited over many electromagnetic cells. These deposits can be rejected by selecting jets with a low fraction of the energy deposited in the electromagnetic calorimeters, f_{EM} , and a low fraction of cells with a bad quality signal shape, $f_{quality}$. Bad quality jets are defined by selecting $|f_{quality}| > 0.8$ and $f_{EM} > 0.95$.
- f_{HEC} , $f_{HECquality}$, E_{neg} are variables used to eliminate energy deposits from sporadic noise bursts in the HEC end-cap calorimeters, in which most of the jet energy comes from a single HEC cell.

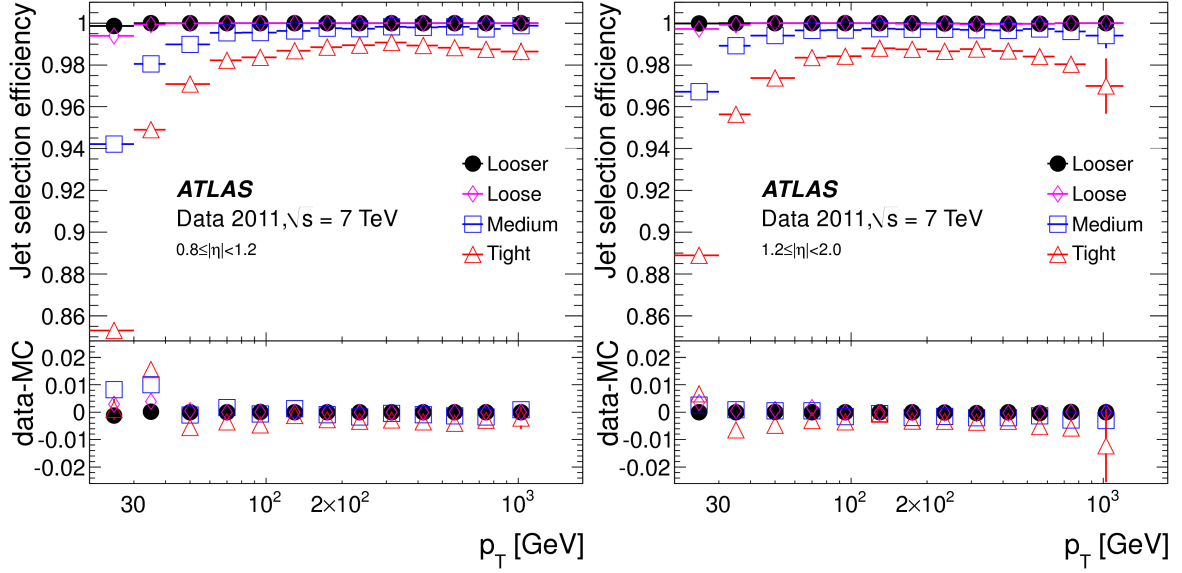


Figure 5.5: The jet selection efficiency for the $0.8 \leq |\eta| \leq 1.2$ (left) and $1.2 \leq |\eta| \leq 2.0$ (right) [129].

These energy deposits can be rejected by selecting jets with a low fraction of the energy deposited in the HEC endcap, f_{HEC} , and good signal shape quality, $f_{HECquality}$. Cells that contain large sporadic noise bursts are also often characterized by negative energy, E_{neg} , due to the capacitive coupling between them.

- t_{jet}, f_{ch}, f_{max} are variables used to eliminate energy deposits from cosmic rays or non-collision backgrounds that do not originate from the interaction point. Energy deposits not originating from the collision point are usually out of sync with the primary interaction in the event, and thus have a different time, t_{jet} with respect to the trigger-measured event time. In addition, these deposits contain low energy close to the interaction point and can be isolated by making additional selections on f_{EM} . Jets reconstructed from non-collision backgrounds also have a low fraction of track p_T compared to jet p_T , referred to as f_{ch} . These jets also have a high fraction of energy deposits in one calorimeter layer, referred to as f_{max} .

Figure 5.5 shows an example of the efficiency of selecting these jet definitions for two ranges in η ($0.8 \leq |\eta| \leq 1.2$ and $1.2 \leq |\eta| \leq 2.0$) as a function of jet p_T . The measurement is performed using methods described in [130]. The remaining η ranges can be found in [129].

5.4.3 Calibration

The default calibration applied to jets is the electromagnetic calibration, derived from electron test beam studies performed using detector components. However, another calibration scheme is necessitated by the fact that calorimeters respond differently to electromagnetically and hadronically interacting particles. Unlike electromagnetic showers, the energy deposited by the hadronic showers is usually much higher than what is registered in the calorimeter. This is because only hadrons interact strongly with the nuclei of the detector material, resulting in the release of undetected energy, termed *invisible energy*. This energy is not detected because it results from the release of energy used to bind the nuclei together. This lower detector response to hadrons must be accounted for by accurately calibrating jets. The *local*

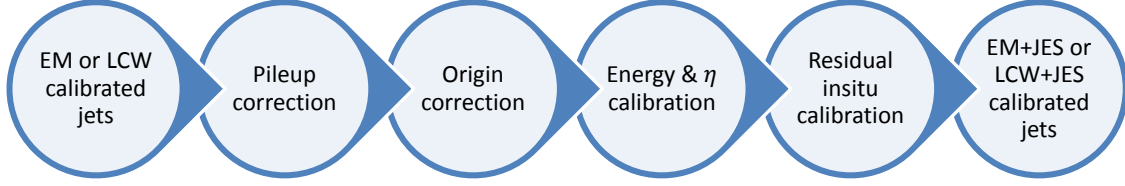


Figure 5.6: The different steps used to calibrate jets. Made by N.Ilic.

cluster weighting (LCW) calibration scheme accounts for lower detector response to hadrons. The LCW calibration is derived by identifying topological clusters as electromagnetic or hadronic based on their energy density and longitudinal shower depth. Correction weights are then derived from the response of pions in MC simulation and applied to the cells in the topological clusters. These weights compensate for differing electromagnetic and hadronic detector response, energy lost in dead material and energy in cells not included in cluster reconstruction.

Additional steps, shown in Figure 5.6, are also used to further refine the electromagnetic and LCW scales. A pileup offset correction corrects for the fact that the jet energy is increased due to pile-up. This correction is derived from MC simulation as a function of η and jet p_T to correct for the calibration's dependence on N_{PV} and μ . An additional pileup correction is applied that is based on a *jet area* method [129]. In this method, ρ is defined as the median of the jet momentum divided by the jet area and corresponds to the energy density from pileup. To remove pileup energy, the jet size multiplied by ρ is subtracted from the jet energy. After the pileup correction, the jet's tracks are corrected to point the jet in the direction of the primary vertex instead of the centre of the detector. After the origin correction, an MC-based energy and η calibration are applied that correct the jet energy in the detector to the true energy of the jet in MC simulation. This correction, referred to as the Jet Energy Scale (JES), is the largest correction (10-60%) and compensates for energy lost in the detector due to cracks and neutral particles, as well as the lower response to hadrons in the case of the electromagnetic calibration. There are separate JES corrections derived for the electromagnetic and LCW calibrations. JES corrections are smaller for LCW jets due to the intermediate cluster calibration step.

The final corrections applied to the jet energy scale are derived from in-situ calibrations. This calibration involves selecting events in which jets are balanced by well-measured objects, and calibrating the jet energy accordingly. Events containing Z +jets and γ +jets are used to calibrate lower p_T jets. Higher p_T jets are calibrated from multi-jet events in which the well measured low p_T jets balance a high p_T jet. Jets with an energy greater than 1.5 TeV are calibrated from test beam studies in which pions with energies up to 250 GeV are sent through the detector [131]. Since in-situ methods are performed in central detector regions as a function of jet p_T , additional corrections are applied to jets in different η regions. Forward jets are calibrated by analysing di-jet events, in which the energy of a central jet is used to calibrate the energy of a forward jet.

5.4.4 Pileup Suppression

The Jet Vertex Fraction (JVF) is a variable used to separate jets originating from the primary vertex and pileup events. It is defined for each jet, as the sum of the p_T of tracks originating from the primary vertex divided by the sum of the p_T of all jet-matched tracks in the jet:

$$\text{JVF} = \left| \frac{\sum_{\text{tracks}} p_T^{PV}}{\sum_{\text{tracks}} p_T^{all}} \right|. \quad (5.2)$$

JVF = 1 corresponds to jets which originate from the primary vertex, JVF < 1 corresponds to jets which have some tracks originating from pileup vertices, and JVF = 0 corresponds to jets whose tracks all originate from pileup vertices. Thus selecting on higher values of JVF is helpful in identifying jets originating from the primary vertex as opposed to pileup vertices.

5.4.5 Identifying b -quark jets

There are over 8 million top quark events contained in the 25 fb^{-1} dataset. The top quarks subsequently decay to bottom quarks which recombine to form b -hadrons. Identifying, or *tagging*, jets that originate from b -hadrons leads to efficient reduction of top events that are backgrounds to many searches for new physics processes. Since b -hadrons have longer lifetimes ($\tau \sim 10^{-12} \text{ s}$), the b -quark jets will have a vertex displaced from the primary vertex. Thus, tagging b -jets is largely dependent on accurate track reconstruction and accurate impact parameter measurements. The tracks used in b -tagging algorithms are required to satisfy various quality criteria in order to differentiate them from the tracks of converted photons and other long-lived particles such as K_S and Λ [132]. Hadrons containing c -quarks have lifetimes somewhat shorter than those of the b -hadrons, and thus their displaced vertices are closer to the interaction point. b -hadrons are also heavier and their decay products tend to have higher momenta than those of c -hadrons. A common way to classify b -jets is the multivariate MV1 algorithm [132]. This algorithm takes the IP3D, SV1 and JetFitter algorithms, described below, and combines the most discriminating output variables from these algorithms in a neural network. The MV1 is trained using b -jets as the signal and light flavour jets as the background. The output of the MV1 is a tag weight, which gives the probability of a jet originating from a b -quark.

The IP3D algorithm identifies b -jets using predefined MC distributions of the transverse and longitudinal impact parameter significances, d_0/σ_{d_0} and z_0/σ_{z_0} , for b -, c - and light-flavour (u, d, g) jets. The d_0/σ_{d_0} and z_0/σ_{z_0} distributions, which give more weight to tracks that are measured accurately, are represented by a two-dimensional histogram. The pre-defined MC histograms are then compared to the data of the jet being analyzed using a likelihood ratio that tests the light flavour and b -jet hypotheses.

The SV0 and SV1 algorithms are based on identifying secondary vertices that are found by searching for jet tracks which intersect far away from the primary vertex. These algorithms use the decay length significance, L_{3D}/σ_{3D} , measured in three dimensions, to distinguish between b -, c - and light-jets. The SV1 is a more sophisticated algorithm that builds a likelihood ratio based on two-dimensional and one-dimensional histograms of vertex variables. The two-dimensional histogram is built from the invariant mass of tracks from the vertex, and the ratio of the sum of energies of tracks in the vertex to the sum of energies of all tracks in the jet. The one dimensional histogram is the number of vertices containing two tracks. The distance, ΔR , between the jet axis and a line drawn between the primary and secondary vertex is also used as a discriminating variable.

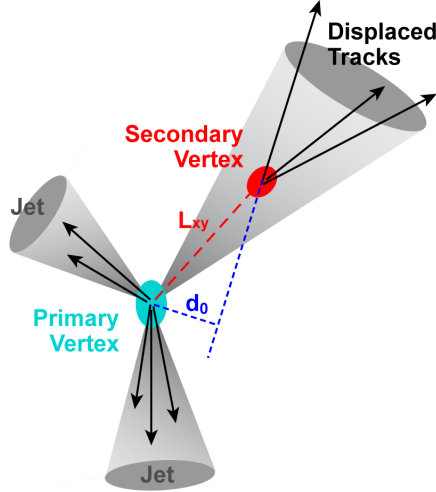


Figure 5.7: A representation showing the displaced secondary vertex of a b -jet. If the secondary vertex is on the opposite side of the interaction point, the track impact parameters and decay lengths are assigned to be negative [133].

The JetFitter algorithm exploits topological differences between b - and c -jets. This algorithm calculates the approximate time of flight for b -hadrons, by finding a common line on which the primary, b - and c -vertices lie. This algorithm uses a likelihood ratio with similar variables as the SV1, and in addition considers the flight length significance of the vertices.

Different b -tagging algorithms have different efficiencies for identifying b -jets and different probabilities of misidentifying c - and light-jets as b -jets. These efficiencies are calculated from simulated $t\bar{t}$ events as a function of p_T and η , as well as from data in b -, c - and light-jet enriched regions as a function of jet p_T . Scale factors are applied to simulated events in order to correct for the difference in efficiencies in data and simulation. The scale factors are defined as the ratio of the b -tag efficiencies in simulation and data, $SF(p_T, f) = \epsilon_{data}^f / \epsilon_{MC}^f$, and are dependent on jet p_T , and jet flavour, f . The b , c , and light flavour tagging efficiencies as a function of p_T and η for the MV1 algorithm are shown in Figure 5.8.

For every algorithm, working points are defined which depend on the b -jet efficiency as measured in simulation. The MV1 algorithm is calibrated to different working points, which are selected by choosing specific values of the output jet weights. The values are tuned to obtain b -jet efficiencies of 60%, 70%, and 80%, as measured in simulated $t\bar{t}$ events.

5.5 Taus

5.5.1 Reconstruction

Tau leptons are heavy (1776.82 MeV) compared to muons (105.7 MeV) and electrons (0.511 MeV), and thus decay before reaching the detector. They can only be identified by their decay products, which can include electrons, muons or pions along with the tau neutrino, ν_τ . The hadronic decays, τ_{had} , have a branching ratio of 65%, while the leptonic decays, τ_e/τ_μ , have a 35% branching ratio. Since it is not possible to distinguish leptonically decaying taus from electrons and muons, tau identification focuses on hadronic decays. Taus can decay to two, three or four pions. For example, a negatively charged tau

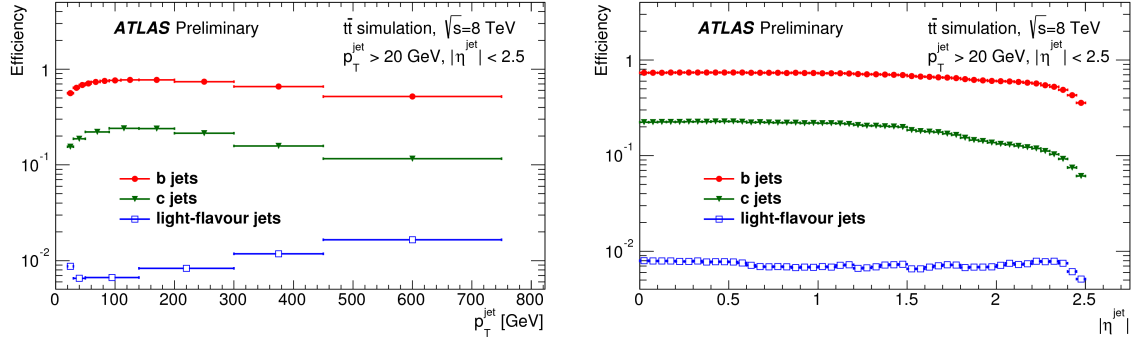


Figure 5.8: Efficiency of the MV1 algorithm to select b , c , and light flavour jets, as a function of jet p_T (left) and $|\eta|$ (right)[132]. The 70% working point is shown.

lepton can decay via $\tau^- \rightarrow \pi^- \pi^0 \nu_\tau / \pi^- \pi^+ \pi^- \nu_\tau / \pi^- \pi^+ \pi^- \pi^0 \nu_\tau$. Taus are reconstructed based on whether they contain one or three charged decay particle tracks, referred to as *one-prong* or *three-prong* decays.

The pions can be distinguished from other jets by their narrow shower shapes, and the fact that they usually have one isolated track associated to them. The narrow shower shapes are due to the fact that leptonically decaying pions produce electromagnetic showers. Tau leptons are identified by searching for one or three tracks from the pions forming a jet with a narrow shower shape. The π^0 mesons do not leave a track in the ID and are not identified in tau reconstruction.

The tau algorithm starts by searching for anti- k_T jets, which have a size $\Delta R = 0.4$. The kinematic variables described below are used to distinguish between tau and quark and gluon jets.

- f_{core}^{corr} : This variable is the fraction of energy in the central cone of the jet which is defined by $\Delta R < 0.1$. It tends to be higher for tau lepton decays since taus decay to pions, which, when decaying electromagnetically, result in narrow shower shapes.
- R_{track} : This variable is the p_T weighted track distance from the tau axis. This value peaks at lower values for tau decays.
- ΔR_{max} : This variable is the distance of the track farthest from the tau axis. This variable peaks at lower values for tau leptons since the charged tracks from tau lepton decays are collimated in a narrower cone than those of quark and gluon jets.
- S_T^{flight} : This variable describes the significance of the reconstructed secondary vertex. This variable peaks at higher values for tau decays.

5.5.2 Identification

The kinematic variables described above are used to separate τ_{had} from jets using three different methods. One method places selections on kinematic distributions to distinguish τ_{had} leptons from q/g jets. A second method involves separating the τ_{had} signal from other backgrounds using the log-likelihood-ratio [134]. This method uses the kinematic variables to create one dimensional probability distribution functions (PDFs) in bins of tau p_T . The final likelihood is calculated based on *loose*, *medium*, and *tight* working points, which correspond to the identification efficiencies of 70%, 60% and 40% (65%, 55%, 35%) for one-prong (three-prong) taus, respectively.

The third method feeds the kinematic variables into a multivariate algorithm, called the *Boosted Decision Tree* (BDT), which is trained using MC distributions to distinguish τ_{had} from q/g jets [134]. The BDT method also identifies tau leptons at the same working point efficiencies as the likelihood method. All of the methods treat one- and three-pronged tau decays separately.

The tau leptons can be distinguished from electrons since they have wider and longer showers in the calorimeters. In addition, unlike tau leptons, electrons cause transition radiation detected in the TRT. Muons have a probability to leave energy in the hadronic calorimeter, which can resemble tau signatures. These energy deposits are disregarded if they overlap with a muon reconstructed in the MS.

5.5.3 Calibration

Since the tau algorithm considers jets calibrated at the LCW scale, it already takes into account the lower response of the detector to hadrons, the energy deposited outside of reconstructed cells, and the dead detector material. An additional scale specific to tau leptons is derived using MC samples that simulate $W \rightarrow \tau\nu$ and $Z \rightarrow \tau\tau$ events. Using these samples the pileup offset is subtracted, the energy response to taus is determined, and an η -dependant correction is applied [135]. The pileup offset is calculated by observing the dependence of the tau p_T on the number of reconstructed vertices. The energy scale correction is calculated by comparing the true tau energy before reconstruction to the reconstructed tau energy as a function of p_T and η . The η correction is applied to compensate for the energy that is lost in poorly instrumented detector regions. This correction is calculated by comparing the true to the reconstructed η in MC. All of the corrections are calculated separately for one- and three-prong tau leptons.

5.6 Muons

5.6.1 Reconstruction

Muons leave tracks in the Inner Detector and Muon Spectrometer. Muons originating from the interaction point do not lose a significant amount of energy in the calorimeter and do not have a large amount of energy deposited around them. This is because muons do not give off Bremsstrahlung radiation and mainly lose their energy by acting as minimum ionizing particles. There are four different types of muons that are commonly used: *standalone* (SA), *combined* (CB), *segment-tagged* (ST), and *calorimeter-tagged* (CaloTag).

- Standalone (SA) muons are identified in the MS, and their tracks are extrapolated back to the interaction point. This is performed by the Muonboy algorithm [136], which searches for hits in the muon trigger chambers to identify regions of activity (ROA). Muon tracks are then formed from the muon segments in all the muon chambers in the ROA. The muon track is then extrapolated to the beam line, taking into account scattering and energy loss in the calorimeter. The energy lost in the calorimeter is calculated by considering how much detector material the muon traverses. SA muons are identified over the η range covered by the MS ($\eta < 2.7$).
- Combined (CB) muon algorithms use ID as well as MS information to form muon tracks. For this analysis, combined muons are identified using the STATistical COMbination (STACO) combined algorithm [136]. This algorithm first finds tracks in the ID and MS that satisfy certain quality

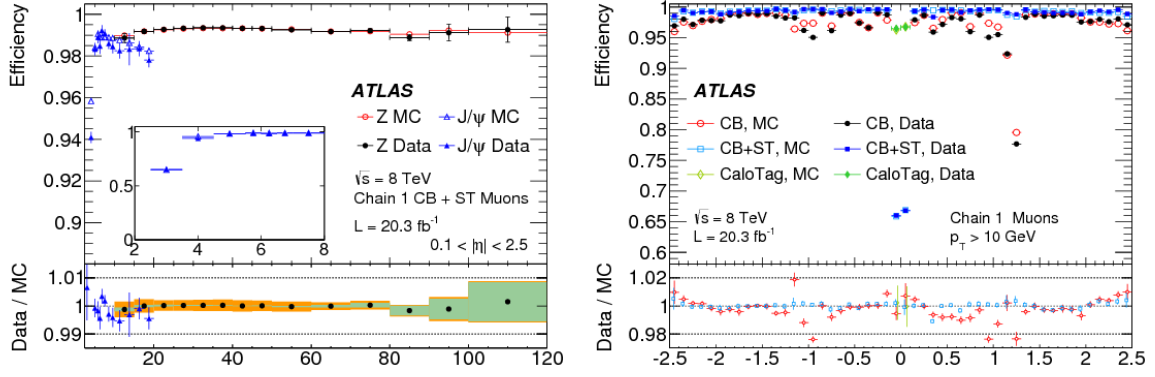


Figure 5.9: The muon reconstruction efficiencies for CB+ST muons as a function of muon p_T (left) and for CB, CB+ST and CaloTag muons as a function of η (right). The box inside the plot on the left is a zoom of the low- p_T region. The CB, and CB+ST muons are shown for $0.1 < |\eta| < 2.5$, while the CaloTag muons are shown for $|\eta| < 0.1$ [137].

criteria based on the number of ID and MS hits and holes. The tracks in the ID and MS are crudely matched in η and ϕ and are required to have the same charge. The algorithm then matches these tracks to each other using a χ^2 fit. The fit is defined as $\chi^2_{match} = (\mathbf{T}_{MS} - \mathbf{T}_{ID})^T (\mathbf{C}_{MS} - \mathbf{C}_{ID})^{-1} (\mathbf{T}_{MS} - \mathbf{T}_{ID})$, where $\mathbf{T}$ is the vector of the five track parameters described in Section 5.1, and $\mathbf{C}$ is the covariance matrix between them. The track parameters of the final muon track are the ones that give the lowest χ^2 . These parameters are given by $\mathbf{T} = (\mathbf{C}_{ID}^{-1} + \mathbf{C}_{MS}^{-1})^{-1} (\mathbf{C}_{ID}^{-1} \mathbf{T}_{ID} + \mathbf{C}_{MS}^{-1} \mathbf{T}_{MS})$. As a result of this procedure, the p_T of the reconstructed muon is the weighted sum of the ID and MS measurement. CB muons are identified up to ranges covered by the ID ($\eta < 2.5$).

- Segment-tagged (ST) muons are constructed using algorithms that extrapolate ID tracks to the MS to form muons. The algorithm used is called Mutag [136], and is useful for identifying low energy muons that do not always reach the outer muon chambers. It matches ID tracks with Muonboy segments that were not already used in the STACO algorithm. A χ^2 fit is used to match the ID to the inner MS tracks. The input variables to the fit are the tracking parameters described in Section 5.1. ST muons are identified over the range covered by the ID ($\eta < 2.5$).
- Calorimeter-tagged (CaloTag) muons are used in the $|\eta| < 0.1$ range where the muon chamber coverage is absent due to the space needed for services (cabling, cooling pipes, etc.). These muons are constructed by identifying inner detector tracks as muons if they are associated to calorimeter energy deposits consistent with a minimum ionizing particle.

The first three types of muons are collected into a group called the STACO Muon Collection. The STACO muon collection combines different muon identifications to optimize the reconstruction in different areas of the detector. By construction there is no overlap between the STACO and Mutag algorithms, and the overlap between STACO/Mutag and Muonboy is removed. The STACO muon collections contain combined muons when ID and MS information is available. It contains Standalone muons when a muon track can not be reconstructed in the ID due to the lower η coverage of the ID. Finally, it contains muon segments if a low- p_T muon does not reach the outer chambers, or at $|\eta| < 0.1$. Since muons from the hard scatter do not leave a significant amount of energy around them, they are required to be well

isolated in the detector, meaning that there should not be large energy deposits in a certain ΔR cone around the muon. The size of the cone depends on the analysis.

Figure 5.9 shows the muon reconstruction efficiency for various muon types as a function of p_T on the left and η on the right. The data points are from $Z \rightarrow \mu\mu$ and $J/\psi \rightarrow \mu\mu$ events for CB and CB+ST muons, and $Z \rightarrow \mu\mu$ for CaloTag muons.

Additional requirements are made that ensure that the energy of the muon is isolated from other deposits. The isolation criteria are specific to the analysis and are described in Section 5.8.

5.6.2 Calibration

The energy scale of muons is calibrated using $Z \rightarrow \mu\mu$ and $J/\psi \rightarrow \mu\mu$ events. To account for the fact that resolution smears the measured value, the distribution of muon p_T is multiplied by a Gaussian distribution. In addition, scale factors are applied that correct the muon p_T . The smearing and scale corrections account for the energy lost in the detector before the MS, imperfect knowledge of the magnetic field, and multiple scattering. The scale factors are dependent on η and ϕ .

5.7 Missing Transverse Energy

In collisions at the LHC, the particles collide along the z axis and thus have zero total momentum in the transverse x, y plane before the collision. From the conservation of momentum law, the total amount of momentum in the transverse plane after the collision should also be zero. If the vector sum of all the identified objects in the event does not equal zero, the missing transverse momentum is defined as the negative sum of the transverse momenta of all objects. This is a vector quantity that is referred to as the missing transverse energy (MET). It results from the presence of undetectable particles such as neutrinos and dark matter, or from other objects that are poorly reconstructed such that their energy was wrongly measured. The MET can be calculated from objects in the calorimeters, denoted by the vector quantity, $\mathbf{E}_T^{miss}$; from tracks in the inner detector, denoted by the vector quantity $\mathbf{p}_T^{miss(trk)}$; or from a combination of both, denoted by the vector quantity $\mathbf{p}_T^{miss}$. The magnitudes of these vector quantities are denoted by E_T^{miss} , $p_T^{miss(trk)}$ and p_T^{miss} .

5.7.1 Calorimeter Based Missing Transverse Energy

Calorimeter based MET, denoted as $\mathbf{E}_T^{miss}$, is constructed mainly from the energy deposits in the calorimeter. It is defined in the x and y plane from the sum of the calorimeter energy $\mathbf{E}_T^{miss,calo}$, muon momenta, $\mathbf{p}_T^{miss,\mu}$, and the correction applied to the energy lost in the cryostats, $\mathbf{E}_T^{miss,cryo}$, as shown in equation 5.3. The x and y components are then summed in quadrature (equation 5.3) to obtain the quantity E_T^{miss} (equation 5.4), located at an angle ϕ away from the x -axis (equation 5.5)

$$E_{x(y)}^{miss} = E_{x(y)}^{miss,calo} + p_{x(y)}^{miss,\mu} + E_{x(y)}^{miss,cryo} \quad (5.3)$$

$$E_T^{miss} = -\sqrt{(E_x^{miss})^2 + (E_y^{miss})^2} \quad (5.4)$$

$$\phi^{miss} = \arctan\left(\frac{E_y^{miss}}{E_x^{miss}}\right). \quad (5.5)$$

The muon term of the missing transverse energy is calculated from the muons : $E_{x(y)}^{miss,\mu} = -\sum_{muons} E_{x(y)}$. Combined muons, which have matching ID tracks, are used for $|\eta| < 2.5$. In the $2.5 < |\eta| < 2.7$ range standalone muons from the MS only are used, and outside of the muon acceptance, at $|\eta| > 2.7$ the muon measurement is made from the calorimeter-tagged muons. For isolated muons, meaning they are not located within $\Delta R < 0.3$ of a jet, the muon p_T does not include the energy lost by the muon in the calorimeter. For non-isolated muons, the energy lost by the muon in the calorimeter cannot be separated from the jet energy. In this case the muon p_T includes the energy lost by the muon in the calorimeter if there is a significant discrepancy between the muon p_T in the ID and MS.

The correction that is made for the energy lost in the cryostats, $E_{x(y)}^{cryo}$, is calculated by analysing the jet energy lost in the last layer of the electromagnetic calorimeter (E_{EM3}) and the first layer of the hadronic calorimeter (E_{HAD}). The lost energy is then calculated using

$$E_{x(y)}^{cryo} = -\sum_{jets} w^{cryo} \sqrt{E_{EM3} \times E_{HAD}}, \quad (5.6)$$

where w^{cryo} is a weight based on the calibration scheme used [138].

The calorimeter term, $E_{x,y}^{miss,calo}$, contains several different types of calibration techniques. The two most optimal calibrations are Local Hadronic Topological calibration using the LCW calibration, and an object-based calibration, referred to as the Refined Final calibration. In the Refined Final calibration, the $E_{x,y}^{miss,calo}$ term, defined in equation 5.7, is made from electrons, photons, hadronically decaying tau leptons, jets, low- p_T (soft) jets, energy the muons left in the calorimeter, and other un-clustered energy deposits, called *CellOut*. Each term in equation 5.7 is the negative sum of the cell energies inside a specific object:

$$E_{x(y)}^{miss,calo} = E_{x(y)}^{miss,e} + E_{x(y)}^{miss,\gamma} + E_{x(y)}^{miss,\tau} + E_{x(y)}^{miss,jets} + E_{x(y)}^{miss,softjets} + E_{x(y)}^{miss,CellOut} \quad (5.7)$$

Each of the objects in equation 5.7 is calibrated individually as explained below.

- $E_{x(y)}^{miss,e}$ contains cut-based medium quality electrons with $p_T > 10$ GeV, calibrated at the default electron calibration explained in Section 5.2.
- $E_{x(y)}^{miss,\gamma}$ contains tight quality photons with $p_T > 10$ GeV, calibrated at the electromagnetic scale.
- $E_{x(y)}^{miss,\tau}$ contains tight quality tau leptons with $p_T > 10$ GeV, calibrated at the LCW scale.
- $E_{x(y)}^{miss,jets}$ contains anti- k_T jets with $p_T > 20$ GeV, calibrated at the LCW and JES scales.
- $E_{x(y)}^{miss,softjets}$ contains anti- k_T jets with $7 \text{ GeV} < p_T < 20 \text{ GeV}$ calibrated at the LCW scale.
- $E_{x(y)}^{miss,CellOut}$ contains topological clusters, calibrated at the LCW scale, that are not included in the other objects. This term also includes low- p_T tracks from particles that do not reach the calorimeter. When topological clusters are matched to tracks, the track energies are used due to their better momentum resolution at low energy.

The CellOut term also contains the energy that muons deposit while traversing the calorimeter. Since this energy is also included in the muon terms, it is double counted. In order to avoid this double

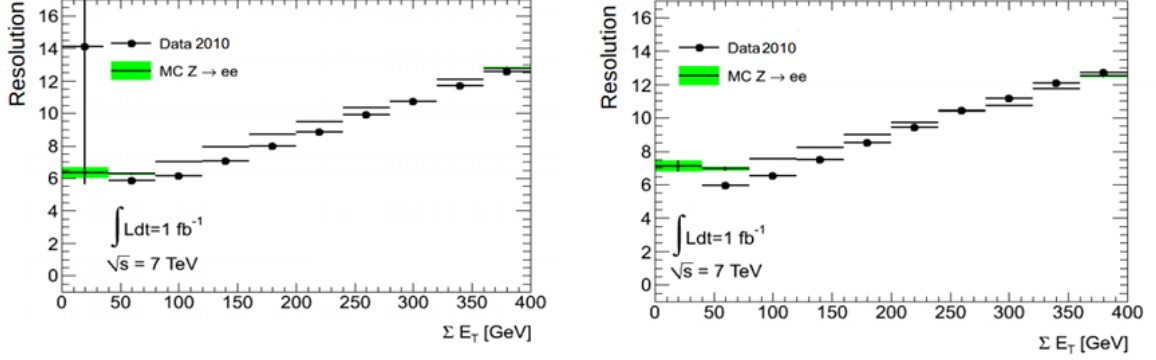


Figure 5.10: Resolution, in GeV, projected along the A_Z axis of the Refined Final (left) and Local Hadronic Topological (right) distributions, as measured in $Z \rightarrow ee$ events. The $Z \rightarrow \mu\mu$ measurements are similar. Made by N.Ilic.

counting, the measured/predicted muon energy loss in the calorimeter is subtracted from the muon momentum.

The performance of the Local Hadronic Topological and Refined Final calibrations have been studied using $Z \rightarrow ee/\mu\mu$ events. These events do not have neutrinos in them and are thus expected to have zero $\mathbf{E}_T^{miss}$. The resolution of $\mathbf{E}_T^{miss}$ is defined as the width of the $\mathbf{E}_T^{miss}$ distribution. Assuming that most objects in an event are accurately measured, this width should be narrow (~ 10 GeV). The Local Hadronic Topological and Refined Final calibrations have similar resolutions, as is shown in Figure 5.10.

However, by studying the hadronic recoil of the $Z \rightarrow ee/\mu\mu$ system it was found that the Refined Final calibration performed better than the Local Hadronic Topological calibration. If the objects were perfectly calibrated, the $Z \rightarrow ee/\mu\mu$ processes should be balanced by the hadronic recoil such that the value of $\mathbf{E}_T^{miss}$ is zero. Since electrons and muons are well calibrated objects, any deviation of $\mathbf{E}_T^{miss}$ from zero indicates an improper calibration of $\mathbf{E}_T^{miss}$. Figure 5.11 shows the mean $\mathbf{E}_T^{miss}$ along the axis parallel to the momentum of the Z boson ($\mathbf{p}_{T,Z}$), defined as $\mathbf{A}_z = \frac{(\mathbf{p}_T^{\ell^+} + \mathbf{p}_T^{\ell^-})}{|\mathbf{p}_T^{\ell^+} + \mathbf{p}_T^{\ell^-}|}$, where $\mathbf{p}_T^{\ell}$ are the momenta of the electrons or muons from the Z decay. This figure shows that when using the Hadronic Topological calibration the mean of the $\mathbf{E}_T^{miss}$ along the $\mathbf{p}_{T,Z}$ axis deviates more from zero than the Refined Final calibration, implying a larger bias. Nevertheless both calibrations deviate from the expectation of zero by only a few GeV.

The bias in the Refined Final calibration can be further studied by separating events containing jets with $p_T > 20$ GeV, from events that have no jets above this threshold. These plots are shown in Figure 5.12 for $Z \rightarrow ee/\mu\mu$ events. The fact that the bias does not exist in events containing higher p_T jets indicates that the higher p_T jet calibration correctly balances the leptons from the Z decays. The bias in events with zero jets then indicates that the problem is in the modelling of low- p_T hadronic recoil. Nevertheless the bias is only on the order of a few GeV and does not impact this physics analysis.

5.7.2 Track Based Missing Transverse Energy

There are fewer potential sources of error associated with matching vertices to their tracks than to their calorimeter deposits. For this reason, a definition of MET based on tracks is less sensitive to errors introduced in matching objects to vertices. Thus a track-based MET, denoted by $\mathbf{p}_T^{miss(trk)}$, is less

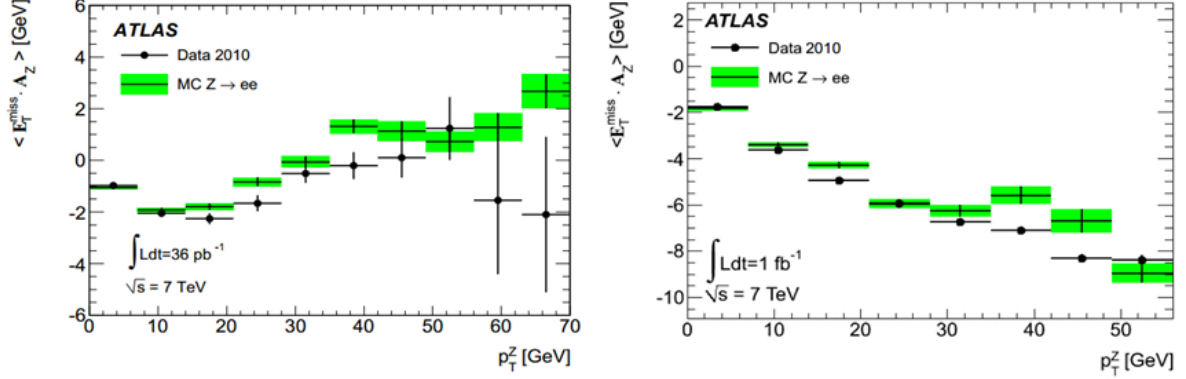


Figure 5.11: The mean of E_T^{miss} projected along the Z p_T axis for the Refined Final (left) and Local Hadronic Topological (right) calibrations. The $Z \rightarrow ee$ events are shown, but the $Z \rightarrow \mu\mu$ events show the same patterns. Made by N.Ilic in [139].

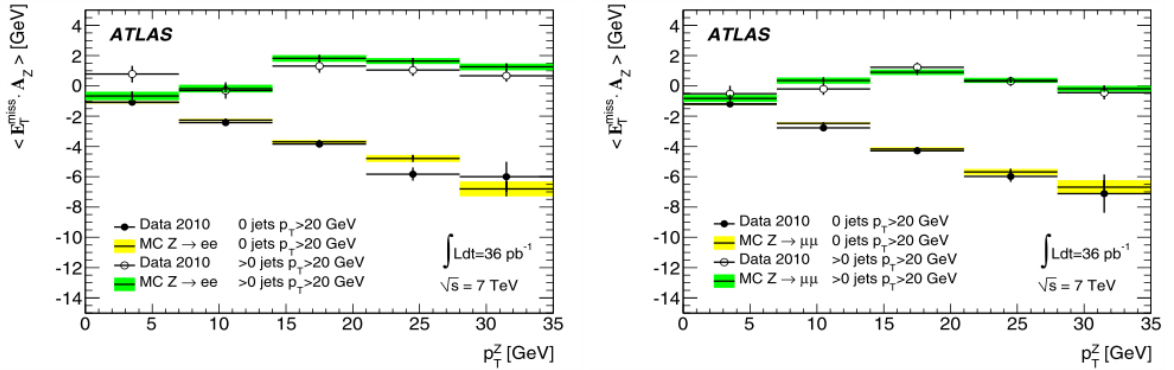


Figure 5.12: The mean of E_T^{miss} projected along the Z p_T axis for the Refined Final calibration in $Z \rightarrow ee$ (left) and $Z \rightarrow \mu\mu$ (right) events, separated by jet multiplicity. Made by N.Ilic in [139].

sensitive to pileup. The $\mathbf{p}_T^{miss(trk)}$ definition is constructed from the negative sum of all tracks:

$$\mathbf{p}_T^{miss(trk)} = - \sum_{i \text{ tracks}} \mathbf{p}_{T,i}. \quad (5.8)$$

The tracks are required to satisfy the conditions: ≥ 1 nPixHits, ≥ 6 nSiHits, $|\eta| < 2.5$, and $p_T > 500$ MeV. They are also required to have $d_0^{PV} < 1.5$ mm and $z_0^{PV} \sin(\theta) < 1.5$ mm.

An additional definition of MET uses the jet and electron calorimeter deposits instead of the tracks. In this case, the jet and electron track momenta can be replaced by the calorimeter energy:

$$\mathbf{p}_T^{miss} = - \sum_{i \text{ tracks}} \mathbf{p}_{T,i} + \sum_{j \text{ jets}} (\mathbf{p}_{T,j}^{trk} - \mathbf{p}_{T,j}^{calo}) + \sum_{e \text{ electrons}} (\mathbf{p}_{T,e}^{trk} - \mathbf{p}_{T,e}^{calo}). \quad (5.9)$$

The jets used in equation 5.9 satisfy $p_T > 25$ (30) GeV for $|\eta| < 2.4$ (> 2.4). They are also required to have $|\text{JVF}| > 0.5$ if they satisfy $p_T < 50$ GeV and $|\eta| < 2.4$. Tracks are matched to jets if they are located within a cone of $\Delta R = 0.4$ around the jet. The electrons used have a $p_T > 10$ GeV.

5.8 Objects Used in the $H \rightarrow WW^*$ Analysis

Muons from the STACO combined muon collection are used in the $H \rightarrow WW^*$ analysis.

The electrons used in the analysis that have $E_T > 25$ GeV satisfy the medium cut-based requirement that is applied by the single-lepton trigger. Electrons with lower momentum are more likely to be mistaken for light-flavour jets or electrons resulting from photon conversions. This is because selections used to identify electrons are less efficient for low- p_T electrons since their showers are wider and noise can play a more significant role. Additionally, the jet p_T spectrum falls steeply and thus there are many low- p_T jets which can be confused with electrons. Since electrons with lower momentum are more likely to be mistaken for jets, electrons with $10 \text{ GeV} < E_T < 25 \text{ GeV}$ have more strict selection criteria and are required to satisfy the very tight likelihood requirement. Using the likelihood definition reduces backgrounds by 35% when compared to the cut-based definitions.

Additional requirements are made to reduce contributions from photon conversions. These requirements include rejecting electron candidates that are missing a hit in the inner most layer of the Pixel detector, and rejecting candidates whose track is part of a photon conversion vertex.

Requirements are also made on lepton impact parameters and isolation. Electrons are required to satisfy $|d_0^{PV}|/\sigma_{d_0^{PV}} < 3.0$, and $|z_0^{PV} \sin \theta| < 0.4$ mm. Muons are required to satisfy $|d_0^{PV}|/\sigma_{d_0^{PV}} < 3.0$, and $|z_0^{PV} \sin \theta| < 1.0$. The isolation requirements are based on variables calculated from the ID and calorimeter. The ID-based isolation requires the sum of tracks, $\sum p_T$, divided by the electron E_T (muon p_T) to be lower than 0.06 at the lowest lepton energies, and 0.10 (0.12) at the highest electron (muon) energies. The tracks that are included in the sum must satisfy $p_T > 400$ (1000) MeV for electrons (muons). These tracks are also required to be within a $\Delta R = 0.4$ of the primary vertex if the lepton transverse momentum satisfies $p_T < 15$ GeV. The tracks are required to be within a distance of $\Delta R = 0.3$ around the primary vertex if the lepton transverse momentum satisfies $p_T > 15$ GeV. The calorimeter-based isolation is defined as the sum of transverse energy, $\sum E_T$, deposited in calorimeter cells at a distance $\Delta R < 0.3$ around the lepton candidate, divided by the E_T (p_T) of the electron (muon). Energy deposits located 0.125×0.175 in $\Delta\eta \times \Delta\phi$ around the electron cluster, and within $\Delta R < 0.05$ are excluded from

$\sum E_T$. The selected value of the isolation varies monotonically with the lepton energy. This value is 0.20 for electrons that satisfy $10 \text{ GeV} < E_T < 15 \text{ GeV}$ and increases to 0.28 for electrons that satisfy $E_T > 25 \text{ GeV}$. The value is 0.06 for muons satisfying $10 \text{ GeV} < p_T < 15 \text{ GeV}$ and increases to 0.28 for muons satisfying $p_T > 25 \text{ GeV}$.

Jets reconstructed with the anti- k_t algorithm and radius of $\Delta R = 0.4$ are used in the $H \rightarrow WW^*$ analysis. Jets with $p_T < 50 \text{ GeV}$ and $|\eta| < 2.4$ are required to satisfy $\text{JVF} > 0.5$.

If two leptons or a lepton and jet are close to each other in $\eta - \phi$ space, one of the objects is removed. "Removed" in this sense means that the reconstructed object is not used in the event. Electron candidates that have tracks in the MS are removed. An electron is removed if it is within a distance $\Delta R < 0.1$ of a muon, since this is usually an indication of muons undergoing bremsstrahlung in the ID or calorimeter. Since high energy electrons are always reconstructed as jets, jets are removed if they are within $\Delta R = 0.3$ of an electron. If a muon is found within $\Delta R = 0.3$ of a jet, the muon is removed, since it likely originates from heavy-flavour decay. Finally if two electrons are within $\Delta R = 0.1$ of each other, the electron with the higher E_T is retained.

The p_T^{miss} definition of MET is used to define the discriminating variables. However, when selections are made on the MET to separate the Higgs signal from background, different definitions of MET are used depending on the channel. An additional definition is constructed for the $H \rightarrow WW^*$ analysis, in which the MET is projected along the nearest reconstructed object. This definition is called *relative* MET, denoted by $E_{T,\text{rel}}^{\text{miss}} (p_{T,\text{rel}}^{\text{miss}})$, and is shown in equation 5.10 for the calorimeter-based MET:

$$\begin{aligned} E_{T,\text{rel}}^{\text{miss}} &\equiv E_T^{\text{miss}} \sin \Delta\Phi \text{ for } \Delta\Phi < \frac{\pi}{2} \\ &\equiv E_T^{\text{miss}} \text{ elsewhere.} \end{aligned} \tag{5.10}$$

In equation 5.10, Φ is the angle between E_T^{miss} and the closest object. This definition applies to the track-based MET definitions as well. The relative MET reduces the effects of mis-measured objects in which the MET is located near the object. The effect of selecting different definitions of MET to separate the signal from the background was evaluated in each channel and the optimized definitions were chosen. The MET values optimized for each channel are obtained with the MET definitions described below.

- In the different-flavour channel the p_T^{miss} definition is used since it has the best resolution. In the ≥ 2 -jet VBF different-flavour channel, there are no selections made on MET to separate the signal from the background.
- In the 0-, 1-jet same-flavour channels the $p_{T,\text{rel}}^{\text{miss}(\text{trk})}$ and $E_{T,\text{rel}}^{\text{miss}}$ definitions are used. These definitions reject the most DY background, which is dominant in the same-flavour channel.
- In the ≥ 2 -jet VBF same-flavour channel the p_T^{miss} and E_T^{miss} are used since they provide the most efficient DY rejection.

Chapter 6

The $H \rightarrow WW^*$ Search Strategy

The general search strategy employed in order to extract the $H \rightarrow WW^*$ signal involves defining a phase space that narrows in on the ggF and VBF signal processes by utilizing kinematic distributions that are different for the signal and backgrounds. The exact value in the distribution of variables that separates the signal from the background is referred to as a *cut*. Cuts are applied to isolate a signal-enriched phase space, referred to as a *signal region* (SR), and a background rich *control region* (CR). The control regions are used to normalize the backgrounds in the signal regions using data whenever possible. The control regions are defined to be as close as possible to the signal regions in order to eliminate the uncertainty associated with extrapolating background information from the control region to the signal region. When it is not possible to extract a background normalization from a control region due to low statistics or the difficulty of isolating the background, the background is estimated from other data-driven techniques or MC simulation. When backgrounds are estimated from MC simulation, their predictions are often validated in *validation regions* (VR), which isolate the specific background.

In order to prevent biases when choosing the optimal cut values, the data in the signal region are not looked at. This process is called *blinding*, and ensures that no biases are introduced by data in the signal region. The transverse mass of the objects in an event, m_T , defined in Section 6.1, is used as the final discriminating variable that separates the signal from the background. The m_T distribution in the signal and control regions is fed into the statistical analysis framework described in Chapter 7. The uncertainties associated with MC simulation due to experimental and theoretical sources are also included in the statistical analysis. The statistics framework evaluates whether the observed data are consistent with the Standard Model Higgs theory being tested. The expected statistical results are obtained while the analysis is blinded, and the observed results are obtained after unblinding. The various steps required in the analysis are graphically represented in Figure 6.1.

Kinematic selections used to reduce the backgrounds and extract the ggF and VBF signal processes are described in Sections 6.1. Section 6.2 describes the methods for estimating various backgrounds. The systematic uncertainties on the signal and background processes are described in Section 6.3. The 7 TeV and 8 TeV data are treated in a similar manner. The figures and tables are shown for the 8 TeV data, unless otherwise specified. The differences in treatment of 7 and 8 TeV data are presented in Section 6.4.

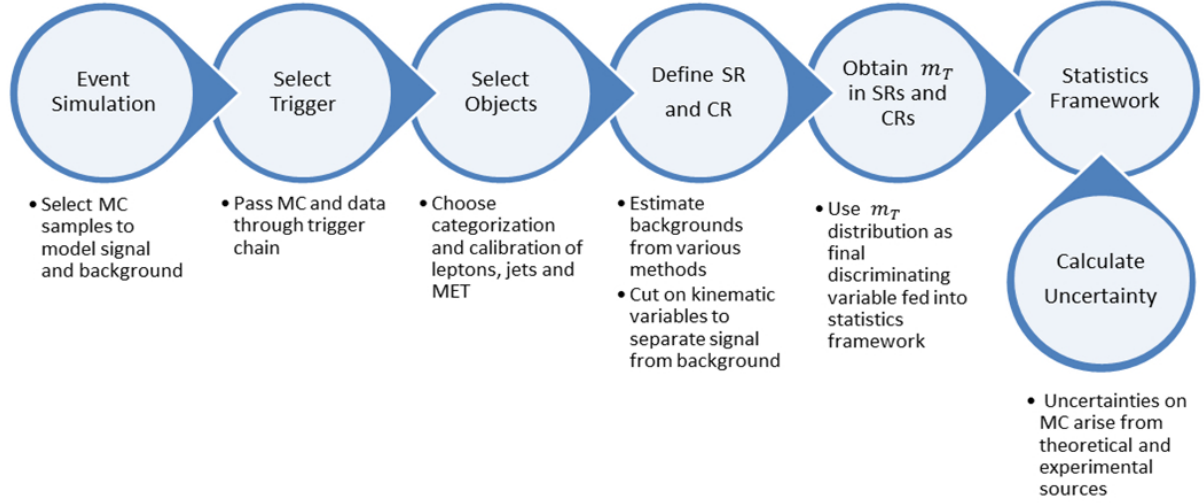


Figure 6.1: The steps performed in order to obtain the final information used to obtain results within the statistics framework. Made by N.Ilic.

6.1 Signal Extraction

Feynman diagrams for the ggF and VBF production processes are shown in Figure 6.2. In ggF Higgs production, a Higgs boson is produced from two gluons through a quark triangle. In VBF Higgs production the initial quarks radiate two bosons, which combine to create a Higgs particle. In VBF production, there is no colour flow between the incoming quarks and the Higgs system, and thus, at the matrix-element level, the incoming quarks fragment into two high-energy jets that have a large rapidity gap between them. The leptons in VBF events tend to lie in the centre of the detector between the forward jets.

Several kinematic variables whose distributions are different between the signal and background are used to separate the two. The cut values used to reject the backgrounds have been optimized for all of the ggF and VBF channels separately. The VBF analysis uses a Boosted Decision Tree (BDT) method described in Section 6.1.2, which uses discriminating variables as BDT input instead of cutting on them.

The kinematic variables that are specific to the Higgs topology and used to select Higgs events are summarized below.

- n_j : The different signal regions are split by the number of jets, n_j . These jets are defined as having $p_T > 25$ GeV for jets with $|\eta| < 2.4$ and $p_T > 30$ GeV for jets with $2.4 < |\eta| < 4.5$. Jets in the forward detector regions have higher momentum requirements in order to suppress jets from pileup.
- $\Delta\phi_{\ell\ell}$: This variable is the azimuthal angle of the di-lepton system. The Higgs boson is a spin-0 particle, and thus the two WW^* bosons from the Higgs decay have opposite spin polarization. Since angular momentum is conserved, the resulting lepton and neutrino decay states will have their spins aligned with the spin of the W s, as shown in Figure 6.3. Due to these spin correlations, the leptons from the $H \rightarrow WW^*$ decays will emerge from the interaction point near each other resulting in lower $\Delta\phi_{\ell\ell}$ values than obtained from background processes. This variable is efficient in isolating the signal from Standard Model WW background, which peaks at larger values of the

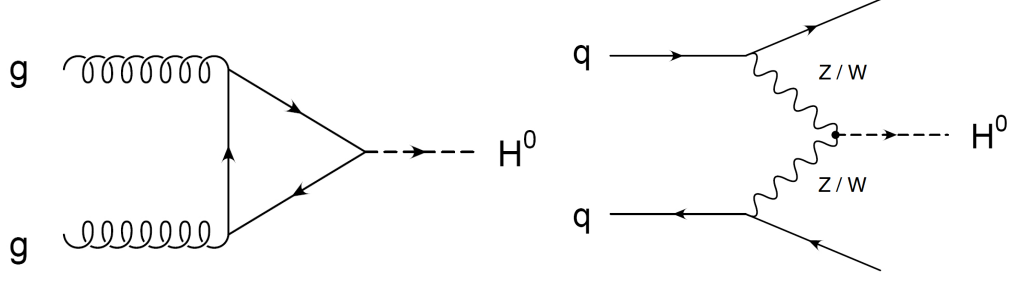


Figure 6.2: The ggF Higgs production process (left) and VBF Higgs production process (right) [13].

$\Delta\phi_{\ell\ell}$ distribution.

- $m_{\ell\ell}$: This variable is the invariant mass of the two leptons that originate from the hard scatter. Events with low invariant mass (few GeV) tend to originate from non- WW di-boson background, while events with an invariant mass around the W mass mainly arise from Standard Model WW events. Thus the Higgs signal can best be isolated by selecting on invariant masses between these two values.
- m_T : This variable is the transverse mass of all the objects in the event and is used as the final discriminating variable after all of the other cuts are made. It is defined as

$$m_T = \sqrt{(E_T^{\ell\ell} + p_T^{miss})^2 - |\mathbf{p}_T^{\ell\ell} + \mathbf{p}_T^{miss}|^2}, \quad (6.1)$$

where $E_T^{\ell\ell} = \sqrt{(p_T^{\ell\ell})^2 + m_{\ell\ell}^2}$.

The kinematic variables used to reject backgrounds are described below.

- $|m_{\ell\ell} - m_Z| > 15$ GeV (Z -veto): This variable is the difference between the calculated invariant mass of the leptons, and mass of the Z boson. This difference should be greater than 15 GeV in order to eliminate events around the Z mass.
- $\Delta\phi_{\ell\ell, \mathbf{p}_T^{miss}}$: This variable is the azimuthal angle between the two leptons and the direction of $\mathbf{p}_T^{miss}$. When an object is mis-measured in an event, this angle is close to zero, meaning the $\mathbf{p}_T^{miss}$ is near the leptons. Multi-jet and W +jets events that enter the signal region have mis-measured objects and are efficiently rejected with this variable. The Drell-Yan background is also reduced using this variable.
- m_T^ℓ : This variable is the transverse mass of each lepton. Since there is missing energy in the event, the mass is difficult to calculate exactly, and is obtained from the dot product of the lepton momentum, $\mathbf{p}_T^\ell$ and $\mathbf{p}_T^{miss}$: $m_T^\ell = \sqrt{2\mathbf{p}_T^\ell \cdot \mathbf{p}_T^{miss}(1 - \cos \Delta\Phi)}$, where $\Delta\Phi$ is the azimuthal angle between the lepton and $\mathbf{p}_T^{miss}$. The m_T^ℓ is higher for events containing real W bosons, and lower for backgrounds such as multi-jet and $Z/\gamma^* \rightarrow \tau\tau$. The m_T^ℓ variable is calculated for each lepton, and a cut is made on the higher of the two to reject these backgrounds.
- $m_{\tau\tau} < m_Z - 25$ GeV ($Z \rightarrow \tau\tau$ veto). This cut is used in the ≥ 1 -jet channels, under the assumption of the *collinear approximation* method [140]. This method describes the reconstruction of the invariant mass in tau-tau decays containing one jet and assuming that the neutrinos in the decay

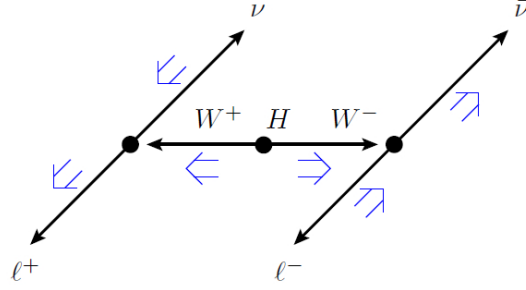


Figure 6.3: The $H \rightarrow WW^*$ decay, where the small arrows indicate the direction in which the particles are travelling, while the big arrows indicate their spin projections. The Higgs boson decays to W bosons which have opposite spins. The W bosons then decay into leptons whose spins are aligned. The V-A nature of the W decay leads to a small opening angle between the charged leptons in the laboratory frame.

are collinear with the tau decay products, and that they are the only source of MET. In this case the mass is given by $m_{\tau\tau} = \frac{m_{vis}}{\sqrt{x_1 x_2}}$, where m_{vis} is the invariant mass of the visible decay products and $x_{1(2)} = \frac{p_{vis1(2)}}{p_{vis1(2)} + p_{miss1(2)}}$ are the momentum fractions carried by the decay products. Here, $p_{vis(miss)}$ are the momenta of the visible (invisible) decay products. This cut is used to keep events in a window below the Z mass.

- $n_b = 0$ (b -veto): This variable is the number of b -tagged jets with $p_T > 20$ GeV. By requiring that there are no jets that originate from bottom quarks, the top background is largely reduced. The b -tagging algorithm used is MV1 with an operating point of 85% efficiency.
- $p_T^{\ell\ell}$: This variable is the magnitude of the vector sum of the lepton transverse momenta. It tends to be higher for signal events and lower for the $Z\gamma^*$ events.
- f_{recoil} : This variable is only defined in the same-flavour analysis and is described in Section 6.2.5.3. It uses the hadronic activity recoiling against the hard scatter system to reduce the Z/γ^* background in the same-flavour channels.
- VBF veto: This selection is used to eliminate the VBF contamination in the ≥ 2 -jet ggF channel. The selection is based on events failing either the Central Jet Veto (CJV), Opposite Lepton Veto (OLV) or having a BDT score > -0.48 . The CJV, OLV cuts, and BDT method are described in detail in Section 6.1.2.

There are common selections applied to all channels, referred to as a common *pre-selection*. The pre-selection requires two leptons of opposite-charge. The higher energy lepton, referred to as the *leading* lepton, is required to have a transverse momentum greater than 22 GeV, denoted by $p_T^{\ell 1} > 22$ GeV. The lower energy lepton, referred to as the *sub-leading* lepton, is required to have a transverse momentum greater than 10 GeV, denoted by $p_T^{\ell 2} > 10$ GeV. In order to reduce backgrounds such as $Z/\gamma^* + \text{jets}$ and multi-jet, $m_{\ell\ell}$ is required to be greater than 10 GeV for the different-flavour channels, and greater than 12 GeV for the same-flavour channels. Finally a Z -veto is performed in order to eliminate events originating from Z decays. The pre-selection criteria are summarized in Table 6.1. The distributions of the number of jets are shown in Figure 6.4 after the pre-selection stage. This shows that there are many backgrounds

Objective	Selection	ggF			VBF
		$n_j = 0$ (DF+SF)	$n_j = 1$ (DF+SF)	$n_j \geq 2$ (DF)	$n_j \geq 2$ (SF+DF)
Pre-selection	lepton p_T	$p_T^{\ell(2)} > 22(10)$ GeV			
	$m_{\ell\ell}$	$> 10(12)$ GeV for DF (SF)			
	charge	opposite			
	Z-Veto	$ m_{ll} - m_Z > 15$ GeV (SF)			
	n_j	0	1	≥ 2	
Reject Background	MET	$p_T^{miss} > 20$ GeV in DF			$p_T^{miss} > 40$ GeV & $E_T^{miss} > 45$ GeV in SF
		$E_{T,rel}^{miss} > 40$ GeV in SF			
	$p_{T,rel}^{miss(trk)} > 40$ GeV in SF	$p_{T,rel}^{miss(trk)} > 35$ GeV in SF	—	—	
	$\Delta\phi_{\ell\ell,p_T^{miss}}$	$> \pi/2$ radians	—	—	—
	$p_T^{\ell\ell}$	> 30 GeV	—	—	—
	b -veto	—	$n_b = 0$		
	$Z \rightarrow \tau\tau$ -veto	—	$m_{\tau\tau} < m_Z - 25$ GeV		
	m_T^ℓ	—	> 50 GeV	—	—
	VBF/VH veto	—	—	used	—
f_{recoil}	< 0.1 in SF			—	—
Select Signal	$m_{\ell\ell}$	< 55 GeV			BDT input
	$\Delta\phi_{\ell\ell}$	< 1.8 radians			BDT input
	CJV	—	—	—	$C_{j3} > 1$
	OLV	—	—	—	$C_{\ell 1} < 1, C_{\ell 2} < 1$
	$\Delta\phi_{\ell\ell}, m_{\ell\ell}, \Delta y_{jj}$ m_{jj}, p_T^{tot}, m_T $\sum C_\ell, \sum_{\ell,j} m_{\ell,j}$	—	—	—	BDT input

Table 6.1: The cuts made on kinematic variables to reduce the backgrounds and enhance the ggF and VBF signal in the SF and DF channels for all jet multiplicities. The ordering of the cuts in the table does not necessarily correspond to the order in which the cuts are applied.

remaining after the pre-selection criteria are applied. In order to reduce these backgrounds, additional cuts are applied in each of the regions defined by different jet multiplicities. These cuts are shown in the Reject Background section of Table 6.1. In order to select the ggF and VBF signal topologies, cuts shown in the Select Signal section of Table 6.1 are applied.

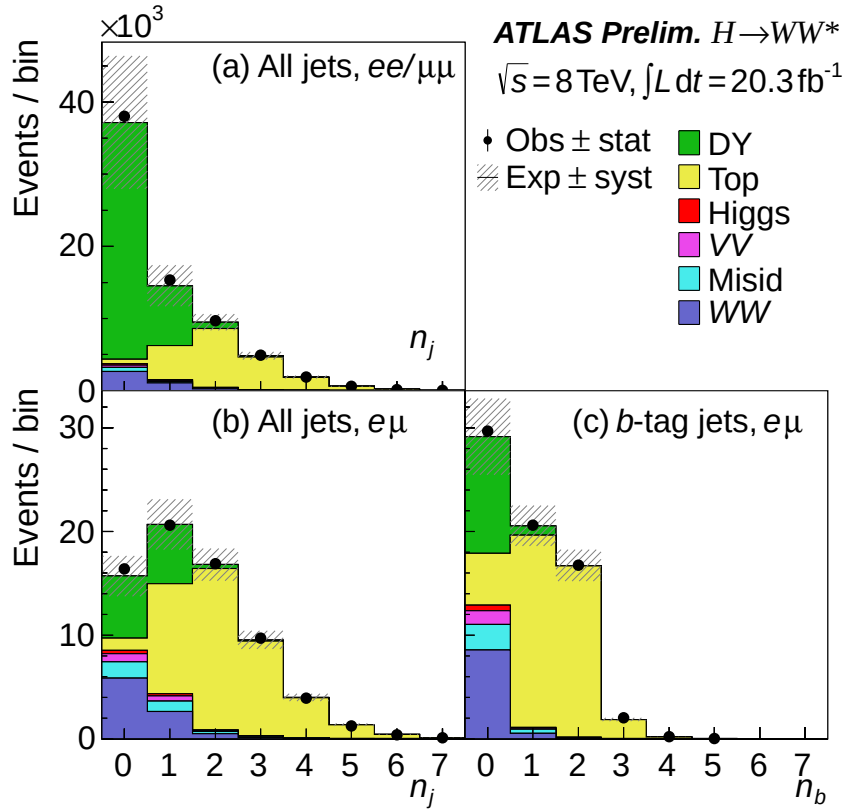


Figure 6.4: The jet multiplicity distributions for jets (n_j) and b -jets (n_b) after the pre-selections and MET cuts are made. The dots represent the observed data, and the error bars represent the corresponding statistical uncertainties (stat). The solid lines represent MC simulation and the bands around them represent the systematic uncertainties (syst) from experimental and theoretical sources [141].

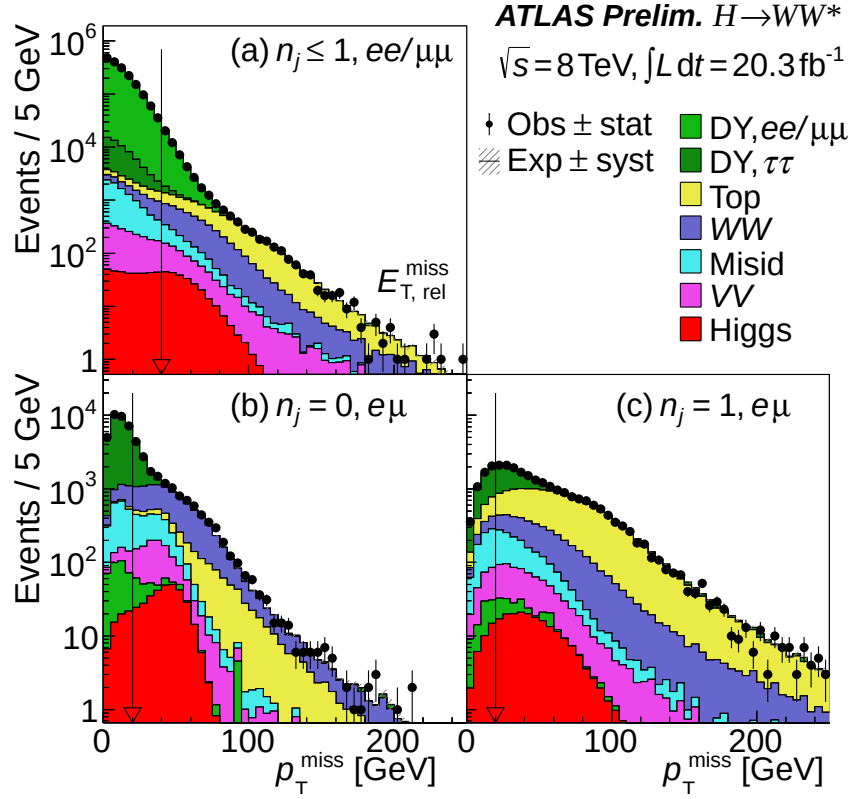


Figure 6.5: The MET variables used to reject backgrounds in the ggF channel after selections up to the MET cuts. The arrows indicate the cut for each variable to reject additional backgrounds [141].

6.1.1 ggF Analysis

As mentioned in Section 6, the ggF production process is searched for in the same-flavour and different-flavour, 0-, 1-jet, and different-flavour ≥ 2 -jet channels. The ggF signal is extracted by applying cuts to reduce the backgrounds and enhance the signal topology, as shown in Table 6.1. The distributions of the MET after the pre-selection cuts are shown in Figure 6.5. The remaining discriminating variables are shown in Figure 6.6 for the 0-jet channel, Figure 6.7 for the 1-jet channel, and Figure 6.8 for the ≥ 2 -jet channel.

The final discriminating variable used to separate the signal from the background after all of the cuts have been made is the m_T distribution. This distribution is used as input to the statistical analysis described in Chapter 7. The m_T distributions for the different channels are shown in Figure 6.9 for the 8 TeV data, and Figure 6.10 for the 7 TeV data after all of the cuts have been made.

The different-flavour, 0- and 1-jet signal regions are additionally split by $m_{\ell\ell}$ and $p_T^{\ell 2}$. The $m_{\ell\ell}$ splitting is performed by separating events that satisfy $10 \text{ GeV} < m_{\ell\ell} < 30 \text{ GeV}$ and ones that satisfy $30 \text{ GeV} < m_{\ell\ell} < 55 \text{ GeV}$. The division in sub-leading lepton momenta is performed for regions satisfying: $10 \text{ GeV} < p_T^{\ell 2} < 15 \text{ GeV}$, $15 \text{ GeV} < p_T^{\ell 2} < 20 \text{ GeV}$ and $p_T^{\ell 2} > 20 \text{ GeV}$. The motivation for splitting in $m_{\ell\ell}$ and $p_T^{\ell 2}$ is to maximize sensitivity by exploiting the different signal-to-background ratios in different regions. For example, using this configuration, the large W +jets background in the low- $p_T^{\ell 2}$ region is isolated to only one region and impacts the sensitivity only in that region. The $m_{\ell\ell}$ and $p_T^{\ell 2}$ distributions

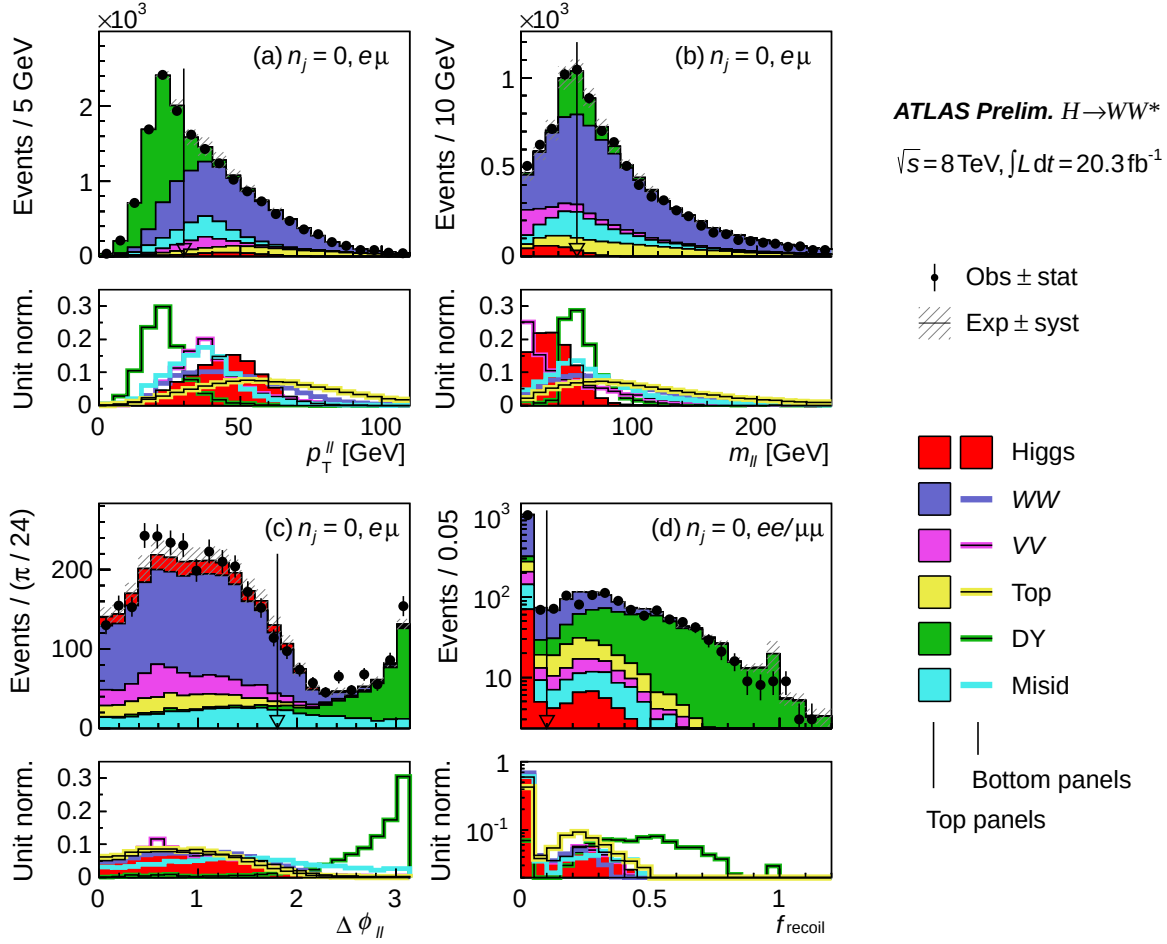


Figure 6.6: The kinematic distributions used to discriminate between the ggF signal and its backgrounds in the 0-jet channel. The $p_T^{\ell\ell}$ distribution is shown requiring the selections up to the $p_T^{\ell\ell}$ cut (upper left). The $m_{\ell\ell}$ distribution is shown up to the selection on the $m_{\ell\ell}$ cut (upper right). The $\Delta\phi_{\ell\ell}$ distribution is shown up to the selection on the $\Delta\phi_{\ell\ell}$ cut (lower left). The f_{recoil} distribution is shown up to the selection on the f_{recoil} cut. The arrows indicate the cuts applied to each distribution. The bottom panel shows the distributions normalized to the unit area in order to emphasize the shape differences [141].

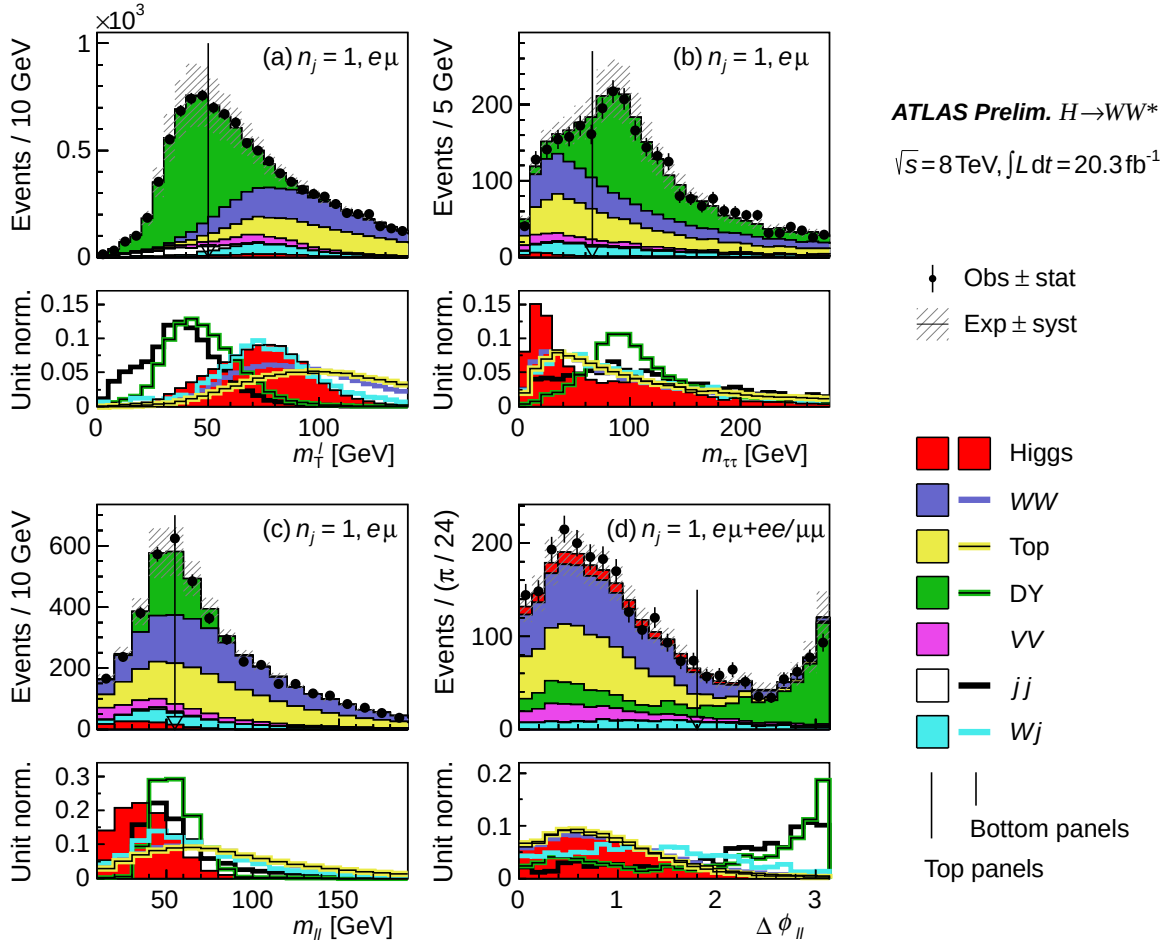


Figure 6.7: The kinematic distributions used to discriminate between the ggF signal and its backgrounds in the 1-jet channel. The m_T^ℓ distribution is shown requiring the selections up to the m_T^ℓ cut (upper left). The $m_{\tau\tau}$ distribution is shown up to the selection on the $m_{\tau\tau}$ cut (upper right). The $m_{\ell\ell}$ distribution is shown up to the selection on $m_{\ell\ell}$ (lower left). The $\Delta\phi_{\ell\ell}$ distribution is shown up to the selection on $\Delta\phi_{\ell\ell}$ (lower left). The arrows indicate the cuts applied to each distribution. The bottom panel shows the distributions normalized to the unit area in order to emphasize the shape differences. The W +jets and multi-jet backgrounds are shown separately and denoted by Wj and jj , respectively [141].

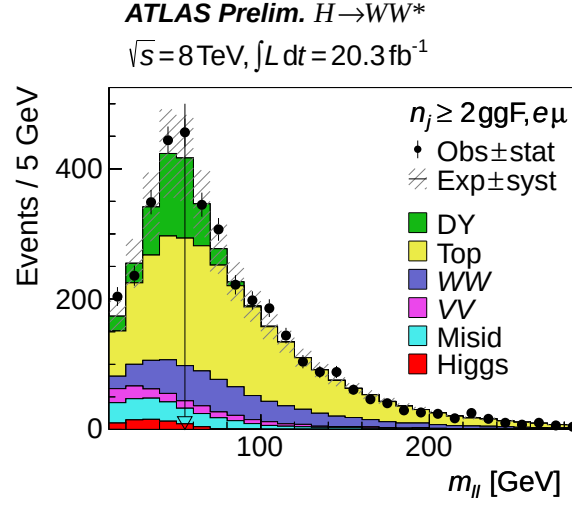


Figure 6.8: The di-lepton invariant mass distribution, $m_{\ell\ell}$, used to discriminate between the ggF signal and its backgrounds in the ≥ 2 -jet channel. The plot is made with the cuts up to the selection on $m_{\ell\ell}$, and the arrow indicates where the cut is made [141].

after all selections are shown in Figures 6.11 and Figure 6.12, respectively, for the 8 TeV data. Figure 6.13 shows the same variables after all selections for the 7 TeV data.

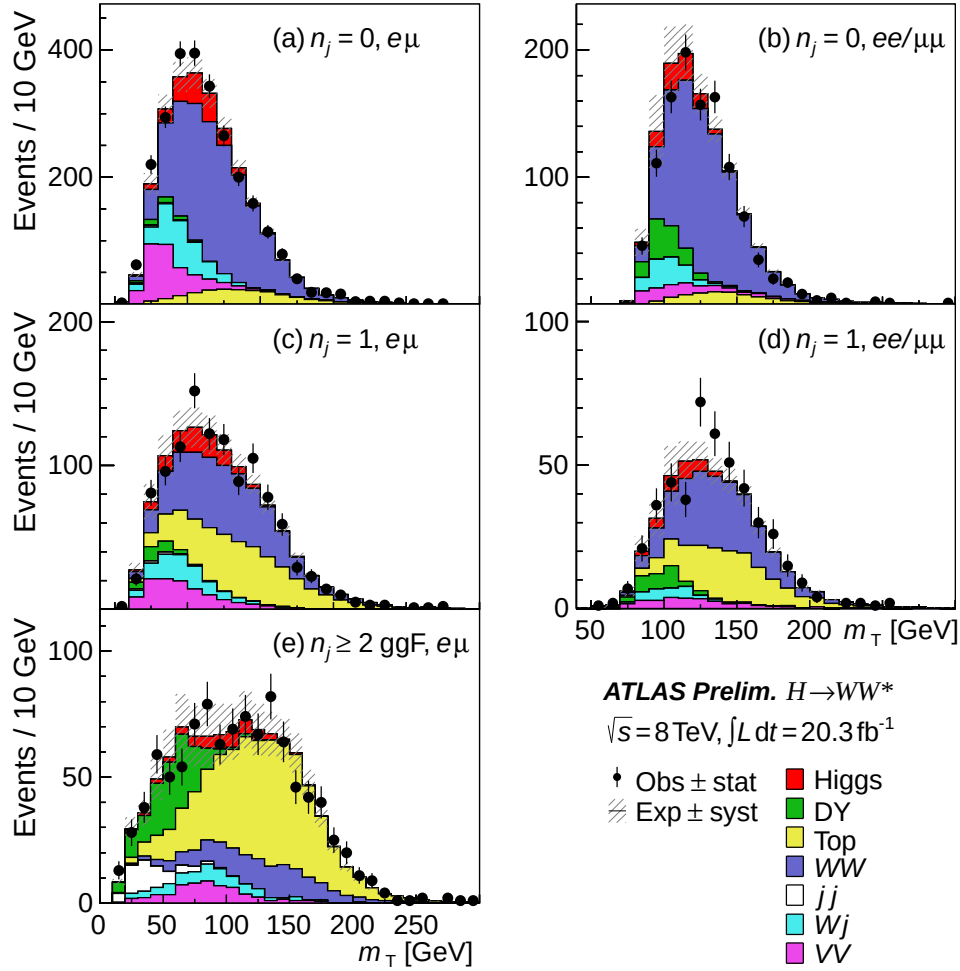


Figure 6.9: The transverse mass distribution, m_T , used as the final discriminant after all the selections are made, for the 8 TeV data. The W +jets and multi-jet backgrounds are shown separately and denoted by Wj and jj , respectively [141].

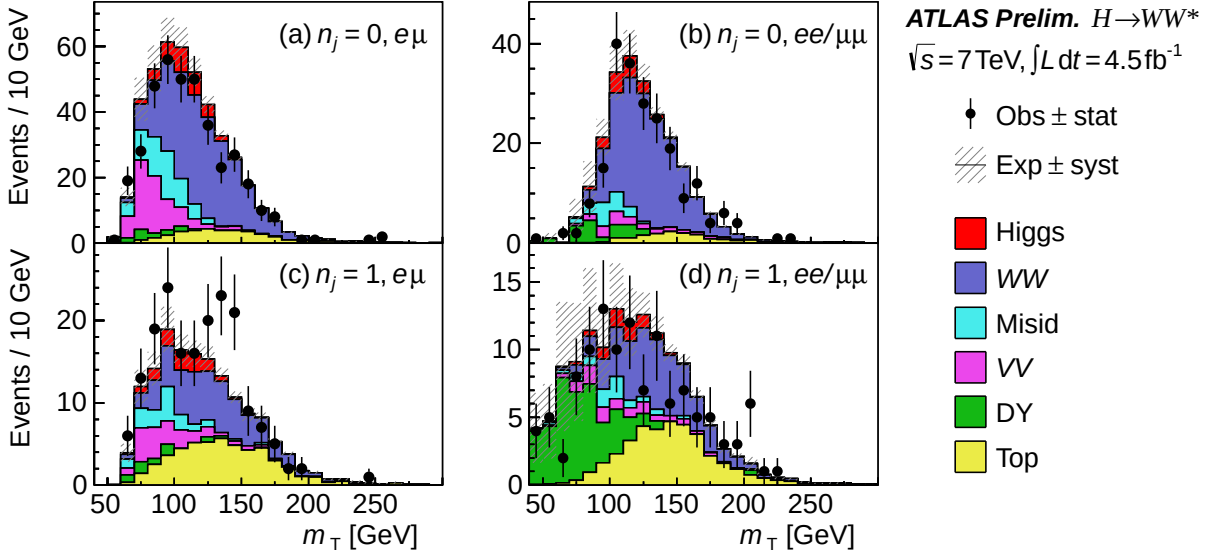


Figure 6.10: The transverse mass distribution, m_T , used as the final discriminant after all the selections are made for the 7 TeV data [141].

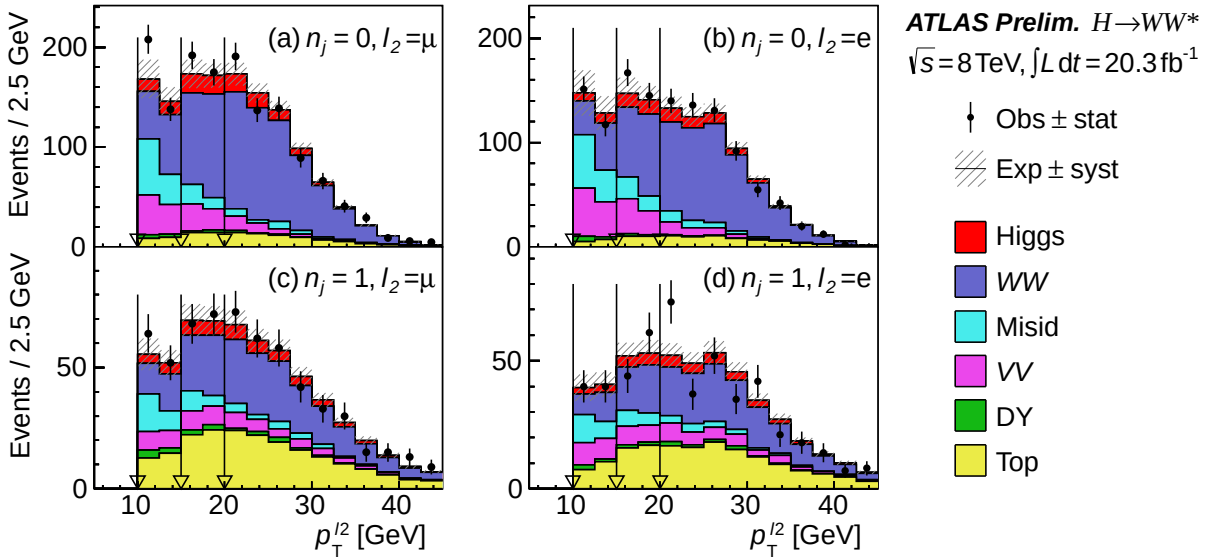


Figure 6.11: The sub-leading lepton p_T distribution, p_T^{l2} , used to split the signal region after all selections for 8 TeV data. The arrows indicate the boundaries at which the splitting is performed [141].

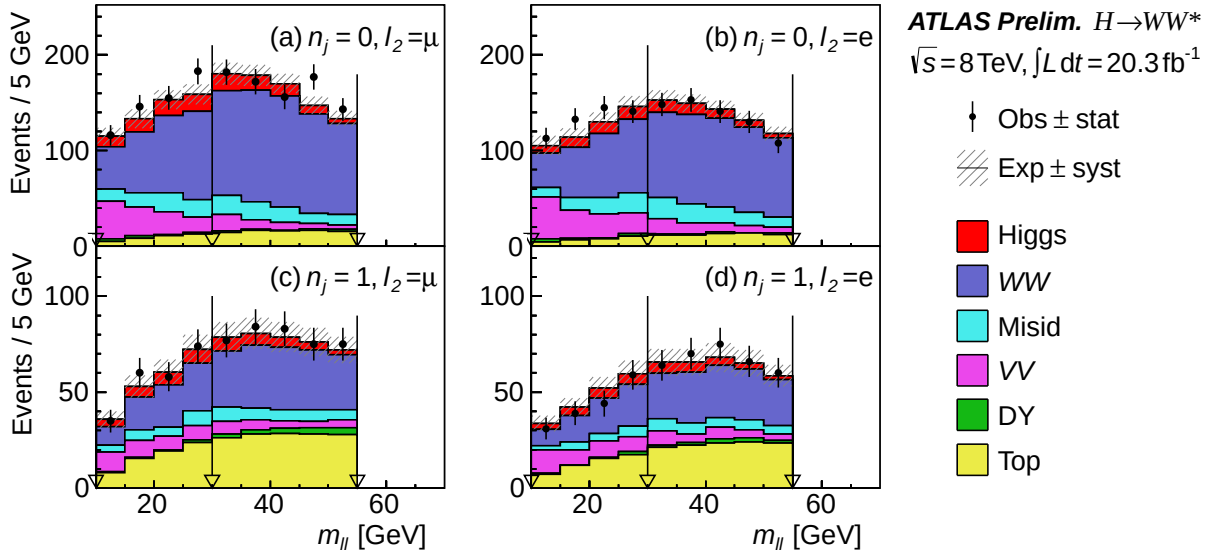


Figure 6.12: The di-lepton invariant mass distribution, $m_{\ell\ell}$, used to split the signal region after all selections for the 8 TeV data. The arrows indicate the boundaries at which the splitting is performed [141].

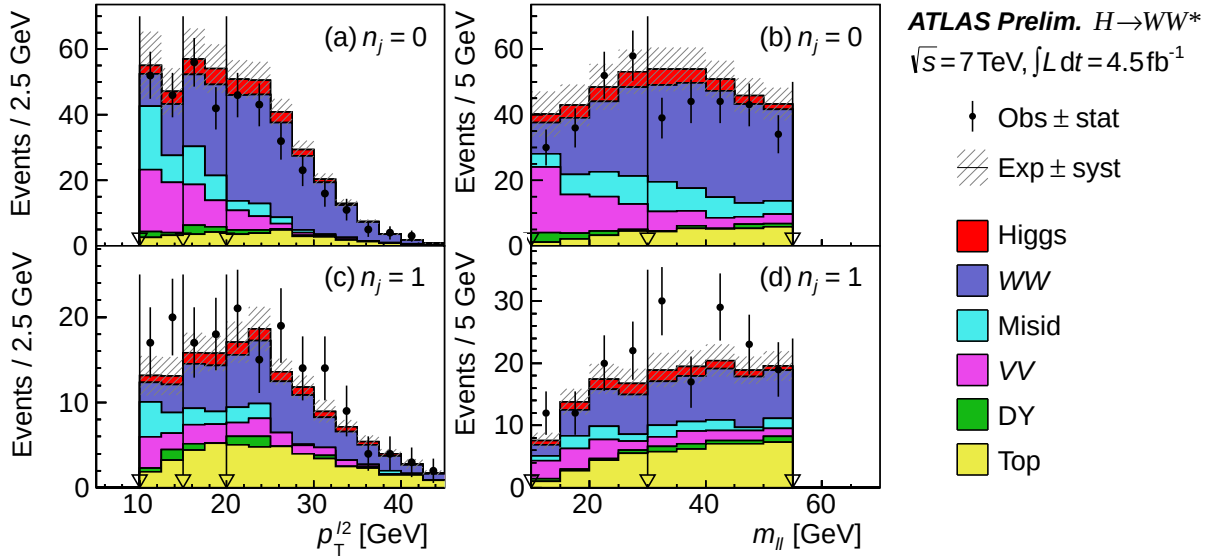


Figure 6.13: The di-lepton invariant mass distribution, $m_{\ell\ell}$ (left) and sub-leading lepton momenta distribution, $p_T^{\ell 2}$ (right) used to split the signal region after all selections for the 7 TeV data. The arrows indicate the boundaries at which the splitting is performed [141].

6.1.2 VBF Analysis

As mentioned in Chapter 6, the VBF topology contains two highly energetic jets that are oriented in the forward regions of the detector. The VBF search channel thus contains final states with two forward jets, same-flavour or different-flavour leptons and MET.

The VBF analysis is performed using the BDT method. This method provides better sensitivity than the standard cut-based analysis since it can combine lepton and jet kinematic variables in non-trivial ways and benefits from knowledge about their correlations. Signal and background MC events are fed into the BDT algorithm along with kinematic variables that discriminate the signal from the background. A *tree* is then *trained*, meaning that cuts are made on each kinematic variable that result in the best signal and background separation. Starting with the initial events, a cut is made on a kinematic variable that separates signal-like events into a signal-like sub-sample, called a *signal leaf*, and a background-like sub-sample, called a *background leaf*. The two sub-samples are then analyzed again using the best discriminating variable, and a cut is again made to separate the signal and background into different leaves. This division is repeated until the signal and background leaves have reached a minimum number of events, or until a specified signal purity is reached in each leaf.

At the end of this process there might be mis-classified events, especially in leaves where there is no clear signal and background separation. These events are identified by placing higher weights on signal events in background leaves and background events in signal leaves than on correctly classified events. From these higher weighted, mis-classified events, a new tree is trained. This process is repeated until many trees are formed. The different decision trees are then averaged in order to obtain a BDT output discriminant. The BDT output is a combination of cut values, which range from -1 (corresponding to background-like leaves) to 1 (corresponding to signal-like leaves). The data events are then analyzed by the BDT algorithm and given a BDT output score from -1 to 1, depending on whether their variable distributions are closer to the signal or background. The BDT score is denoted by O_{BDT} .

The BDT algorithm also must decide how many trees to use, how many decisions (nodes) each tree contains, and how many events are analyzed in each node. A scan is performed testing different values of these parameters and a set is chosen based on the best ratio of signal to square root of background events ($S/\sqrt{B}$). This ratio is referred to as a *significance*, and quantifies the difference between signal and background events. The binning of the BDT score distribution has been optimized to obtain the maximal expected significance while maintaining reasonable per-bin MC statistics. Four bins with boundaries $[-0.48, 0.3, 0.78]$ are chosen, and the lowest background-like bin is excluded since it does not increase the significance. The lowest background-like bin is the one below -0.48.

If there are insufficient statistics in each node during the training process, proper signal and background separation cannot be achieved. This phenomenon is referred to as over-training a BDT. Checks for over-training are performed by training a BDT on an independent sample and comparing it to the initial one. If the BDT outputs of the samples are similar, no over-training is present.

The training and cross check samples both have pre-selection criteria applied to them before they are input into the BDT algorithm. In addition, the samples are required to have ≥ 2 jets to enhance the VBF topology, contain a b -veto to reduce the top background, contain a $Z \rightarrow \tau\tau$ veto and MET cuts in order to suppress $Z\gamma^*$ backgrounds. The $Z \rightarrow \tau\tau$ veto also reduces $H \rightarrow \tau\tau$ contamination. The two jets with the highest p_T and satisfying $\Delta\eta > 3.6$ and m_{jj} (invariant di-jet mass) > 600 GeV are referred to as *tagged* jets. They are presumed to arise from the initial quarks that radiated the bosons that fused to form a Higgs boson. In addition to the above criteria, requirements on the *centrality* of the leptons

and additional jets in the event are applied, as described below.

- C_ℓ : This variable is the lepton centrality, defined as

$$C_\ell = \left| \eta_\ell - \frac{\sum \eta_{jj}}{2} \right| / \frac{\Delta \eta_{jj}}{2}, \quad (6.2)$$

where η_ℓ is the pseudorapidity of the leptons, $\eta_{jj} = \eta_{j1} + \eta_{j2}$ and $\Delta \eta_{jj} = |\eta_{j1} - \eta_{j2}|$, with $\eta_{j1(2)}$ representing the η of the leading (sub-leading) jet. The C_ℓ variable is zero when η_ℓ is located between the two jets, and goes to one as η_ℓ approaches the jet η . When $|\eta_\ell| > |\eta_j|$, $C_\ell > 1$. This variable is used to reject events in which the leptons are not located between the tagged jets in pseudorapidity. A cut, referred to as the Opposite Lepton Veto (OLV) is defined as $C_{\ell 1} < 1$ and $C_{\ell 2} < 1$. When this cut is applied, it reduces a large amount of top background.

- C_{j3} : This variable is the centrality of a third jet in the event. It is defined the same way as the lepton centrality, but using the η of the third jet instead of the lepton. This variable is used to eliminate jets that are located between the two tagged jets in pseudorapidity. A cut, referred to as the Central Jet Veto (CJV), is made on $C_{j3} > 1$ for jets with $p_T > 20$ GeV. This cut is efficient in eliminating WW events that contain two jets, whose jets tend to lie in the central region.

The discriminating variables used as the input to the BDT are $\Delta \phi_{\ell\ell}$, $m_{\ell\ell}$, Δy_{jj} , m_{jj} , p_T^{tot} , m_T , $\sum C_\ell$ and $\sum_{\ell,j} m_{\ell,j}$. The $\Delta \phi_{\ell\ell}$, $m_{\ell\ell}$, m_T variables were described in the previous section, and the remaining ones are specific to the VBF analysis and described below.

- p_T^{tot} : This variable is the magnitude of the total transverse momentum of the event defined as $p_T^{tot} = p_T^{\ell 1} + p_T^{\ell 2} + p_T^{miss} + \sum p_T^{jets}$. The VBF signal has lower values of the total transverse momentum since all the objects in the event balance each other. Background events in which soft gluon radiation recoils against the $\ell\ell + 2$ jet system have higher transverse mass.
- Δy_{jj} : This variable describes the rapidity separation between the tagged jets in an event, which tends to be higher for a VBF signal than backgrounds.
- m_{jj} : This variable is the invariant mass of the two highest- p_T jets. This variable is higher for jets originating from VBF production than most background processes.
- $\sum C_\ell$: This variable is the sum of the lepton centrality for the two leptons: $\sum C_\ell = C_{\ell 1} + C_{\ell 2}$. This variable tends to be lower for the VBF processes since in VBF production the leptons tend to be in the central regions of the detector.
- $\sum_{\ell,j} m_{\ell,j}$: This variable is the sum of the invariant masses of all of the four lepton-jet pairs. This value is higher for signal than most background events since VBF events tend to have forward jets and central leptons, resulting in large opening angles between the jets and leptons.

The selection criteria applied and training variables used are summarized in Table 6.1. The power of the BDT input variables to discriminate the signal from the background events is shown in Figure 6.14. The BDT distribution, shown in Figure 6.15 for 7 and 8 TeV data, is used as the final discriminating variable, after the BDT training. The distribution is shown in terms of the BDT bin numbers 1, 2 and 3, which correspond to the boundaries on the BDT score set at $[-0.48, 0.3, 0.78]$.

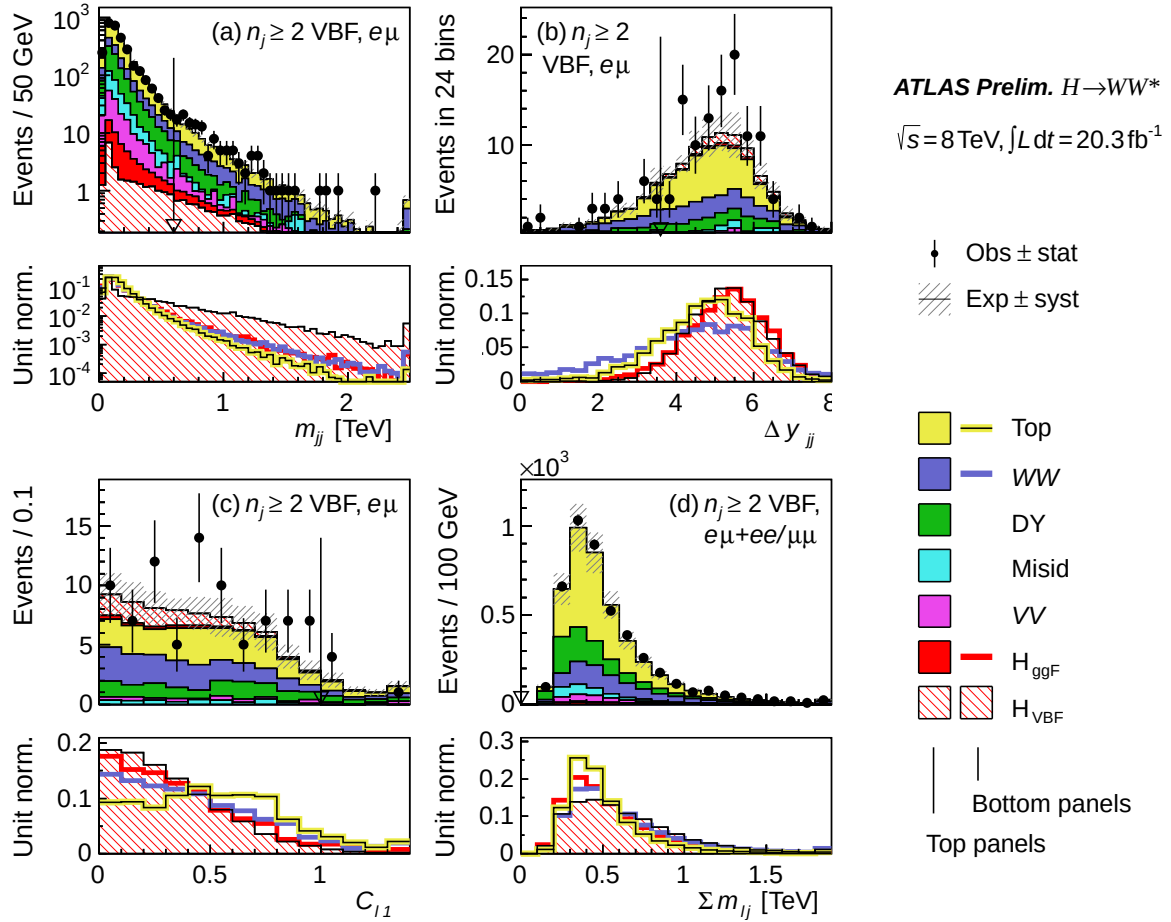


Figure 6.14: The kinematic distributions used to discriminate between the VBF signal and its backgrounds. The m_{jj} distribution is shown up to the selection on m_{jj} (upper left). The Δy_{jj} distribution is shown up to the selection on Δy_{jj} (upper right). The C_{l1} distribution is shown up to the selection on C_{l1} (lower left). The Σm_{lj} distribution is shown up to the selection on $m_{\tau\tau}$. The m_{jj} , Δy_{jj} and Σm_{lj} distributions are used as BDT inputs, and the C_{l1} variable is cut on. The arrows in the first two plots indicate where the best signal and background separation occurs. The bottom panel shows the distributions normalized to the unit area in order to emphasize the shape differences [141].

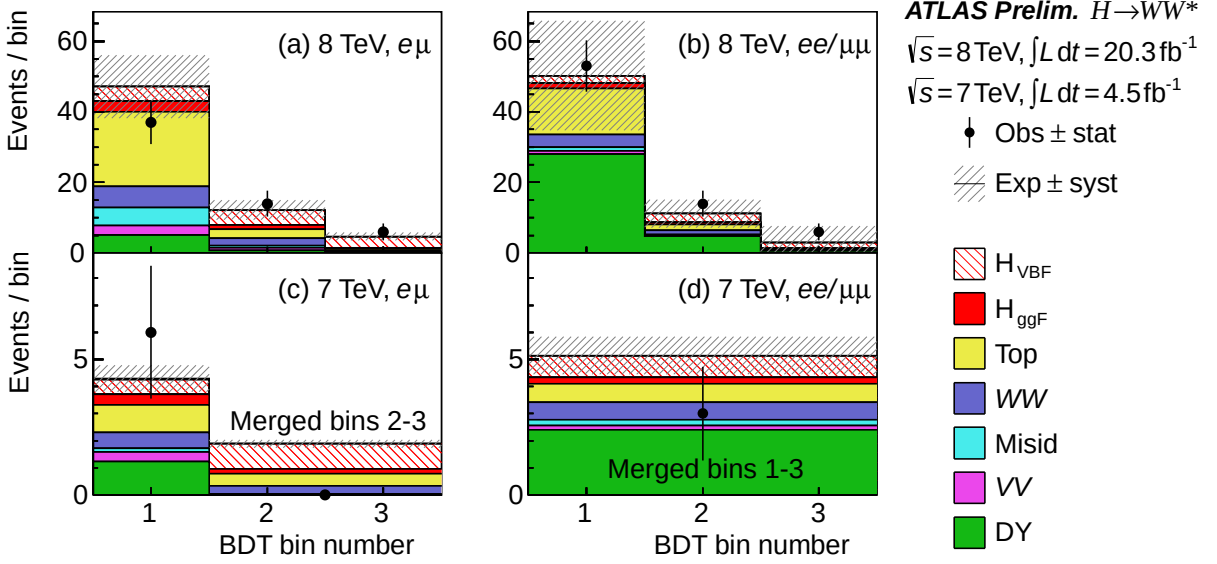


Figure 6.15: The BDT distribution used as the final discriminant after all the selections are made for the 7 and 8 TeV data. The BDT bin numbers correspond to boundaries set on the BDT score of $[-0.48, 0.3, 0.78]$ [141].

Channel	WW	Top	$Z \rightarrow \tau\tau$	$Z/\gamma^* \rightarrow ee/\mu\mu$	W+jets/QCD	VV
ggF $n_j = 0$						
$e\mu$	CR	CR	CR	MC	Data	CR
$ee\mu\mu$	CR ($e\mu$)	CR ($e\mu$)	CR ($e\mu$)	Data	Data	MC + VR
ggF $n_j = 1$						
$e\mu$	CR	CR	CR	MC	Data	CR
$ee\mu\mu$	CR ($e\mu$)	CR ($e\mu$)	CR ($e\mu$)	Data	Data	MC + VR
ggF $n_j \geq 2$						
$e\mu$	MC	CR	CR	MC	Data	MC + VR
VBF $n_j \geq 2$						
$e\mu$	MC	CR	CR	MC	Data	MC + VR
$ee\mu\mu$	MC	CR	CR	Data	Data	MC + VR

Table 6.2: Summary of estimation methods for various backgrounds for the ggF and VBF production processes. The methods include: normalizing the background from a control region (CR); estimating it from data-driven methods (Data); normalizing the background from Monte Carlo simulation (MC); and normalizing it from MC and validating it in a validation region (MC+VR). When the $ee/\mu\mu$ backgrounds are normalized from the $e\mu$ CRs due to a lack of statistics in the $ee/\mu\mu$ regions, the estimation technique is denoted by CR ($e\mu$).

6.2 Background Estimation

There are many backgrounds to ggF and VBF Higgs production, including WW , top ($t\bar{t}$, Wt), Z/γ^* +jets (DY), W +jets, multi-jet (QCD), and non- WW di-boson (WZ , ZZ , $W\gamma$, $W\gamma^*$). These backgrounds are estimated using different methods, which are described in this section. The estimation techniques include calculating backgrounds using data in control regions, MC simulation estimates, which are validated in validation regions, or data-driven methods. A summary of the different background estimation techniques for each channel is shown in Table 6.2.

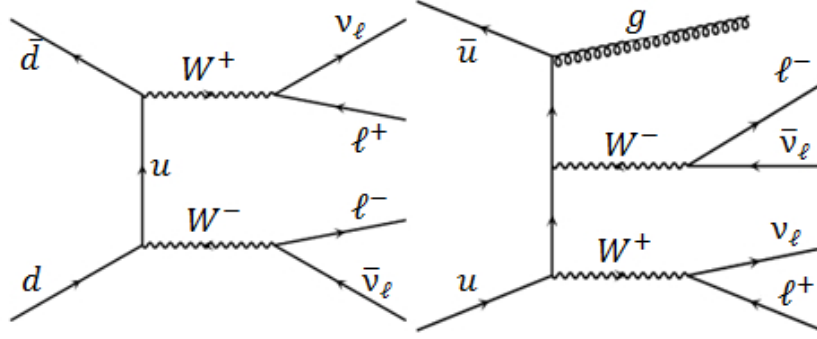


Figure 6.16: Feynman diagrams showing the WW background produced with 0 jets (left) and 1 jet (right). Made by N.Ilic.

6.2.1 WW Boson Production

The Standard Model WW boson production, shown in Figure 6.16, can produce the same final states as the signal. This is the largest background in the different-flavour channels. In the 0- and 1-jet channels, it is estimated from a control region defined by exploiting the fact that events resulting from Standard Model and Higgs processes have different kinematic distributions. In the ≥ 2 -jet channels, it is estimated from MC simulation due to the difficulty of eliminating top events in a ≥ 2 -jet WW control region.

6.2.1.1 WW Estimate in the 0- and 1-jet Channels

The number of WW events in the signal region is estimated by using information from data and MC simulation in a control region that targets WW events.

Given the number of MC and data events in the control region, it is possible to estimate the number of MC events in the signal region using

$$N_{\text{SR}}^{WW} = \frac{N_{\text{CR}}^{WW, \text{data}} \cdot N_{\text{SR}}^{WW, \text{MC}}}{N_{\text{CR}}^{WW, \text{MC}}}. \quad (6.3)$$

In equation 6.3, N represents the number of events, the SR and CR subscripts indicate whether the events are measured in the signal region or control region, and the data and MC superscripts indicate whether the WW events are taken from data or MC simulation. Equation 6.3 can be rewritten in terms of a normalization factor, which uses the data and MC comparison in the control region to normalize the MC in the signal region. Equation 6.3 can also be rewritten in terms of an extrapolation factor, which represents the extrapolation of information from the control region to the signal region, and whose theoretical uncertainties can be calculated. These two representations of equation 6.3 are demonstrated in points (1) and (2) below.

1. Equation 6.3 can be rewritten as

$$N_{\text{SR}}^{WW} = \frac{N_{\text{CR}}^{WW, \text{data}}}{N_{\text{CR}}^{WW, \text{MC}}} \cdot N_{\text{SR}}^{WW, \text{MC}} = \mu_{WW} N_{\text{SR}}^{WW, \text{MC}} \quad (6.4)$$

where $\frac{N_{\text{CR}}^{WW, \text{data}}}{N_{\text{CR}}^{WW, \text{MC}}}$, is a normalization parameter, defined as μ_{WW} , that corrects for MC imperfections in the signal region. It is calculated by fitting MC simulation to data in the control region. The

WW normalization factors are calculated in the different-flavour control region, but are applied to the different-flavour and same-flavour signal regions. The non- WW backgrounds in the control region are estimated using the techniques described in the remainder of this section.

2. In order to quantify whether extrapolating information from the defined control region to the signal region is reasonable, equation 6.3 can be rewritten as

$$N_{\text{SR}}^{WW} = N_{\text{CR}}^{WW, \text{data}} \cdot \frac{N_{\text{SR}}^{WW, \text{MC}}}{N_{\text{CR}}^{WW, \text{MC}}} = N_{\text{CR}}^{WW, \text{data}} \alpha_{WW}. \quad (6.5)$$

The $\frac{N_{\text{SR}}^{WW, \text{MC}}}{N_{\text{CR}}^{WW, \text{MC}}}$ term in equation 6.5 is called an extrapolation factor, α_{WW} , and is derived from MC simulation. The α_{WW} factor is calculated by rearranging equation 6.5 to solve for α_{WW} . The number of WW events in data in the control region is obtained by subtracting the non- WW events, $N_{\text{CR}}^{\text{bkg}}$, from the total data events in the control region: $N_{\text{CR}}^{WW, \text{data}} = N_{\text{CR}}^{\text{data}} - N_{\text{CR}}^{\text{non-}WW}$. The non- WW events, $N_{\text{CR}}^{\text{non-}WW}$, are obtained from the techniques used to estimate the other backgrounds. The α_{WW} factor is calculated separately for all different-flavour and same-flavour signal regions. The α_{WW} factor is not applied as a scaling factor anywhere; its uncertainties, which are associated with extrapolating information from the control region to the signal region, are calculated from MC simulation and applied. The calculation of the uncertainties is described in Section 6.3, and its implementation in the statistical procedure is outlined in Chapter 7.

The WW control region is defined using different-flavour events since the same-flavour channels have much lower statistics due to worse signal and background discrimination. The cuts on the WW control region isolate WW events, while remaining as close as possible to the signal region cuts. The cuts in the control and signal regions are close to each other in order to ensure that the kinematic distributions are similar between the regions and the uncertainties on extrapolation are reduced. The $m_{\ell\ell}$ variable can be used to separate the signal from the WW background, as can be seen in Figures 6.6, 6.7 and 6.8. To define the 0- and 1-jet WW control regions the pre-selection requirements are applied. The cut on the momentum of the sub-leading lepton is $p_T^{\ell_2} > 15$ GeV, instead of $p_T^{\ell_2} > 10$ GeV as is applied in the signal region in order to minimize contamination from other backgrounds such as W +jets. The number of WW events in the WW control region divided by the total number of events in the region is referred to as the *purity*. The purity of the WW control region is 60% and 40% in the 0- and 1-jet control regions respectively. The low purity is due to the top contamination in these regions.

The 0-jet WW control region has upper and lower bounds on $m_{\ell\ell}$. The lower bound is the opposite of the cut made on the signal region and separates the signal from the WW background. The upper bound is made in order to ensure similar kinematics in signal and control regions. A $\Delta\phi_{\ell\ell}$ cut is made to remove the $Z\gamma^* \rightarrow \tau\tau$ background.

The 1-jet WW control region has the same cuts as the signal region up to the m_T^ℓ cut in order to remove top, multi-jet and $Z/\gamma^* \rightarrow \tau\tau$ backgrounds. The $m_{\tau\tau} < m_Z - 25$ GeV cut is not applied in the 1-jet control region, as is done in the signal region, since it would remove 30% of the WW background. Instead a cut of $m_{\tau\tau} < |m_Z - 25|$ GeV is applied, which retains events below and above the Z mass window. In the 1-jet channel a higher $m_{\ell\ell}$ cut (≥ 80 GeV) is applied than in the signal region in order to remove the remaining $Z \rightarrow \tau\tau$ background.

The exact selection criteria for the 0- and 1-jet WW control regions are shown in Table 6.3. Fig-

WW Control Region	
$n_j = 0$ DF	$n_j = 1$ DF
pre-selection	pre-selection
$p_T^{\ell 2} > 15$ GeV	$p_T^{\ell 2} > 15$ GeV
$p_T^{miss} > 20$ GeV	$p_T^{miss} > 20$ GeV
$\Delta\phi_{\ell\ell} < 2.6$ radians	$n_b = 0$
$55 < m_{\ell\ell} < 110$ GeV	$m_{\tau\tau} < m_Z - 25 $ GeV
	$m_T^\ell > 50$ GeV
	$m_{\ell\ell} > 80$ GeV

Table 6.3: The selection cuts used for the 0- and 1-jet different-flavour WW control regions.

Figure 6.17 shows the corresponding transverse mass distribution, m_T , used as the final discriminating variable.

6.2.1.2 WW Estimate in the ≥ 2 -jet Channels

It is difficult to define a WW control region in the ≥ 2 -jet ggF and VBF channels due to the large top contamination. Thus this background is estimated from MC simulation in these channels. As mentioned in Section 4.4, the SHERPA $WW+2$ jet EW and $WW+2$ jet QCD samples are used for the estimation.

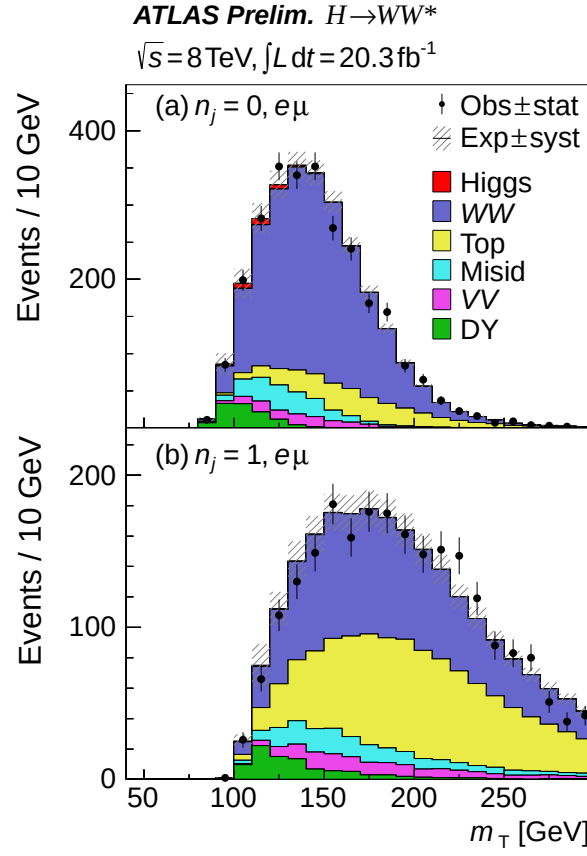


Figure 6.17: The transverse mass, m_T , used as the final discriminating variable, in the WW 0-jet (top) and 1-jet (bottom) control region. The MC simulation is multiplied by the normalization factor, μ_{WW} [141].

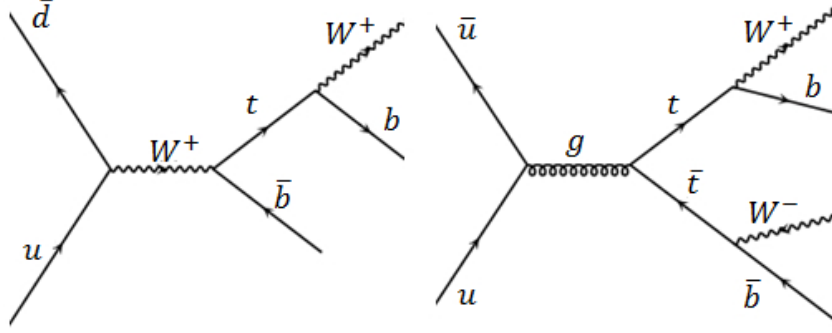


Figure 6.18: Feynman diagrams showing the single-top background (left) and $t\bar{t}$ background (right). Made by N.Ilic.

6.2.2 Top Quark Production

Processes with final states consisting of a single top quark accompanied by a W boson (Wt), and top and anti-top quarks ($t\bar{t}$) have a large production cross section and are the second largest backgrounds in the different-flavour channels. These backgrounds, shown in Figure 6.18, enter the signal region when one of the final state bottom quarks is mis-identified as a jet or lepton, or missed because it falls into an uninstrumented region. The presence of bottom quarks in the final states allows for the estimation and reduction of this background using b -tagging algorithms.

6.2.2.1 Top Estimate in the 0-jet Channel

In the 0-jet channel the number of top quark events in the signal region is estimated by predicting how many top events would exist in a 0-jet region after the pre-selection and 0-jet requirement, referred to as the Top, 0j region. Defining a 0-jet region containing top events is difficult since top decays have jets in their final states. Thus the number of events in this type of region is estimated from an all inclusive jet region, a 0-jet region and a region containing at least one b -tagged jet, as described below. Equation 6.6 shows how the Top, 0j region is used in the estimation of top events in the signal region:

$$\begin{aligned}
 N_{\text{SR}}^{\text{top}} &= \frac{N_{\text{Top, 0j}}^{\text{exp}} \cdot N_{\text{SR}}^{\text{top, MC}}}{N_{\text{Top, 0j}}^{\text{top, MC}}} \\
 &= \mu_{\text{top}} \cdot N_{\text{SR}}^{\text{top, MC}} \\
 &= N_{\text{Top, 0j}}^{\text{exp}} \cdot \alpha_{\text{top}}.
 \end{aligned} \tag{6.6}$$

In analogy with the WW control region estimate, equation 6.6 is rewritten in terms of a normalization factor $\mu_{\text{top}} = \frac{N_{\text{Top, 0j}}^{\text{exp}}}{N_{\text{Top, 0j}}^{\text{top, MC}}}$ in the second line, and extrapolation factor $\alpha_{\text{top}} = \frac{N_{\text{SR}}^{\text{top, MC}}}{N_{\text{Top, 0j}}^{\text{top, MC}}}$ in the third line. To obtain the number of top events in the signal region, the expected number of top events is multiplied by μ_{top} .

The number of expected top events in the Top, 0j region, $N_{\text{Top, 0j}}^{\text{exp}}$, is estimated by multiplying the number of top events in a top control region, $N_{\text{CR}}^{\text{top}}$, by the probability that an event passes the 0-jet

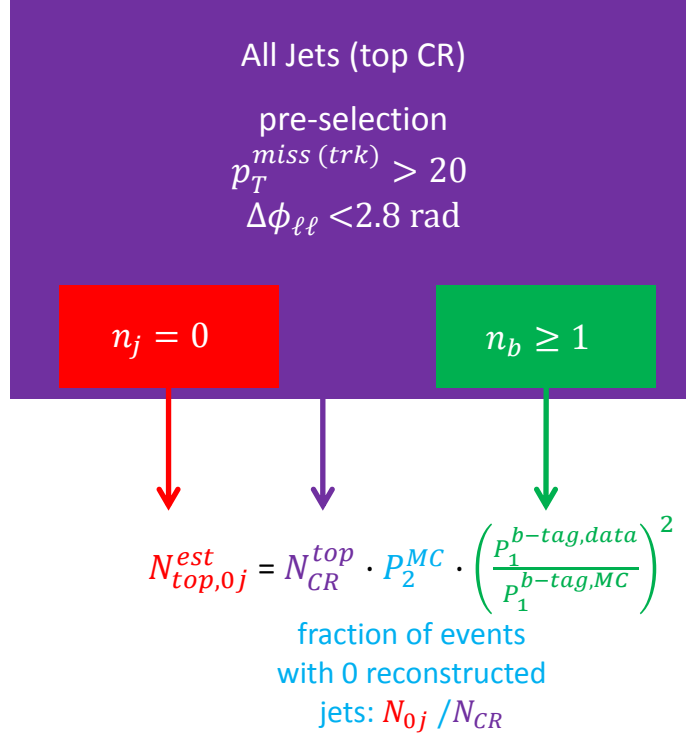


Figure 6.19: A representation of the different regions defined in order to obtain an estimate of top events in the 0-jet top region.

veto, P_2^{exp} :

$$\begin{aligned}
 N_{\text{Top}, 0j}^{\text{exp}} &= N_{\text{CR}}^{\text{top}} \cdot P_2^{\text{exp}} \\
 &= (N_{\text{CR}}^{\text{data}} - N_{\text{CR}}^{\text{non-top}}) \times P_2^{\text{exp}}.
 \end{aligned} \tag{6.7}$$

The top control region is a superset of the signal region, defined by applying the pre-selection cuts, a $p_T^{miss(trk)} > 20$ GeV requirement, and a $\Delta\phi_{\ell\ell} < 2.8$ radians cut to reject $Z/\gamma^* \rightarrow \tau\tau$ for DF events. The top control region is defined only for different-flavour events, and the resulting normalization factor is used for same-flavour events. This region makes no selection on the number of jets, and is 74% pure in top events. The number of top events in this region, $N_{\text{CR}}^{\text{top}}$, is obtained by subtracting the number of non-top events from the number of data events: $N_{\text{CR}}^{\text{data}} - N_{\text{CR}}^{\text{non-top}}$. The non-top events in the top control region are estimated from a data-driven method in the case of W +jets, and MC simulation for the other processes. When MC estimations are used their normalization factors are also applied.

The probability of top events passing the 0-jet veto, P_2^{exp} , is obtained by multiplying the corresponding probability in MC, P_2^{MC} , by a correction factor from data. The P_2^{MC} is the fraction of events in the top CR that pass the 0-jet veto. The correction factor from data is obtained by calculating the

Top Control Regions		
$n_j = 1$ SF+DF	$n_j \geq 2$ ggF DF	$n_j \geq 2$ VBF SF+DF
pre-selection $p_T^{miss} > 20$ GeV in DF $E_{T,rel}^{miss} > 40$ GeV in SF $n_b \geq 1$ $m_{\tau\tau} < m_Z - 25$ GeV in DF $m_T^\ell > 50$ GeV f_{recoil} in SF $m_{\ell\ell} < 55$ GeV $p_{T,rel}^{miss} > 35$ GeV in SF $\Delta\phi_{\ell\ell} < 1.8$ radians	pre-selection $p_T^{miss} > 20$ GeV $n_b = 0$ VBF/VH veto $m_{\ell\ell} < 80$ GeV	pre-selection $p_T^{miss} > 40$ GeV in SF $E_T^{miss} > 45$ GeV in SF CJV OLV

Table 6.4: The selection cuts for the 1- and ≥ 2 -jet top control regions.

probability of a single jet passing the 0-jet veto ($P_1^{\text{data (MC)}}$). Thus P_2^{MC} can be obtained from

$$\begin{aligned}
P_2^{\text{exp}} &= P_2^{\text{MC}} \cdot \left(\frac{P_1^{\text{data}}}{P_1^{\text{MC}}} \right)^2 \\
&\simeq P_2^{\text{MC}} \cdot \left(\frac{P_1^{b\text{-tag, data}}}{P_1^{b\text{-tag, MC}}} \right)^2.
\end{aligned} \tag{6.8}$$

The second line of the above equation shows that the $P_1^{\text{data (MC)}}$ can be determined from a b -tagged region. The probability of a single jet passing the 0-jet veto equals the probability for an event to have no jets reconstructed in addition to the one that is tagged ($P_1^{b\text{-tag}}$). This factor is derived from the same top control region that in addition requires at least one b -tagged jet.

The $P_1^{b\text{-tag}}$ probability is the fraction of events that contain only the tagged b -jet (no additional jets), $N_{0 \text{ add-jet}}^{b\text{-tag}}$, over the total number of events that contain b -tagged jets $N_{\text{all}}^{b\text{-tag}}$:

$$P_1^{b\text{-tag}} = \frac{N_{0 \text{ add-jet}}^{b\text{-tag}}}{N_{\text{all}}^{b\text{-tag}}}. \tag{6.9}$$

Equation 6.8 is valid under the assumption that the probability of either jet in a two-jet event surviving the jet veto is the same as the probability of a single jet surviving squared: $P_2 = P_1^2$. This assumption was validated using MC: the two probabilities agree to within 2%. The MC ratio, $\frac{P_2^{\text{MC}}}{(P_1^{b\text{-tag, MC}})^2}$, in equation 6.8, is referred to as the MC correction factor, f_{MC} . The regions used to estimate the top events in the Top, 0j region are summarized in Figure 6.19.

6.2.2.2 Top Estimate in the 1-jet Channel

The top background in the 1-jet signal region is estimated from a 1-jet top control region, defined for different-flavour and same-flavour events. A 2-jet top control region is also used in order to reduce the uncertainties associated with b -tagging. In analogy to the WW and 0-jet top estimates, the number of top events in the 1-jet signal region can be written as

$$N_{\text{SR}}^{\text{top}} = \frac{N_{1\text{j-CR}}^{\text{top,data}} \cdot N_{\text{SR}}^{\text{top,MC}}}{N_{1\text{j-CR}}^{\text{top,MC}}}. \tag{6.10}$$

In equation 6.10, the 1j-CR subscripts refer to a top 1-jet control region, which is defined using almost all the same cuts as the signal region, but requiring at least one b -tagged jet. The exact selection is shown in Table 6.4. Equation 6.10 can be rewritten as

$$N_{\text{SR}}^{\text{top}} = \frac{N_{\text{1j-CR}}^{\text{top, data}}}{\varepsilon_{\text{tag, 1j-CR}}^{\text{MC}}} \times (1 - \varepsilon_{\text{tag, 1j-CR}}^{\text{MC}}). \quad (6.11)$$

In equation 6.11, $\varepsilon_{\text{tag, 1j-CR}}^{\text{MC}}$ is the efficiency, calculated from MC simulation, for a jet originating from a top decay to be b -tagged in the 1j-CR. This efficiency is calculated in MC simulation within a top enriched phase space, and is found to be 73%.

Using equation 6.11, it is possible to obtain the effect the b -tagging efficiency has on the overall top uncertainty:

$$\frac{\sigma(N_{\text{SR}}^{\text{top}})}{N_{\text{SR}}^{\text{top}}} = \frac{\sigma(\varepsilon_{\text{tag, 1j-CR}}^{\text{MC}})}{(1 - \varepsilon_{\text{tag, 1j-CR}}^{\text{MC}}) \cdot \varepsilon_{\text{tag, 1j-CR}}^{\text{MC}}}. \quad (6.12)$$

In equation 6.12, $\sigma(N_{\text{SR}}^{\text{top}})$ represents the uncertainty on the top estimate, while $\sigma(\varepsilon_{\text{tag, 1j-CR}}^{\text{MC}})$ represents the uncertainty on the b -tagging efficiency. Since the efficiency is 73%, a small uncertainty on the efficiency can have a large effect on the uncertainty of the top estimate. In order to reduce this effect, the efficiency is calculated using a data-driven method in a 2-jet control region that is near the signal region. This 2-jet control region contains mostly $t\bar{t}$ events and is defined using the same selection as the 1-jet control region, but requires two jets. The non-top events are subtracted from this region using MC simulation. In an event containing $t\bar{t}$ quarks, the jet that is not b -tagged is called the probe jet. The efficiency in the 2-jet region, $\varepsilon_{\text{tag, 2j-CR}}$, is the fraction of events in which the probe jet is also b -tagged.

Equation 6.13 shows how the number of top events in the signal region is obtained using the 2-jet efficiency:

$$N_{\text{SR}}^{\text{top}} = \frac{N_{\text{1j-CR}}^{\text{top, data}}}{\varepsilon_{\text{tag, 2j-CR}}^{\text{data}} \times f_{\text{correction}}} \times (1 - \varepsilon_{\text{tag, 2j-CR}}^{\text{data}} \times f_{\text{correction}}). \quad (6.13)$$

An MC correction factor, $f_{\text{correction}}$, is used to correct any biases that might be introduced in calculating an efficiency in a 2-jet region and using it for a 1-jet estimate. The correction factor is the ratio of the 1-jet MC efficiency of 73% and the MC estimate of the 2-jet efficiency:

$$f_{\text{correction}} = \frac{\varepsilon_{\text{tag, 1j-CR}}^{\text{MC}}}{\varepsilon_{\text{tag, 2j-CR}}^{\text{MC}}}. \quad (6.14)$$

Equation 6.13, with the $f_{\text{correction}}$ term substituted in, can be rewritten as equation 6.15. This equation is rewritten in the second line in terms of normalization factors.

$$\begin{aligned} N_{\text{SR}}^{\text{top}} &= \frac{N_{\text{1j-CR}}^{\text{Top, data}}}{\frac{\varepsilon_{\text{tag, 2j-CR}}^{\text{data}}}{\varepsilon_{\text{tag, 2j-CR}}^{\text{MC}}} \times \varepsilon_{\text{tag, 1j-CR}}^{\text{MC}}} \times \left(1 - \frac{\varepsilon_{\text{tag, 2j-CR}}^{\text{data}}}{\varepsilon_{\text{tag, 2j-CR}}^{\text{MC}}} \times \varepsilon_{\text{tag, 1j-CR}}^{\text{MC}}\right) \\ &= \frac{\mu_{\text{top}} \times N_{\text{1j-CR}}^{\text{top, mc}}}{\mu_{\varepsilon} \times \varepsilon_{\text{tag, 1j-CR}}^{\text{MC}}} \times (1 - \mu_{\varepsilon} \times \varepsilon_{\text{tag, 1j-CR}}^{\text{MC}}) \end{aligned} \quad (6.15)$$

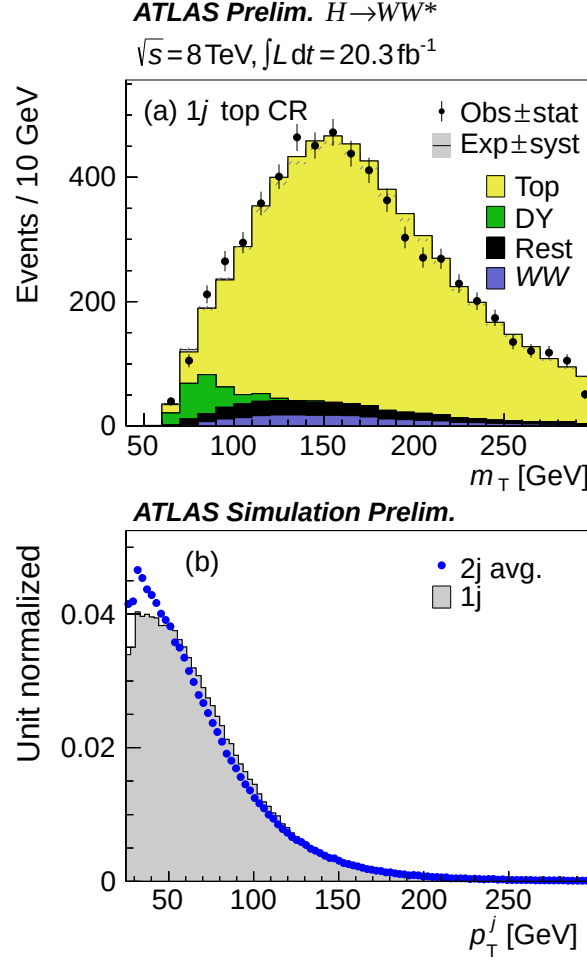


Figure 6.20: The transverse mass distribution, m_T , used as the final discriminating variable, in the 1-jet top control region with the MC normalized using the 1-jet normalization factor (top). The average jet p_T distribution in the top MC simulation in the 2-jet top region (2j avg.) compared to the jet p_T distribution in top MC simulation in the 1-jet top control region (1j) (bottom) [141].

In the second line of equation 6.15, $\mu_{\text{top}} = \frac{N_{1\text{j-CR}}^{\text{top, data}}}{N_{1\text{j-CR}}^{\text{top, mc}}}$ is the normalization factor that normalizes data to MC in the 1-jet top control region. The $\mu_\epsilon = \frac{\epsilon_{\text{tag, 2j-CR}}^{\text{data}}}{\epsilon_{\text{tag, 2j-CR}}^{\text{MC}}}$ is a normalization factor for the b -tagging efficiency.

Figure 6.20 shows the modelling of the kinematic variables in the 1-jet and 2-jet top control regions. The bottom plot in this figure compares the jet p_T distributions in the MC simulation in the 1-jet and 2-jet top control regions. The good agreement demonstrates that the procedure of extrapolating information from the 2-jet region to the 1-jet is justified.

6.2.2.3 Top Estimate in the ≥ 2 -jet Channels

The top background in the ≥ 2 -jet ggF and VBF channels is estimated directly from a 2-jet control region. The two jet normalization factor, defined as the ratio of data to MC simulation in the control region, is used to normalize the top MC events in the signal region, as shown below

$$N_{\text{SR}}^{\text{top}} = \mu_{\text{top}} N_{\text{SR}}^{\text{top, MC}}. \quad (6.16)$$

In the ≥ 2 -jet ggF channel the control region is defined using the same selection as the signal region and includes the pre-selection cuts, the ≥ 2 jets selection, the b -jet veto, and the VBF/VH veto, but requires a $m_{\ell\ell} > 80$ GeV cut. The $m_{\ell\ell}$ cut ensures that the control region is orthogonal to the signal region, and thus a b -jet veto is applied in the control region to reduce a large b -tagging uncertainty. The selection criteria for the control region are summarized in Table 6.4. This top control region is approximately 70% pure in top events.

In the VBF channel, the 2-jet top control region is defined using the same selection as the signal region, but requiring at most one b -tagged jet. The number of b -tagged jets is limited to one in order to ensure that the flavour composition of the tagged jets in the control region remains similar to that of the signal region. The selection criteria for the control region are summarized in Table 6.4. The purity of this control region is 87%. The top normalization factor is defined for the first BDT bin and is combined in the second and third BDT bins due to a lack of statistics in these bins. The normalization factors are calculated separately for the first BDT bin, and for the last two BDT bins combined. Figure 6.21 shows the m_{jj} distribution, and BDT score distribution used as the final discriminating variable in the VBF top control region.

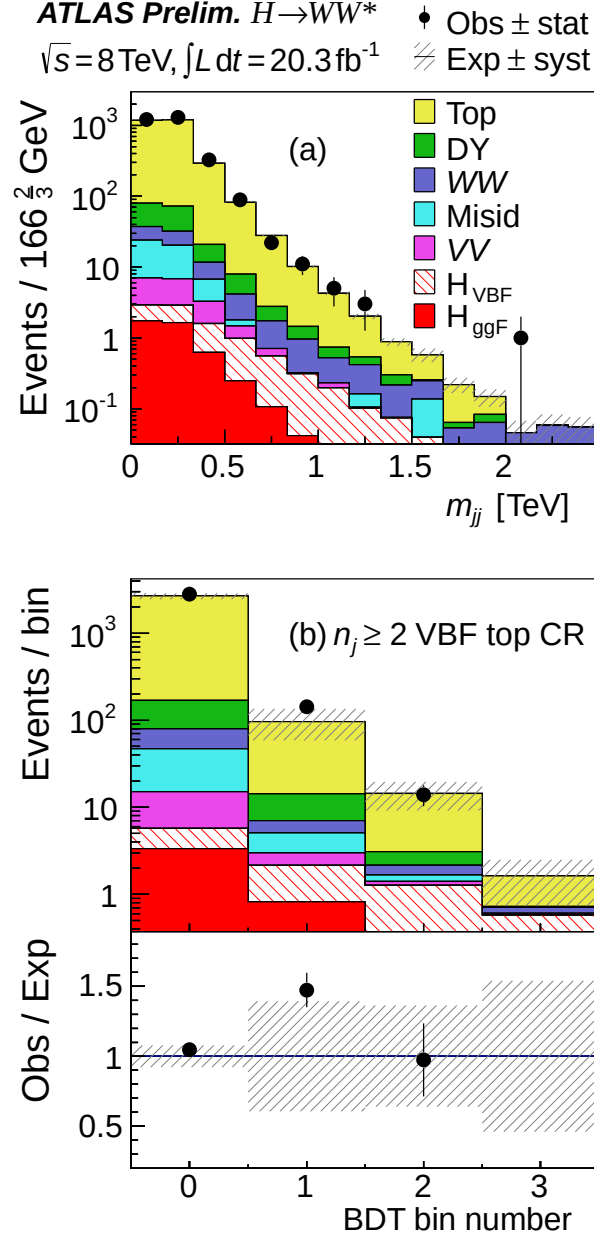


Figure 6.21: The di-jet invariant mass distribution, m_{jj} , distribution (top) and BDT score distribution (bottom) in the VBF 2-jet top control region. The bottom panel in the lower plot shows the ratio of data to MC simulation and the associated uncertainty [141].

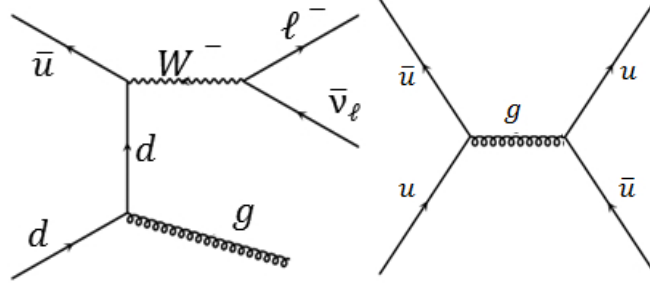


Figure 6.22: Feynman diagrams showing the W +jets background (left) and multi-jet background (right). Made by N.Ilic.

6.2.3 W +jets and Multi-jet Production

The W +jets background consists of W production in association with quarks or gluons that are misidentified as leptons. A Feynman diagram for this process is shown on the left of Figure 6.22.

The multi-jet, also called QCD, background consists of processes in which two or more jets are produced, as shown on the right of Figure 6.22. This background enters the signal region when two jets are mis-identified as leptons. Although the latter occurs rarely, a substantial amount of multi-jet background enters the signal region due to its large cross section.

All of the channels use the same method for the W +jets and multi-jet estimate. Since it is difficult to model jets faking electrons in MC simulation, these backgrounds are estimated using a data-driven method, called the *fake factor* method. The method defines three different data samples: a signal sample, a W +jets control sample and a multi-jet control sample. The three samples isolate these respective processes by selecting either 0, 1, or 2 jets faking leptons. The leptons classified as identified (*id*) leptons satisfy the stringent quality criteria used in the signal region. The leptons identified as anti-identified (*anti-id*) satisfy selection criteria that enhance the presence of jets misidentified as leptons [142]. The three data samples are then denoted by $N_{\text{id+id}}$ for signal, $N_{\text{id+anti-id}}$ for W +jets and $N_{\text{anti-id+anti-id}}$ for multi-jet:

$$\begin{aligned}
 N_{\text{id+id}} &= N_{\text{id+id}}^{\text{multi-jet}} + N_{\text{id+id}}^{W+\text{jets}} + N_{\text{id+id}}^{\text{EW, MC}} \\
 N_{\text{id+anti-id}} &= N_{\text{id+anti-id}}^{\text{multi-jet}} + N_{\text{id+anti-id}}^{W+\text{jets}} + N_{\text{id+anti-id}}^{\text{EW, MC}} \\
 N_{\text{anti-id+anti-id}} &= N_{\text{anti-id+anti-id}}^{\text{multi-jet}} + N_{\text{anti-id+anti-id}}^{W+\text{jets}} + N_{\text{anti-id+anti-id}}^{\text{EW, MC}}
 \end{aligned} \tag{6.17}$$

In equation 6.17, $N^{\text{multi-jet}}$, $N^{W+\text{jets}}$ and N^{EW} are event yields of the multi-jet, W +jets, and other backgrounds, respectively. The subscripts refer to whether the *id* or *anti-id* leptons are selected. The MC denotes that the EW background, containing processes in which the leptons originate from $W \rightarrow \ell\nu$, $Z/\gamma^* \rightarrow \ell\ell$, and γ conversions, are estimated from MC simulation. The W +jets samples are estimated as described in Section 6.2.3.1, while multi-jet samples are estimated as described in Section 6.2.3.2.

An extrapolation factor, referred to as the fake factor, is used to estimate the amount of W +jets and multi-jet background in the signal sample from the W +jets and multi-jet control samples. The fake factor represents the rate at which jets fake electrons. It is defined as the ratio of the number of jets that satisfy the *id* selection, N_{id} , to the number of jets that satisfy the *anti-id* criteria, $N_{\text{anti-id}}$:

$$f_\ell = \frac{N_{\text{id}}}{N_{\text{anti-id}}}. \tag{6.18}$$

In the above equation ℓ denotes leptons, representing the fact that the fake factor is defined for electrons and muons separately.

6.2.3.1 W +jets Estimate in All Channels

The number of W +jets in the signal sample is defined by multiplying the number of W +jets events in the control sample by the fake factor:

$$\begin{aligned} N_{\text{id+id}}^{W+\text{jets}} &= f_\ell \times N_{\text{id+anti-id}}^{W+\text{jets}} \\ &= f_\ell \times (N_{\text{id+anti-id}} - N_{\text{id+anti-id}}^{\text{EW}} - N_{\text{id+anti-id}}^{\text{multi-jet}}). \end{aligned} \quad (6.19)$$

In the above equation, the EW component is estimated from MC simulation, and the multi-jet component is estimated as described in Section 6.2.3.2. Since the fake factors for same-charge (SC) leptons and opposite-charge (OC) leptons are different, the W +jets estimate is split into same-charge and opposite-charge estimates:

$$\begin{aligned} N_{\text{SR}}^{W+\text{jets}} &= N_{\text{id+id}}^{W+\text{jets(OC)}} = f_\ell^{\text{OC}} \cdot N_{\text{id+anti-id}}^{W+\text{jets(OC)}} \\ N_{\text{SC CR}}^{W+\text{jets}} &= N_{\text{id+id}}^{W+\text{jets(SC)}} = f_\ell^{\text{SC}} \cdot N_{\text{id+anti-id}}^{W+\text{jets(SC)}}. \end{aligned} \quad (6.20)$$

The same-charge estimate is needed since the $W\gamma, W\gamma^*, WZ$ and ZZ backgrounds are estimated from a same-charge control region (SC CR), as described in Section 6.2.4.

Since Z +jets events have a similar flavour composition, a Z +jets sample is used to estimate the fake factor. The W +jets and Z +jets fake factors are somewhat different due to differences in the jet kinematics and the fact that their production modes include different b , c and light quark fractions. Thus, additional MC-based correction factors, $\frac{f_{W+\text{jets}}^{\text{OC}}}{f_{Z+\text{jets}}}$ and $\frac{f_{W+\text{jets}}^{\text{SC}}}{f_{Z+\text{jets}}}$, are applied to account for the fact that the W +jets and Z +jets fake factors are different:

$$\begin{aligned} N_{\text{SR}}^{W+\text{jets}} &= N_{\text{id+id}}^{W+\text{jets(OC)}} = f_{\ell, Z+\text{jets}}^{\text{OC}} \cdot \frac{f_{W+\text{jets}}^{\text{OC}}}{f_{Z+\text{jets}}} N_{\text{id+anti-id}}^{W+\text{jets(OC)}} \\ N_{\text{SC CR}}^{W+\text{jets}} &= N_{\text{id+id}}^{W+\text{jets(SC)}} = f_{\ell, Z+\text{jets}}^{\text{SC}} \cdot \frac{f_{W+\text{jets}}^{\text{SC}}}{f_{Z+\text{jets}}} N_{\text{id+anti-id}}^{W+\text{jets(SC)}}. \end{aligned} \quad (6.21)$$

When calculating the correction factor, the W +jets and Z +jets MC simulation can be used since any jet modelling issues that exist are present in both samples and are cancelled by the fact that a ratio is taken.

The fake factor is measured as a function of lepton p_T and η . The same-charge fake factor is 10-50% higher than the opposite-charge fake factor since the same-charge and opposite-charge events have different quark flavour fractions. These differences are taken into account when calculating the uncertainties on the fake factor, which are essentially the deviation of $\frac{f_{W+\text{jets}}}{f_{Z+\text{jets}}}$ from 1.

Figure 6.23 shows the muon and electron fake factors as a function of muon p_T and electron E_T . The calculation of the fake factor from Z +jets data is compared to the Z +jets and same-charge/opposite-charge W +jets simulation in ALPGEN+PYTHIA 6.

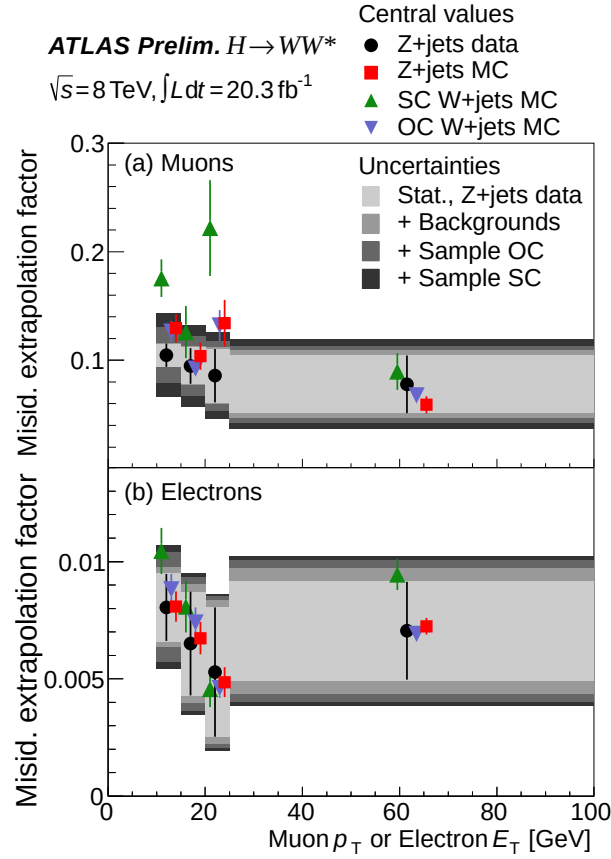


Figure 6.23: The fake factor, labelled Misid. extrapolation factor, for muons (top) and electrons (bottom). The fake factors derived from Z +jets data, and MC simulation and W +jets same-charge and opposite-charge MC simulation are shown. The grey bands represent the uncertainties: Stat. represents the statistical uncertainties primarily due to the number of jets identified as leptons in the Z +jets sample; Background is the uncertainty from the electroweak MC samples subtracted from the Z +jets data; Sample is the variation of the fake factor when comparing the Z +jets to the opposite-charge and same-charge W +jets MC samples [141].

6.2.3.2 Multi-jet Estimate in All Channels

Two different multi-jet estimates are required. The first multi-jet estimate needed is $N_{\text{id+anti-id}}^{\text{multi-jet}}$, which is used to subtract the multi-jet background from the W +jets control sample, as shown in equation 6.19. The second multi-jet estimate is used to estimate the contamination of multi-jet events in the signal sample: $N_{\text{id+id}}^{\text{multi-jet}}$.

Multi-jet Estimate for W +jets Subtraction The multi-jet estimate required for the multi-jet subtraction in the W +jets sample is given by

$$\begin{aligned} N_{\text{id+anti-id}}^{\text{multi-jet}} &= 2 \cdot f_{\text{di-jets}}'' \cdot N_{\text{anti-id+anti-id}}^{\text{multi-jet}} \\ &= 2 \cdot f_{\text{di-jets}}'' \cdot (N_{\text{anti-id+anti-id}} - N_{\text{anti-id+anti-id}}^{W+\text{jets, MC}} - N_{\text{anti-id+anti-id}}^{\text{EW, MC}}), \end{aligned} \quad (6.22)$$

where the primed fake factors are defined below. Equation 6.22 shows that the multi-jet background that contains only one mis-identified jet, $N_{\text{id+anti-id}}^{\text{multi-jet}}$, can be estimated by multiplying the events in the multi-jet sample, $N_{\text{anti-id+anti-id}}^{\text{multi-jet}}$, by the probability of a jet faking a lepton, $f_{\text{di-jet}}$. The $N_{\text{anti-id+anti-id}}^{\text{multi-jet}}$ events are obtained by subtracting the small W +jets and EW backgrounds, generated in MC simulation, from the anti-id+anti-id sample. The factor of two in equation 6.22 is included to account for the fact that either of the two jets in a multi-jet sample can be the mis-identified one.

The $f_{\text{di-jets}}$ factor is a fake factor calculated from a di-jet sample. This di-jet sample selects events that contain two jets by requiring a low MET cut. The contamination from W and Z events is reduced by requiring low- m_T values and vetoing events whose $m_{\ell\ell}$ is near the Z mass.

The di-lepton trigger is used to define the anti-id+anti-id multi-jet samples. When defining the id+anti-id W +jets samples, the id lepton is triggered on, and the anti-id lepton is then constructed from a looser set of criteria than those required by the lepton trigger [142]. For the multi-jet sample, both leptons are anti-id leptons that originate from jets and thus do not satisfy the conditions requested by the lepton trigger. For this reason a di-lepton trigger is needed that selects leptons that satisfy the anti-id lepton requirements.

Multi-jet Estimate in Signal Sample The multi-jet estimate in the signal sample is obtained by applying the fake factor two times to a multi-jet sample containing two anti-id leptons, $N_{\text{anti-id+anti-id}}^{\text{multi-jet}}$, as shown below:

$$\begin{aligned} N_{\text{SR}}^{\text{multi-jet}} &= N_{\text{id+id}}^{\text{multi-jet}} = f_{\text{di-jets}}' \cdot f_{\text{di-jets}}'' \cdot N_{\text{anti-id+anti-id}}^{\text{multi-jet}} \\ &= f_{\text{di-jets}}' \cdot f_{\text{di-jets}}'' \cdot (N_{\text{anti-id+anti-id}} - N_{\text{anti-id+anti-id}}^{W+\text{jet, MC}} - N_{\text{anti-id+anti-id}}^{\text{EW, MC}}). \end{aligned} \quad (6.23)$$

The anti-id multi-jet sample is obtained by subtracting the W +jets and EW contamination from the overall anti-id sample, $N_{\text{anti-id+anti-id}}$, using MC simulation.

By requiring two anti-id leptons that are likely faked from jets, the contribution from heavy flavour processes greatly increases. In order to minimize this bias, a factor is calculated that corrects for the presence of the other lepton. This correction factor is derived from MC simulation and applied to the fake factors. The MC sample used for the derivation of the correction factor has limited statistics since it is rare for two jets to be misidentified as leptons. The lepton to which the fake factor applied is called the *near-side* lepton, while the remaining lepton is referred to as the *away-side* lepton. The fake

factor, $f'_{\text{di-jets}}$, is corrected for the presence of an away-side identified lepton with a correction factor c' : $f' = c'f$. The fake factor, $f''_{\text{di-jets}}$, is corrected for the presence of an away-side anti-identified lepton, with correction factor c'' : $f'' = c''f$. The correction factor takes into account the fraction of change in jet flavour due to the presence of an away-side lepton and is defined as

$$c = \frac{1}{f_{\text{di-jets}}} \cdot \frac{N_{LF} \cdot \xi_{LF} + N_b \cdot \xi_b + N_c \cdot \xi_c}{D_{LF} \cdot \xi_{LF} + D_b \cdot \xi_b + D_c \cdot \xi_c}. \quad (6.24)$$

In equation 6.24, N_{LF}, N_b, N_c represent anti-id leptons of the light flavour, b , and c quarks respectively, while D_{LF}, D_b, D_c are the corresponding id leptons. The ξ factor in equation 6.25 is the change in the jet flavour once the one fake lepton is selected in an event:

$$\xi_X = \frac{J_X^{\text{awayside}} / J_{\text{all}}^{\text{awayside}}}{J_X / J_{\text{all}}}. \quad (6.25)$$

In equation 6.25, J is the number of jets, X is a place holder for the jet flavour, and the superscript corresponds to the presence of an away-side lepton, which is identified (anti-identified) when calculating c' (c''). A $\xi = 1$ value corresponds to no changes in the jet flavour, while a $\xi < 1$ ($\xi > 1$) value corresponds to an increase (decrease) of that particular jet flavour.

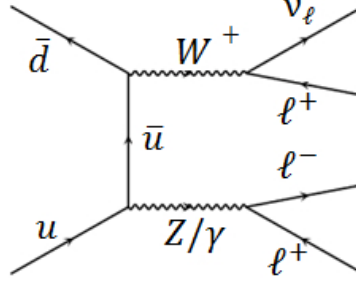


Figure 6.24: Feynman diagram showing the non- WW di-boson background. Made by N.Ilic.

6.2.4 Non- WW Di-boson ($W\gamma, W\gamma^*, WZ, ZZ$) Production

The non- WW di-boson backgrounds are $W\gamma, W\gamma^*, WZ$ and ZZ and account for 10% of the total estimated background in the different-flavour channels. The $W\gamma, W\gamma^*$ and WZ backgrounds are the biggest, and usually have leptons in the final state as is shown by the Feynman diagram in Figure 6.24. These non- WW di-boson backgrounds usually enter the signal region when one of the leptons is missed by falling in the crack regions, or is not reconstructed. The $W\gamma$ background usually enters the signal region when an electron-positron pair from a photon conversion is mis-identified as a single electron.

6.2.4.1 Non- WW Di-boson Estimate in the 0- and 1-jet Different-Flavour Channel

In the 0- and 1-jet different-flavour channels, the number of non- WW di-boson events in the signal region, N_{SR}^{VV} , is estimated from the MC simulation in the signal region, $N_{\text{SR}}^{VV, \text{MC}}$, multiplied by a normalization factor, μ_{VV} :

$$N_{\text{SR}}^{VV} = \mu_{VV} N_{\text{SR}}^{VV, \text{MC}}. \quad (6.26)$$

The normalization factor corrects the MC prediction in the signal region by comparing it to data in a same-charge control region defined to collectively target all non- WW di-boson production. The shape of the non- WW di-bosons distribution is estimated from MC simulation in order to preserve relative shape differences between the different non- WW di-bosons.

Defining a control region containing same-charge leptons rejects the signal and dominant backgrounds such as top and WW , but preserves the non- WW di-boson yields. The γ, γ^* , and Z bosons have an equal probability of producing a same-charge or opposite-charge lepton as the one produced by the accompanying W . For this reason, the same-charge non- WW di-boson events in the same-charge control region provide a good approximation to the amount of opposite-charge non- WW di-boson events in the signal region. The same-charge control region is defined using all the events that pass the signal region cuts (including the $\Delta\phi_{\ell\ell}$) and requiring same-charge instead of opposite-charge leptons. The selection criteria are listed in Table 6.5. The advantage of defining the signal and control regions with the same selection criteria is the reduction of extrapolation uncertainties. The distributions of the transverse mass, m_T , which is used as the final discriminating variable, and the sub-leading lepton momentum, $p_T^{\ell 2}$, in the same-charge control region are shown in Figure 6.25.

Same Charge Control Region	
$n_j = 0$ (DF)	$n_j = 1$ (DF)
pre-selection	pre-selection
same-charge leptons	same-charge leptons
$p_T^{miss} > 20$ GeV	$p_T^{miss} > 20$ GeV
$\Delta\phi_{\ell\ell, MET} > \pi/2$	$n_b = 0$
$p_T^{\ell\ell} > 30$ GeV	$m_{\tau\tau} < m_Z - 25$ GeV
$m_{\ell\ell} < 55$ GeV	$\max m_T^\ell > 50$ GeV
$\Delta\phi_{\ell\ell} < 1.8$ radians	$m_{\ell\ell} < 55$ GeV
	$\Delta\phi_{\ell\ell} < 1.8$ radians

Table 6.5: The selection cuts used for the 0- and 1-jet same-charge control regions.

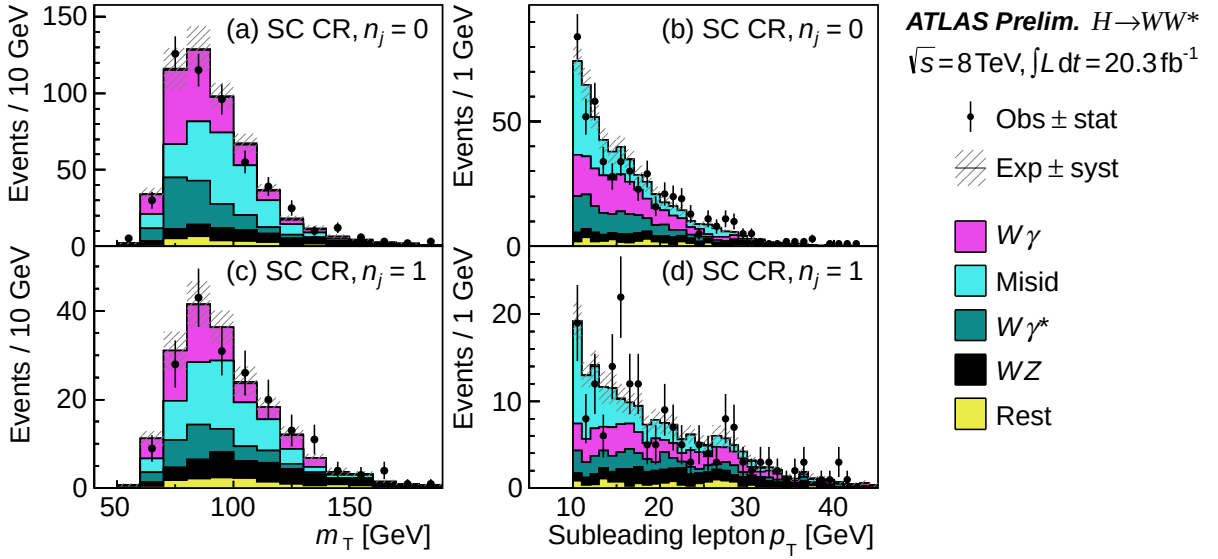


Figure 6.25: The kinematic distributions used in the same-charge control region. The transverse mass distribution, m_T , used as the final discriminating variable in 0-jet channel (top left) and 1-jet channel (bottom left). The sub-leading lepton momentum distribution, $p_T^{\ell 2}$ in the 0-jet channel (top right) and 1-jet channel (bottom right). The *Rest* in the legend represents the remaining backgrounds not listed [141].

6.2.4.2 Non- WW Di-boson Estimate in the 0-,1-jet Same-Flavour and ≥ 2 -jet Channels

In the 0- and 1-jet same-flavour channels, the same-charge and opposite-charge lepton pairs in events have different topologies, requiring additional extrapolation uncertainties. For this reason, the non- WW di-bosons in the same-flavour channel are predicted from MC simulation rather than the same-charge control region. The ≥ 2 -jet ggF and VBF channels also estimate the non- WW di-bosons from MC simulation.

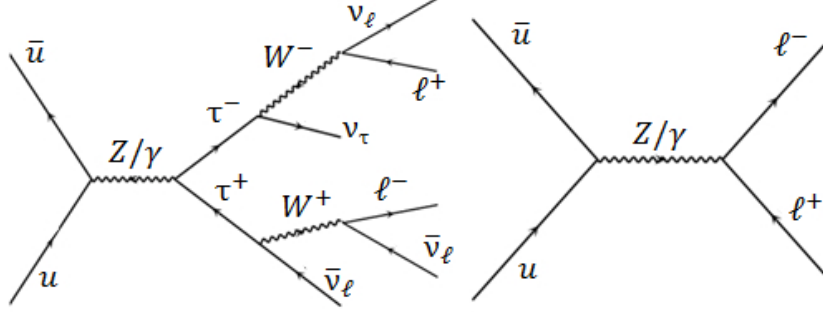


Figure 6.26: Feynman diagrams showing the Z/γ^* +jets background decaying to $\tau^+\tau^-$ (left) and $ee/\mu\mu$ (right). Made by N.Ilic.

6.2.5 Drell-Yan (DY) Production

The Drell-Yan (DY) background arises from $Z\gamma^*$ bosons decaying to leptons, as shown in Figure 6.26. The $\tau^+\tau^-$ final states decay to neutrinos and oppositely charged W 's and are thus a large background for the different-flavour channel. The ee and $\mu\mu$ final states are the largest background in the same-flavour channels. These final states can also contain jets due to initial- or final-state radiation.

6.2.5.1 p_T^Z Correction

The p_T^Z distribution in the ALPGEN+HERWIG samples does not match the data well, as discussed in [142]. This effect is more visible in the 0-jet channel, and is attributed to poor modelling of soft jet terms. In order to correct for this, the $p_T^{\ell\ell}$ distribution is re-weighted. The weights are derived by comparing data to DY MC simulation in $\mu\mu$ +0-jet events in a region around the Z mass. The contributions from non-DY events are subtracted from the data using MC simulation. The weights are derived as a function of $p_T^{\ell\ell}$, and then applied to the true Z boson momentum (before reconstruction), p_T^Z , for leptonic decays in the 0-jet channel.

6.2.5.2 $Z/\gamma^* \rightarrow \tau\tau$ Estimate in All Channels

The $Z/\gamma^* \rightarrow \tau\tau$ background is estimated from a control region in all channels. The same formula applied to the WW and top estimations is used, as shown below:

$$N_{\text{SR}}^{Z \rightarrow \tau\tau} = \mu_{Z \rightarrow \tau\tau} N_{\text{SR}}^{Z \rightarrow \tau\tau, \text{MC}}. \quad (6.27)$$

In equation 6.27, $N_{\text{SR}}^{Z \rightarrow \tau\tau}$, is the number of estimated $Z/\gamma^* \rightarrow \tau\tau$ events in the signal region, which is obtained by scaling the MC events in the signal region, $N_{\text{SR}}^{Z \rightarrow \tau\tau, \text{MC}}$, by the normalization factor $\mu_{Z \rightarrow \tau\tau}$. The control region selects the $Z \rightarrow \tau\tau$ process by cutting on different-flavour events with low- $m_{\ell\ell}$ and high- $\Delta\phi_{\ell\ell}$. The exact cuts applied to the control region in the different channels are shown in Table 6.6. In the ggF channels only a different-flavour control region is defined and the resulting normalization factor is applied to same-flavour events. In the VBF channel, same-flavour and different-flavour control regions are defined and one combined normalization factor is used. The purity of $Z/\gamma^* \rightarrow \tau\tau$ in the 0-, 1-, ≥ 2 -jet ggF, and ≥ 2 -jet VBF, channels is 91%, 80%, 74% and 82% respectively. MC extrapolation factors are calculated and their associated uncertainties are applied as described in Section 6.3. The

$Z/\gamma^* \rightarrow \tau\tau$ Control Regions			
$n_j = 0$ (DF)	$n_j = 1$ (DF)	$n_j \geq 2$ ggF (DF)	$n_j \geq 2$ VBF (DF +SF)
pre-selection $p_T^{miss} > 20$ GeV $m_{\ell\ell} < 80$ GeV $\Delta\phi_{\ell\ell} > 2.8$ radians	pre-selection $p_T^{miss} > 20$ GeV $n_b = 0$ $m_T^\ell > 50$ GeV $m_{\ell\ell} < 80$ GeV $m_{\tau\tau} > m_Z - 25$ GeV	pre-selection $p_T^{miss} > 20$ GeV VBF/VH veto $m_{\ell\ell} < 70$ GeV $\Delta\phi_{\ell\ell} > 2.9$ radians	pre-selection $p_T^{miss} > 40$ GeV in SF $E_T^{miss} > 45$ GeV in SF $n_b = 0$ $m_{\ell\ell} < 80$ (75) GeV in DF (SF) $66 < m_{\tau\tau} < 116$ GeV $O_{BDT} > -0.48$

Table 6.6: The selection cuts used to select the $Z \rightarrow \tau\tau$ control regions.

transverse mass, m_T , used as the final discriminating variable, for the 0- and 1- jet $Z \rightarrow \tau\tau$ control regions is shown in Figure 6.27.

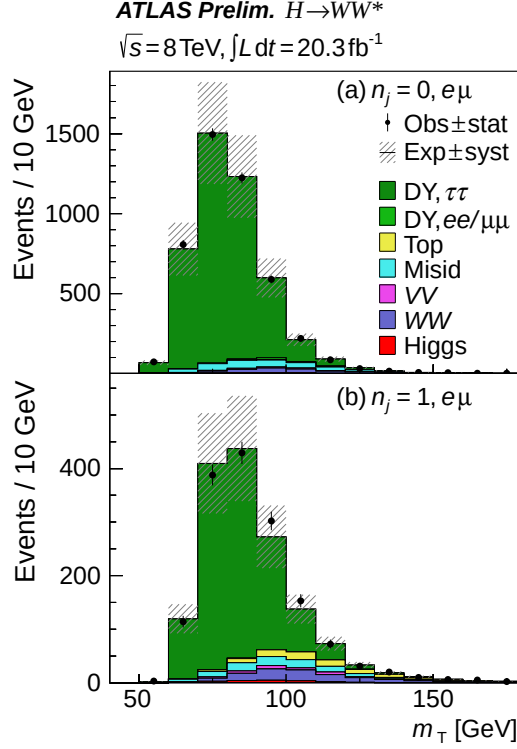


Figure 6.27: The transverse mass distribution, m_T , used as the final discriminating variable, shown in the 0-jet (top) and 1-jet (bottom) $Z \rightarrow \tau\tau$ control region [141].

6.2.5.3 $Z/\gamma^* \rightarrow ee/\mu\mu$ Estimate in the ggF Channels

In 0-, 1-, ≥ 2 -jet ggF different-flavour channels, the $Z/\gamma^* \rightarrow ee/\mu\mu$ background is very small and taken from MC simulation.

The $Z \rightarrow ee/\mu\mu$ background is the largest background in the same-flavour channels and is estimated using the data-driven *Pacman* method. The Pacman method relies on the fact that the distribution of the low-energy (soft) hadronic activity that balances the di-lepton system is very different between the $Z \rightarrow ee/\mu\mu$ process and all others.

Soft Hadronic Recoil The Drell-Yan events in this phase space have two boosted leptons that emerge from the collision point close to each other and have a low invariant mass. Since there are no neutrinos, and therefore no real MET in these processes, the di-lepton system is balanced by hadronic recoil. The hadronic recoil consists of low- p_T jets, especially in the 0-jet channel. These soft jets are reconstructed as Inner Detector tracks and low- p_T calorimeter clusters. The hadronic activity is characterized by the f_{recoil} variable and is calculated from data since MC simulation cannot be trusted to accurately model low-energy jets. In the 0-jet channel, f_{recoil} is defined as

$$f_{recoil} = \frac{\left| \sum_{i=0}^{n_j} \text{JVF}_i \cdot \mathbf{p}_T^i \right|}{p_T^{\ell\ell}}. \quad (6.28)$$

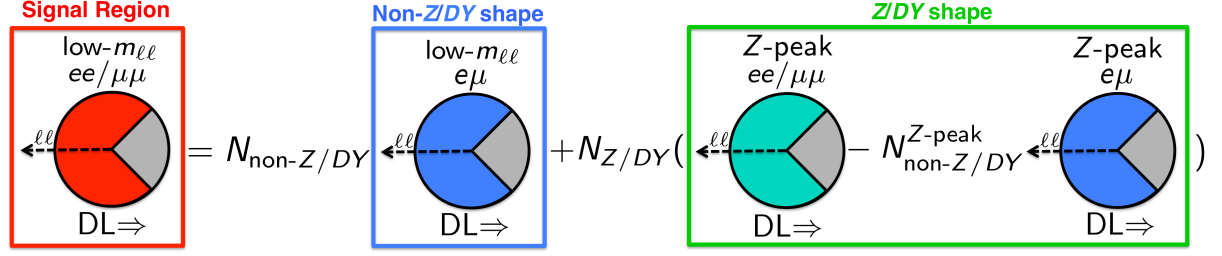


Figure 6.28: A graphical representation of the Pacman method [142].

Since the soft jets balance the di-lepton system they are located in the quadrant opposite to the di-lepton momenta, $p_T^{\ell\ell}$. Therefore the soft jet momenta in equation 6.28, p_T^i , are the momenta of the soft jets that satisfy the condition $\frac{3\pi}{4} < \Delta\phi_{\ell\ell, \text{soft jets}} < \frac{5\pi}{4}$. The f_{recoil} variable is calculated by dividing the sum of the momenta of these soft jets by the momentum of the di-lepton system. In order to reduce the effect of jets from pileup, the momentum of the hadronic jets is also multiplied by the jet vertex fraction, JVF. Thus jets from pileup, which have a lower JVF, are given a lower weight in the sum. Jets used in the f_{recoil} definition are required to satisfy $p_T > 10$ GeV. Equation 6.28 can be extended to the 1-jet case by replacing $p_T^{\ell\ell}$, with the momenta of the jet, di-lepton system, $p_T^{\ell\ell j}$.

The f_{recoil} distribution is very different for DY events and the rest of the signal and background processes which contain neutrinos, and thus real MET. For this reason, f_{recoil} is used to reject DY background in the same-flavour channel as well as estimate the remaining background using the Pacman method.

Pacman Method The Pacman method calculates the efficiency of the f_{recoil} cut for DY and non-DY events and uses it to estimate the remaining DY background in the signal region. A graphical representation of the Pacman method is shown in Figure 6.28.

The non-DY efficiency, $\epsilon^{\text{non-DY}}$, is the fraction of events in data passing the f_{recoil} cuts in a Non-DY region, as shown in equation 6.29. This region, represented by the blue box in Figure 6.28, consists of DF events passing the same sample selections as those applied to the SF signal region and is 100% pure in non-DY events. In equation 6.29, the N_0 represents events that have passed the f_{recoil} cut:

$$\epsilon^{\text{non-DY}} = \frac{N_{\text{DF}}^{\text{non-DY region}}}{N_{\text{DF}}^{\text{non-DY region}}}. \quad (6.29)$$

The DY efficiency, ϵ^{DY} , is the fraction of events in data passing the f_{recoil} cut in a same-flavour region near the Z mass ($|m_{\ell\ell} - m_z| < 15$ GeV). This region, called the Z -peak region, is represented by the green box in Figure 6.28. It is only 50% pure in DY events since most of the other same-flavour signal region selections are applied to this region (the $m_{\ell\ell}$ requirement is omitted). Due to the lack of purity, the non-DY events must be subtracted from the Z -peak region. The subtraction is achieved by selecting different-flavour events in the Z -peak region (100% pure in non-DY events), as is represented in the second half of the green box in Figure 6.28. This subtraction is normalized by a factor taken from the MC estimate of different-flavour events in the same-flavour Z -peak region, $N_{\text{non-DY}}^{Z\text{-peak}}$. The efficiency of the non-DY contribution from different-flavour data in the Z -peak is given by

$$\epsilon_{Z\text{-peak}}^{\text{non-DY}} = \frac{N_{\text{DF}}^{Z\text{-peak}}}{N_{\text{DF}}^{Z\text{-peak}}}. \quad (6.30)$$

The final DY efficiency, extracted from the region presented by the green box in Figure 6.28, is given by

$$\epsilon^{DY} = \frac{N_{\text{SF}}^{Z\text{-peak}} - \epsilon_{Z\text{-peak}}^{\text{non-DY}} \times N(\text{non-DY})_{\text{SF}}^{Z\text{-peak}}}{N_{\text{SF}}^{Z\text{-peak}} - N(\text{non-DY})_{\text{SF}}^{Z\text{-peak}}}. \quad (6.31)$$

The DY and non-DY efficiencies on the f_{recoil} cut, measured in data, can then be used to estimate the number of DY events in the same-flavour signal region, $N_{\text{SR}}^{Z \rightarrow ee/\mu\mu}$, as shown below:

$$N_{\text{SR}}^{Z \rightarrow ee/\mu\mu} = \epsilon^{DY} \times \frac{N_{\text{SF}}^{\text{SR}} - \epsilon^{\text{non-DY}} \times N_{\text{SF}}^{\text{SR}}}{\epsilon^{DY} - \epsilon^{\text{non-DY}}}. \quad (6.32)$$

The above estimate relies on the assumption that the relative fractions of each non-DY process are the same in different-flavour and same-flavour channels. This assumption is true due to flavour universality, and thus using the f_{recoil} cut efficiency in different-flavour data to describe non-DY component in same-flavour data is justified.

6.2.5.4 $Z/\gamma^* \rightarrow ee/\mu\mu$ Estimate in the VBF Channels

In the different-flavour ≥ 2 -jet VBF channel, the $Z/\gamma^* \rightarrow ee/\mu\mu$ background is small and is estimated from MC simulation.

The $Z \rightarrow ee/\mu\mu$ background is the largest background in the same-flavour channels and is estimated using the data-driven *ABCD* method. The events in the signal region, referred to as region A, are estimated from a Z control region, defined using low-MET values, referred to as region B. To compensate for the fact that the estimate uses two regions in different MET ranges, the estimate is scaled by the ratio of high to low MET regions in a Z -peak region. The high and low-MET regions are referred to as C, and D respectively. The exact equation used for the $Z/\gamma^* \rightarrow ee/\mu\mu$ estimate in the signal region is given by

$$N_{\text{SR}}^{\text{DY}} = N_{\text{A}}^{\text{DY}} N_{\text{B}}^{\text{DY}} \cdot \frac{N_{\text{C}}^{\text{DY}}}{N_{\text{D}}^{\text{DY}}} \cdot f_{\text{non-closure}}. \quad (6.33)$$

In equation 6.33, the number of DY events is obtained by subtracting the data from the non-DY MC simulation: $N^{\text{DY}} = N^{\text{data}} - N^{\text{non-DY, MC}}$, in each of the regions. The non closure factor, $f_{\text{non-closure}}$ represents the differences in the cut efficiency of the MET cut in the Z -peak and low- $m_{\ell\ell}$ regions:

$$f_{\text{non-closure}} = \frac{N_{\text{A}}/N_{\text{B}}}{N_{\text{B}}/N_{\text{C}}}. \quad (6.34)$$

The exact selections used to define the A, B, C and D regions are shown in Table 6.7.

6.3 Systematic Uncertainties

In every analysis there are many uncertainties on signal and background processes that originate from the fact that these processes are not generated in MC simulation with absolute accuracy. In addition to this, there exist experimental uncertainties that can originate from imperfections in the way a detector

$Z/\gamma^* \rightarrow ee/\mu\mu \geq 2\text{-jet VBF Control Regions}$	
A (SR)	C (Z CR)
pre-selection	pre-selection
CJV	CJV
OLV	OLV
$E_T^{miss} > 45 \text{ GeV}$	$p_T^{miss} > 45 \text{ GeV}$
$m_{\ell\ell} < 75 \text{ GeV}$	$ m_{\ell\ell} - m_Z < 15 \text{ GeV}$
B (Z CR)	D (Z CR)
pre-selection	pre-selection
CJV	CJV
OLV	OLV
$25 \text{ GeV} < E_T^{miss} < 45 \text{ GeV}$	$25 \text{ GeV} < E_T^{miss} < 45 \text{ GeV}$
$m_{\ell\ell} < 75 \text{ GeV}$	$ m_{\ell\ell} - m_Z < 15 \text{ GeV}$

Table 6.7: The selection cuts used to define regions for the ABCD method for the $Z \rightarrow ee/\mu\mu$ estimate in the VBF channel.

is modelled, or detector objects are identified. The sources of these uncertainties are described in this section.

6.3.1 Experimental Uncertainties

The experimental uncertainties include uncertainties on the measurement of the trigger efficiencies, and uncertainties on the measurement of object identification efficiencies, calibration scales, and resolution. In addition, uncertainties are calculated on the efficiency of tagging jet flavours, as well as on the luminosity measurement.

6.3.1.1 Trigger

The trigger uncertainties are calculated using tag-and-probe methods from $Z/\gamma^* \rightarrow \text{events}$ [70, 71]. They are less than 1% and denoted by [MU TRIGGER, EL TRIGGER, DIL TRIGGER] in Table 6.8.

6.3.1.2 Flavour Tagging

The uncertainties on the b -tagging scale factors depend on many experimental and theoretical sources. In addition, they also depend on the p_T of jets. In order to reduce the number of variations needed to account for all of the uncertainties and their p_T dependencies the *eigenvector* method is used. This method reduces the number of variations by constructing covariance matrices that take into account the uncertainties and p_T variations. For example, given two sources of uncertainty A and B which depend on six p_T bins, the procedure is:

1. Construct a 6×6 covariance matrix that characterizes the dependence of the b -tagging scale factor on the 6 p_T bins for uncertainty A. Since bin-to-bin correlations are assumed, this matrix has non-zero off-diagonal elements.
2. Repeat step 1. for uncertainty B.
3. Sum these matrices to get a 6×6 covariance matrix for uncertainties on A+B.

4. Diagonalize the summed matrix, to obtain six eigenvectors/eigenvalues. The eigenvectors times the square root of the corresponding eigenvalues represent independent variations that can be applied as uncertainties.

In place of generic uncertainties, A and B, the procedure above is applied to many sources of uncertainties, which include the life time uncertainty of b -hadrons, jet related uncertainties, pileup related uncertainties, etc. The values of each of the b -tagging variations are called [BTag B1EFF-BTag B6EFF]. The eigenvalues are varied up and down once to account for all the p_T and systematics dependencies of the b -tagging factor. The variation of the eigenvalues as a function of p_T is given in Table 6.8. The size of the uncertainties is quoted for a range of p_T values; however, in the analysis only the eigenvalues themselves are used since otherwise the p_T dependence would be double counted.

The uncertainties calculated on flavour tagging c - and light-jets do not use the eigenvector method. The uncertainties on these scale factors are due to theoretical and experimental sources such as uncertainties on jets, pileup, etc. The c -jet uncertainties are dependant on jet p_T , while the light jet uncertainties vary as a function of p_T as well as η . The uncertainties are determined by tracking how much the scale factors change when a systematic uncertainty is varied by $\pm 1\sigma$ (assuming it is parametrized by a Gaussian distribution). The c - and light-jet uncertainties are referred to as [BTag CEFF, BTag LEFF], respectively, and are summarized in Table 6.8.

6.3.1.3 Electron efficiency, scale, resolution

The uncertainties on electrons are associated with the efficiency of identifying electrons, the certainty in calibrating them to a certain scale, as well as evaluating the resolution of their energies. The efficiency of identifying electrons is dependant on the identification as well as reconstruction efficiency. The uncertainties are evaluated by analysing $Z \rightarrow ee$, $J/\psi \rightarrow ee$ and $W \rightarrow e\nu$ events before isolation and impact parameter cuts [71, 118]. These uncertainties vary depending depending on the E_T and η of the electron. These uncertainties are denoted by [EL EFF RECO, EL EEFF ID] for the reconstruction and identification efficiencies, respectively, and [EL ESCALE, EL RES] for the scale and resolution uncertainties, respectively. Their values are quoted in Table 6.8.

The efficiency due to additional isolation and impact parameter cuts applied to the $H \rightarrow WW^*$ analysis is also calculated. These systematic uncertainties are determined using the Z tag-and-probe method, and depend on the E_T of the electron. They are quoted as [EL EFF ISO] in Table 6.8.

In addition, an uncertainty is applied to electrons that come from converted photons. This uncertainty is calculated from Z/γ^* events, and depends on the E_T of the electron. This uncertainty is referred to as [VGammaShapeLepPt] in Table 6.8.

6.3.1.4 Muon efficiency, scale, resolution

The uncertainties on the muon efficiency, scale and energy resolution are obtained from measurements of $Z \rightarrow \mu\mu$, $J/\psi \rightarrow \mu\mu$ and $W \rightarrow \mu\nu$ events. These uncertainties depend on the muon p_T and η . The uncertainty on the momentum resolution is calculated from muons in the inner detector, as well as the Muon Spectrometer. In Table 6.8, the muon uncertainties are denoted by [MU EFF, MU ESCALE] for the reconstruction efficiency and scale uncertainty, and [MU ID RES, MU MS RES] for the ID and MS resolution uncertainty. Additional p_T dependant uncertainties on isolation and vertex identification are calculated and are referred to as [MU ISO] in Table 6.8.

6.3.1.5 Jet Energy Resolution, Jet Energy Scale

The jet energy resolution (JER) and scale (JES) are uncertainties related to jet calibration and resolution. The JER uncertainty is calculated from in-situ methods and ranges from 2% to 40% depending on the jet p_T and η . The largest uncertainty is at the minimum cut value used to select the jet p_T . This uncertainty is denoted by [JER] in Table 6.8.

The JES uncertainty is a function of jet p_T and η and is $< 7\%$. The different sources of JES uncertainties are summarized in Table 6.8. The JES uncertainties are separated into four categories: the absolute in-situ JES uncertainty, the relative in-situ JES uncertainty, the pileup average, and the flavour composition and flavour response. In addition to these uncertainties there are uncertainties on the jet energy scale for b -jets and uncertainties on the jet reconstruction between the full simulation and fast ATLAS simulations. Several of the JES uncertainties utilize the eigenvector method.

The absolute in-situ JES uncertainty is the sum in quadrature of uncertainties derived by calibrating the jet p_T in a fixed detector region. Absolute in-situ JES uncertainties include:

- in-situ detector 1: This uncertainty is derived from in-situ methods using Z +jets, γ +jets and multi-jet events. It represents the dominant eigenvector of a linear combination of all detector related systematic uncertainties, such as the LAr energy scale, muon energy scale, the purity of γ +jet selection, and many others.
- in situ modelling 1: This uncertainty is derived from in-situ methods but represents the uncertainty of MC modelling instead of detector effects. It is the dominant eigenvector of a linear combination of all MC-related uncertainties, such as muon smearing, the effect of the 2^{nd} jet veto, and the $\Delta\phi$ cut in the $Z\gamma$ +jets in-situ samples.
- high p_T jets: This is the uncertainty associated with the calibration of jets with $p_T > 1.5$ TeV. This uncertainty is obtained from pion test beam and by analysing high-energy jets.

The relative in-situ JES uncertainty is the sum in quadrature of uncertainties derived by calibrating jets based on information in other detector regions. These uncertainties include:

- η intercalibration modelling: This uncertainty is calculated as a function of η and p_T and represents the MC modelling effects in di-jet samples used to calibrate forward jets.
- η intercalibration stat+method: This is the statistical uncertainty associated with the calibration of forward jets from the di-jet sample. This uncertainty also includes the uncertainty on the smoothing method used to reduce large bin-to-bin fluctuations by migrating events from one bin to the next [129].

The pileup average is the sum in quadrature of different uncertainties due to pileup effects. These uncertainties include:

- in-time pileup: After the N_{PV} pileup correction, the residual dependence of jet energy on the N_{PV} is taken into account in this uncertainty.
- out-of-time pileup: After the μ pileup correction, the residual dependence of jet energy on μ is taken into account in this uncertainty.

- pileup p_T : This is the uncertainty associated with the dependence of the jet area suppression method on the jet p_T .
- pileup ρ topology: This uncertainty is derived from MC simulation and is the dependence of the jet-energy density, ρ , on the event topology. Event topology refers to what type of particles the event contains ($t\bar{t}$, di-jet, no jets, etc.).

Flavour composition and flavour response uncertainties are on the gluon versus quark composition of jets. They include:

- flavour composition: In-situ methods are derived from Z/γ +jets and multi-jet processes that are mainly produced through quarks. Thus an additional, MC-based, uncertainty is needed to account for the number of gluons versus quarks in an event. The flavour composition uncertainty is calculated separately for different samples (signal, WW , $t\bar{t}$).
- flavour response: Since quarks and gluons initiate different parton showers, the detector response to gluon versus quark initiated jets is different. This uncertainty, derived from MC, takes into account the fact that the jet energy scale is different for quark and gluon jets.

The remaining uncertainties are:

- b -JES: This is the uncertainty on the b -jet scale.
- non-closure AFII: This is an the uncertainty on the difference between events reconstructed with the fast versus full ATLAS simulation.

All of the uncertainties above affect only the normalization of the MC background, and do not change the shape of the m_T distribution significantly. In addition to the uncertainties above, the uncertainty associated with using the JVF cut was also studied and found to be negligible. The sizes of these different uncertainties are shown in Table 6.8.

6.3.1.6 Missing Transverse Energy

The uncertainties on the magnitude of MET arise from several sources depending on the MET definition. Each of the objects in the $\mathbf{E}_T^{miss}$ term has uncertainties associated to it. These uncertainties are also propagated to the $\mathbf{E}_T^{miss}$ term. The $\mathbf{p}_T^{miss}$ is composed of tracks and jet and electron calorimeter deposits whose corresponding uncertainties are also propagated to the $\mathbf{p}_T^{miss}$ term. The only additional uncertainty applied on both MET terms originates from soft processes. The total uncertainty on the magnitude of the MET is the sum in quadrature of the detector object uncertainties and the uncertainties on the soft term.

The uncertainties on the soft term are calculated by exploiting the balance between the hard processes and the hadronic recoil in $Z \rightarrow \mu\mu$ events. The $\mathbf{E}_T^{miss}$ is split into the hard component, consisting of energy from muons, electrons and jets, and a soft component consisting of all other lower energy components, $\mathbf{E}_T^{miss, CellOut}$. The $\mathbf{p}_T^{miss}$ is split into high-energy tracks and low-energy tracks denoted by $\mathbf{p}_T^{miss, soft}$. The soft terms are split into components parallel (L) and perpendicular (P) to the hard components. Since there are no neutrinos in the event these components should be zero. The perpendicular component is consistent with the expectation of zero. The deviation from zero in the longitudinal component represents the fake MET originating from poorly modelled hadronic recoil.

The uncertainties are calculated by *scaling* and *smearing* the soft MET components. Scaling refers to varying the average value of the soft terms and observing the effect on the event yields. Smearing refers to artificially widening the resolution of the soft term by convolving it with a Gaussian function, and observing the effects on the event yields. For example, smearing the term up refers to widening the MET resolution, while smearing down refers to narrowing it.

The systematic uncertainties are obtained by performing six variations on the magnitudes of the longitudinal and perpendicular soft terms for the calorimeter- and track-based MET. The soft term is mapped as a function of the hard term momenta in bins of μ in order to take into account the pileup dependence. The six variations on the magnitudes of the soft terms consist of:

- Scaling the average of the magnitude of the longitudinal soft terms ($< E_L^{miss, CellOut} > / < p_L^{miss, soft} >$) up and down.
- Smearing the resolution of the magnitude of the longitudinal and perpendicular soft terms ($E_{L(P)}^{miss, CellOut} / p_{L(P)}^{miss, soft}$) up and down while treating them as fully correlated.
- Smearing the resolution of the magnitude of the longitudinal and perpendicular soft terms ($E_{L(P)}^{miss, CellOut} / p_{L(P)}^{miss, soft}$) one up and the other down while treating them as fully anti-correlated.

The variations on the magnitude of the soft term of $\mathbf{E}_T^{miss}$ are added in quadrature to give an uncertainty of 17% for $E_{T,rel}^{miss} > 45$ GeV. The four dominant variations (out of a total of six) are applied as systematic uncertainties on $\mathbf{E}_T^{miss}$. These include the scaling of the average soft term up/down, and the bigger of the two resolution smearings. In Table 6.8, the systematic uncertainties on the $\mathbf{E}_T^{miss}$ soft term, are referred to as [MET RESOSOFT, MET SCALESOFT], where RESO denotes resolution smearings and SCALE denotes scaling of the mean.

When adding in quadrature the variations on the magnitude of the soft term of $\mathbf{p}_T^{miss}$, an uncertainty of 30% is obtained for $p_{T,rel}^{miss} > 45$ GeV. The uncertainties of the $\mathbf{p}_T^{miss}$ soft term are referred to as [TRACKMET, RESOPARA SOFT, TRACKMET RESOPERP SOFT, TRACKMET SCALESOFT] in Table 6.8, where PARA denotes the parallel MET components and PERP denotes the perpendicular MET components.

The $\mathbf{p}_T^{miss(trk)}$ definition has the same uncertainties as $\mathbf{p}_T^{miss}$ for overlapping tracks. These uncertainties are fully correlated between the two definitions. There are no uncertainties related to jets or electrons applied to this term.

6.3.1.7 Luminosity

The luminosity is obtained using luminosity-sensitive detectors such as LUCID, BCM and the FCal [49]. It is calculated from measurements of beam parameters, as was shown in equation 3.1 in Chapter 3. To obtain the luminosity, the beam-separation method is employed in which beams are separated by steps of a known distance in order to obtain beam parameters [49]. This method has several uncertainties, many of which are related to the quality of the beam [49]. The luminosity uncertainties are 2.8 (1.8)% for the 8 (7) TeV data, and are denoted by [LUMI] in Table 6.8.

6.3.2 Theoretical Uncertainties

The signal and background processes that are estimated from MC simulation have MC-related theoretical uncertainties applied to them. These uncertainties are obtained by calculating the differences in the

Uncertainty on	Source	Reference Name	Size of Uncertainty (%)
trigger	electron muon di-lepton	EL TRIGGER MU TRIGGER DIL TRIGGER	$\left. \begin{array}{l} \\ \\ \end{array} \right\} < 1$
flavour tagging	b -tag eigenvector	BTag B1EFF BTag B2EFF BTag B3EFF BTag B4EFF BTag B5EFF BTag B6EFF	0.01 - 0.6 vs p_T 0.01 - 0.4 vs p_T 0.01 - 0.7 vs p_T 0.6 - 1.5 vs p_T 0.2 - 4.8 vs p_T 1.1 - 7.8 vs p_T
	c -tag efficiency	BTag CEFF	6 - 14 vs p_T
	light-tag efficiency	BTag LEFF	9 - 19 vs p_T/η
electron	reconstruction efficiency	EL EFF RECO	0.1 - 1.0 vs E_T, η
	identification efficiency	EL EFF ID	0.2 - 2.7 vs E_T, η
	energy scale	EL ESCALE	~ 0.4 vs E_T, η
	energy resolution	EL RES	~ 1 vs E_T, η
	additional cuts	EL ISO	0.6 - 1.6 vs E_T
	$\gamma \rightarrow e^+e^-$ conversion	VGammaShapeLepPt	0.18 - 25 vs E_T
muon	reconstruction efficiency	MU EFF	< 0.46 vs p_T, η
	energy scale	MU ESCALE	< 0.50 vs p_T, η
	energy resolution	MU MS/ID RES	< 1 vs p_T, η
	additional cuts	MU ISO	0.5-2.7 vs p_T
jet	jet energy resolution	JER	2-40 vs p_T, η
	absolute in-site JES	JES 2012 Detector1 JES 2012 Modelling1 JES 2012 HighPt	$\left. \begin{array}{l} \\ \\ \end{array} \right\} 1 - 2.5$ vs p_T, η
	relative in-situ JES	JES Eta Modelling JES 2012 Eta StatMethod	$\left. \begin{array}{l} \\ \end{array} \right\} 0 - 5$ vs p_T, η
	average pileup	JES NPV JES MU JES 2012 PilePt JES 2012 PileRho HWW	$\left. \begin{array}{l} \\ \\ \\ \end{array} \right\} 0 - 5$ vs p_T, η
	flavour composition	JES FlavComp HWW WW JES FlavComp HWW tt JES FlavComp HWW other	$\left. \begin{array}{l} \\ \\ \end{array} \right\} 0.2 - 3$ vs p_T, η
	flavour response	JES FlavResp	~ 1 vs p_T, η
	b -JES	JES BJET	~ 1.5 vs p_T, η
	full vs fast sim	JES NonClosure AFII	~ 0.5 vs p_T, η
MET	scale $< E_L^{miss, CellOut} >$	MET SCALESOFT	$\left. \begin{array}{l} \\ \end{array} \right\} 17$ ($E_{T,rel}^{miss} > 45$ GeV)
	smear $E_{L(P)}^{miss, CellOut}$	MET RESOSOFT	
	scale $< p_L^{miss, soft} >$	TRACKMET SCALESOFT	$\left. \begin{array}{l} \\ \\ \end{array} \right\} 30$ ($p_{T,rel}^{miss} > 45$ GeV)
	smear $p_L^{miss, soft}$	TRACKMET RESOPARA SOFT	
	smear $p_P^{miss, soft}$	TRACKMET RESOPERP SOFT	
luminosity	luminosity	LUMI	2.8 (1.8) for 8 (7) TeV

Table 6.8: The source and size of all the experimental uncertainties as a function of the different variables they depend on, denoted by *vs* in the last column. The *Reference Name* denotes the short form naming convention of each uncertainty.

production cross sections and branching ratios that arise from higher-order corrections, variations in PDF sets used, underlying event and parton shower (UEPS) models employed, and differences in matching matrix-element level calculations to parton showers. The uncertainties on higher-order corrections are probed by independently varying the μ_F/μ_R scales from 1/2 to 2. The PDF uncertainties are calculated by comparing the central values of two PDFs, and varying the different eigenvectors within the same PDF. The uncertainty resulting from eigenvector calculations is taken as $\frac{1}{2}\sqrt{\sum_i (X_i^+ - X_i^-)^2}$, where X_i^+ and X_i^- are the up and down variations corresponding to up and down eigenvectors. The final PDF uncertainty is the sum in quadrature of the eigenvector uncertainty, and the difference between the nominal values of two PDF sets. The uncertainties on UEPS are obtained by comparing generators with different underlying event and parton shower models. The uncertainties in the method used by different generators to match the matrix-element calculations to parton showers are calculated by comparing two different generators. This uncertainty is referred to as a *generator* uncertainty.

Any residual uncertainty that is not accounted for in the cross section and branching ratio uncertainty is included in the acceptance uncertainty. Acceptance uncertainties account for different event yields at different stages of the cutflow. Acceptance uncertainties are also calculated by varying μ_F/μ_R scales, UEPS, PDF sets and generators.

When a background is estimated from a control region, the theoretical uncertainties are on the extrapolation from the control to the signal region. The extrapolation uncertainties are also calculated by varying the μ_F/μ_R scales, UEPS, PDF sets and generators.

6.3.2.1 Signal

The uncertainties on the signal consist of branching ratio and cross section uncertainties. The uncertainties on the branching ratio are obtained from the LHC Higgs Yellow Report [13]. They consist of uncertainties on the branching ratio of the Higgs boson decaying to WW^* and $\tau\tau$. These uncertainties are denoted by [BR VV, BR TAU TAU] and are shown for a Higgs mass of $m_H = 125$ GeV in Table 6.8. The calculation of the cross section uncertainties is described separately for the ggF and VBF processes below.

ggF The sources of the cross section uncertainty can be grouped into the three categories described below.

1. **Total σ :** The overall cross section (σ) uncertainties are taken from the LHC Higgs Yellow Report [13]. The uncertainties on σ are mostly due to uncertainties in higher-order correction calculations, and are probed by varying μ_F/μ_R from 1/2 to 2. In Table 6.9, the total cross section uncertainties are shown and denoted by [QCDScale ggH] for the ggF process. In addition to scale uncertainties, the PDF uncertainties on the total cross section are also calculated. The PDF uncertainties are denoted by [pdf Higgs gg] for the ggF process in Table 6.9.
2. **Jet Binning:** Since the convergence of the total cross section calculation for the ggF process is poor at higher order, simply varying the scale to obtain higher-order corrections results in an underestimation of uncertainties due to the cancellations between the scale dependence of the perturbative series and the effects of the jet veto on the Sudakov factors [143]. In order to avoid this, the cross section uncertainty is evaluated in jet bins of 0, 1, ≥ 2 jets using a method called the *jet veto efficiency*. This method calculates uncertainties on cross sections for each jet bin σ_N , by

assuming that the uncertainties on the efficiency of vetoing a jet ϵ_N , and on the total cross section σ_{tot} are uncorrelated. Using this assumption, the cross section for each bin can be modelled as

$$\sigma_0 = \epsilon_0 \sigma_{tot} \quad \sigma_1 = \epsilon_1 (1 - \epsilon_0) \sigma_{tot} \quad \sigma_{\geq 2} = (1 - \epsilon_1)(1 - \epsilon_0) \sigma_{tot}. \quad (6.35)$$

The jet veto efficiency, ϵ_0 , is the probability of an event not having a jet and depends on the p_T of a jet that is rejected. The ϵ_1 efficiency is the probability of an event not having a second jet, given that it has one jet. This term depends on the p_T of the jet in an event, as well as the p_T of the rejected jet. The uncertainties on each jet bin can then be calculated, as shown below:

$$\delta\sigma_0^2 = \delta\sigma_{tot}^2 + \delta\epsilon_0^2 \quad (6.36)$$

$$\delta\sigma_1^2 = \delta\sigma_{tot}^2 + \left(\frac{\epsilon_0}{1 - \epsilon_0}\right)^2 \delta\epsilon_0^2 + \delta\epsilon_1^2$$

$$\delta\sigma_{\geq 2}^2 = \delta\sigma_{tot}^2 + \left(\frac{\epsilon_0}{1 - \epsilon_0}\right)^2 \delta\epsilon_0^2 + \left(\frac{\epsilon_1}{1 - \epsilon_1}\right)^2 \delta\epsilon_1^2. \quad (6.37)$$

In the above equations, the uncertainties on the variables are denoted by δ , and the total cross section σ_{tot} is taken from The Higgs Yellow Report [13]. To evaluate uncertainties on the jet veto efficiencies, three different definitions of ϵ are used. These definitions differ by higher-order terms and are shown below:

$$\epsilon_0^{(a)} = 1 - \frac{\sigma_{\geq 1}^{\text{NLO}}}{\sigma_{\text{tot}}^{\text{NNLO}}} \quad \epsilon_0^{(b)} = 1 - \frac{\sigma_{\geq 1}^{\text{NLO}}}{\sigma_{\text{tot}}^{\text{NLO}}} \quad \epsilon_0^{(c)} = 1 - \frac{\sigma_{\geq 1}^{\text{NLO}}}{\sigma_{\text{tot}}^{\text{LO}}} + \left(\frac{\sigma_{\text{tot}}^{\text{NLO}}}{\sigma_{\text{tot}}^{\text{LO}}} - 1\right) \frac{\sigma_{\geq 1}^{\text{LO}}}{\sigma_{\text{tot}}^{\text{LO}}} \quad (6.38)$$

$$\epsilon_1^{(a)} = 1 - \frac{\sigma_{\geq 2}^{\text{NLO}}}{\sigma_{\geq 1}^{\text{NNLO}}} \quad \epsilon_1^{(b)} = 1 - \frac{\sigma_{\geq 2}^{\text{NLO}}}{\sigma_{\geq 1}^{\text{NLO}}} \quad \epsilon_1^{(c)} = 1 - \frac{\sigma_{\geq 2}^{\text{NLO}}}{\sigma_{\geq 1}^{\text{LO}}} + \left(\frac{\sigma_{\geq 1}^{\text{NLO}}}{\sigma_{\geq 1}^{\text{LO}}} - 1\right) \frac{\sigma_{\geq 2}^{\text{LO}}}{\sigma_{\geq 1}^{\text{LO}}}. \quad (6.39)$$

The differences in definitions (a), (b), (c) are characterized by next-to-next-to-next-to-leading-order (NNNLO) corrections, and thus the resulting uncertainties on ϵ probe these higher-order corrections. The ϵ uncertainties are calculated by independently varying μ_F and μ_R from 1/2 to 2 of definition (a), and comparing it to the nominal value of definitions (a), (b), and (c). The final uncertainties are taken as either the scale uncertainty applied to scheme (a) or the difference in central values between scheme (a) and (b)/(c), depending on which is larger. Since the $\sigma_{\geq 1}^{\text{NNLO}}$ calculation does not exist, the $\epsilon_1^{(a)}$ calculation is not possible and the uncertainty is taken from the average of (b) and (c) scale variations. The ϵ_0 terms and scale variations are calculated in JETVHETO [144], while the ϵ_1 terms and scale variations are calculated in MCFM. The uncertainties are denoted by [QCDscale ggH PTH m01] for the uncertainty on ϵ_0 , and [QCDscale ggHe1] for the uncertainty on ϵ_1 , and are shown in Table 6.9. The value of the efficiencies and their uncertainties are shown in Figure 6.29.

3. **Acceptance:** Acceptance uncertainties account for the difference in event yields after selection criteria that arise from higher-order corrections, UEPS, PDF, matrix element to parton shower

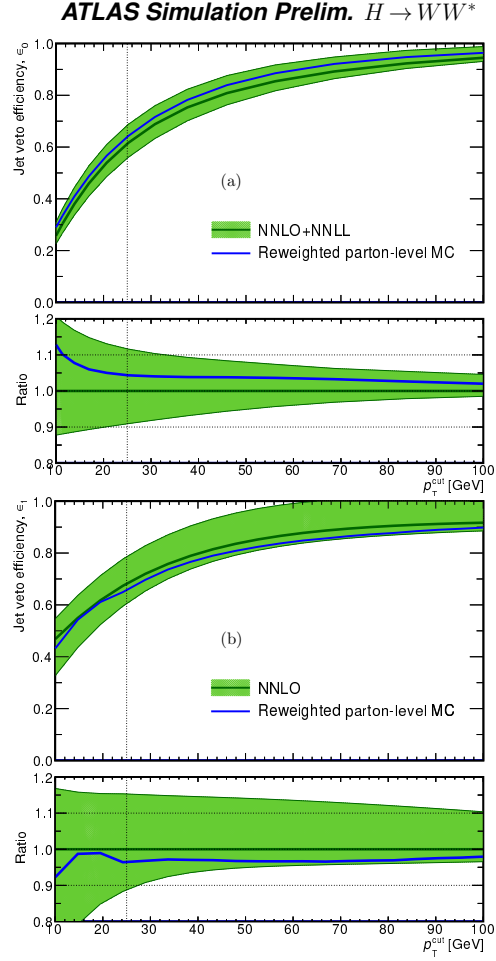


Figure 6.29: The jet veto efficiency for the first jet (top) and second jet (bottom) inclusive ggF Higgs production and its uncertainty as a function of the rejected jet threshold, p_T^{cut} [141].

matching models and modelling of the Higgs boson p_T . These uncertainties are calculated separately for 0-, 1- and ≥ 2 -jet selections. The uncertainties are calculated in a phase space as close as possible to the final $H \rightarrow WW^*$ selection.

The acceptance uncertainties due to scale variations are calculated in POWHEG+PYTHIA 8 by independently varying μ_R and μ_F from 1/2 to 2. For the ≥ 2 -jet channels, scale uncertainties are calculated in MCFM, since POWHEG is an NLO generator of inclusive Higgs production and is unable to probe scale variations in the ≥ 2 -jet bin. These uncertainties are shown in Table 6.9, and are referred to as [QCDscale ggH ACCEPT].

Acceptance uncertainties on PDFs are evaluated as the sum in quadrature of the difference between the central values of CT10 and MSTW2008NLO PDF sets, and the eigenvectors variations within CT10. The PDF uncertainty is called [pdf Higgs gg ACCEPT] in Table 6.9.

The effect of UEPS on the acceptance is considered by comparing POWHEG showered with PYTHIA 6/8 to POWHEG showered with HERWIG. In Table 6.9, this uncertainty is called [Higgs UEPS].

The generator acceptance uncertainties refer to the comparison made between two different generators in order to probe different methods of matching matrix-element calculations to parton showers. To obtain the generator uncertainty, the POWHEG+HERWIG generator is compared to MC@NLO+HERWIG. In Table 6.9, this uncertainty is denoted by [Matching ACCEPT].

Finally, the acceptance uncertainty on modelling of the Higgs p_T distribution is evaluated. The scale is changed in POWHEG+PYTHIA 8 and the impact on the Higgs p_T spectrum is observed. The difference in acceptance due to changing the scale is $\leq 1\%$ for 0- and 1-jet, and $< 2\%$ for ≥ 2 -jet ggF channels. The effect of these uncertainties is small and is neglected in the analysis.

VBF The VBF process contains only EW vertices, and is thus well described by LO calculations. The effect of the higher-order EW corrections was calculated and found to be negligible. The uncertainties on the VBF process include uncertainties on higher-order QCD calculations, as well as UEPS and PDF uncertainties. These uncertainties are summarized below.

1. **Scale:** The scale uncertainty is evaluated by varying μ_F and μ_R from 1/2 to 2. The variation in scale leads to shape variations of the BDT spectrum. This uncertainty on the shape variations due to the QCD scale is calculated in each BDT bin and denoted by [QCDscale qqH ACCEPT] in Table 6.9. The effect of the scale uncertainty on the overall yield takes into account the cross section and acceptance uncertainty and is denoted by [QCDscale qqH] in Table 6.9.
2. **PDF:** In the VBF analysis, the PDF uncertainties are evaluated on the overall yield. The PDF uncertainty is calculated by comparing the CT10 and NNPDF sets. The eigenvector variations within each PDF set are also calculated. The final PDF uncertainty is taken as the larger of the eigenvector variations in each set or the difference between the two sets. This uncertainty takes into account the cross section and acceptance uncertainties and is called [pdf Higgs qq] in Table 6.9.
3. **UEPS:** The uncertainty on the UEPS is obtained by comparing POWHEG showered with HERWIG to POWHEG showered with PYTHIA 8. This uncertainty is evaluated for each BDT bin and takes into account the cross section and acceptance uncertainty. It is referred to as [HiggsVBF UEPS BDT 2j HWW] in Table 6.9.

Process	Uncertainty on	Source	Reference Name	Size (%)
$H \rightarrow WW^*/\tau\tau$	branching ratio	on $H \rightarrow WW^*$	BR VV	[+4.3, -4.2]
		on $H \rightarrow \tau\tau$	BR TAUTAU	[+5.7, -5.6]
ggF	total σ	scale PDF	QCDscale ggH pdf Higgs gg	7.5 [-6.9,+7.5]
	jet binning	ϵ_0 ϵ_1	QCDscale ggH pTH m01 QCDscale ggHe1	1.1/2.0/2.0 in 0/1/ $\geq$ 2-jet 15.3/27.5 in 1/ $\geq$ 2-jet
	acceptance	scale PDF UEPS generator	QCDscale ggH ACCEPT pdf Higgs gg ACCEPT Higgs UEPS Matching ACCEPT	1.0 - 9.0 vs SR 2.7 - 3.3 vs SR 1.6 - 13 vs SR 1.3 - 6.8 vs SR
VBF	BDT shape	scale	QCDscale qqH ACCEPT	1/3/3 vs SR
	$\sigma \oplus$ acceptance	scale PDF UEPS generator	QCDscale qqH pdf Higgs qq HiggsVBF UEPS BDT 2j VBF Higgs MODEL BDT 2j	0.5 4 (3.5) for VBF (VH) 0.32/5.2/14.4 vs SR 4.2
VH	σ	scale on VH	QCDscale VH	0.2-1.6 for WH(ZH)

Table 6.9: The theoretical uncertainties on the ggF and VBF signal for a Higgs mass of $m_H = 125$ GeV. For several uncertainties a range is shown since they depend on the jet multiplicity or signal region they are applied to. The *vs SR* denotes the dependencies of the uncertainties on the different signal regions, which are the three BDT bins.

4. **Generator:** The uncertainty on matching matrix-element-level calculations to parton showers is evaluated by comparing the aMC@NLO [145] and POWHEG generators, when both are showered with HERWIG. This uncertainty takes into account the cross section and acceptance uncertainty and is called [VBF Higgs MODEL BDT 2j] in Table 6.9.

6.3.2.2 Background

The uncertainties on the background processes vary depending on whether the backgrounds are estimated from MC, control regions, or data-driven methods. The backgrounds estimated from MC have scale, PDF, UEPS and generator uncertainties applied to them. The backgrounds estimated from control regions have uncertainties on the extrapolation factor, which are derived by varying the scale, PDF, UEPS and generators. The backgrounds derived with data-driven methods have uncertainties related to the specific estimation technique and are addressed in Section 6.3.3.

WW Uncertainties in the 0- and 1-jet Channels The WW background is derived from a control region and thus has uncertainties on the extrapolation factor. Additional uncertainties are applied on the m_T shape of the WW distribution. Finally uncertainties on the extrapolation due to the $gg \rightarrow WW$ processes are calculated. These uncertainties are described below.

1. **Uncertainties on α_{WW} :** The extrapolation factor, α_{WW} , is defined using well measured leptons, and thus the uncertainty on it is dominated by theoretical uncertainties. The WW production process can result from $q\bar{q} \rightarrow WW$ and $gg \rightarrow WW$ processes. Since $q\bar{q} \rightarrow WW$ makes up 95 (93)%

of the WW background in the 0-(1-) jet channel, the $q\bar{q} \rightarrow WW$ extrapolation uncertainties are described in detail and discussed in this section. The uncertainties on α_{WW} due to the $q\bar{q} \rightarrow WW$ process are due to differences in scale, PDF modelling, UEPS, matching matrix-element to parton shower modelling, and missing higher-order electroweak corrections. These uncertainties are evaluated for the $qqWW$ process and are also applied to the $ggWW$ process. They are evaluated separately for each same-flavour and different-flavour signal region. The uncertainties on the extrapolation factors are calculated according to the equation: $\frac{\alpha_{\text{var}} - \alpha_{\text{nom}}}{\alpha_{\text{nom}}}$, where α_{nom} is the nominal value of the extrapolation factor, and α_{var} is the value obtained from variations in MC simulation. The scale is varied in order to account for the effect of missing higher-order terms which affect the WW kinematics, and thus α_{WW} . The scale, defined by the di-boson mass, is varied in amc@NLO . The resulting uncertainties are called [QCDScale VV ACCEPT] and are shown in Table 6.13.

The PDF uncertainties are calculated by observing the difference in α_{WW} obtained using the nominal sample PDF, CT10 and the alternative MSTW2008 and NNPDF2.3 PDF sets. The CT10 PDF eigenvectors are also varied in order to obtain the uncertainty on the value of α_{WW} . In Table 6.13, the sum in quadrature of PDF uncertainties is called [pdf qq ACCEPT].

UEPS uncertainties are obtained by measuring the changes in α_{WW} when the nominal NLO matrix-element-level generator is used with different parton shower generators: PYTHIA 8, PYTHIA 6 or HERWIG. The UEPS uncertainties are called [WW MTSHAPEPSUE] in Table 6.13. The name contains SHAPE in it so that this uncertainty can be correlated with the shape uncertainty discussed below.

Generator uncertainties are calculated by comparing two NLO matrix-element-level generators with different matching schemes, but the same parton shower generator. The nominal matrix-element-level generator, POWHEG is compared to amc@NLO when both use the HERWIG generator for parton showering. The generator uncertainties are denoted by [WW MTSHAPEMATCHING] in Table 6.13. The name contains SHAPE in it so that this uncertainty can be correlated with the shape uncertainty discussed below.

In addition to the scale, PDF, UEPS, and generator uncertainties, the effect of higher-order electroweak corrections is also evaluated. This is done in order to account for the fact that higher-order electroweak corrections to di-boson production lead to a $\sim 4\%$ difference on the inclusive cross section. Since the impact of the corrections depends on the phase space, a re-weighting tool exists to test this impact on each analysis. When incorporating this tool in the calculation of α_{WW} , the effect is less than 2%. This uncertainty is called [WW EWCORR HWW] in Table 6.13.

2. **m_T shape:** The m_T distribution of WW events in the signal region changes depending on the scale, UEPS, and matching of matrix-element to parton shower scheme (generator). Changing the PDF of the generator has little effect on the shape of the m_T distribution. The scale uncertainties are calculated with amc@NLO . The UEPS uncertainties are calculated by comparing the m_T shape distribution in POWHEG+PYTHIA 8 to POWHEG+HERWIG. The generator uncertainties are calculated by comparing POWHEG+HERWIG to amc@NLO +HERWIG. For each comparison, the two m_T distributions are divided by each other to obtain the deviation from one. The reciprocal of this deviation is taken in order to symmetrize the difference in the m_T shape. In this way an envelope of uncertainty is constructed for each bin in the m_T shape distribution. In the case of scale uncertainties, the envelope is constructed for the scale variation, which provides an m_T shape

that is most discrepant from the nominal one. A linear fit is performed around this uncertainty envelope in order to make the up and down uncertainties continuous as a function of m_T . The linear extrapolation of the UEPS, matching and scale uncertainties are added in quadrature in order to obtain the final m_T shape uncertainty. In Table 6.13, these uncertainties are called [WW MTSHAPESCALE, WW MTSHAPEPSUE, WW MTSHAPEMATCHING] for the scale, shape, and generator uncertainties respectively. These are correlated with the extrapolation uncertainties described above.

3. **Extrapolation due to the $gg \rightarrow WW$ Process:** The $q\bar{q}/gg \rightarrow WW$ processes are both normalized using the WW control region with a single normalization parameter. Since the WW background consists mostly of $q\bar{q} \rightarrow WW$ events, an uncertainty is needed to account for the fact that information is extrapolated from the $q\bar{q} \rightarrow WW$ to the $gg \rightarrow WW$ events. The $gg \rightarrow WW$ component is small and thus α_{WW} can be estimated as

$$\begin{aligned}\alpha_{WW} &= \frac{N_{q\bar{q},gg}^{SR} + N_{gg}^{SR}}{N_{q\bar{q},gg}^{CR} + N_{gg}^{CR}} \\ &\approx \alpha_{q\bar{q}} + N_{gg}^{SR}/N_{q\bar{q},gg}^{SR} - N_{gg}^{CR}/N_{q\bar{q},gg}^{CR}.\end{aligned}\tag{6.40}$$

The uncertainties on the last two terms in equation 6.40 are dominated by the theoretical normalization uncertainty on N_{gg} , which is 26 (33)% in the 0- (1-) jet channels. Thus this is the uncertainty on α_{WW} due to the $q\bar{q} \rightarrow WW$ to $gg \rightarrow WW$ extrapolation. In practice, this uncertainty is applied on the WW normalization factor, and is denoted by [ggWW XS] in Table 6.13.

WW Uncertainties in ≥ 2 -jet Channels The WW background in the ≥ 2 -jet ggF and VBF channels is predicted from MC simulation consisting of $WW+2$ jets EW and QCD samples, which have theoretical uncertainties associated with them. These uncertainties are separated into a cross section uncertainty and modelling uncertainty as described below. The calculation of the VBF uncertainties is described, but the ggF uncertainties follow a similar procedure.

1. **Modelling:** The largest uncertainty on the $WW+2$ jets samples arises from comparing the LO SHERPA and MADGRAPH [146] generators. The SHERPA sample includes its own parton showering, while the MADGRAPH sample is showered with PYTHIA 6. This uncertainty, referred to as modelling, therefore takes into account generator differences in matrix-element to parton shower matching, as well as the parton shower modelling. The uncertainty is calculated by comparing the SHERPA and MADGRAPH yields after the VBF pre-selection in each BDT bin. The uncertainties in the three BDT bins are calculated to be [16%, 12%, 10%] for the EW sample, and [-14%, -8%, 12%] for the QCD sample, as shown in Table 6.12. In Table 6.13, these uncertainties are denoted by [EW MODEL VV BDT 2j] and [QCD WW Modelling BDT 2j] for the EW and QCD samples, respectively. For the QCD sample, there is an additional 27% uncertainty added due to the difference in the inclusive yield when comparing SHERPA and MADGRAPH. This uncertainty is called [QCDscale VV2in BDT 2j] in Table 6.13.
2. **Uncertainty on σ :** The uncertainty on the production cross section is evaluated by varying the scale, PDF and analysing the possible interferences of the $WW+2$ jet EW and QCD processes with each other, and with the Higgs boson processes.

The PDF uncertainty was calculated inclusively for all the channels by comparing the nominal

CT10 PDF to CTEQ within MADGRAPH. The resulting PDF uncertainty was found to be $\sim 3\%$ for the EW samples and $\sim 4\%$ for the QCD samples for all channels. This uncertainty is called [pdf qq] in Table 6.13.

The scale uncertainties were calculated by varying the dynamic MADGRAPH scale, defined by $m^2 + p_T^2$, by a factor of two up and down. This yielded an uncertainty of $\sim 3\%$ on the EW sample and $\sim 13\%$ on the QCD sample. A constant scale was also varied by a factor of two up and down as a cross-check, and yielded similar results.

To obtain the uncertainties on interferences, the cross sections of the EW, QCD and EW+QCD samples were evaluated before and after a VBF phase space selection, as shown in Table 6.10. This selection includes $E_T^{miss} > 20$ GeV, $p_T^\ell > 15$ GeV, $m_{\ell\ell} < 60$ GeV, $p_T^j > 25$ GeV, $m_{jj} > 500$ GeV, $|\Delta\eta(j, j)| > 2.8$, and $\Delta R(j, j) > 0.5$. The table demonstrates that even after these loose cuts, the cross sections of these backgrounds are comparable to the VBF signal.

Channel	σ_{VBF} (fb)		σ_{EW} (fb)		σ_{QCD} (fb)		σ_{EW+QCD} (fb)	
	Before	After	Before	After	Before	After	Before	After
$e\nu e\nu$	1.412	0.242	4.176	0.393	79.54	0.473	N/A	
$\mu\nu\mu\nu$	1.412	0.241	4.189	0.401	79.57	0.462	85.50	0.685
$e\nu\mu\nu$	1.419	0.249	4.031	0.775	76.17	1.213	82.15	1.944

Table 6.10: Cross sections for VBF signal and $WW + 2$ -jets EW, QCD and EW+QCD backgrounds for $m_H = 125$ GeV before and after loose VBF cuts. The cross section calculations were performed in MADGRAPH. Calculated by N.Ilic.

The uncertainties on the interference between EW and QCD background samples were calculated by comparing the cross sections of the $WW+2$ jets EW and $WW+2$ jets QCD samples to the cross section of the $WW+2$ jets QCD+EW sample:

$$\left(\frac{\sigma_{EW} + \sigma_{QCD} - \sigma_{EW+QCD}}{\sigma_{EW+QCD}} \right) \cdot 100. \quad (6.41)$$

Using the cross sections before cuts in Table 6.10 resulted in a QCD-EW interference uncertainty of 2% for all channels.

The interference between the EW background and Higgs boson was determined by generating this background with and without a Higgs boson. The interference effects between the EW background processes and Higgs processes were calculated by dividing the cross sections of these processes, as shown below:

$$\left(\frac{\sigma_{EW \text{ without Higgs}} + \sigma_{Higgs} - \sigma_{EW \text{ with Higgs}}}{\sigma_{EW \text{ with Higgs}}} \right) \cdot 100. \quad (6.42)$$

The resulting uncertainties are shown in Table 6.11 for Higgs masses ranging from 125 to 600 GeV. Table 6.11 shows the Higgs interference uncertainties after the VBF like selection for the ee channel, but similar results were obtained for the $\mu\mu$ and $e\mu$ channels. The uncertainty due to the interference between the Higgs and the EW background is taken for a Higgs mass of $m_H =$

125 GeV before the VBF phase space cuts. There is no interference between the Higgs and the $WW+2$ jets QCD sample.

The scale, generator and interference uncertainties are summarized in Table 6.12 for the $WW + 2$ jets EW and QCD samples.

Higgs Mass (GeV)	Before Cuts	After Cuts
125	1.17%	0.35%
150	6.44%	3.50%
300	0.27%	1.81%
600	0.72%	1.92%

Table 6.11: Uncertainties on the interference between the EW background and the Higgs boson signal, before and after loose VBF cuts. The uncertainties are shown for the ee channel, but similar results for the $\mu\mu$ and $e\mu$ channels were obtained. Calculated by N.Ilic.

Sample	Source	Normalization	BDT Shape
EW $WW+2j$	Generator modelling	-	[16%, 12%, 10%]
	QCD-EW interference	2%	-
	Higgs-EW interference (at $m_H = 125$ GeV)	1.2%	-
	PDF	3%	-
	QCD scale	3%	-
QCD $WW+2j$	Generator modelling	-	[-14%, -8%, 12%]
	PDF	4%	-
	QCD Scale	13%	-
	Generator Overall Yield	27%	-

Table 6.12: Summary of theory uncertainties for the $WW + 2$ jets EW and QCD backgrounds in the VBF BDT analysis. Calculated by N.Ilic.

The scale uncertainty on the $WW + 2$ jets EW sample at $m_H = 125$ GeV before VBF cuts, interference uncertainty between the EW and QCD processes, and interference uncertainty between the EW and Higgs processes are summed in quadrature and denoted by [QCDscale VV BDT 2j] in Table 6.13. For the $WW + 2$ jets QCD sample, the scale uncertainty is already accounted for in the modelling uncertainty.

Top Uncertainties in the 0-jet Channel The uncertainties on the top background in the 0-jet channel are a combination of the uncertainties on α_{top} and f_{MC} . Since the same samples are used to calculate the uncertainties on α_{top} and f_{MC} , there is a correlation between them. In order to account for this, the uncertainty on the product of the two correction factors is calculated for each of the sources. The uncertainties on the $\alpha_{\text{top}} \times f_{\text{MC}}$ due to scale, PDF, generator, hadronization/parton shower, variations of the single-top cross section and interference between top samples are calculated. They are summed in quadrature and referred to as [TOP SCALEF THEO 0j] in Table 6.13. The statistical uncertainty on $\alpha_{\text{top}} \times f_{\text{MC}}$ is called [TOP SCALEEF STATS 0j] in Table 6.13. In addition the effect of non-top samples on f_{MC} is calculated and denoted by [TOP SCALENONTOP 0j] in Table 6.13. The calculation of each uncertainty is described below.

1. **Uncertainties on α_{top} :** The top 0-jet background is predicted from a control region and thus has uncertainties on the extrapolation factor α_{top} . The uncertainties on α_{top} are due to differences

in PDFs, scale variations, generator and hadronization/parton shower models, variations in single top cross section and interferences between single top and $t\bar{t}$ processes.

The scale uncertainty is derived in MC@NLO by varying the scales from 1/2 to 2. The PDF uncertainties are derived by comparing the CT10 PDF to MSTW2008 and NNPDF2.3, as well as using CT10 PDF eigenvectors. The generator and parton shower uncertainties are calculated by comparing MC@NLO+HERWIG to POWHEG+HERWIG samples, as well as ALPGEN+HERWIG samples to MC@NLO+HERWIG.

In addition to the scale, PDF and PS uncertainties, the single top cross section is also varied by $\pm 30\%$ in order to evaluate its effect on α_{top} . These uncertainties are required since the single top and $t\bar{t}$ processes are estimated together, and they would otherwise be overlooked. The interference between single top and $t\bar{t}$ processes is calculated by using the *diagram removal* or *diagram subtraction* scheme. When generating Wt events, the diagram removal scheme removes NLO Wt diagrams that are doubly resonant, while the subtraction scheme modifies the NLO Wt cross section by using a subtraction term that cancels the $t\bar{t}$ contribution.

The shape of the top background does not change significantly when the variations described in this section are made.

2. **Uncertainties on f_{MC} :** Theoretical uncertainties are calculated on the MC correction factor $f_{\text{MC}} = \frac{P_2^{\text{MC}}}{(P_1^{b\text{-tag, MC}})^2}$. The uncertainties are calculated in the same manner as the uncertainties on the extrapolation factor. They take into account the PDF, scale, generator and hadronization/parton shower model, the relative single top cross section variation, and the $t\bar{t}/Wt$ interference.

Top Uncertainties in the 1-jet Channel The uncertainties on the top contribution in the 1-jet channel consist of uncertainties on the correction factor, $f_{\text{correction}}$, and uncertainties on the extrapolation factor, α_{top} . These uncertainties are described below.

1. **Uncertainties on $f_{\text{correction}}$:** Since the correction factor is derived from MC simulation, there are theoretical uncertainties associated with it. The uncertainties on the matrix element, PDF, scale, parton shower, single top interference, and single top cross section are evaluated and added in quadrature to give a final uncertainty on $f_{\text{correction}}$. The procedure followed to obtain these uncertainties is similar to the one used in the calculation of the top 0-jet uncertainties. The uncertainty on the correction factor is referred to as [btag21j extrapol] in Table 6.13.
2. **Uncertainties on α_{top} :** Since the top background is extrapolated into the same-flavour channels, as well as the WW CR, there are four extrapolation factors calculated. The extrapolation uncertainties are calculated by considering variations in the QCD scale, PDF, UEPS and matrix-element calculations. The scale uncertainties are calculated by varying the scale in MC@NLO. The PDF uncertainties are calculated by summing in quadrature the comparison of the nominal CT10NLO PDF to MSTW2008NLO and the variation of eigenvectors of the CT10NLO PDF. The UEPS uncertainties are obtained by comparing POWHEG+HERWIG to POWHEG+PYTHIA. The uncertainties on the matrix-element calculations are obtained by comparing MC@NLO+HERWIG to POWHEG+HERWIG. The uncertainties on extrapolation are shown in Table 6.13, and referred to as [TOP SCALE, TOP PDF, TOP PS, TOP ME].

Top Uncertainties in the ≥ 2 -jet ggF Channel The top background in the ≥ 2 -jet ggF channel is estimated from a control region and thus the associated extrapolation uncertainties are calculated, as described below.

1. **Uncertainty on α_{top} :** The top background in the ≥ 2 -jet region is calculated from a control region and has uncertainties on the extrapolation factor. The uncertainty on the extrapolation factor is calculated by taking into account the scale, PDF, UEPS and generator differences. The scale uncertainty is calculated by varying the scales in MC@NLO+HERWIG. The PDF uncertainty is obtained from the sum in quadrature of CT10 eigenvectors and the difference between CT10 and MSTW predictions. The UEPS uncertainty is obtained by comparing MC@NLO+HERWIG and POWHEG+PYTHIA. The generator uncertainty, which takes into account the matrix level differences, is obtained by comparing the MC@NLO and POWHEG generators. These uncertainties are called [TOP Scale, TOP PDF, TOP PS, TOP ME] in Table 6.13.

Top Uncertainties in the ≥ 2 -jet VBF Channel The top background in the ≥ 2 -jet VBF channel is estimated from a control region and thus the associated extrapolation uncertainties are calculated, as described below.

1. **Uncertainties on α_{top} :** The uncertainties on the extrapolation factor are calculated to account for differences in generators between matrix-element generation, QCD scale, parton shower and PDF sets. Matrix-element-level uncertainties are obtained from an MC@NLO and ALPGEN comparison. The PDF and shower uncertainties are neglected since they are smaller than the statistical uncertainties of the MC sample. The sum in quadrature of these uncertainties is called [TOP THEO BDT 2j] in Table 6.13.

DY Uncertainties in the 0- and 1-jet Different-Flavour Channels The $Z \rightarrow \tau\tau$ process is the dominant DY background in the DF channels and is estimated from a control region. Thus there are extrapolation uncertainties calculated on it.

1. **Uncertainties on $\alpha_{Z \rightarrow \tau\tau}$:** The $Z \rightarrow \tau\tau$ background is calculated from a control region in all channels. Since there is DY contamination in the WW CR, the extrapolation uncertainties are calculated there as well. The scale uncertainties are evaluated by varying the dynamic scale in ALPGEN. The PDF uncertainty was calculated by comparing the nominal CTEQ6LO PDF set to CT10, MSTW2008, and NNPDF2.3, along with eigenvector variations in CT10. The UEPS uncertainty is computed by comparing the ALPGEN generator showered with HERWIG to PYTHIA 6, after the samples are re-weighted to correct for $p_T^{\ell\ell}$ mis-modelling. In Table 6.13 the scale, PDF, and UEPS uncertainties on the extrapolation factor are called [ZTAUTAU SCALE, ZTAUTAU PDF, and ZTAUTAU MODELING], respectively.

In addition to the scale, PDF and UEPS uncertainties, the extrapolation factor also contains uncertainties on the $p_T^{\ell\ell}$ weights. As explained in Chapter 4, the mis-modelling of the $p_T^{\ell\ell}$ spectrum in ALPGEN is corrected for by applying weights derived from data to MC ratios in a Z peak region. The weights depend on the cuts applied on $m_{\ell\ell}$ and MET. Thus the systematic uncertainty is quoted as the effect of changing the $m_{\ell\ell}$ and MET cuts in the Z -peak region. These uncertainties are called [ZTAUTAU PTZREW], and are shown in Table 6.13.

The uncertainty on $p_T^{\ell\ell}$ re-weighting is computed by comparing the distributions in ALPGEN+PYTHIA 6

Bkg	Uncertainty on	Source	Reference Name	Size (%)
All	σ	PDF	pdf qq	0.3 - 0.4
WW	σ	PDF	pdf gg	0.4
	$\alpha_{WW, 01j}$	scale	QCDscale VV ACCEPT	0.71 - 3.2 vs SR
		PDF	pdf qq/gg ACCEPT	0.44 - 1.1 vs SR
		EW correct	WW EWCorr HWW	0.14 - 2.8 vs SR
	$\alpha_{WW, 01j}$ & $m_{T,01j}$ shape	generator PSUE	WW MTSHAPEMATCHING WW MTSHAPEPSUE	0.44 - 5.6 vs SR 1.0 - 3.6 vs SR
	$m_{T, 01j}$ shape	scale	WW MTSHAPESCALE	< 20 vs SR/CR
	$\alpha_{WW, 01j}$	$q\bar{q}$ to gg extrap	ggWW XS	26
top	$\alpha_{\text{top}, 0j} \times f_{\text{MC}}$	modelling m_T shape	EW MODEL VV BDT 2j	16/12/10 vs SR
		scale/int	QCDscale VV BDT 2j	10
		modelling m_T shape modelling	QCD WW Modelling BDT 2j QCDscale VV2in BDT 2j	-14/-8/12 in vs SR 27
	$f_{\text{corr}, 1j}$	scale/PDF/PS/int statistics non-top	TOP SCALEEF THEO 0j TOP SCALEEF STATS 0j TOP SCALEEF NONTOP 0j	4.0 - 5.7 vs SR/CR 2.3 vs SR/CR 2.7 vs SR/CR
	$\alpha_{\text{top}, 1j}$	scale/PDF/PS/ scale	btag21j extrap	0.8
		PDF generator PS	TOP SCALE TOP PDF TOP ME TOP PS	0.6 - 1.1 vs SR/CR 0.08 - 0.12 vs SR/CR 2 - 2.4 vs SR/CR 1.8 - 3 vs SR/CR
		scale PDF UEPS generator	TOP Scale TOP PDF TOP PS TOP ME	0.6 - 1 vs SR/CR 0.08 - 0.3 vs SR/CR 1.2 - 3 vs SR/CR 2 - 3.2 vs SR/CR
$\alpha_{\text{top}, \text{VBF}}$	scale/PDF/gen.	TOP THEO BDT 2j HWW	10 - 21 vs SR/CR	
DY	$\alpha_{Z \rightarrow \tau\tau, 012j}$	scale PDF PS $p_T^{\ell\ell}$ weight	ZTAUTAU SCALE ZTAUTAU PDF ZTAUTAU MODELLING ZTAUTAU PTZREW	1.6 - 10.3 vs SR/CR 1.4 - 2.1 vs SR/CR 2 - 8 vs SR/CR 16 - 19 vs SR/CR
		MC	statistics	ZTAUTAU PYTHIAMCSTAT
$W\gamma^*$	k -factor	scale	QCDscale VV	7.5
	C	scale	WgsJetBin0 WgsJetBin1 WgsJetBin2	6.5 30 26
			acceptance	PDF
	m_T shape	scale	Wgs MTscale	–
$W\gamma$	k -factor	scale	QCDscale VV	6.1
	σ	scale	QCDscale Wg ACCEPT0j QCDscale Wg ACCEPT1j QCDscale Wg ACCEPT2j	9 53 100
			acceptance	PDF
$Z\gamma^*/ZZ$	k -factor	scale	QCDscale VV	5

Table 6.13: The uncertainties on the backgrounds for the 8 TeV analysis. Many uncertainties depend on the control and signal region they are applied to, which is denoted by *vs SR/CR*.

and ALPGEN+PYTHIA 8. This uncertainty is found to be smaller than the MC statistical uncertainty on the sample. Thus the MC uncertainty is the only one applied and denoted by [ZTAUTAU PYTHIAMCSTAT] in Table 6.13.

Uncertainties on non- WW Di-bosons The sum of non- WW di-boson backgrounds is normalized using a same-charge control region. However theoretical uncertainties are not needed on the extrapolation factor, α_{VV} , since the same-charge control region and signal regions are created using the same selection criteria. The only difference between the phase space of these two regions is that one contains same-charge leptons, while the other contains opposite-charge leptons. The relative compositions of non- WW di-boson backgrounds are taken from MC simulation, and thus MC-related systematic uncertainties must be applied to each background. The MC-related systematic uncertainties are described for each non- WW di-boson background below.

Uncertainties on $W\gamma^*$ The theoretical uncertainties calculated on the $W\gamma^*$ background include the uncertainties on the k -factor, jet re-weighting, acceptance and m_T shape.

1. **k -factor:** The $W\gamma^*$ sample is generated in SHERPA and corrected to NLO calculations with MCFM. The scale uncertainty on the k -factor takes into account the cross section uncertainty, and is named [QCDscale VV] in Table 6.13.
2. **Jet re-weighting:** The modelling of the jet multiplicity in the SHERPA ≤ 1 parton sample can be improved by re-weighting it to a Sherpa ≤ 2 parton sample. The jet re-weighting factors, C , have uncertainties on them, which are calculated by varying the μ_F scales in each jet bin. The uncertainties on C are referred to as [WgsJetBin0, WgsJetBin1, WgsJetBin2] in Table 6.13.
3. **Acceptance:** The acceptance uncertainties are negligible compared to the uncertainties on the jet-reweighting. The PDF acceptance uncertainties on the k -factor have not been explicitly calculated but are expected to be $\sim 3\%$, and are denoted by [pdf Wgs ACCEPT HWW] in Table 6.9.
4. **m_T shape:** The uncertainties on the m_T shape of the $W\gamma^*$ samples are evaluated by varying the scale, as well as by comparing the SHERPA ≤ 1 parton and ≤ 2 parton samples. These uncertainties are called [Wgs MTscale] in Table 6.13.

Uncertainties on $W\gamma$ The uncertainties on $W\gamma$ include the uncertainties on the k -factor, per bin cross section and acceptance.

1. **k -factor:** The $W\gamma$ events are simulated by the LO generator, ALPGEN, and corrected to the NLO generator MCFM. The uncertainty on the k -factor is calculated by varying the μ_F and μ_R scales in MCFM. The scale uncertainty on the k -factor is referred to as [QCDscale VV] in Table 6.13.
2. **Cross section uncertainties for each jet bin:** The change in the cross section of $W\gamma$ due to scale variations is calculated for each jet bin. The μ_F and μ_R scales are varied and the effect of the acceptance on $\sigma_{\geq 0}$ and $\sigma_{\geq 1}$ jet bins is observed. Here, $\sigma_{\geq 0}$ ($\sigma_{\geq 1}$) is the cross section for processes with ≥ 0 - (≥ 1 -) jets. This method is referred to as the Stewart-Tackman procedure and provides a more reliable uncertainty estimate than scale variations on the total cross section [143]. These jet bin scale uncertainties are calculated by assuming that uncertainties on inclusive multi-jet cross sections are uncorrelated, and can be modelled by $\sigma_0 = \sigma_{\geq 0} - \sigma_{\geq 1}$ and $\sigma_1 = \sigma_{\geq 1} - \sigma_{\geq 2}$. Since

MCFM is an NLO generator that is not able to calculate $\sigma_{\geq 2}$, the individual sum of events with up to five partons in the final state is used to estimate this cross section. These uncertainties are called [QCDscale Wg ACCEPT0j, QCDscale Wg ACCEPT1j, QCDscale Wg ACCEPT0j] in Table 6.13.

3. **Acceptance:** Most acceptance uncertainties are negligible compared to the jet bin uncertainties. The acceptance uncertainties due to PDF variations are not explicitly calculated, but are expected to be $\sim 3\%$, and appear as [pdf Wg ACCEPT WW] in Table 6.13.

Uncertainties on $Z\gamma^*/ZZ$ The uncertainties on the $Z\gamma^*/ZZ$ are due to uncertainties on the k -factor.

1. **k -factor:** The $Z\gamma^*/ZZ$ sample was generated in SHERPA and corrected to the cross section obtained from MCFM. The uncertainties on the k -factor are calculated by performing scale variations in MCFM. They are referred to as [QCDscale VV] in Table 6.13.

6.3.3 Uncertainties on Data-Driven Methods

The W +jets and $Z \rightarrow ee/\mu\mu$ backgrounds are estimated using data-driven methods. The uncertainties on these backgrounds are described in this section.

6.3.3.1 Fake Factor Uncertainties in W +jets and Multi-jet Estimate

The uncertainties on the fake factors are neither fully experimental nor theoretical uncertainties since the multi-jet and W +jets estimations are partially derived from data. The fake factor uncertainties are due to a combination of effects observed in data and MC simulation. The main sources of uncertainty are the differences in the fake factors between the W +jets and Z +jets/multi-jet samples, the effects of pileup, and the effect of real lepton contamination in the di-jet control sample. The statistical uncertainties on the MC samples used in calculating the fake factors are also included. The MC simulation is used only for the subtraction of backgrounds that are not estimated using the fake factor method, such as for the electroweak background. The uncertainties on the fake factors are derived separately for electrons and muons as a function of lepton p_T .

Multi-jet Uncertainty (Di-jet Fake Factor) The uncertainties on the di-jet fake factor mostly affect the multi-jet background estimate. These uncertainties include the differences between the di-jets and Z +jets samples, the effects of pileup, the electroweak lepton contamination in the di-jet sample and statistics of MC samples. These uncertainties are described below.

1. **W +jets and di-jet difference:** The di-jet fake factors are applied to the W +jets sample, and the differences between the fake factors in the two samples are quoted as an uncertainty. The differences originate from different jet kinematics and different heavy flavour fractions in the two samples. This is estimated by comparing the fake factors in the PYTHIA 8 di-jet sample and ALPGEN+PYTHIA 6 W +jets sample. The difference is evaluated as a function of lepton p_T . The electron fake factors differ by up to 60%, while the muon fake factors differ by up to 40%.
2. **Pileup:** The effects of pileup are accounted for by calculating the fake factor as a function of μ . This uncertainty is calculated as a function of lepton η and p_T and is less than 10%.

3. **Lepton contamination subtraction:** The effects of leptons from W/Z bosons contaminating the di-jet control sample is calculated as an uncertainty. This contamination is estimated by varying the number of W/Z events that are subtracted from the di-jet sample. This uncertainty is derived as a function of lepton p_T .

Since the leading uncertainty on the di-jet fake factor is due to the differences between W +jets and di-jets samples, the di-jet uncertainties on the multi-jet samples are grouped into three main categories, neglecting differences between e and μ final states. The uncertainty due to the W +jets and di-jets sample differences is called [FakeRateCorr QCD HWW], the uncertainty due to pileup and lepton contamination subtraction is called [FakeRateOther QCD HWW], and the uncertainties due to MC statistics are called [FakeRateStat QCD HWW]. These uncertainties are shown in Table 6.13.

W +jets Uncertainty (Z +jets Fake Factor) The biggest uncertainty on the W +jets contribution is due to the uncertainty on the fake factor. The uncertainties on the fake factor are derived from the differences in the W +jets and Z +jets sample, the effects of pileup, real W/Z lepton contamination in the Z +jets sample, and statistics of MC samples. These uncertainties are described below.

1. **Differences between the Z +jets and W +jets samples:** The Z +jets fake factor is applied to the W +jets sample. The ratio of the W +jets and Z +jets fake factor is calculated in ALPGEN+PYTHIA, ALPGEN+HERWIG and POWHEG+PYTHIA8. The largest lower and upper deviation from unity is taken as the uncertainty on the W +jets fake factor. The opposite-charge and same-charge fake factors need to be properly correlated since they are also used when estimating the non- WW di-boson background in the same-charge control region. The opposite-charge and same-charge factors are not fully correlated since the opposite-charge and same-charge samples do not have the same composition; however they are also not uncorrelated since they contain the same processes. Thus the uncertainty is split into correlated and uncorrelated components. The correlated part describes the $W + b\bar{b}$ processes that are similar between opposite-charge and same-charge events, while the uncorrelated part describes the $W + c$ processes, which mainly appear in the opposite-charge sample.
2. **Pileup:** As with the uncertainty on the di-jet fake factor, the variation of the fake factor as a function of μ is used as a pileup uncertainty.
3. **Lepton contamination subtraction:** The number of leptons from W/Z events subtracted from the Z +jets sample is varied in order to obtain the uncertainty due to lepton contamination.

The uncertainties due to W +jets and Z +jets differences are called [FakeRate EL/MU Uncorrl OC, FakeRate EL/MU Corrl OC, FakeRate EL/MU Uncorrl SC, FakeRate EL/MU Corrl SC], where for example [FakeRate EL/MU Uncorrl OC] describes the uncorrelated component of the e/μ opposite-charge fake factor. The uncertainties on the pileup and lepton contamination are called [FakeRate EL/MU Other HWW]. The statistical uncertainties on the fake factors are called [FakeRate EL Stat]. All of the uncertainties depend on the lepton p_T . These uncertainties are shown in Table 6.14.

6.3.3.2 Pacman Uncertainties in DY Estimate

The same-flavour channels use the Pacman method, which contains uncertainties on the cut efficiencies. The $\epsilon^{\text{non-DY}}$ and $\epsilon_{Z\text{-peak}}^{\text{non-DY}}$ efficiencies are measured using different-flavour events and applied to same-

Background	Uncertainty on	Source	Reference Name	Size (%)
multi-jet	$f_{\text{di-jet}}$	sample diff. pileup/ ℓ cont. statistics	FakeRateCorr QCD FakeRateOther QCD FakeRateStat QCD	< 60 (40) for $e(\mu)$ 1.8-4.2 0.5-5.0 vs p_T
W +jets	$f_{e,Z+\text{jets}}$	sample diff.	FakeRate EL Uncorr1 OC FakeRate EL Uncorr1 SC FakeRate EL Corrl	~ 16 ~ 30 ~ 11
		pileup/ ℓ cont. statistics	FakeRate EL Other HWW FakeRate EL Stat	included in? 5-8 for OC/SC
	$f_{\mu,Z+\text{jets}}$	sample diff.	FakeRate MU Uncorr1 OC FakeRate MU Uncorr1 SC FakeRate MU Corrl	~ 17 ~ 47 ~ 13
		pileup/ ℓ cont. statistics	FakeRate MU Other HWW FakeRate MU Stat	N/A 8-14 for OC/SC
DY pacman	$\epsilon^{\text{non-DY}}$	SF/DF diff.	PM EFF f recoil NDY SR	0.8-2.0 vs SR/CR
	$\epsilon_{Z\text{-peak}}^{\text{non-DY}}$	SF/DF diff.	PM EFF f recoil NDY ZP	1.9-4.5 vs SR/CR
	ϵ^{DY}	high/low $m_{\ell\ell}$ diff.	PM EFF f recoil DY	5.1-32 vs SR/CR
DY ABCD	BDT	generator	ZLEPLEP ABCD BDT0 2j	4
			ZLEPLEP ABCD BDT1 2j	10
			ZLEPLEP ABCD BDT2 2j	60
	2 BDT bins	scale/PDF/PS	QCDscale ZLEPLEP ABCD 2j	11
	MET Cut	statistics	ZLEPLEP ABCD METEFF 2j	18

Table 6.14: The uncertainties for data-driven backgrounds for the 8 TeV dataset. The *vs SR/CR* notation represents that many uncertainties depend on the signal and control region to which they are applied. The *diff* and *cont* represent condensed notation for difference and contamination.

flavour events. In order to account for the differences that might exist in the different- and same-flavour events, uncertainties are calculated by comparing the two samples in MC simulation. The uncertainty on $\epsilon^{\text{non-DY}}$ is evaluated as the ratio of the efficiencies in non-DY same-flavour events to opposite flavour events in the low- $m_{\ell\ell}$ region. The statistical uncertainty on the MC samples is also calculated and the final systematic is denoted by [PM EFF f recoil NDY SR0j, PM EFF f recoil NDY SR1j] in Table 6.14. Similarly, the uncertainty on $\epsilon_{Z\text{-peak}}^{\text{non-DY}}$ is calculated by taking the ratio of the efficiencies of non-DY events in same-flavour and opposite flavour samples in the Z -peak region. Together with the MC statistical uncertainty, this term is called [PM EFF f recoil NDY ZP0j, PM EFF f recoil NDY ZP1j] in Table 6.14.

The uncertainty on ϵ^{DY} is also calculated in order to account for the extrapolation of the Z -peak region to the low- $m_{\ell\ell}$ region. This uncertainty is evaluated by calculating the ratio between the f_{recoil} efficiencies in the Z -peak region and the low- $m_{\ell\ell}$ regions. The ratio is calculated in ALPGEN+HERWIG and ALPGEN+PYTHIA, and the larger of the two is taken as the uncertainty. Together with the MC statistical uncertainty, these uncertainties are named [PM EFF f recoil DY0j, PM EFF f recoil DY1j] in Table 6.14.

6.3.3.3 ABCD Method Uncertainties in DY Estimate

The uncertainties on the DY estimate in the ≥ 2 -jet VBF channel are due to differences in the bin-by-bin BDT shape distribution, as well theory uncertainties on the last two BDT bins. The ABCD method is data-driven but theory uncertainties are needed since the last two BDT bins are normalized with the same normalization factor. The theory uncertainties due to scale variations, parton shower, and PDF sets are considered. These variations were performed in SHERPA for the last two BDT bins. The uncertainty in the most sensitive bin is applied, and is referred to as [QCDscale ZLEPLEP ABCD 2j] in Table 6.14.

The differences in the BDT shape are calculated by comparing ALPGEN+HERWIG to ALPGEN+PYTHIA. These uncertainties are calculated for each BDT bin and denoted by [ZLEPLEP ABCD BDT0 2j, ZLEPLEP ABCD BDT1 2j, ZLEPLEP ABCD BDT2 2j] in Table 6.13. The statistical uncertainty on the efficiency of the MET cut is also calculated and denoted by [ZLEPLEP ABCD METEFF 2j] in Table 6.14.

6.4 Modifications for 7 TeV Data Analysis

The treatment of the 7 TeV data contains several differences with respect to the 8 TeV data. The two data sets are treated differently since they have different pileup conditions and different signal to background ratios. The 0- and 1-jet channels in the 7 TeV data are treated the same as in the 8 TeV data. One of the primary differences between the 7 and 8 TeV data is that in the 7 TeV data, the ≥ 2 -jet channel only considers VBF production. Using the 7 TeV data, the VBF different-flavour analysis uses a BDT method, and uses a two bin BDT score as the final discriminant. The 7 TeV VBF same-flavour analysis uses a cut-based analysis, similar to the 0- and 1-jet channel since there are not enough statistics for a BDT method.

Other differences in the treatment of 7 and 8 TeV data include object definitions, kinematic selections and background estimation techniques. Single leptons triggers were used to select the 7 TeV data. The triggers use a muon p_T cut of 18 GeV and electron cut of 20 or 22 GeV, depending on the data taking period. The same muon identification criteria are used as for the 8 TeV analysis. The electrons are identified using the tight cut-based selection without a GSF fit. Tighter isolation criteria are required

since, due to lower statistics, it is more difficult to estimate backgrounds with mis-identified leptons in the 7 TeV data. The jet identification and selection criteria are the same as for the 8 TeV data. However, lower pileup levels in the 7 TeV data allow for the increase of the JVF cut to 0.75 in order to reject more background while maintaining similar signal yields.

The lower pileup levels allow for looser selection criteria for the 7 TeV data than the 8 TeV data. The E_T^{miss} cut in the same-flavour channel is lowered to 35 GeV, while the $p_T^{miss(trk)}$ cut is not used. The lower MET cuts are compensated for by a higher cut on $p_T^{\ell\ell}$ of 40 GeV in the 0-jet channel, and the addition of a $p_T^{\ell\ell j} > 35$ GeV cut in the 1-jet channel. The f_{recoil} cut is reduced to 0.2 (0.5) in the 0- and 1-jet channels.

There are a few differences in the background estimations between the 7 TeV and 8 TeV data. The W +jets background estimation uses a multi-jet fake factor instead of a Z +jets fake factor. The non- WW di-boson backgrounds are estimated from MC simulation since there is not a sufficient number of events in the 7 TeV data to construct a same-charge control region.

The experimental uncertainties on the 7 TeV data are obtained using the same techniques as for the 8 TeV data. The uncertainties on the data-driven backgrounds are also calculated for the 7 TeV data using the same methods as for the 8 TeV data. The theoretical uncertainties on the extrapolation factors for WW , top and $Z/\gamma^* \rightarrow \tau\tau$ derived for 8 TeV data are applied to the 7 TeV data.

Chapter 7

Statistical Analysis Techniques

The data collected are tested against MC predictions the using frequentist statistical method. Tests are performed to quantify the compatibility of the data and MC simulation by minimizing a profile likelihood ratio [147]. The m_T distribution and BDT score, in the case of the VBF analysis, are used as the discriminating variables in the signal and control regions. The construction of the likelihood ratio is described in Section 7.1, the definition of the test statistic and fitting procedure is described in Section 7.2, the construction of the probability distribution function of the test statistic is explained in Section 7.3, and the method for obtaining results and interpreting them is described in Section 7.4.

7.1 The Likelihood Definition

The likelihood function is defined as

$$\mathcal{L}(\hat{\mu}, \theta) = \prod_{\substack{\text{flavours} \\ \text{jets}}} P(N_{obs}, \hat{\mu}N_{SR}^{sig} + N_{SR}^{bkg}) \times \prod_{\theta} N(\tilde{\theta}|\theta). \quad (7.1)$$

In equation 7.1, $P(N_{obs}, \hat{\mu}N_{SR}^{sig} + N_{SR}^{bkg})$ represents the information contained in the signal regions. It is the Poisson probability of getting an observed number of events, N_{obs} , given that there are a $\hat{\mu}N_{SR}^{sig}$ number of signal events, and N_{SR}^{bkg} number of background events in the signal region. The N_{SR}^{bkg} represents the sum of the N_{SR}^{WW} , N_{SR}^{top} , N_{SR}^{VV} , N_{SR}^{W+jets} , $N_{SR}^{multi-jet}$, $N_{SR}^{Z \rightarrow \tau\tau}$ and $N_{SR}^{Z \rightarrow ee/\mu\mu}$ values, which are predicted by the estimation techniques described in Chapter 6. The $\hat{\mu}$ is a scaling factor that represents the strength of the hypothesized signal of the theory being tested. It is called a *parameter of interest* and is extracted from the fitting procedure. The Poisson probability is calculated for each jet multiplicity and lepton flavour in the analysis and then a product is taken of these variables.

Each individual Poisson probability is a product of the Poisson probabilities calculated in each bin of the analysis, as shown below:

$$P(N_{obs}, \hat{\mu}N_{SR}^{sig} + N_{SR}^{bkg}) = \prod_{i=1}^{N_{bins}} \frac{(\hat{\mu}N_{SR,i}^{sig} + N_{SR,i}^{bkg})^{n_i}}{n_i!} e^{-(\hat{\mu}N_{SR,i}^{sig} + N_{SR,i}^{bkg})}. \quad (7.2)$$

In the above equation N_{bins} is the number of bins and $N_{SR,i}^{sig}$ and $N_{SR,i}^{bkg}$ are the number of signal and background events, respectively, in each bin.

The numbers of background and signal events are constrained by information extracted outside of the signal region, such as control region measurements, theoretical calculations or detector performance studies. Such measurements are called supporting, or *auxiliary*, measurements and are represented by $N(\tilde{\theta}|\theta)$ in equation 7.1. The nuisance parameters, given by θ , represent systematic uncertainties that reflect the fact that the signal and background yields cannot be known with absolute certainty due to theoretical and experimental limitations. The $\tilde{\theta}$ variable is known as a *global observable* and represents the events in the supporting measurement.

The functional form of $N(\tilde{\theta}|\theta)$ depends on the type of systematic uncertainty it represents. There are four general cases outlined below.

7.1.1 Control Region

One example of an auxiliary measurement involves using a control region to estimate the number of background events in the signal region. In this case, the number of background events in the signal region is estimated by normalizing the MC background to the data in the control region: $N_{\text{SR}}^{\text{bkg}} = \hat{\mu}_{\text{bkg}} N_{\text{SR}}^{\text{bkg, MC}}$.

The normalization factor, $\hat{\mu}_{\text{bkg}}$, is extracted by fitting the number of simulated background events, $N_{\text{CR}}^{\text{bkg, MC}}$, to the number of data events observed in the control region, $N_{\text{obs, CR}}$. It represents the $\hat{\mu}_{WW}$, $\hat{\mu}_{\text{top}}$, $\hat{\mu}_{VV}$ and $\hat{\mu}_{Z \rightarrow \tau\tau}$ values, introduced in the background estimation section. The hat denotes the fact that these normalization factors are obtained by fitting the data in the MC during the fitting procedure. In this case $N(\tilde{\theta}|\theta)$ has the Poisson distribution

$$N(\tilde{\theta}|\theta) = P(N_{\text{obs, CR}} | \hat{\mu}_{\text{bkg}} N_{\text{CR}}^{\text{bkg, MC}}(\hat{\mu}_{\text{bkg}})) = \prod_{j=1}^{M_{\text{bins}}} \frac{(\hat{\mu}_{\text{bkg},j} N_{\text{CR},j}^{\text{bkg, MC}}(\hat{\mu}_{\text{bkg},j}))^{m_j}}{m_j!} e^{-\hat{\mu}_{\text{bkg},j} N_{\text{CR},j}^{\text{bkg, MC}}(\hat{\mu}_{\text{bkg},j})}. \quad (7.3)$$

The Poisson distribution is calculated for each bin in the control region and multiplied over all bins for M_{bins} bins. In each bin, the number of MC events in a control region, $N_{\text{CR},j}^{\text{bkg, MC}}$, is dependant on the number of signal events in the control region, $\hat{\mu}_j N_{\text{CR},j}^{\text{sig}}$, the number of events targeted by the control region, $\hat{\mu}_{\text{bkg},j} N_{\text{CR, target},j}^{\text{bkg, MC}}$, and the number of events from other background contamination, $N_{\text{CR, other},j}^{\text{bkg}}$, as shown below:

$$N_{\text{CR},j}^{\text{bkg, MC}}(\hat{\mu}_{\text{bkg}}) = \hat{\mu}_j N_{\text{CR},j}^{\text{sig, MC}} + \hat{\mu}_{\text{bkg},j} N_{\text{CR, target},j}^{\text{bkg, MC}} + N_{\text{CR, other},j}^{\text{bkg}}. \quad (7.4)$$

The number of the other backgrounds in the control regions is obtained from the estimation techniques described in the background section.

7.1.2 Normalization Uncertainties

When a systematic uncertainty affects only the normalization of the m_T distribution, $N(\tilde{\theta}|\theta)$ is described by a unit Gaussian distribution, as shown below:

$$N(\tilde{\theta}|\theta) = G(\tilde{\theta}|\theta, 1). \quad (7.5)$$

The parametrization of the uncertainty is chosen such that $\theta = 0$ corresponds to the nominal value of the uncertainty. The up and down variations of the systematic uncertainty are parametrized by $\theta = \pm 1$ and correspond to the $\pm 1\sigma$ values of the Gaussian function. For example, if the source of the

systematic uncertainty is the jet energy scale which is measured to within a $\pm 3\%$ uncertainty, $\theta = 0$ would correspond to the simulated signal and background events with the nominal jet energy scale, while $\theta = \pm 1$, would correspond to the event yields when the jet energy scale is varied by $\pm 3\%$.

The effects that the systematic uncertainties have on the expected number of signal and background events are modelled by equations 7.6 and 7.7 respectively:

$$N^{\text{sig, MC}}(\vec{\theta}) = N_0^{\text{sig, MC}} \prod_k^{N_{\text{syst}}} (1 + \epsilon_k)^{\theta_k} \quad (7.6)$$

$$N^{\text{bkg, MC}}(\vec{\theta}) = N_0^{\text{bkg, MC}} \prod_k^{N_{\text{syst}}} (1 + \epsilon_k)^{\theta_k}. \quad (7.7)$$

In equations 7.6 and 7.7, $N_0^{\text{sig, MC}}$ and $N_0^{\text{bkg, MC}}$ are the MC signal and background yields corresponding to the nominal values of the nuisance parameters, assuming there is no systematic uncertainty on them. The different members of the $\vec{\theta}$ vector represent all of the different sources systematic uncertainties. In order to obtain the changes in the yields when the systematic term is varied within its uncertainty, the nominal values are varied by $(1 + \epsilon)^\theta$. A graphical representation of this is shown on the left of Figure 7.1. The variations are performed for each systematic uncertainty k , for N_{syst} uncertainties. The $(1 + \epsilon)^\theta$ term is also known as the *response function*: $\nu(\theta) = \kappa^\theta$. Each ϵ_k is calculated by setting $\theta = \pm 1$ and rearranging equations 7.6 and 7.7, as shown in equations 7.8 and 7.9:

$$\epsilon_{k+} = \frac{N_{0,k}^{\text{sig, MC}} + N_{0,k}^{\text{bkg, MC}}}{N_k^{\text{sig, MC}}(1) + N_k^{\text{bkg, MC}}(1)} - 1 \quad (7.8)$$

$$\epsilon_{k-} = \frac{N_{0,k}^{\text{sig, MC}} + N_{0,k}^{\text{bkg, MC}}}{N_k^{\text{sig, MC}}(-1) + N_k^{\text{bkg, MC}}(-1)} - 1. \quad (7.9)$$

A few examples of normalization uncertainties include experimental uncertainties such as the jet energy scale, jet energy resolution and electron/muon resolution.

7.1.3 Shape Uncertainties

When a systematic uncertainty changes the shape of the m_T distribution, $N(\tilde{\theta}|\theta)$ is described by a unit Gaussian distribution, as shown in equation 7.5. The change to nominal signal and background yields in all regions, N_0^{sig} and N_0^{bkg} , due to the systematic uncertainties is described by

$$N^{\text{sig}}(\vec{\theta}) = N_0^{\text{sig}} \prod_k^{N_{\text{syst}}} (1 + \epsilon_k \theta_k) \quad (7.10)$$

$$N^{\text{bkg}}(\vec{\theta}) = N_0^{\text{bkg}} \prod_k^{N_{\text{syst}}} (1 + \epsilon_k \theta_k). \quad (7.11)$$

In the above equations, each ϵ_k is calculated by setting $\theta = \pm 1$. The response function is different from the one used for normalization uncertainties because of the historical evolution of the software framework used for the statistical analysis: RooFit [148]. Previously RooFit could not properly perform the integration required to normalize the $(1 + \epsilon)^\theta$, so the $(1 + \epsilon\theta)$ approximation was adopted. The two

schemes give equivalent results to first order when systematic uncertainties are small.

Most uncertainties, including those for the electron efficiency, b -tagging and trigger, have a shape component as well as a normalization component. The only example of a shape-only systematic uncertainty is the m_T shape of the WW distribution.

7.1.4 Statistical Uncertainties

Statistical uncertainties are modelled by a Poisson distribution, as shown below:

$$N(\tilde{\theta}|\theta) = P(\tilde{\theta}|\theta M). \quad (7.12)$$

In equation 7.12, M is the nominal value of $\tilde{\theta}$. For example, in the case of MC statistical uncertainties, M is the number of MC events. The nominal signal and background yields are affected by the statistical uncertainties, as shown in equations 7.13 and 7.14:

$$N^{\text{sig, MC}}(\vec{\theta}) = N_0^{\text{sig, MC}} \prod_k^{N_{\text{sys}}} \theta_k \quad (7.13)$$

$$N^{\text{bkg, MC}}(\vec{\theta}) = N_0^{\text{bkg, MC}} \prod_k^{N_{\text{sys}}} \theta_k. \quad (7.14)$$

7.2 The Test Statistic and Fitting Procedure

The likelihood on its own does not provide useful information since it is arbitrary up to a multiplicative constant. Thus ratios of likelihoods are used to test one hypothesized theory against another. For example, the likelihood ratio $\lambda = \frac{\mathcal{L}(N|H_0)}{\mathcal{L}(N|H_1)}$ can be used to distinguish between the null hypothesis, H_0 , and the alternative hypothesis, H_1 , given dataset N . The motivation for using a ratio of likelihoods, as opposed to other functions of the data, is that the ratio has the highest statistical power according to the Neyman-Pearson lemma [149]. In this case, separation power is defined as the probability of rejecting the null hypothesis when the null hypothesis is false.

Two commonly used definitions of the likelihood ratio for LHC experiments are shown in equations 7.15 and 7.16:

$$\lambda(\mu) = \frac{\mathcal{L}(\mu, \hat{\theta})}{\mathcal{L}(\hat{\mu}, \hat{\theta})} \quad (7.15)$$

$$\tilde{\lambda}(\mu) = \begin{cases} \frac{\mathcal{L}(\mu, \hat{\theta}(\mu))}{\mathcal{L}(\hat{\mu}, \hat{\theta})}, & \hat{\mu} > 0 \\ \frac{\mathcal{L}(\mu, \hat{\theta}(\mu))}{\mathcal{L}(0, \hat{\theta}(0))}, & \hat{\mu} \leq 0 \end{cases}. \quad (7.16)$$

To compare two hypotheses, the data are fitted to the MC simulation by maximizing the likelihood ratio. Instead of maximizing the likelihood ratio in equation 7.15, its logarithm is minimized since this is mathematically equivalent but computationally easier. Thus the test statistic is defined as

$$t_\mu = -2 \ln \lambda(\mu) = -2 \ln \frac{\mathcal{L}(\mu, \hat{\theta})}{\mathcal{L}(\hat{\mu}, \hat{\theta})}. \quad (7.17)$$

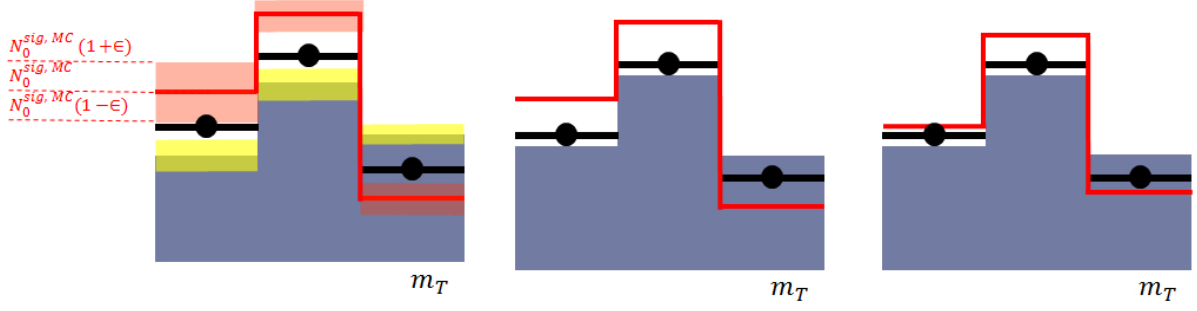


Figure 7.1: Before the fit (left): A visual representation showing the boundaries in which the signal and background yields are allowed to vary during the fitting procedure. The red line represents the nominal signal yield, while the pink band represents the bounds in which the signal yield can vary to best fit the black data points. The purple represents the background, and the yellow bands represent the bounds within which the MC background yields can vary. After conditional fit (middle): The signal yield is fixed, while the background varies within its statistical uncertainty (yellow band) to best fit the black data points. After unconditional fit (right): The signal and background vary within their statistical uncertainties (pink and yellow bands) to best fit the black data points.

The fit is performed twice, once in the numerator in equation 7.17, and once in the denominator. In the numerator the value of the signal strength, μ , is kept fixed to the value being tested. The tested values are usually 0, corresponding to the absence of a signal, and 1, corresponding to the signal predicted by the SM. The signal and background MC predictions are allowed to float within their systematic uncertainties in order to best fit the data points. Fixing the signal strength, while allowing other nuisance parameters to float, is referred to as a *conditional* fit. After this fit is performed the nuisance parameters take on new values, $\hat{\theta}$, which maximize $\mathcal{L}$ and are referred to as the conditional *maximum-likelihood estimators* (MLEs). A visual representation of this is shown by the middle illustration of Figure 7.1. In this illustration, the signal yield is fixed to its nominal value and the background yield is allowed to float within its systematic uncertainties in order to best fit the data.

In the denominator the signal strength is allowed to float with the background yields within the systematic uncertainties. This is called an *unconditional* fit and the resulting best fit values of the nuisance parameters, $\hat{\mu}$ and $\hat{\theta}$, are unconditional MLEs. The $\hat{\mu}$ value is a parameter of interest for this analysis as it quantifies the strength of the hypothesized SM signal. A visual representation of an unconditional fit is shown in the right illustration in Figure 7.1. In this illustration, the number of background and signal yields is adjusted within their systematic uncertainty in order to best fit the data.

7.2.1 Discovery Test Statistic

The test statistic used for the rejection of a null hypothesis, referred to as a discovery test statistic, involves setting $\mu = 0$, as shown below:

$$q_0 = \begin{cases} -2 \ln \lambda(0), & \hat{\mu} > 0 \\ 0, & \hat{\mu} \leq 0 \end{cases} = \begin{cases} -2 \ln \frac{\mathcal{L}(0, \hat{\theta})}{\mathcal{L}(\hat{\mu}, \hat{\theta})}, & \hat{\mu} > 0 \\ 0, & \hat{\mu} \leq 0 \end{cases}. \quad (7.18)$$

This test statistic is 0 when the fitted value of the signal strength satisfies $\hat{\mu} \leq 0$. This condition corresponds to the case when the number of data events is less than or equal to the expectation corresponding to the background-only hypothesis.

In order to avoid losing information at $q_0 = 0$, the test statistic is *uncapped*, meaning it is allowed to take on negative values, as shown below:

$$q_0 \rightarrow r_0 = \begin{cases} -2 \ln \lambda(\mu), & \hat{\mu} > 0 \\ +2 \ln \lambda(\mu), & \hat{\mu} \leq 0 \end{cases} = \begin{cases} -2 \ln \frac{\mathcal{L}(0, \hat{\theta})}{\mathcal{L}(\hat{\mu}, \hat{\theta})}, & \hat{\mu} > 0 \\ +2 \ln \frac{\mathcal{L}(0, \hat{\theta})}{\mathcal{L}(\hat{\mu}, \hat{\theta})}, & \hat{\mu} \leq 0 \end{cases}. \quad (7.19)$$

7.2.2 Upper Limit Test Statistic

When setting an upper limit on the signal strength, μ , the test statistic q_u , shown in equation 7.20, is used:

$$\tilde{q}_\mu = \begin{cases} -2 \ln \tilde{\lambda}(\mu), & \hat{\mu} < \mu \\ 0, & \hat{\mu} \geq \mu \end{cases} = \begin{cases} -2 \ln \frac{\mathcal{L}(\mu, \hat{\theta}(\mu))}{\mathcal{L}(0, \hat{\theta}(0))}, & \hat{\mu} \leq 0 \\ -2 \ln \frac{\mathcal{L}(\mu, \hat{\theta}(\mu))}{\mathcal{L}(\hat{\mu}, \hat{\theta})}, & 0 < \hat{\mu} < \mu \\ 0, & \hat{\mu} \geq \mu \end{cases}. \quad (7.20)$$

This test statistic takes into account three cases. The first case occurs when the signal strength satisfies $\hat{\mu} \leq 0$, corresponding to the case when there are fewer events observed in the data than expected with a background-only hypothesis. In this case the test statistic representing the background-only model ($\mu = 0$) is used in the denominator. The second case occurs when the number of events measured in data is greater than the background-only hypothesis ($0 < \hat{\mu}$), but less than the signal hypothesis being tested ($\hat{\mu} < \mu$). This case is consistent with the presence of the predicted signal, and thus a test statistic with a floating signal strength in the denominator is used. In the third case, there are at least as many events measured in data than the expected background plus signal events ($\hat{\mu} \geq \mu$). In this case the test statistic is 0, since an excess of events should not impact an upper limit that is meant to quantify a deficit of *events*.

In order to avoid losing information at $q_\mu = 0$, the test statistic is uncapped and allowed to take on negative values, as shown below:

$$\tilde{q}_\mu \rightarrow \tilde{r}_\mu = \begin{cases} -2 \ln \tilde{\lambda}(\mu), & \hat{\mu} < \mu \\ +2 \ln \tilde{\lambda}(\mu), & \hat{\mu} \geq \mu \end{cases} = \begin{cases} -2 \ln \frac{\mathcal{L}(\mu, \hat{\theta}(\mu))}{\mathcal{L}(0, \hat{\theta}(0))}, & \hat{\mu} \leq 0 \\ -2 \ln \frac{\mathcal{L}(\mu, \hat{\theta}(\mu))}{\mathcal{L}(\hat{\mu}, \hat{\theta})}, & 0 < \hat{\mu} < \mu \\ +2 \ln \frac{\mathcal{L}(\mu, \hat{\theta}(\mu))}{\mathcal{L}(\hat{\mu}, \hat{\theta})}, & \hat{\mu} \geq \mu \end{cases}. \quad (7.21)$$

7.3 PDFs of Test Statistics

The signal strength, $\hat{\mu}$, is obtained by fitting the MC prediction to the data for one experiment. If there were many experiments performed and many datasets collected, one would obtain a distribution of $\hat{\mu}$ values, which are assumed to follow a Gaussian distribution with mean μ' and variance σ :

$$f(\hat{\mu}|\mu') = \frac{dP}{d\hat{\mu}} = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(\hat{\mu}-\mu')^2}{2\sigma^2}}. \quad (7.22)$$

Figure 7.2 shows the distribution of $\hat{\mu}$, with mean μ' and variance σ . Using the above equation it is then possible to calculate the probability distribution of the test statistic, $f(\tilde{q}_\mu, \mu')$ or $f(\tilde{r}_\mu, \mu')$, under many repeated experiments. The μ in $\tilde{q}_\mu$ ($\tilde{r}_\mu$) refers to the value of the signal strength being tested,

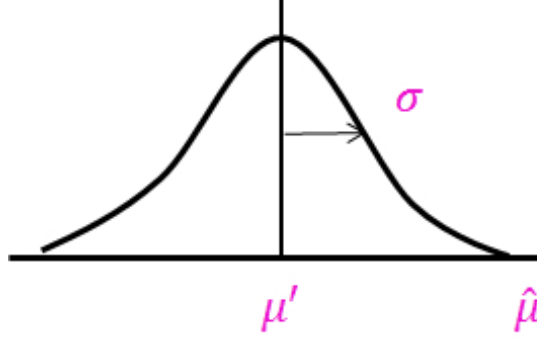


Figure 7.2: The distribution of $\hat{\mu}$ values if many experiments were performed. The mean value is μ' , which is assumed to be the real value in the data. The variance is σ .

while the μ' is the value of the signal strength that is assumed to exist in the data. The probability distribution function for a single parameter of interest can be found for a data size, N , by using the Wald approximation shown in equations 7.23 and 7.24:

$$-2 \ln \lambda(\mu) = \frac{(\mu - \hat{\mu})^2}{\sigma^2} + O(1/\sqrt{N}) \quad (7.23)$$

$$-2 \ln \tilde{\lambda}(\mu) = \begin{cases} -2 \ln \lambda(\mu), & \hat{\mu} > 0 \\ -2 \ln \lambda(\mu) + 2 \ln \lambda(\mu), & \hat{\mu} \leq 0 \end{cases} = O(1/\sqrt{N}) + \begin{cases} (\frac{\mu - \mu'}{\sigma})^2, & \hat{\mu} > 0 \\ (\frac{\mu}{\sigma})^2 - \frac{2\mu\mu'}{\sigma^2}, & \hat{\mu} \leq 0 \end{cases} \quad (7.24)$$

The $O(1/\sqrt{N})$ term can be neglected in the large sample limit. The probability distribution for the uncapped test statistic is given by

$$f(\tilde{r}_\mu, \mu') = \frac{dP}{d\tilde{r}_\mu} = \frac{dP}{d\hat{\mu}} \frac{d\hat{\mu}}{d\tilde{r}_\mu}. \quad (7.25)$$

The $\frac{dP}{d\hat{\mu}}$ term is the probability distribution of $\hat{\mu}$ obtained from equation 7.22, while $\frac{d\hat{\mu}}{d\tilde{r}_\mu}$ is obtained by rearranging and differentiating the Wald equation in the large sample limit. The probability distribution function for the uncapped test statistics is then obtained, as shown below [150]:

$$f(\tilde{r}_\mu | \mu') = \begin{cases} \frac{1}{2} \frac{1}{\sqrt{2\pi}} \frac{1}{(\mu/\sigma)} e^{-\frac{1}{2} \left(\frac{\tilde{r}_\mu - (\mu^2 - 2\mu\mu')/\sigma^2}{2\mu/\sigma} \right)^2}, & \tilde{r}_\mu \geq (\frac{\mu - \mu'}{\sigma})^2 \\ \frac{1}{2} \frac{1}{\sqrt{2\pi\tilde{r}_\mu}} e^{-\frac{1}{2} \left(\sqrt{\tilde{r}_\mu} - \frac{\mu - \mu'}{\sigma} \right)^2}, & 0 < \tilde{r}_\mu < (\frac{\mu - \mu'}{\sigma})^2 \\ \frac{1}{2} \frac{1}{\sqrt{-2\pi\tilde{r}_\mu}} e^{-\frac{1}{2} \left(-\sqrt{-\tilde{r}_\mu} - \frac{\mu - \mu'}{\sigma} \right)^2}, & \tilde{r}_\mu \leq 0 \end{cases} \quad (7.26)$$

The cumulative distribution function is obtained by integrating over the phase space of the PDF, as shown in equation 7.27:

$$F(\tilde{r}_\mu | \mu') = \begin{cases} \Phi\left(\frac{\tilde{r}_\mu - (\mu^2 - 2\mu\mu')/\sigma^2}{2\mu/\sigma}\right), & \tilde{r}_\mu \geq (\frac{\mu - \mu'}{\sigma})^2 \\ \Phi\left(\sqrt{\tilde{r}_\mu} - \frac{\mu - \mu'}{\sigma}\right), & 0 < \tilde{r}_\mu < (\frac{\mu - \mu'}{\sigma})^2 \\ \Phi\left(-\sqrt{-\tilde{r}_\mu} - \frac{\mu - \mu'}{\sigma}\right), & \tilde{r}_\mu \leq 0 \end{cases} \quad (7.27)$$

where

$$\Phi(x) = \int_{-\infty}^x e^{-\frac{t^2}{2}} dt. \quad (7.28)$$

For the discovery test statistic, where the $\mu = 0$ hypothesis is being tested, the simplified equations for the PDF and cumulative PDF are given by [150]:

$$f(r_0|\mu') = \begin{cases} \frac{1}{2} \frac{1}{\sqrt{2\pi r_0}} e^{-\frac{1}{2}(\sqrt{r_0} - \frac{\mu - \mu'}{\sigma})^2}, & r_0 > 0 \\ \frac{1}{2} \frac{1}{-\sqrt{2\pi r_0}} e^{-\frac{1}{2}(-\sqrt{r_0} - \frac{\mu - \mu'}{\sigma})^2}, & r_0 \leq 0 \end{cases} \quad (7.29)$$

$$F(r_0|\mu') = \begin{cases} \Phi(\sqrt{r_0} - \frac{\mu - \mu'}{\sigma}), & r_0 > 0 \\ \Phi(-\sqrt{-r_0} - \frac{\mu - \mu'}{\sigma}), & r_0 \leq 0 \end{cases}. \quad (7.30)$$

In order to evaluate the probability density functions in equations 7.26 - 7.30, the variance (σ^2) is required. This value can be obtained analytically, or with an *Asimov* dataset, which is less computationally demanding. These two methods are described below.

7.3.1 Obtaining σ Analytically

In the large sample limit (when the $O(1/\sqrt{N})$ term is neglected), the standard deviation, σ , of $\hat{\mu}$ can be obtained from the covariance matrix of the nuisance parameters, $V_{ij} = \text{cov}[\hat{\theta}_i, \hat{\theta}_j]$, where $\hat{\theta}_i$ represents $\hat{\mu}$ and the nuisance parameters. For a large sample, the inverse of the covariance matrix can be written as

$$V_{ij}^{-1} \frac{\partial^2 \ln \mathcal{L}}{\partial \theta_i \partial \theta_j}. \quad (7.31)$$

The standard deviation is obtained by evaluating the covariance matrix at $\theta_0 = \mu : \sigma^2 = V_{00}$. This can be done by performing many repeated experiments.

7.3.2 Obtaining σ using Asimov Data

The previous method requires generating MC simulations for repeated experiments, which is computationally time consuming. The σ value can also be estimated by using a representative dataset, called an Asimov dataset, that suppresses the statistical fluctuations in the $\hat{\mu}$ distribution [147]. This is achieved by generating the Asimov data using values of μ and θ that are expected in the data. This means setting the maximum likelihood estimators to their expected values, $\hat{\mu} = \mu'$ and $\hat{\theta} = \theta$. The Asimov dataset is then used to evaluate the Asimov likelihood, $\mathcal{L}_A$, and corresponding profile likelihood ratio, λ_A :

$$\lambda_A(\mu) = \frac{\mathcal{L}_A(\mu, \hat{\theta})}{\mathcal{L}_A(\hat{\mu}, \hat{\theta})} = \frac{\mathcal{L}_A(\mu, \hat{\theta})}{\mathcal{L}_A(\mu', \theta)}. \quad (7.32)$$

The variance, σ^2 , can then be obtained by fitting the MC simulation to the Asimov data to obtain the test statistic $q_{\mu,A} = -2 \ln \lambda_A(\mu)$. The Asimov test statistic can then be used in the rearranged Wald equation to obtain σ^2 :

$$\sigma^2 = \frac{(\mu - \mu')^2}{q_{\mu,A}}. \quad (7.33)$$

Thus using the Asimov dataset, σ can be obtained. It is then used to calculate the test statistics and PDFs. The test statistics and PDFs can then be used to obtain final statistics results explained in the

next section.

7.4 Statistics Results

The fitting of MC to data simulation is performed on the profile likelihood ratio in order to obtain information about the discrepancy between the data and the predicted theory. The p -value, significance (Z) and confidence-level plots showing the upper limits on the signal strength are used to quantify this discrepancy. These values are obtained using the PDFs described in the previous section.

7.4.1 p values

The definitions of test statistics imply that $0 \leq \lambda \leq 1$, with higher λ values corresponding to better agreement between data and the hypothesized value of μ . The p -value is used to quantify the discrepancy between the data and the hypothesis. It represents the probability of obtaining a measured test statistic that is more discrepant than the one observed, under the assumption that the signal strength in the data is given by μ' . Mathematically this is obtained by integrating the probability density function of the test statistic.

In the case of a discovery, one is interested in quantifying how many more events exist in the data than are predicted by the background-only hypothesis. In this case, it is assumed that there is no signal in the data, $\mu' = 0$, and that the p_0 value is calculated by integrating the discovery test statistic, $q_0(r_0)$, from the observed value $r_{0,obs}$ to infinity (equation 7.34). The expected p_0 , $p_{0,exp}$, is obtained by integrating under the same distribution, but from the expected test statistic value, $r_{0,exp}$ to infinity (equation 7.35). The $r_{0,exp}$ value is obtained from the median of $f(r_0, 1)$, which describes the distribution of r_0 under the assumption that the predicted signal exists in the data ($\mu' = 1$) (equation 7.36). The p values can also be expressed in terms of the cumulative PDFs, as shown in the second line of the equations below:

$$\begin{aligned} p_0 &= \int_{r_{0,obs}}^{\infty} f(r_0|\mu' = 0, \hat{\theta}(0)) dr_0 \\ &= 1 - F(r_0|0) = 1 - \Phi(\sqrt{r_0}) \end{aligned} \quad (7.34)$$

$$p_{0,exp} = \int_{r_{0,exp}}^{\infty} f(r_0|\mu' = 0, \hat{\theta}(0)) dr_0, \quad (7.35)$$

where

$$r_{0,exp} = \text{med}[r_0|\mu' = 1, \hat{\theta}(1)]. \quad (7.36)$$

When trying to find an upper limit on the signal strength, the p -values are obtained from the $\tilde{r}_\mu$, as shown in 7.37. For limit setting, $\tilde{r}_{\mu,exp}$, is the integral of the $\tilde{r}_\mu$ test statistic assuming there is no signal in the data, $\mu' = 0$ (equation 7.38):

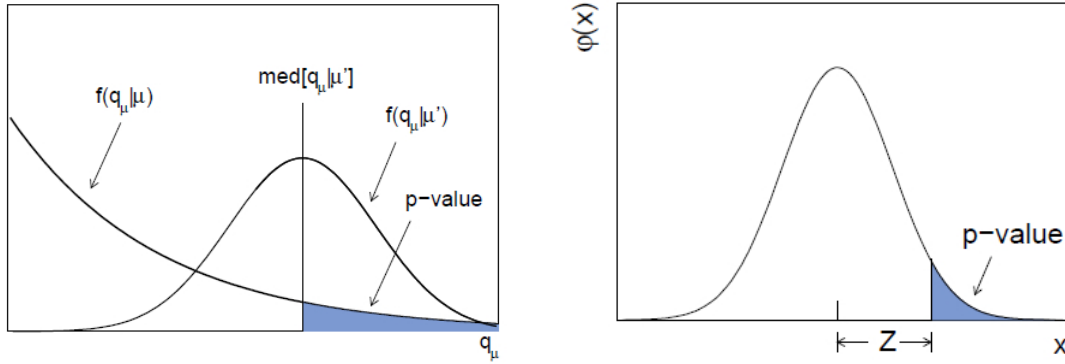


Figure 7.3: The visual representation of the p -value as the integral over the PDF of the test statistic (left). The relationship between the p -value and significance, Z (right) [147].

$$\begin{aligned}
 p_\mu &= \int_{\tilde{r}_{\mu,obs}}^{\infty} f(\tilde{r}_\mu | \mu, \hat{\theta}_\mu) d\tilde{r}_\mu \\
 &= 1 - F(\tilde{r}_\mu | \mu) = 1 - \Phi(\sqrt{\tilde{r}_\mu})
 \end{aligned} \tag{7.37}$$

$$p_{\mu,exp} = \int_{\tilde{r}_{\mu,exp}}^{\infty} f(\tilde{r}_\mu | \mu, \hat{\theta}_\mu) d\tilde{r}_\mu \tag{7.38}$$

where

$$\tilde{r}_{\mu,exp} = \text{med}[\tilde{r}_\mu | \mu' = 0, \hat{\theta}(0)]. \tag{7.39}$$

In order to define the limit, it is necessary to define the p_b value:

$$\begin{aligned}
 p_b &= \int_{-\infty}^{\tilde{r}_{\mu,obs}} f(\tilde{r}_\mu, \mu' = 0, \hat{\theta}(0)) d\tilde{r}_\mu \\
 &= F(\tilde{r}|0).
 \end{aligned} \tag{7.40}$$

The graphical representation of p_μ is shown in the left diagram of Figure 7.3.

7.4.2 Significance

The significance, Z_μ , is the number of σ the tested μ is away from the assumed μ' in the data. The p -value can be converted into a significance using

$$Z_\mu = \Phi^{(-1)}(1 - p_\mu) = \sqrt{\tilde{r}_\mu}. \tag{7.41}$$

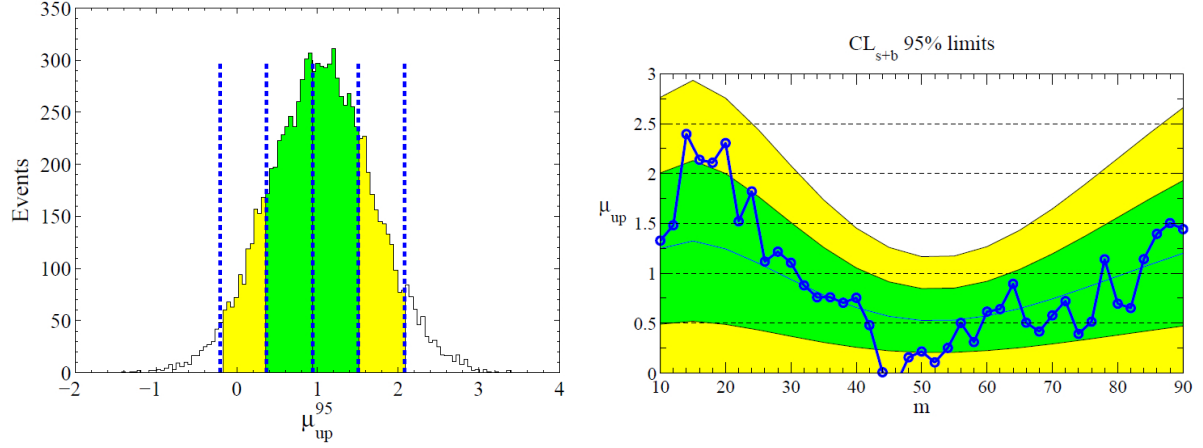


Figure 7.4: The upper limit on μ and its associated $\pm 1(2) \sigma$ error band in green (yellow) (left). The upper limit on μ as a function of different mass points (right) [147].

When using the discovery test statistic, equation 7.41 simplifies to

$$Z_0 = \sqrt{r_0}. \quad (7.42)$$

A graphical representation of the relationship between the significance and p value is shown on the right in Figure 7.3.

7.4.3 Confidence Level Plots

The confidence level is defined as $CLs = \frac{p_\mu}{1-p_b}$. The motivation for including the power of the test, $1-p_b$, in the denominator is to avoid the rejection of μ values for large downward fluctuations of the data. For upward fluctuations, p_b goes to 0 as CLs goes to p_μ . The PDFs $f(\tilde{r}_\mu|\mu' = 0)$ and $f(\tilde{r}_\mu|\mu' = 1)$ are scanned over different μ values until two are found that satisfy the condition $CLs = \frac{p_\mu}{1-p_b} = 0.05$. The 0.05 value is chosen by convention. It is then possible to solve for μ and quote this value as the upper limit on the signal strength with a 95% certainty. The upper limit on μ is called μ_{up} .

The expected statistical variation on μ_{up} can be represented by error bands that show $\pm N\sigma$ deviations from μ_{up} . The error bands are denoted as μ_{up+N} . They can be obtained by generating many pseudo-experiments. However this is computationally demanding, and thus an estimation method utilizing the Asimov dataset is used to obtain these values. The error bands are the N^{th} quantile of the $f(\mu_{up}|0)$ distribution. These can be obtained by finding the N^{th} quantile of $f(\mu|0)$, and then mapping the $f(\mu|0)$ distribution to the $f(\mu_{up}|0)$ distribution. The exact steps are described below [150].

1. The N^{th} quantile of the $f(\hat{\mu}|0)$ distribution is obtained. Using the Wald approximation and the expression for significance (equation 7.41), it follows that $N(\mu, 0) = \sqrt{-2 \ln q_{\mu,A}}$. Here the Asimov dataset used for $q_{\mu,A}$ is generated at $\mu' = 0$.
2. A mapping from the $f(\hat{\mu}|0)$ to the $f(\mu_{up}|0)$ distribution is created. Using the expression in step 1, μ_A^N for an Asimov dataset generated for the N^{th} quantile (A^N) is obtained. Similarly, the other nuisance parameters for A^N (θ_A^N) are extracted by performing a fit in the numerator of $q_{\mu,A}(\mu_A^N)$. The Asimov dataset is then constructed using μ_A^N and θ_A^N .

3. The A^N is then used to solve the $CLs = 0.05$ equation for μ_{up+N} .

The left illustration in Figure 7.4 shows μ_{up} , along with its μ_{up+N} error bands for one mass point. The error bands are calculated for $N = \pm 1$ in green, and $N = \pm 2$ in yellow. When this plot is made as a function of many mass points, the right plot in Figure 7.4 is obtained.

7.4.4 Pull Plots and Uncertainty on $\hat{\mu}$

The systematic uncertainties are often calculated within a very general phase space whose definition depends on the uncertainty under consideration. For example, when calculating the b -tagging uncertainties, an inclusive phase space containing top events is selected. After performing an unconditional fit, the uncertainties take on new values, given by the MLEs. The MLEs are values that are within the original systematic uncertainties of the nuisance parameters. The MLEs are better suited to the analysis given the specific phase space that is being investigated. The change in the systematic uncertainty from its nominal value (θ_0) to its MLE value ($\hat{\theta}$) is called a *pull*, defined as $\hat{\theta}/\Delta\theta$. Here, $\Delta\theta$ is the change of the nuisance parameter from θ_0 to $\hat{\theta}$. The pull is visually demonstrated on the left side of Figure 7.5. In this figure the nuisance parameter, θ , is parametrized by a Gaussian function. The nominal value of the nuisance parameter is set to zero ($\theta_0 = 0$). The $\pm\sigma$ lines represent the uncertainties within which the nuisance parameter is allowed to float during the fitting procedure. The red line is the MLE, representing the value that nuisance parameter takes on after an unconditional fit is performed.

The pulls are also shown in the pull plot on the right in Figure 7.5. The pull is shown by the black line, and the amount it deviates from 0 is read off from the bottom axis. The pull plot also shows the impact of each systematic uncertainty on the $\hat{\mu}$ value before and after an unconditional fit is performed. Before the fit, the impact on $\hat{\mu}$ is calculated by inputting $\pm 1\sigma$ uncertainties and observing how $\hat{\mu}$ changes. After the fit is performed, the impact on $\hat{\mu}$ is evaluated as

$$\Delta\hat{\mu}_i = |\hat{\mu}(\theta_{allfree}) - \hat{\mu}(\theta_{i, fixed} = \hat{\theta} \pm \sigma)|. \quad (7.43)$$

Equation 7.43 shows that first a fit is performed letting all nuisance parameters float and obtaining $\hat{\mu}(\theta_{allfree})$. Then a fit is performed in which the nuisance parameter of interest is set to its $\pm 1\sigma$ values and $\hat{\mu}(\theta_{i, fixed} = \hat{\theta} \pm \sigma)$ is obtained. The two $\hat{\mu}$ values are subtracted from each other to obtain the impact of the fixed nuisance parameter on $\hat{\mu}$.

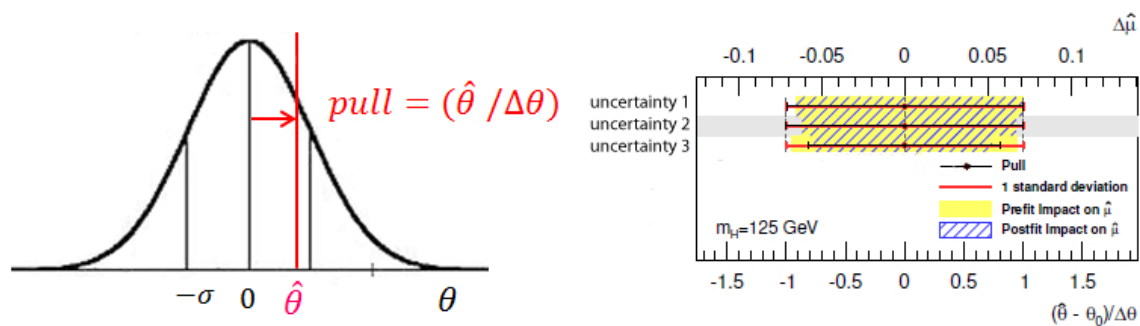


Figure 7.5: The representation of a pull as the change in the value of the systematic uncertainty from its nominal value to its MLE value after an unconditional fit (left). The pulls plot, where the pulls are shown by the black lines and their values are read off from the bottom axis (right). The impact of uncertainties on $\hat{\mu}$ before and after the unconditional fit are shown by the blue and red hashed lines and read off from the top axis in the same plot on the right.

Chapter 8

Results

This chapter presents the results obtained in the search for the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ process. The results are quoted when testing a signal hypothesis of a Higgs mass at $m_H = 125.36 \pm 0.41$ GeV. This choice was motivated by the results of the Higgs search in the $ZZ^* \rightarrow \ell\ell$ and $\gamma\gamma$ decay modes [151]. Included in the signal process is associated Higgs production, in which a Higgs is produced together with a W and Z boson. The associated production, referred to as VH production, is grouped with the VBF signal assuming the SM value for the ratio σ_{VBF}/σ_{VH} . The $H \rightarrow \tau\tau$ contribution is also treated as the signal, assuming SM branching ratios. The VH and $H \rightarrow \tau\tau$ production together account for $\leq 1\%$ of the signal.

The final m_T and BDT score distributions, along with the number of signal and background events contained in them, are shown in Section 8.1. The normalization factors for the various backgrounds are also shown in this section. The exclusion limits on the Higgs mass are presented in Section 8.2. The discovery significance for the $H \rightarrow WW^*$ signal is shown in Section 8.3. The Higgs couplings to fermions and bosons are presented in Section 8.6, and the cross section measurement is described in Section 8.7.

8.1 Event Yields and Distributions

The normalization factors obtained for various backgrounds are shown in Table 8.1. The m_T distribution in the ggF analysis, and BDT score in the VBF analysis are used as the discriminating variable in the statistical procedure. All of the normalization factors, except the μ_{top} in the 0-jet channel, are obtained by fitting the data to the MC in the control regions. The μ_{top} in the 0-jet channel is not a free parameter in the statistical fit, but is calculated independently and used as input.

The number of signal and background events contained within the m_T distributions is shown in Table 8.2 for the 8 TeV data and Table 8.3 for the 7 TeV data. The distributions used in the fitting procedure are split by $m_{\ell\ell}$ and $p_T^{\ell 2}$ for different-flavour events in the 0- and 1- jet regions. However, this splitting is not performed in the Tables in order to reduce the number of tables that would be required to display the same information. The actual distributions used in the statistical procedure for the 8 TeV data are shown in Figure 8.1 for the different-flavour 0- and 1-jet events, Figure 8.2 for same-flavour 0- and 1-jet events, Figure 8.3 for ≥ 2 -jet ggF events and Figure 8.4 for ≥ 2 -jet VBF events. The m_T distribution for the 7 TeV data in the 0- and 1-jet channels is shown in Figure 8.5. The 7 TeV VBF analysis has a low sensitivity and is not shown. Figure 8.6 shows the m_T distribution for the same-

Category	$\hat{\mu}_{WW}$	$\hat{\mu}_{\text{top}}$	$\hat{\mu}_{VV}$	$\hat{\mu}_{Z \rightarrow \tau\tau}$
8 TeV data				
$n_j = 0$	1.22 ± 0.03	1.08 ± 0.02	0.92 ± 0.07	1.00 ± 0.02
$n_j = 1$	1.05 ± 0.05	1.06 ± 0.03	0.96 ± 0.12	1.05 ± 0.04
$n_j \geq 2$, ggF	—	1.05 ± 0.03	—	1.00 ± 0.09
$n_j \geq 2$, VBF bin 1	—	1.58 ± 0.15	—	0.90 ± 0.30
$n_j \geq 2$, VBF bins 2-3	—	0.95 ± 0.31	—	
7 TeV data				
$n_j = 0$	1.09 ± 0.08	1.12 ± 0.06	—	0.89 ± 0.04
$n_j = 1$	0.98 ± 0.12	0.99 ± 0.04	—	1.10 ± 0.09
$n_j \geq 2$, VBF bins 1-3	—	0.82 ± 0.29	—	1.52 ± 0.91

Table 8.1: The normalization factors obtained for each of the backgrounds. The uncertainties are due to the limited number of events available in the MC samples.

flavour and different-flavour 0- and 1-jet channels for all the $m_{\ell\ell}$ and $p_T^{\ell 2}$ regions. The bottom panel of this figure shows the data, from which the background is subtracted, compared to the MC simulation of the Higgs signal. A large peak is observed in a wide mass range. Examples of the signal candidates are shown in Figure 8.7.

8.2 Exclusion Limits

The exclusion limits are computed using the modified frequentist method, CL_S , as described in Chapter 7. The expected and observed exclusion limits for a Higgs boson as a function of the Higgs mass are shown on the left of Figure 8.8. The dashed line in this figure shows that if the Higgs did not exist, the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ analysis could exclude it down to a mass of 114 GeV at a 95% confidence level. The observed exclusion, shown by the solid line, is only for $132 < m_H < 200$ GeV. This suggests that a signal could be present for masses below 132 GeV. Based on the findings in the $\gamma\gamma$ and ZZ^* channels, an expected exclusion plot is also drawn for $m_H = 125.36$ GeV, and matches the observed limits.

8.3 Higgs Observation in the $WW^* \rightarrow \ell\nu\ell\nu$ Decay Mode

The p_0 and Z_0 values quantify the agreement of data and MC assuming the Higgs does not exist ($\mu = 0$). The p_0 plot as a function of the Higgs mass m_H is shown on the right of Figure 8.8. The expected p_0 is calculated by fitting the MC simulated background to the Asimov dataset, generated assuming the signal does not exist ($\mu = 0$). The observed p_0 is calculated by fitting the data to the MC simulation. The expected and observed results agree within the 1σ uncertainty band. The observed minimum of the p_0 value occurs at $m_H = 130$ GeV and corresponds to a significance of 6.1σ . For a Higgs mass of $m_H = 125.36$, the observed (expected) significance is 6.1 (5.8) σ . This is above the 5σ required to claim the observation of signal in the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ channel. The expected and observed significances in the different channels are shown in Table 8.4.

8.4 Evidence for Vector Boson Fusion Production

Since the ggF contamination is significant in the VBF channel, the ggF contribution is evaluated by fitting the ggF signal regions as well. To obtain the VBF significance, the parameter of interest is set to

Channel	Summary			Background Composition						
	N_{obs}	$N_{\text{SR}}^{\text{bkg}}$	$N_{\text{SR}}^{\text{sig}}$	N_{SR}^{WW}	N_{SR}^t	$N_{\text{SR}}^{t\bar{t}}$	$N_{\text{SR}}^{W+\text{jets}}$	$N_{\text{SR}}^{\text{multi-jets}}$	N_{SR}^{VV}	$N_{\text{SR}}^{\text{DY}}$
$n_j = 0$	3750	3430 ± 90	310 ± 50	2250 ± 95	112 ± 9	195 ± 15	360 ± 60	16 ± 5	420 ± 40	78 ± 21
$e\mu$	1430	1280 ± 40	132 ± 20	830 ± 34	41 ± 3	73 ± 6	149 ± 29	10.1 ± 3.6	167 ± 21	14 ± 2.4
μe	1212	1106 ± 35	100 ± 15	686 ± 29	33 ± 3	57 ± 5	128 ± 31	3.8 ± 1.5	184 ± 23	14 ± 2.4
$ee/\mu\mu$	1108	1040 ± 40	29 ± 15	740 ± 40	39 ± 3	65 ± 5	82 ± 16	2 ± 0.5	68 ± 7	50 ± 21
$n_j = 1$	1596	1470 ± 40	119 ± 26	630 ± 50	150 ± 10	385 ± 20	108 ± 20	8.2 ± 3.0	143 ± 20	51 ± 13
$e\mu$	621	569 ± 19	53 ± 12	241 ± 20	58 ± 4	147 ± 7	51 ± 11	5.7 ± 2.0	53 ± 10	13.8 ± 3.3
μe	508	475 ± 18	41 ± 9	202 ± 17	45 ± 3	119 ± 6	37 ± 9	2.3 ± 0.9	60 ± 10	9.3 ± 2.5
$ee/\mu\mu$	467	427 ± 21	25 ± 6	184 ± 15	46 ± 4	119 ± 10	19 ± 4	0.2 ± 0.1	31 ± 4	28 ± 12
$n_j \geq 2, \text{ggF } e\mu$	1017	960 ± 40	55 ± 11	138 ± 28	56 ± 5	480 ± 40	54 ± 25	62 ± 22	56 ± 18	117 ± 21
$n_j \geq 2, \text{VBF}$	130	99 ± 9	29 ± 4	11 ± 3.5	5.5 ± 0.7	29 ± 5	4.7 ± 1.4	2.8 ± 1.0	4.4 ± 0.9	38 ± 7
$e\mu$ bin 1	37	36 ± 4	8.2 ± 1.3	5.0 ± 1.5	3.0 ± 0.6	15.6 ± 2.6	3.2 ± 1.0	2.3 ± 0.8	2.3 ± 0.7	3.6 ± 1.5
$e\mu$ bin 2	14	6.5 ± 1.3	6.3 ± 0.8	1.7 ± 0.7	0.3 ± 0.4	2.0 ± 1.0	0.4 ± 0.1	0.3 ± 0.1	0.7 ± 0.2	0.6 ± 0.2
$e\mu$ bin 3	6	1.2 ± 0.3	4.2 ± 0.8	0.3 ± 0.1	0.1 ± 0.0	0.3 ± 0.1	–	–	0.1 ± 0.0	0.2 ± 0.1
$ee/\mu\mu$ bin 1	53	46 ± 6	4.2 ± 0.7	3.1 ± 1.0	1.7 ± 0.3	10.1 ± 1.6	0.9 ± 0.2	0.2 ± 0.1	1.0 ± 0.3	28 ± 5
$ee/\mu\mu$ bin 2	14	8.4 ± 1.8	3.6 ± 0.5	0.9 ± 0.3	0.3 ± 0.2	1.2 ± 0.5	0.2 ± 0.1	–	0.3 ± 0.1	5.2 ± 1.7
$ee/\mu\mu$ bin 3	6	1.1 ± 0.4	2.3 ± 0.4	0.1 ± 0.1	0.1 ± 0.0	0.2 ± 0.1	–	–	–	0.5 ± 0.3

Table 8.2: The 8 TeV data signal and background event yields in the signal regions after the fitting procedure is performed. The $e\mu$ (μe) notation denotes that the electron (muon) is the leading lepton. To reduce the table size, the event yields for the 0- and 1-jet channels are not split in $m_{\ell\ell}$ and $p_T^{\ell_2}$. The signal yields include the signal due to ggF and VBF production. The $Z \rightarrow \tau\tau$ and $Z \rightarrow ee/\mu\mu$ events have been merged into one category labelled, $N_{\text{SR}}^{\text{DY}}$. The top events are split by the number of single top and $t\bar{t}$ events denoted by N_{SR}^t and $N_{\text{SR}}^{t\bar{t}}$, respectively. The precision is up to the first decimal place on all of the values.

Channel	Summary			Background Composition						
	N_{obs}	$N_{\text{SR}}^{\text{bkg}}$	$N_{\text{SR}}^{\text{sig}}$	N_{SR}^{WW}	N_{SR}^t	$N_{\text{SR}}^{t\bar{t}}$	$N_{\text{SR}}^{W+\text{jets}}$	$N_{\text{SR}}^{\text{multi-jets}}$	N_{SR}^{VV}	$N_{\text{SR}}^{\text{DY}}$
$n_j = 0$	594	575 ± 24	51.8 ± 8	339 ± 24	20.5 ± 2.1	38 ± 4	74 ± 15	1.3 ± 0.6	79 ± 10	23 ± 6
$e\mu$	185	186 ± 8	19 ± 3	116 ± 8	7 ± 1	14 ± 2	19 ± 5	–	24 ± 3	4.8 ± 1
μe	195	193 ± 12	15 ± 2	95 ± 7	5.3 ± 0.5	10 ± 1	37 ± 9	1.1 ± 0.5	41 ± 6	4 ± 0.9
$ee/\mu\mu$	214	196 ± 11	16 ± 3	128 ± 10	8 ± 1	14 ± 2	18 ± 4	0.2 ± 0.1	14 ± 2	14 ± 5
$n_j = 1$	304	276 ± 15	19.4 ± 4	104 ± 15	22 ± 2	58 ± 6	20 ± 4	3.2 ± 1.6	32 ± 8	38 ± 7
$e\mu$	93	75 ± 4	6.9 ± 1.6	33 ± 5	7 ± 1	18 ± 2	5 ± 1	–	9 ± 2	2.7 ± 0.4
μe	91	76 ± 5	5.4 ± 1.3	28 ± 4	6 ± 1	16 ± 2	10 ± 2	0.7 ± 0.3	14 ± 4	2.3 ± 0.7
$ee/\mu\mu$	120	125 ± 8	6 ± 2	43 ± 8	9 ± 2	24 ± 6	5 ± 1	2.5 ± 1.2	9 ± 1	33 ± 6
$n_j \geq 2, \text{VBF}$	9	7.8 ± 1.8	3.6 ± 0.4	1.2 ± 0.4	0.3 ± 0.1	1.6 ± 0.8	0.4 ± 0.1	0.1 ± 0	0.5 ± 0.2	3.4 ± 1.5
$e\mu$ bin 1	6	3 ± 0.9	1 ± 0.2	0.5 ± 0.2	0.2 ± 0.1	0.9 ± 0.5	0.1 ± 0	0.1 ± 0	0.3 ± 0.1	0.8 ± 0.6
$e\mu$ bin 2-3	0	0.7 ± 0.2	1.3 ± 0.2	0.2 ± 0.1	–	0.3 ± 0.2	–	–	–	–
$ee/\mu\mu$ bins 1-3	3	4.1 ± 1.3	1.2 ± 0.2	0.5 ± 0.2	0.1 ± 0	0.4 ± 0.3	0.3 ± 0.1	–	0.2 ± 0.1	2.5 ± 1.1

Table 8.3: The 7 TeV data signal and background event yields in the signal regions after the fitting procedure is performed. The signal yields include the signal due to ggF and VBF production. The precision is up to the first decimal place on all of the values. To reduce the table size, the event yields for the 0- and 1-jet channels are not split in $m_{\ell\ell}$ and $p_T^{\ell_2}$.

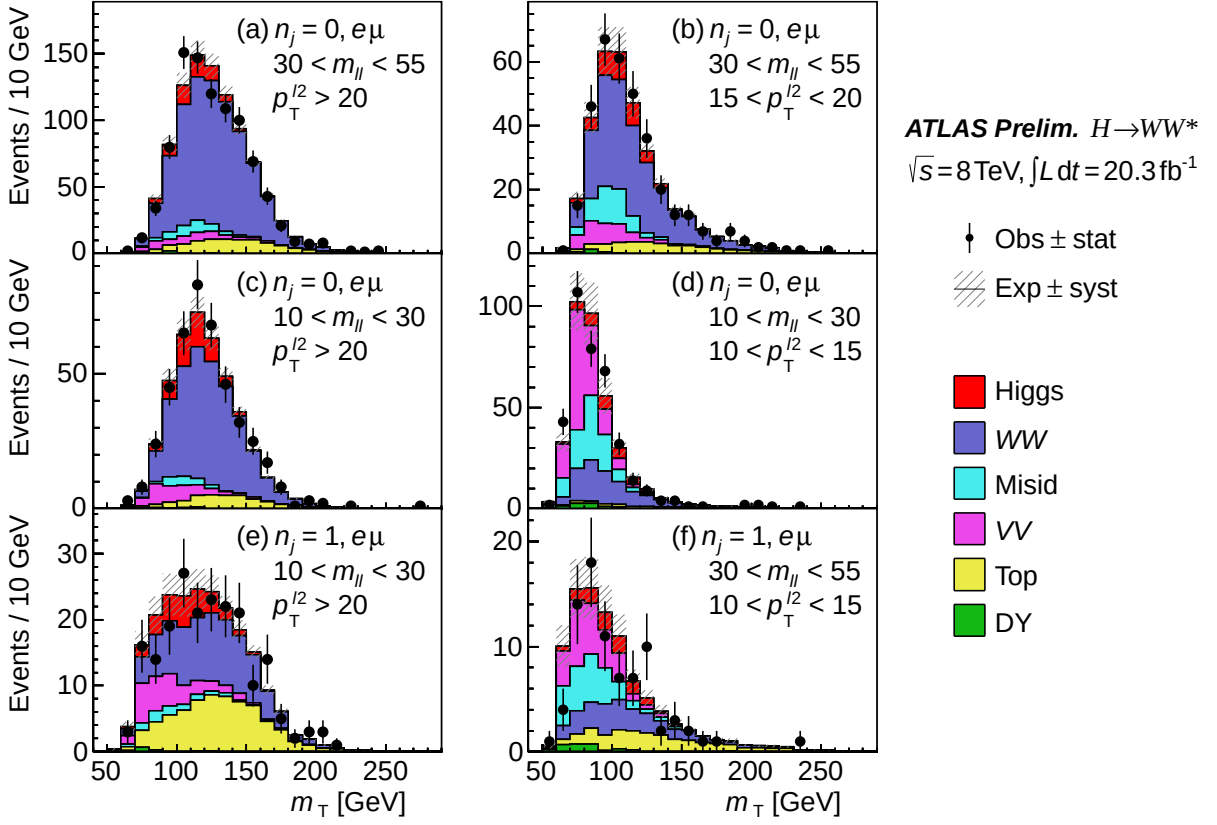


Figure 8.1: The transverse mass distribution, m_T , for the 8 TeV data in the 0- and 1-jet, $e\mu$ ggF signal regions, split by $m_{\ell\ell}$ and $p_T^{\ell 2}$ after the fit is performed. The signal is scaled by the fitted signal strength, $\hat{\mu}$, and the background is scaled by the normalization factor $\hat{\mu}_{\text{bkg}}$ [141].

Sample	$Z_{0, \text{exp}}$	$Z_{0, \text{obs}}$
$N_j = 0$	3.71	4.09
$N_j = 1$	2.61	2.49
$N_j \geq 2j$ ggF	1.20	1.44
$N_j \geq 2j$ VBF	3.38	3.84

Table 8.4: The expected and observed significances in the different channels. To obtain the VBF significance, the ggF process is treated as a background.

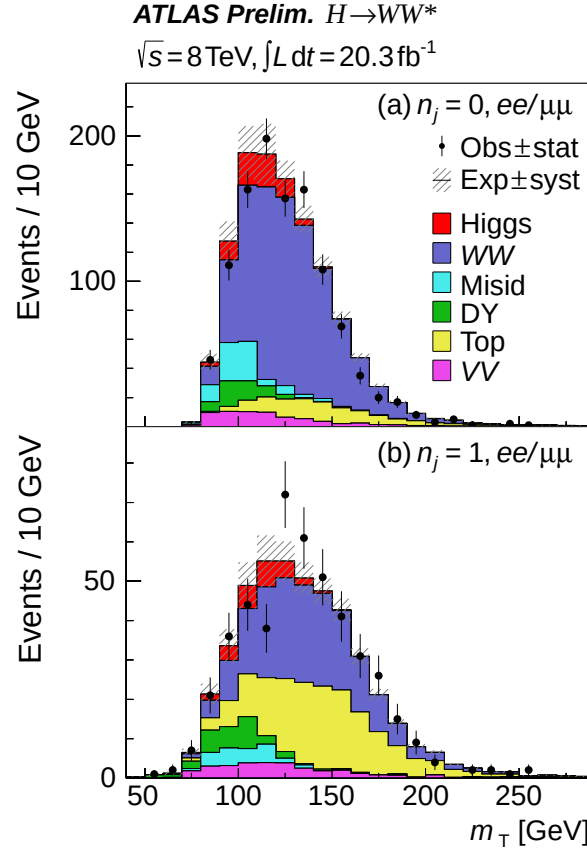


Figure 8.2: The transverse mass distribution, m_T , for the 8 TeV data in the 0- and 1-jet, $ee/\mu\mu$ ggF signal regions after the fit is performed. The signal is scaled by the fitted signal strength, $\hat{\mu}$, and the background is scaled by the normalization factor $\hat{\mu}_{\text{bkg}}$ [141].

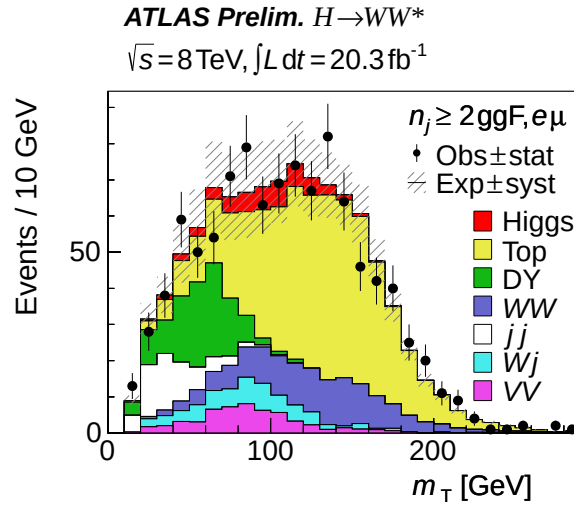


Figure 8.3: The transverse mass distribution, m_T , for the 8 TeV data in the ≥ 2 -jet, $e\mu$ ggF signal regions after the fit is performed. The signal is scaled by the fitted signal strength, $\hat{\mu}$, and the background is scaled by the normalization factor $\hat{\mu}_{\text{bkg}}$ [141].

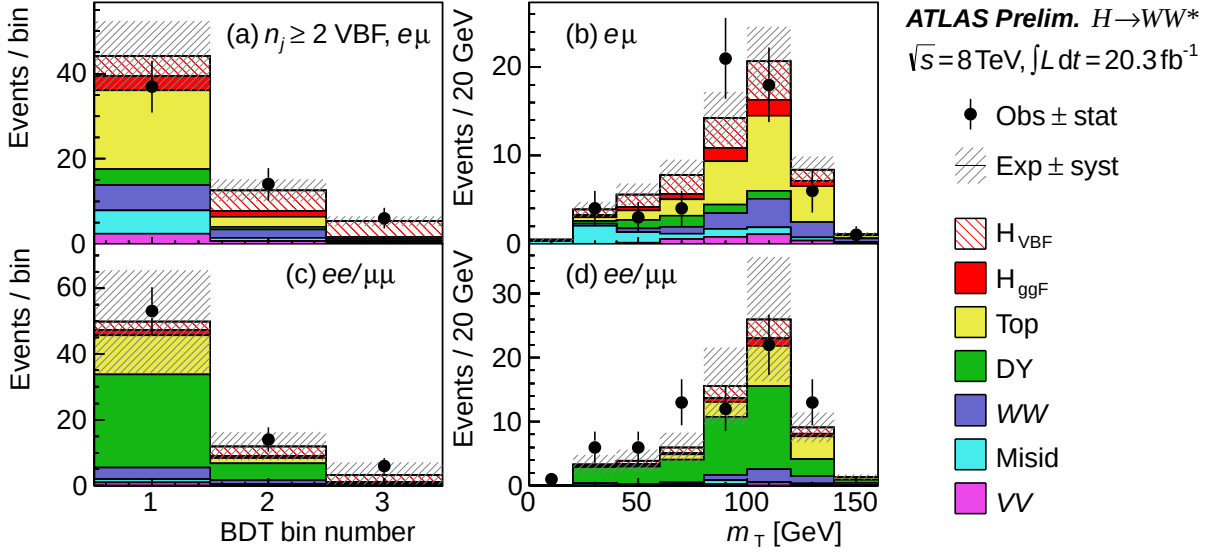


Figure 8.4: The BDT score distribution (left) and transverse mass, m_T (right), for the 8 TeV data in the ≥ 2 -jet, $e\mu$ and $ee/\mu\mu$ VBF signal regions after the fit is performed. The signal is scaled by the fitted signal strength, $\hat{\mu}$, and the background is scaled by the normalization factor $\hat{\mu}_{\text{bkg}}$ [141].

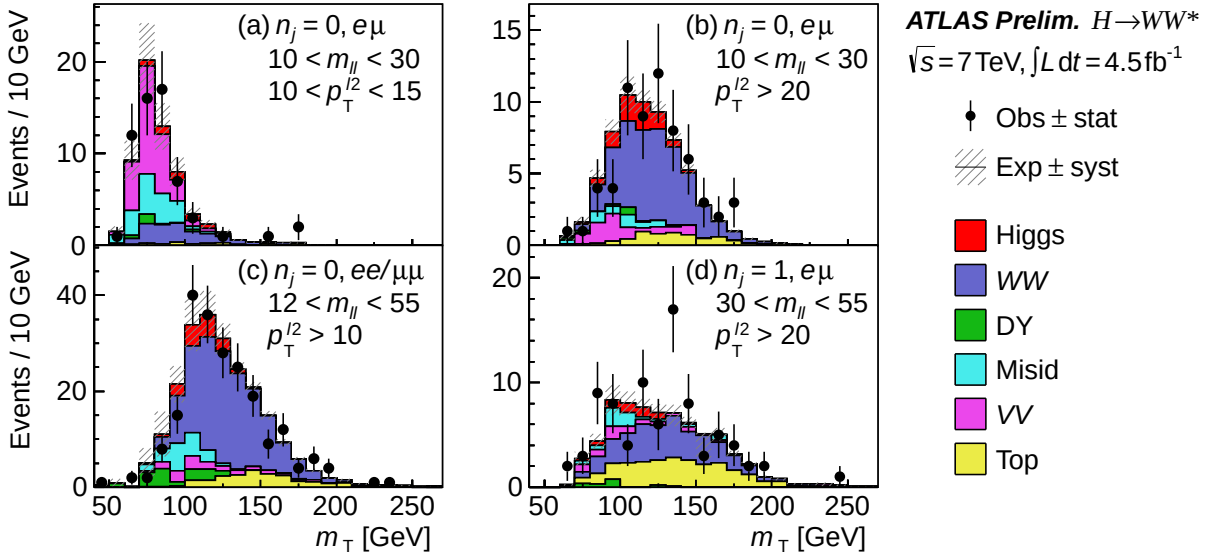


Figure 8.5: The transverse mass, m_T , distribution for the 7 TeV data in the 0- and 1-jet, $e\mu$ and $ee/\mu\mu$ ggF signal region for specific $m_{\ell\ell}$ and $p_T^{\ell\ell}$ ranges after the fit is performed. The signal is scaled by the fitted signal strength, $\hat{\mu}$, and the background is scaled by the normalization factor $\hat{\mu}_{\text{bkg}}$ [141].

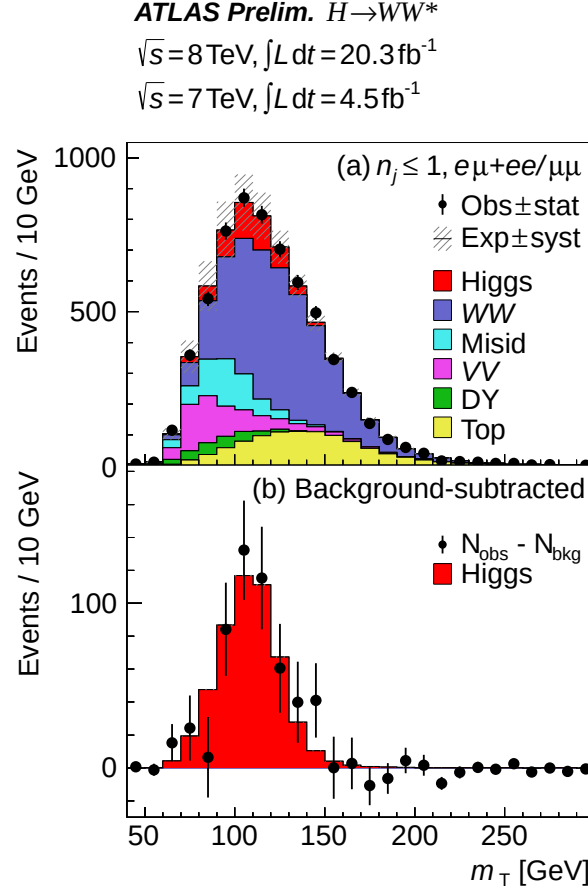


Figure 8.6: The transverse mass distribution, m_T , for the 7 and 8 TeV data in the 0- and 1-jet, $e\mu+ee/\mu\mu$ ggF signal regions, split by $m_{\ell\ell}$ and $p_T^{\ell 2}$ after the fit is performed. The signal is scaled by the fitted signal strength, $\hat{\mu}$, and the background is scaled by the normalization factor $\hat{\mu}_{\text{bkg}}$ [141]. The lower plot compares the MC simulation to background subtracted data.

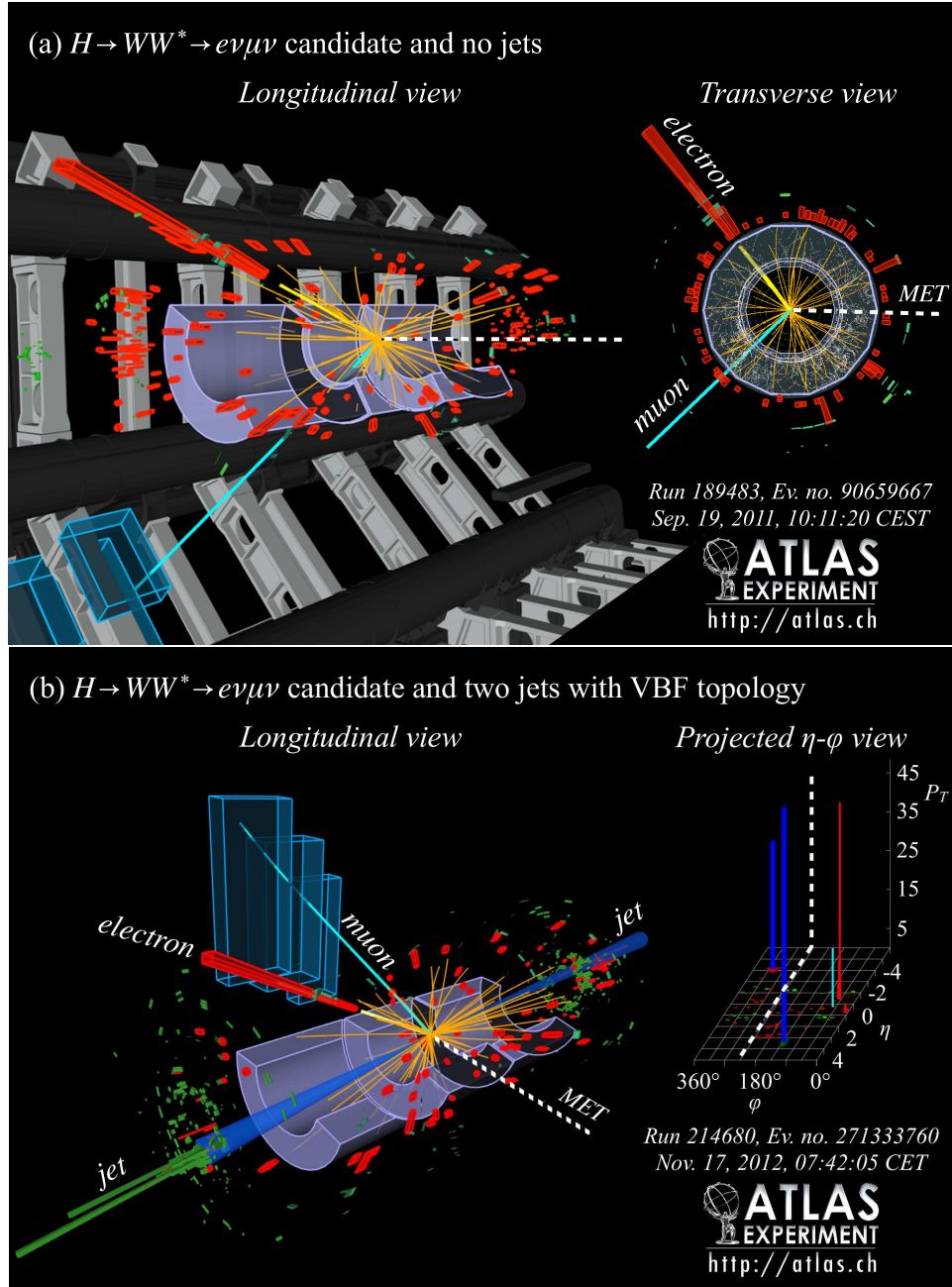


Figure 8.7: Event displays of the $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ candidate in the 0-jet (top) and ≥ 2 -jet VBF channels (bottom). The electron is represented by the red rectangle, the muon is denoted by the blue lines, the jets are shown by the blue cones, and the MET, representing the neutrino energy is represented by the dotted white line. The event in the top panel contains the properties: $p_T^e = 33$ GeV, $p_T^\mu = 24$ GeV, $m_{\ell\ell} = 48$ GeV, $\Delta\phi_{\ell\ell} = 1.7$, $p_T^{miss} = 37$ GeV and $m_T = 98$ GeV. The event in the bottom panel contains the properties: $p_T^e = 51$ GeV, $p_T^\mu = 15$ GeV, $m_{\ell\ell} = 21$ GeV, $\Delta\phi_{\ell\ell} = 0.1$, $p_T^{j1} = 67$ GeV, $p_T^{j2} = 41$ GeV, $m_{jj} = 1.4$ TeV, $\Delta y_{jj} = 6.6$, $p_T^{miss} = 59$ GeV, and $m_T = 127$ GeV [141].

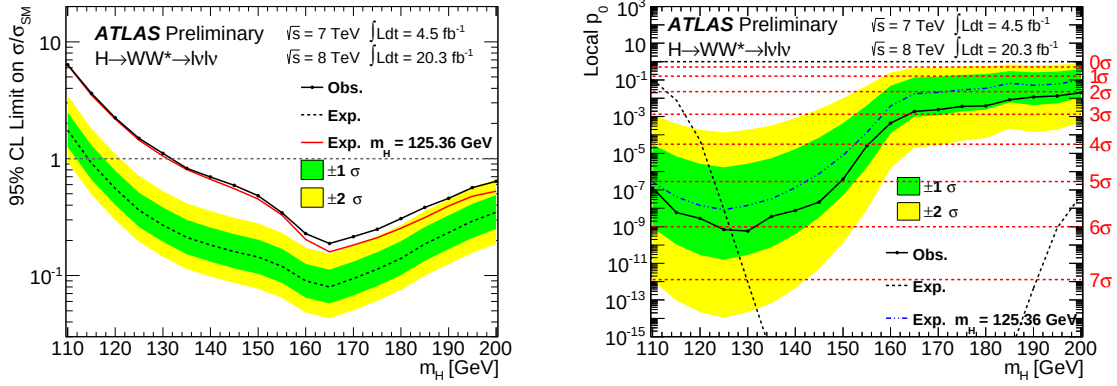


Figure 8.8: The expected and observed exclusion limits (left). The expected and observed values of p_0 as a function of the Higgs mass, m_H (right). The observed values are represented by the solid line. The dots on the solid line represent the masses at which the values are evaluated. The mass points in between the dots are extrapolated. The expected curves, represented by the dotted line are shown for all mass points, and for $m_H = 125.36$ GeV. Made by N.Ilic.

the ratio of the VBF and ggF signal strengths, μ_{VBF}/μ_{ggF} . Minimizing the likelihood with respect to this ratio yields

$$\frac{\mu_{VBF}}{\mu_{ggF}} = 1.25^{+0.79}_{-0.52}. \quad (8.1)$$

The likelihood value at $\mu_{VBF}/\mu_{ggF} = 0$ is equivalent to testing the $\mu_{VBF} = 0$ hypothesis. This can thus be interpreted as the observed significance of VBF production. The observed significance, evaluated at $m_H = 125.36$ GeV, is 3.2σ . This matches the expected significance of 2.7σ , and establishes evidence for VBF production. This is different from the value obtained in Table 8.4, since the ggF process is treated as a signal in the statistical fit, whereas it was treated as a background to obtain the values in the table.

8.5 Signal Strength

In order to quantify the compatibility of the data with the MC simulation, the signal strength is extracted by fitting the data to the MC simulation. This fitted signal strength, denoted by $\hat{\mu}$, is shown as a function of m_H in the left of Figure 8.9. The signal strength depends on the Higgs mass because the WW^* branching fraction depends on the Higgs mass. The observed value of $\hat{\mu}$ matches the expected. The $\hat{\mu}$ value is zero for $m_H > 160$ GeV, and goes to one for Higgs masses around 125 GeV. The large value of $\hat{\mu}$ for masses below 125 GeV is explained by the fact that a Higgs signal at $m_H = 125.36$ GeV is assumed.

The two dimensional likelihood contours are shown as a function of $\hat{\mu}$ and m_H in the right of Figure 8.9. The value of $m_H = 125.36$ GeV is well within the 68% CL contour.

The expected and observed fitted value of the combined signal strength for the VBF and ggF signal is

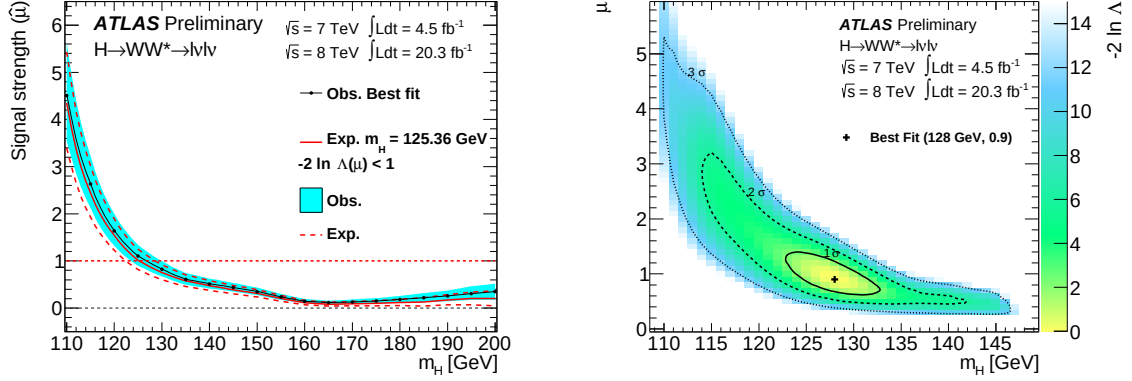


Figure 8.9: The signal strength, $\hat{\mu}$ obtained in the fitting procedure as a function of the Higgs mass m_H (left). The negative log likelihood as a function of m_H and $\hat{\mu}$. Made by N.Ilic.

$$\begin{aligned}
 \hat{\mu} &= 1.08^{+0.16}_{-0.15} \text{ (stat.) } ^{+0.08}_{-0.07} \text{ (expt.) } ^{+0.13}_{-0.11} \text{ (theo.) } \pm 0.03 \text{ (lumi.)} \\
 &= 1.08^{+0.16}_{-0.15} \text{ (stat.) } ^{+0.16}_{-0.13} \text{ (syst.)} \\
 &= 1.08^{+0.22}_{-0.20}
 \end{aligned} \tag{8.2}$$

In equation 8.2, *stat* refers to the statistical uncertainty on the number of observed events in the signal and control regions. The *expt* part represents the experimental systematic uncertainties as well as statistical uncertainties on the MC samples from the control regions not in the statistics fit, and extrapolation factors on the W +jets estimate. The *theo* term represents the theoretical uncertainty on the signal acceptance, cross section, and background extrapolation factors. The *lumi* term represents the uncertainty on the luminosity. The observed value matches the expected value of $\hat{\mu}_{\text{exp}} = 1.00^{+0.16}_{-0.15} \text{ (stat.) } ^{+0.15}_{-0.13} \text{ (syst.)} = 1.00^{+0.22}_{-0.21}$.

In order to verify the relative production of the VBF and ggF processes, the signal strength for the two processes is separated into $\hat{\mu}_{VBF}$ and $\hat{\mu}_{ggF}$. It is possible to perform a simultaneous fit for these two different parameters of interest since the $\hat{\mu}_{ggF}$ value will mostly be affected by the regions optimized for ggF production, while the $\hat{\mu}_{VBF}$ values will mostly be affected by the regions optimized for VBF production. The production of a Higgs boson in association with a W or Z boson is also included and assumed to scale with the VBF production. The two signal strengths are measured together, so that $\hat{\mu}_{VBF}$ also represents VH production. The likelihood scan of $\hat{\mu}_{ggF}$ and $\hat{\mu}_{VBF}$ is shown in Figure 8.5. The fitted ggF and VBF signal strengths, which correspond to the central values in Figure 8.5, are

$$\begin{aligned}
 \hat{\mu}_{ggF} &= 1.01 \pm 0.19 \text{ (stat.) } ^{+0.20}_{-0.17} \text{ (syst.)} \\
 &= 1.01^{+0.27}_{-0.25} \\
 \hat{\mu}_{VBF} &= 1.27^{+0.44}_{-0.40} \text{ (stat.) } ^{+0.29}_{-0.21} \text{ (syst.)} \\
 &= 1.27^{+0.53}_{-0.45}.
 \end{aligned} \tag{8.3}$$

These values are in agreement with the expected values of $\hat{\mu}_{ggF, \text{exp}} = 1.00^{+0.28}_{-0.25}$, and $\hat{\mu}_{VBF, \text{exp}} = 1.00^{+0.51}_{-0.42}$. The contribution of various groupings of systematic uncertainties to the uncertainty on $\hat{\mu}$,

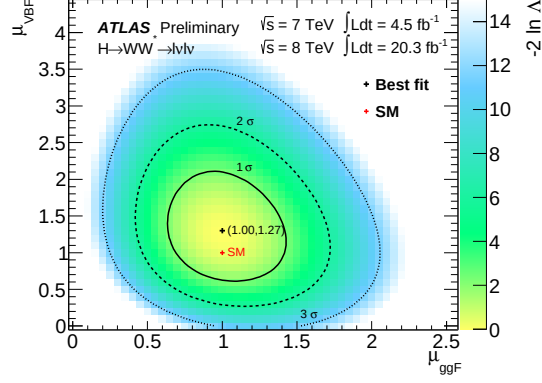


Figure 8.10: The likelihood scan as a function of $\hat{\mu}_{ggF}$ and $\hat{\mu}_{VBF}$, where the 1, 2 and 3 σ deviation contours are shown. Made by N.Ilic.

$\hat{\mu}_{ggF}$ and $\hat{\mu}_{VBF}$ is shown in Table 8.5. The W +jets uncertainties are mostly due to the uncertainties on the fake factors. The $Z/\gamma \rightarrow ee/\mu\mu$ uncertainties are mostly due to the uncertainties on the f_{recoil} variable. The muon and electron uncertainties include uncertainties on the energy scale, momentum correction, trigger efficiencies and isolation efficiencies. The jet uncertainties include the jet energy scale, jet energy resolution and b -tagging efficiencies. The detailed breakdown of the uncertainties on the combined ggF and VBF $\hat{\mu}$ is shown in Table 8.5. The largest uncertainties on $\hat{\mu}$ before and after the fit, and their associated pulls are shown in Figure 8.11.

The observed signal strengths and their uncertainties for all the search categories individually are summarized in Table 8.7. The expected signal strength is always one, and the expected uncertainties are summarized in the same table.

Source	$\hat{\mu}$		$\hat{\mu}_{ggF}$		$\hat{\mu}_{VBF}$	
	+	-	+	-	+	-
Data statistics	0.16	0.15	0.19	0.19	0.44	0.40
Signal Regions	0.12	0.12	0.14	0.14	0.38	0.35
Profiled CR	0.10	0.10	0.12	0.12	0.21	0.18
Profiled SR	–	–	0.03	0.03	0.09	0.08
MC Statistics	0.04	0.04	0.05	0.06	0.05	0.05
Theoretical Syst.	0.13	0.11	0.17	0.14	0.22	0.16
Signal $H \rightarrow WW^*$ BR	0.05	0.04	0.05	0.03	0.07	0.04
Signal ggF normalization	0.06	0.05	0.09	0.06	0.03	0.03
Signal ggF acceptance	0.05	0.04	0.06	0.05	0.07	0.07
Signal VBF normalization	0.01	0.01	–	–	0.07	0.04
Signal VBF acceptance	0.02	0.01	–	–	0.15	0.08
Bkg. WW	0.06	0.06	0.08	0.08	0.07	0.07
Bkg. top	0.03	0.03	0.04	0.04	0.06	0.06
Bkg. W +jets	0.05	0.05	0.06	0.06	0.02	0.02
Others	0.02	0.02	0.02	0.02	0.03	0.03
Experimental Syst.	0.07	0.06	0.08	0.07	0.18	0.14
Bkg. W +jets	0.03	0.03	0.04	0.04	0.02	0.01
Bkg. $Z/\gamma^* \rightarrow ee/\mu\mu$	0.02	0.02	0.03	0.03	0.01	0.01
Muons and electrons	0.04	0.04	0.05	0.04	0.03	0.02
E_T^{miss}	0.02	0.02	0.02	0.01	0.05	0.05
Jets	0.03	0.02	0.04	0.03	0.14	0.11
Others	0.03	0.02	0.03	0.03	0.06	0.06
Luminosity	0.03	0.03	0.03	0.02	0.05	0.03
Total	0.22	0.20	0.27	0.25	0.53	0.45

Table 8.5: The uncertainties on the signal strength for the inclusive Higgs production, ggF production, and VBF production. The *profiled SR (CR)* denotes the uncertainty on the ggF (VBF) signal yield when the parameters in these regions are allowed to float in the fit. The numbers are quoted assuming a Higgs signal at $m_H = 125.36$ GeV. The absence of an entry indicates that the uncertainty is smaller than 0.01 or does not apply [141].

Uncertainty	+	-	Uncertainty	+	-
QCDscale ggH	0.065	0.048	QCDscale ggWW XS	0.008	0.008
WW MTSHAPEMATCHING	0.050	0.049	FakeRateCorr QCD	0.008	0.008
BR VV	0.051	0.038	JES Eta Modelling	0.007	0.008
FakeRate MU Uncorrl OC 2012	0.036	0.036	FakeRate MU Uncorrl SC 2012	0.008	0.007
FakeRate EL Uncorrl OC 2012	0.032	0.032	FakeRate EL Flav 2011	0.007	0.007
TOP ME	0.029	0.029	TRACKMET RESOPERPSOFT12	0.007	0.007
pdf Higgs ggH	0.033	0.024	VBF Higgs MODEL BDT 2j	0.008	0.006
LUMI 2012	0.032	0.025	EL EFF RECOID 15 25 2012	0.007	0.006
QCDscale VV ACCEPT	0.024	0.024	ZTAUTAU BDT0 2j	0.006	0.007
pdf Higgs ggH ACCEPT	0.027	0.020	BTag B6EFF 2012	0.006	0.007
MU ISO	0.024	0.021	TOP SCALEF THEO 0j	0.006	0.006
QCDscale ggH ACCEPT	0.021	0.015	HiggsGGF UEPS BDT 2j	0.007	0.006
pdf qq ACCEPT	0.018	0.018	FakeRateOther QCD	0.006	0.006
QCDscale ggH e1	0.019	0.016	ZTAUTAU MODELING	0.006	0.006
EL ISO	0.018	0.015	ZTAUTAU PYTHIAMC SR 2j	0.006	0.006
BTag LEFF	0.018	0.015	FakeRate EL Stat 10 15 2012	0.006	0.006
EL EFF ID HIGHPT 2012	0.017	0.015	FakeRate MU Other 2011	0.006	0.006
Matching ACCEPT	0.018	0.013	TOP SCALEF NONTOP 0j	0.006	0.005
WW MTSHAPEPSUE	0.015	0.015	QCDscale qqH ACCEPT	0.006	0.005
PM f recoil DY SR0j 2012	0.015	0.015	QCDscale ggH ptH m01	0.006	0.005
PM theta SR0j 2012	0.015	0.012	QCDscale VV	0.005	0.005
TRACKMET RESOPARASOFT12	0.014	0.012	ZLEPLEP ABCD BDT2 2j	0.005	0.006
HiggsVBF UEPS BDT 2j	0.014	0.012	QCDscale ggH m23	0.006	0.005
FakeRate MU Stat 10 15 2012	0.013	0.013	FakeRate EL Other 2012	0.005	0.005
QCDscale Wg ACCEPT2j	0.012	0.013	PM f recoil DY SR1j 2012	0.005	0.004
QCDscale Wg ACCEPT1j	0.012	0.012	EL EFF RECO CORR 2011	0.004	0.004
FakeRate EL Stat GT25 2012	0.012	0.011	QCDscale Wg ACCEPT0j	0.004	0.004
TOP Scale	0.012	0.012	FakeRate MU Stat 20 25 2012	0.004	0.004
FakeRate MU Flav 2011	0.012	0.011	BTag B3EFF 2012	0.004	0.004
TOP THEO BDT 2j	0.011	0.012	FakeRate MU Stat GT25 2012	0.004	0.004
QCDscale VV2in BDT 2j	0.011	0.011	FakeRate EL Stat 20 25 2012	0.004	0.004
ZLEPLEP ABCD METEFF 2j	0.010	0.011	TOP PS	0.004	0.004
ZTAUTAU PTZREW	0.011	0.010	LUMI 2011	0.004	0.004
QCDscale ggH m12	0.011	0.009	PM theta SR1j 2012	0.004	0.003
FakeRate EL Stat 15 20 2012	0.010	0.010	PM f recoil NDY SR0j 2012	0.004	0.004
pdf qq	0.010	0.010	TOP SCALEF STATS 0j 2012	0.004	0.004
WW EWCorr	0.010	0.010	JES FlavComp other	0.004	0.003
VGammaShapeLepPt	0.010	0.010	EL EFF RECOID 15 25 2011	0.004	0.004
MU 2012 TRIG	0.011	0.009	FakeRate EL Corrl 2012	0.004	0.004
FakeRate MU Corrl 2012	0.010	0.010	MU MS RES	0.004	0.003
JER	0.011	0.008	FakeRate EL Other 2011	0.003	0.003
FakeRate MU Stat 15 20 2012	0.009	0.009	FakeRate MU Stat 10 15 2011	0.003	0.003
MU RESCALE 2012	0.011	0.008	WgsJetBin2	0.003	0.003
EL EFF RECO CORR 2012	0.010	0.009	WgsJetBin1	0.003	0.003
EL EFF ID CORRLOW 2012	0.009	0.009	QCD WW Modelling BDT 2j	0.003	0.003
FakeRate EL Uncorrl SC 2012	0.009	0.009	BTag Herwig LEFF	0.003	0.003
EL 2012 TRIG	0.009	0.008	PM f recoil DY SR0j 2011	0.003	0.003
FakeRate MU Other 2012	0.008	0.008	pdf Wg ACCEPT	0.003	0.003
TRACKMET SCALESOFT 2012	0.008	0.008	PM f recoil NDY ZP0j 2012	0.003	0.003
pdf Higgs qqH	0.009	0.007	BTag B4EFF 2012	0.002	0.003

Table 8.6: The observed uncertainties on $\hat{\mu}$. Many uncertainties contain a 2011 or 2012 in the name denoting the data set for which they are evaluated. The Fake Rate uncertainties depend on p_T^ℓ , and the numbers after the name correspond to the p_T^ℓ range the uncertainty applies to, where, for example, 10 15 indicates a range of $10 \text{ GeV} < p_T^\ell < 15 \text{ GeV}$. The remaining uncertainties are smaller and are not shown. Made by N.Ilic.

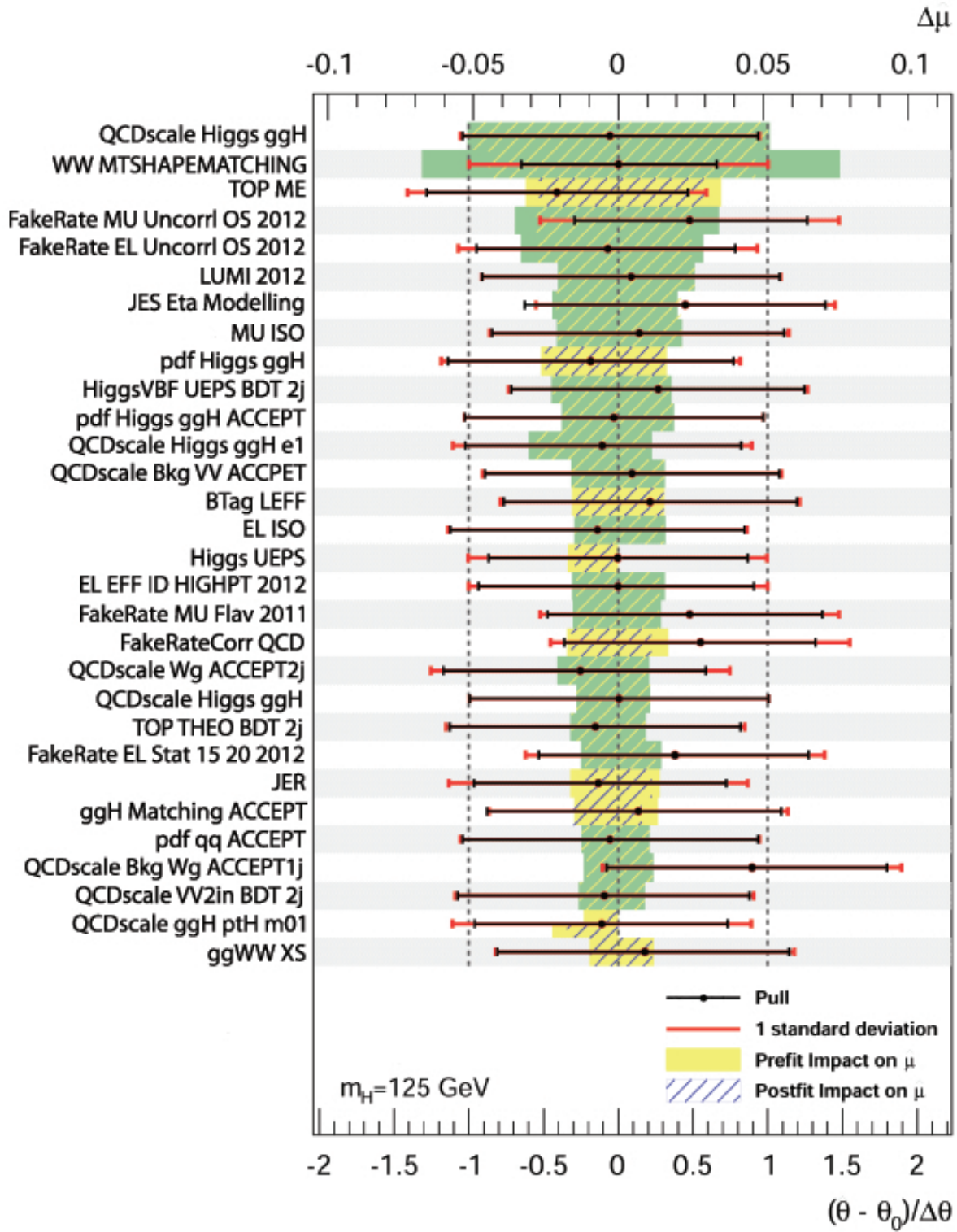


Figure 8.11: The uncertainty on $\hat{\mu}$ before and after the fit is performed, and associated pulls. Made by N.Ilic.

Sample	$\Delta\hat{\mu}_{\text{exp}}$		$\Delta\hat{\mu}_{\text{obs}}$		$\hat{\mu}_{\text{obs}}$
	+	-	+	-	
$N_j = 0$	0.32	0.29	0.34	0.30	1.14
$N_j = 1$	0.44	0.40	0.45	0.40	0.96
$N_j \geq 2$ ggF	0.90	0.84	0.91	0.84	1.20
$N_j \geq 2$ VBF	0.42	0.36	0.45	0.36	1.20

Table 8.7: The observed signal strength and its total uncertainty, as well as the uncertainty on the expected signal strength. The expected signal strength is one in all cases. Made by N.Ilic.

8.6 Coupling of Higgs Boson to Fermions and Gauge Bosons

In order to confirm that the Higgs boson has the properties predicted by the SM, the strengths of the Higgs coupling to fermions and bosons is measured. The production rate of processes is proportional to their couplings squared, g^2 . The measured couplings can be parametrized in terms of the expected SM couplings by defining $\kappa = g/g_{SM}$, where g is the measured coupling and g_{SM} is the SM expectation. The branching ratios and cross sections can then be expressed in terms of κ . To test the values of $\hat{\mu}_{ggF}$ and $\hat{\mu}_{VBF}$, the fermionic (bosonic) couplings are assumed to be the same for all fermions (bosons) and are denoted by κ_F (κ_V). The ggF production cross section is proportional to the fermionic coupling, while the VBF production cross section is proportional to the bosonic coupling. The Higgs to WW^* branching fraction is proportional to κ_V^2 and inversely proportional to a combination of κ_F^2 and κ_V^2 . The signal strengths can be written as [13]

$$\begin{aligned}\mu_{ggF} &= \frac{\sigma \cdot BR(gg \rightarrow H \rightarrow WW^*)}{\sigma_{SM}(gg \rightarrow H) \cdot BR_{SM}(H \rightarrow WW^*)} \propto \frac{\kappa_F^2 \cdot \kappa_V^2}{\kappa_H^2} \\ \mu_{VBF} &= \frac{\sigma \cdot BR(qq \rightarrow H \rightarrow WW^*)}{\sigma_{SM}(gg \rightarrow H) \cdot BR_{SM}(H \rightarrow WW^*)} \propto \frac{\kappa_V^2 \cdot \kappa_V^2}{\kappa_H^2}.\end{aligned}\tag{8.4}$$

In equation 8.4, the κ_H factor represents the total Higgs width and can be written as $(BR_{H \rightarrow f\bar{f}} + BR_{H \rightarrow gg})\kappa_F^2 + (BR_{H \rightarrow VV})\kappa_V^2$, where the small Higgs to $\gamma\gamma$ branching ratio, which depends on the fermion and boson couplings, is excluded. Since the branching ratio of Higgs to fermions and gluons is approximately 0.75, the κ_F^2 term dominates in the denominator. Thus for the ggF process the κ_F^2 approximately cancels, and this process remains sensitive to κ_V^2 . In this approximation, the VBF rate is proportional to κ_V^4/κ_F^2 , providing more sensitivity to κ_F than ggF production.

Figure 8.12 shows the likelihood scan as a function of κ_V and κ_F . The best fit values are observed at

$$\begin{aligned}\kappa_F &= 0.92^{+0.31}_{-0.23} \\ \kappa_V &= 1.04^{+0.10}_{-0.11}.\end{aligned}\tag{8.5}$$

These values are consistent with the SM expectation of one, within their uncertainties. The correlation between these values is obtained from the covariance matrix which contains the second-order mixed partial derivatives of the likelihood. The correlation is found to be $\rho = 0.21$.

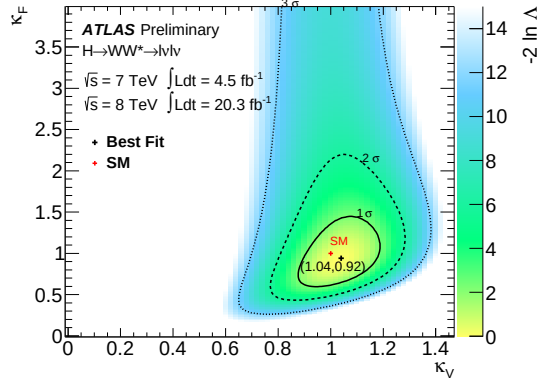


Figure 8.12: Likelihood scan as a function of κ_V and κ_F , showing the 1, 2 and 3 σ deviation contours. Made by N.Ilic.

Selection	$n_j = 0$	$n_j = 1$
Preselection	$p_T^{\ell 1(2)} > 22(10) \text{ GeV}$ Opposite Charge $m_{\ell\ell} > 10 \text{ GeV}$ $p_T^{\nu\nu} > 20 \text{ GeV}$	
n_j -dependant	$\Delta\phi_{\ell\ell,\nu\nu} > \pi/2$ $p_T^{\ell\ell} > 30 \text{ GeV}$ $m_{\ell\ell} < 55 \text{ GeV}$ $\Delta\phi_{\ell\ell} < 1.8 \text{ radians}$	$m_T^\ell > 50 \text{ GeV}$ $m_{\tau\tau} < 66 \text{ GeV}$ $m_{\ell\ell} < 55 \text{ GeV}$ $\Delta\phi_{\ell\ell} < 1.8 \text{ radians}$

Table 8.8: The fiducial region defined for the calculation of fiducial cross sections. The fiducial region is selected using $e\mu$ events. The events in which a W decays to $\tau\nu$ is excluded from the fiducial region, but present in the reconstructed region [141].

8.7 The Higgs Boson Production Cross Section

The cross section times branching ratio, $\sigma \cdot BR(H \rightarrow WW^*)$, is evaluated using the signal strength for a Higgs mass of $m_H = 125.36 \text{ GeV}$. In order to calculate the cross section of the $H \rightarrow WW^*$ process, it is necessary to define a region containing MC events which is as close to the signal region as possible. This region is called the *fiducial* region and is defined using generator level kinematic information. Thus the cuts on MET are replaced by cuts on the momenta of the neutrino system ($p_T^{\nu\nu}$), and the reconstructed lepton momenta is replaced by the generator level four-momentum which is corrected to include FSR by adding the four-momenta of the surrounding photons. The jet momenta are defined after the parton showering and hadronization, but before the detector simulation. The fiducial region is not split in $m_{\ell\ell}$ and $p_T^{\ell 2}$ since a single fiducial cross section measurement is preferred. The exact cuts made on the fiducial region are shown in Table 8.8.

8.7.1 Inclusive Cross Section

The inclusive cross section is evaluated for the 7 TeV and 8 TeV data separately. The observed cross section is given by the product of the expected cross section multiplied by the fitted signal strength, as shown below:

$$\begin{aligned}
(\sigma \cdot BR_{H \rightarrow WW^*})_{\text{obs}} &= \frac{(N_{\text{sig}})_{\text{obs}}}{\mathcal{A} \cdot \mathcal{C} BR_{H \rightarrow \ell \nu \ell \nu}} \cdot \frac{1}{\int L dt} \\
&= \hat{\mu} \cdot (\sigma \cdot BR_{H \rightarrow WW^*})_{\text{exp}}.
\end{aligned} \tag{8.6}$$

In equation 8.6, $(N_{\text{sig}})_{\text{obs}}$ is the number of observed signal events which is extracted from the fit ($(N_{\text{sig}})_{\text{obs}} = \hat{\mu}(N_{\text{sig}})_{\text{MC}}$). The kinematic acceptance, $\mathcal{A}$, is the number of events in the fiducial region divided by the number of events in the MC sample. The correction factor, $\mathcal{C}$, is the number of events passing the signal region divided by the number of events in the fiducial region. The 7 and 8 TeV signal strengths for $\hat{\mu}_{ggF}$ and $\hat{\mu}_{VBF}$ are

$$\begin{aligned}
\hat{\mu}_{ggF}^{7 \text{ TeV}} &= 0.57 \pm 0.52 \text{ (stat.) } {}^{+0.35}_{-0.33} \text{ (syst.) } {}^{+0.13}_{-0.01} \text{ (sig.)} \\
\hat{\mu}_{ggF}^{8 \text{ TeV}} &= 1.09 \pm 0.20 \text{ (stat.) } {}^{+0.18}_{-0.16} \text{ (syst.) } {}^{+0.13}_{-0.08} \text{ (sig.)} \\
\hat{\mu}_{VBF}^{8 \text{ TeV}} &= 1.45 {}^{+0.48}_{-0.43} \text{ (stat.) } {}^{+0.37}_{-0.22} \text{ (syst.) } {}^{+0.11}_{-0.06} \text{ (sig.)}
\end{aligned} \tag{8.7}$$

where *sig* denotes the cross section and branching ratio uncertainties on the signal yield. Using these values the inclusive cross sections are then given by

$$\begin{aligned}
\sigma_{ggF}^{7 \text{ TeV}} \cdot BR_{H \rightarrow WW^*} &= 1.9 \pm 1.7 \text{ (stat.) } {}^{+1.2}_{-1.1} \text{ (syst.) } = 1.9 {}^{+2.1}_{-2.0} \text{ pb} \\
\sigma_{ggF}^{8 \text{ TeV}} \cdot BR_{H \rightarrow WW^*} &= 4.6 \pm 0.9 \text{ (stat.) } {}^{+0.8}_{-0.7} \text{ (syst.) } = 4.6 \pm 1.1 \text{ pb} \\
\sigma_{VBF}^{8 \text{ TeV}} \cdot BR_{H \rightarrow WW^*} &= 0.51 {}^{+0.17}_{-0.15} \text{ (stat.) } {}^{+0.13}_{-0.08} \text{ (syst.) } = 0.51 {}^{+0.22}_{-0.17} \text{ pb.}
\end{aligned} \tag{8.8}$$

The measured cross section values match the expected values of the significance of 3.3 ± 0.4 , 4.2 ± 0.5 and 0.35 ± 0.02 pb, within the uncertainties.

8.7.2 Fiducial Cross Section

A cross section measured in the fiducial region minimizes the amount of theory uncertainties required since they do not need to be applied to MC events outside the fiducial region. The fiducial cross section is defined as

$$\begin{aligned}
\sigma_{\text{fid}} &= \frac{(N_{\text{sig}})_{\text{obs}}}{\mathcal{C}} \cdot \frac{1}{\int L dt} \\
&= \hat{\mu} \cdot (\sigma \cdot BR_{H \rightarrow WW^* \rightarrow e \nu \mu \nu})_{\text{exp}} \cdot \mathcal{A}
\end{aligned} \tag{8.9}$$

This cross section is calculated using $e\mu$ events in the 0- and 1-jet regions in order to minimise the dependence on the type of signal. The values obtained are

$$\begin{aligned}
\sigma_{\text{fid}, 0j}^{ggF} &= 27.5 {}^{+5.4}_{-5.3} \text{ (stat.) } {}^{+4.3}_{-3.7} \text{ (syst.) } = 27.5 {}^{+6.9}_{-6.5} \text{ fb} \\
\sigma_{\text{fid}, 1j}^{ggF} &= 8.4 {}^{+3.1}_{-3.0} \text{ (stat.) } \pm 1.9 \text{ (syst.) } = 8.4 \pm 3.6 \text{ fb.}
\end{aligned} \tag{8.10}$$

These values match the expected values of 19.9 ± 3.3 fb and 7.3 ± 1.8 fb, within their uncertainties.

Chapter 9

Conclusions and Outlook

The search for the Higgs boson produced through gluon fusion and vector boson fusion and decaying to $WW^* \rightarrow \ell\nu\ell\nu$ was presented. For the analysis, 25 fb^{-1} of data, collected in $\sqrt{s} = 7 \text{ TeV}$ and $\sqrt{s} = 8 \text{ TeV}$ proton-proton collisions, was used. The Higgs boson was observed with a local significance of 6.1σ at the Higgs mass around $m_H = 130 \text{ GeV}$, but within a broad mass range. The significance is the same at a Higgs mass of $m_H = 125.36 \text{ GeV}$, which is the Higgs mass measured by the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^*$ searches. The ratio of the expected and observed cross section times branching ratio was found to be $\hat{\mu} = 1.08^{+0.22}_{-0.20}$ at $m_H = 125.36 \text{ GeV}$. These values agree with the expected significance of 5.8σ , and expected signal strength of $1.00^{+0.22}_{-0.21}$. Evidence of vector boson fusion was observed with a significance of 3.2σ and $\hat{\mu}_{VBF} = 1.27^{+0.53}_{-0.45}$. These match the expected values of the significance, $Z_{exp} = 2.7 \sigma$, and signal strength, $\hat{\mu}_{VBF,exp} = 1.00^{+0.51}_{-0.42}$. The coupling of the Higgs boson to fermions and gauge bosons was determined and found to agree with the SM expectation. The inclusive and fiducial cross sections are calculated for the 7 TeV and 8 TeV data. All of the measurements are consistent with the SM predictions within their systematic uncertainties.

After the LHC restarts in 2015, it will provide more data and further possibilities to validate the predictions of the SM, and search for theories that provide solutions to its shortcomings. During the current LHC upgrades, the ATLAS detector is making upgrades to the tracking system. When the LHC restarts, it will operate for three years at $\sqrt{s} = 13-14 \text{ TeV}$, gathering 100 fb^{-1} of data. In 2018 the LHC will shut down for upgrades, during which time ATLAS will make improvements to the trigger system in order to deal with higher trigger rates. After restarting in 2019, the LHC will operate for three years at $\sqrt{s} = 14 \text{ TeV}$ and collect 300 fb^{-1} of data. The final LHC shut down will be in 2023, during which time ATLAS will install a new, higher granularity, more radiation-hard inner tracker. A new triggering scheme, as well as improvements to the muon and calorimeter electronics, will be made. The upgraded High-Luminosity LHC (HL-LHC) will start in 2025, after which the collider is expected to collect 3000 fb^{-1} of data. Due to the large increase in the number of interactions, one of the biggest challenges in the future will be reconstructing objects in the detector with the same accuracy. The average number of interactions per bunch crossing is expected to increase from $\langle \mu \rangle = 20-30$ at 8 TeV to $\langle \mu \rangle = 140$ at 14 TeV.

The new datasets will allow for more precise Higgs measurements needed to further validate the predictions of the SM. Despite the larger branching ratio of Higgs decaying hadronically, most 2010-2012 searches have focused on leptonic Higgs decays, which are easier to separate from their backgrounds.

Process	Value	Current	300 fb ⁻¹	3000 fb ⁻¹
$H \rightarrow \gamma\gamma$	$\Delta\hat{\mu}/\hat{\mu}$	20%	–	$\leq 10\%$
$H \rightarrow ZZ^* \rightarrow 4\ell$	$\Delta\hat{\mu}/\hat{\mu}$	27%	15%	13%
$H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$	$\Delta\hat{\mu}/\hat{\mu}$	30%	17%	15%
$H \rightarrow \tau\tau \rightarrow 2\ell 4\nu$ $/\ell\tau_{had} + 3\nu$	Z	4.1 σ	6.9 σ	–
	$\Delta\hat{\mu}/\hat{\mu}$	31%	15%	–
$H \rightarrow b\bar{b}$	Z	0	3.9 σ	8.8 σ
	$\Delta\hat{\mu}/\hat{\mu}$	100%	25%	14%
$H \rightarrow \mu\mu$	σ	–	2.3 σ	7 σ
	$\Delta\hat{\mu}/\hat{\mu}$	–	46%	21%
$H \rightarrow Z\gamma$	Z	–	2.3 σ	3.9 σ
	$\Delta\hat{\mu}/\hat{\mu}$	–	–	30%

Table 9.1: The significance and uncertainty on $\hat{\mu}$ during the 2010-2012 operational period, as well as the predictions for the 300 fb⁻¹ and 3000 fb⁻¹ data sets. The values are shown for a Higgs mass of ~ 125 GeV [152, 153, 154, 155, 156, 157, 158].

The decay modes that have been explored are $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow 4\ell$, $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$, $H \rightarrow \tau\tau \rightarrow 2\ell 4\nu/\ell\tau_{had} + 3\nu$, and $H \rightarrow b\bar{b}$. Most of these decay channels were considered in all of the Higgs production modes: gluon fusion, vector boson fusion, associated production and $t\bar{t}$ fusion. The $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ search did not consider Higgs production in association with $t\bar{t}$, and the $H \rightarrow b\bar{b}$ channel only included W/Z bremsstrahlung due to the difficulty associated in separating these two processes from other hadronic final states. The current search results are summarized in the *Current* column of Table 9.1. In all of the searches performed the signal strength is close to one. The signal strength quantifies the deviation of the measurement from the predicted value. Thus, the measured signal strength is consistent with the Standard Model prediction within the theoretical and experimental uncertainty. However, the uncertainty on the $\hat{\mu}$ value, denoted by $\Delta\hat{\mu}/\hat{\mu}$, is still quite large, as shown in the first column of Table 9.1. Reducing this uncertainty with the 300 fb⁻¹ and 3000 fb⁻¹ datasets is essential in confirming the properties of the Higgs boson and observing deviations from the Standard Model prediction. Table 9.1 shows that with 300 fb⁻¹ the uncertainty will be reduced by approximately a factor of two, in most of the channels, due to the larger statistics. With the 3000 fb⁻¹ dataset, the improvement is somewhat smaller since the uncertainties are dominated by theoretical sources rather than due to lack of statistics. Table 9.1 shows that the significances in the $H \rightarrow \tau\tau$, and $H \rightarrow b\bar{b}$ channels will also drastically increase with a larger dataset. The significances for the $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^*$ and $H \rightarrow WW^*$ channels are not shown since they will be much larger than the discovery significance of 5 σ . The large improvement in the $H \rightarrow b\bar{b}$ measurement with the 3000 fb⁻¹ data is due to multi-variate analysis techniques, and the predicted improvements in identifying jets originating from b -quarks.

Along with improvements to the current Higgs analyses, several new searches will be within reach with the new datasets. A search for the Higgs boson produced via all production modes and decaying to $\mu\mu$ final states will allow for the possibility to probe the Higgs coupling to second-generation fermions for the first time. The expected sensitivity of these searches is shown in Table 9.1. Another new search within reach is the production of the Higgs boson through gluon fusion and vector boson fusion followed by its decay to $Z\gamma$, where $Z \rightarrow ee/\mu\mu$. This final decay state is particularly interesting since it happens via a loop interaction and is thus sensitive to new particle couplings which can enter through the loop.

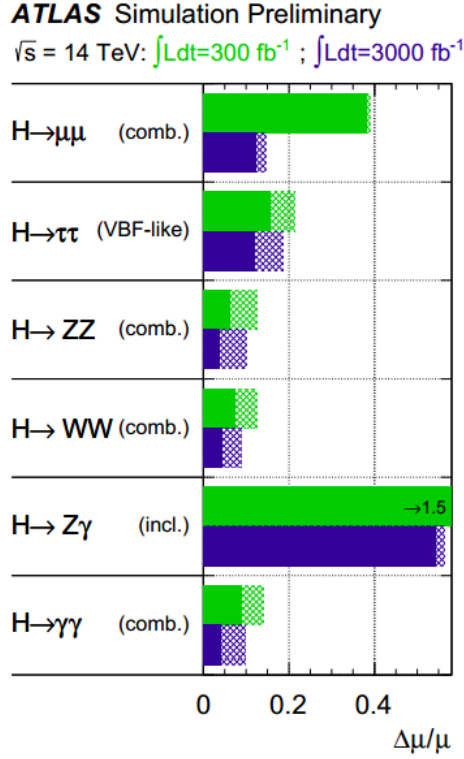


Figure 9.1: The uncertainties on the coupling measurements for the 300 fb^{-1} and 3000 fb^{-1} datasets [152].

The expected search results are shown in Table 9.1.

In order to confirm that the observed Higgs boson has the properties predicted by the Standard Model, the strengths of couplings of different particles to each other will also be measured to higher precision. If no assumption is made on the total Higgs width, then it is only possible to measure the ratio of couplings, denoted by λ . Figure 9.1 shows the uncertainties on the ratio of couplings of different particles to each other. The hashed lines on the bars represent the contributions from the current theoretical uncertainties. There is a factor of three improvement in the precision of coupling measurements obtained in going from the 300 fb^{-1} dataset, represented by the green bars, to the 3000 fb^{-1} dataset, represented by the blue lines. This figure demonstrates that for the 3000 fb^{-1} dataset, it is possible to determine λ to within 3-10% for bosons, gluons and fermions coupling to the Higgs boson. The $Z\gamma$ couplings are the only ones with larger (30%) uncertainties. For the results used in Figure 9.1, the latest results on $H \rightarrow b\bar{b}$ were not available, and thus these inputs were fixed based on the $H \rightarrow \tau\tau$ measurement [158].

The discovery of the Higgs boson has validated the predictions of the SM. Its observation in the $H \rightarrow WW^*$ channel was a crucial factor in confirming the Higgs boson's decay properties. Despite these successes, much of the laws governing the universe lie outside the realm of the SM and continue to elude scientists. Future measurements will allow for more precise determination of predicted Higgs boson properties. The datasets collected after the LHC restarts will further test SM predictions and possibly detect beyond SM physics that can lead to further insight into the functioning of the universe.

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