Measurements of the Standard Model Higgs boson cross sections in the $WW^*$ decay mode with the ATLAS experiment

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Measurements of the Standard Model
Higgs boson cross sections in the
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Abstract

This thesis summarises measurements of the Standard Model Higgs boson production cross sections based on proton–proton collision data at $\sqrt{s} = 13$ TeV produced by the Large Hadron Collider at CERN. By analysing data collected during 2015 and 2016 by the ATLAS experiment, corresponding to an integrated luminosity of $36\,\text{fb}^{-1}$, the Higgs boson gluon–gluon fusion and vector boson fusion production cross sections are measured in the $WW^*$ decay mode. To obtain a high signal to background ratio, the data is filtered for final states with one electron (positron) and one anti-muon (muon) and missing transverse momentum. A major part of the thesis concerns the estimation of backgrounds with misidentified leptons. These backgrounds originate from the production of a $W$ boson and an associated object mistakenly identified as an (anti-)electron or (anti-)muon, and are estimated with data driven techniques. A maximum likelihood fit is performed and the cross sections times branching ratios are simultaneously measured to be $\sigma_{ggF} \cdot B_{H \rightarrow WW^*} = 12.6_{-2.1}^{+2.3} \text{pb}$ and $\sigma_{VBF} \cdot B_{H \rightarrow WW^*} = 0.50_{-0.29}^{+0.30} \text{pb}$ for the gluon–gluon fusion and vector boson fusion modes, respectively. Both systematic and statistical uncertainties are taken into account in the confidence intervals. The corresponding Standard Model predictions are $10.4 \pm 0.6 \text{pb}$ and $0.81 \pm 0.02 \text{pb}$. The observed (expected) significance of the gluon–gluon fusion mode is 6.3 (5.2) standard deviations above the Standard Model background. For the vector boson fusion mode, the observed and expected significances are 1.9 and 2.7 standard deviations, respectively.

A smaller part of the thesis investigates the prospects for measuring the luminosity in the high-luminosity phase of the Large Hadron Collider, to begin in 2026. ATLAS will build and insert a timing detector with silicon pixel technology into the forward region, to cope with the harsh pileup environment present at high luminosity. The capabilities of this detector to provide luminosity measurements are investigated. The number of detector hits is observed to scale linearly with collision multiplicity across the full range of expected multiplicities.
Sammanfattning


En anpassning till data görs för att mäta tvärsmitten för de två produktionskanalerna. Tvärsmitten är en storhet som kvantifierar hur sannolikt det är att Higgsbosonen skapas i en protonkollision. Det kan parametreras som en signalstyrka, lika med kvoten mellan det uppmätta och det förväntade värdet från Standardmodellen. Signalstyrkorna uppmätts till $1.21^{+0.22}_{-0.21}$ för produktion via gluoner och $0.62^{+0.37}_{-0.36}$ för produktion via vektorbosoner. Dessa är inom osäkerhetsintervallet kompatibla med ett värde lika med ett, som är Standardmodellens förutsättelse. Signifikansen för gluon-produktionen motsvarar en fluktuation av bakgrunden med sannolikheten en på 6.7 miljarder. Det uppmätta signalen för vektorboson-produktion har en signifikans svarande mot en bakgrundsfluktuation med sannolikheten en på 35.

Detta är särskilt viktigt under denna fas, och nya metoder för luminositetsmätning kommer att behövas. Luminositeten är proportionell mot antalet kollisioner, vilken kan uppskattas med antalet träffar i detektorn. Med hög tidsupplösning har detektorn dessutom stor potential att kontrollera antalet träffar för bidrag från andra källor, t.ex. strålnings från närliggande aktiverat material.
Acknowledgements

The work presented in this thesis is to a large extent the result of collaborative effort. Research in ATLAS is by construction done together. I am thankful for the unique environment provided by ATLAS and CERN, in which I have grown as a researcher and a person.

First, I would like to thank my supervisor Jonas Strandberg for giving me the opportunity to carry out my studies at KTH. During my undergraduate days, Jonas, then my teacher, inspired me to continue into the field of experimental particle physics. Ever since, Jonas has taught me about particles, statistics and all the ATLAS jargon. No one is better at identifying the heart of the matter and explaining it in simple words.

I am grateful to have been in a group together with Bengt Lund-Jensen. His positivity and generosity cannot be overstated. Thank you for taking us sailing, and for all the stories about what science and education was like in the past.

I am so lucky that Giulia joined our then very small research group at KTH. Her curiosity and drive has helped me to become a better physicist. But, more importantly, she made me realise the importance of having a close colleague. You are one of the main reasons I will look back with joy on my time as a PhD student.

Thank you to the wizards Christian and Alex. To Alex for incredible technical skills, the admirable humility and for being the funniest person in text. Admittedly, the funniest person, period. To Christian for his vast knowledge on a broad range of topics, careful proofreading and your persistent fights against all forms of unreasonability (yes, that’s a word). Your excitement about science, and life, is contagious.

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Chapter 1

Introduction

“Science is competitive, aggressive, demanding. It is also imaginative, inspiring, uplifting”
— Vera Rubin, Bright Galaxies, Dark Matters

The research carried out by ATLAS and the other experiments at the Large Hadron Collider (LHC), concerns the fundamental question of what constitutes our nature. By putting experimental pressure it has helped in shaping the Standard Model of particle physics, the theory describing the particle content and interactions of the universe. While being a hugely successful theory, there are several phenomena and observations for which the framework cannot account. For example, it does not provide any satisfactory candidate particle to explain observations of so-called dark matter. The second run of the LHC begun in 2015 and the research continues to validate the predictions of the Standard Model more precisely, as well as to search for new physics beyond the Standard Model.

This thesis focuses on measurements of the Higgs boson, discovered only six years ago. With this last missing piece of the Standard Model puzzle, the postulated mechanism by which particles attain mass was confirmed. Since then, the measurements of its properties are in agreement with the predictions from the Standard Model. Nonetheless, of the particles known today, it is by far the one we know the least about. Only with continued research and increased precision can the future tell whether the Higgs boson is hiding any answers to the unsolved problems of particle physics.

Detailed in this thesis are measurements of the Higgs boson production cross sections in the gluon–gluon fusion and vector boson fusion channels, using the $WW^*$ decay mode. The dataset corresponds to 36 fb$^{-1}$ of proton–proton collisions at a centre-of-mass energy of 13 TeV, collected by ATLAS in 2015 and 2016. The measurement is complex with a final state containing several different backgrounds, requiring careful estimation. The analysis strategy and background estimation

\[^1\text{Except the force of gravity.}\]
techniques are presented in chapter 6. In chapter 8 the statistical interpretation and results are outlined. Chapter 7 is dedicated to the estimation of backgrounds with misidentified leptons.

In 2026 the High-Luminosity phase of the collider will begin, operating at a luminosity of about four times today’s value. ATLAS will build and insert a timing detector to mitigate the effects of an increased number of parasitic collisions. The prospects for using this detector to measure the luminosity is presented in chapter 4. A precise estimation of the luminosity is key to reaching per cent level precision on Higgs boson properties. This is one of the main objectives of the High-Luminosity phase.

In chapter 2 a short review of the theoretical background is given. This is followed by a summary of the experimental facilities–ATLAS and LHC–in chapter 3. Chapter 5 outlines the reconstruction algorithms and simulation techniques used to construct ATLAS data. After presenting the Higgs boson measurements in chapters 6 to 8 a summary with some concluding remarks is presented in chapter 9.

1.1 Author’s contribution

The work with the measurements of the Higgs boson production cross sections are done in the Higgs Working Group in ATLAS, specifically by an analysis team of approximately 20 people. The main contribution from the author consists of estimation of the misidentified lepton backgrounds presented in chapter 7, in which the author has had a leading role in a small group. The author has been involved in all parts of this work, to a lesser extent in the estimation of the WZ normalisation (as part of the Z+jets fake factor estimation) and the sample composition studies, to a larger extent on the remaining topics. All figures have been produced by the author unless otherwise stated.

Simulated Monte Carlo samples are produced centrally by ATLAS. Scale factors and efficiencies are generally derived by dedicated “combined performance” groups in ATLAS. These groups provide recommendations and prescriptions for the evaluation of associated experimental systematic uncertainties.

Regarding the timing detector presented chapter 4, the author has been part of an ATLAS team of around 30 people studying all aspects of the detector. The investigation of the luminosity measurement capabilities has been carried out by the author and his colleagues in the team at KTH.

All figures in the thesis have been produced by the author unless otherwise stated.

Chapters 2, 3 and 5 follow closely previous work by the author [1].
Chapter 2

Theoretical background

“Things on a very small scale behave like nothing that you have any direct experience about. They do not behave like waves, they do not behave like particles, they do not behave like clouds, or billiard balls, or weights on springs, or like anything that you have ever seen.”

— Richard P. Feynman

This chapter outlines a brief overview of the theoretical framework on which the remainder of the thesis depends. It also presents some of the unsolved problems in particle physics to motivate further research. It follows closely the analogous chapter in a previous work by the author [1].

The bulk of the chapter will be a compact review of the Standard Model of particle physics and will largely be based on references. For further details the reader is referred to any standard textbook on the subject such as Ref. [2].

2.1 The Standard Model

The current framework used in elementary particle physics is the Standard Model (SM) theory [3–5]. It is a quantum field theory aiming at explaining all fundamental particles in the universe and their interactions. The exception is the gravitational interaction, which the SM by construction does not include.

The particle content in the standard model is shown in table 2.1. These particles are elementary, meaning that they are to be considered point-like and have no substructure. The quarks and leptons make up the matter in the universe, and are spin-1/2 fermions. The gauge bosons have spin-1 and are so-called force carrier particles, mediating the strong and electroweak interactions. Lastly, there is the newly discovered Higgs boson, a spin-0 particle responsible for the generation of mass of the elementary particles through a symmetry-breaking process. The properties of the particles and the nature of their interactions is further outlined in section 2.1.1.
Table 2.1: Particle content of the Standard Model. Mass values are retrieved from [6]. Uncertainties on very precise values are omitted.

1The neutrino masses refer to measurements of the individual flavours. However, a limit on the sum of neutrino masses of around 0.14 eV have been set based on cosmological observations. For gluons, the theoretical value is given, but a mass of a few MeV may not be precluded.

While the SM is a hugely successful theory, it does have a number of shortcomings which are highlighted in section 2.1.3.

2.1.1 Review of the elementary particles and their interactions

The visible matter content in the universe are the fermions which are further subdivided into leptons and quarks, as shown in table 2.1. They are all spin-1/2 particles and each have a corresponding anti-particle, denoted with a bar. The electrons, muons and tau leptons carry electric charge $-1$, the quarks $2/3$ or $-1/3$, while the neutrinos do not carry electric charge. Quarks and leptons each come in three generations, or flavours, separated by horizontal dividers in table 2.1. Each lepton generation has its own flavour quantum number associated to it, which in the SM is conserved in all interactions. The masses of the particles differ by several orders of magnitude between the generations, but have otherwise the same properties.

The SM interactions have been observed to obey so-called gauge symmetries. In the language of group theory the SM may be formalised as the gauge group $G_{SM} = SU(2)_L \otimes U(1)_Y \otimes SU(3)_C$. The first two terms denotes the electroweak
interaction, whereas the last term denotes the strong interaction. The electroweak interaction is mediated by the $W^\pm$ and $Z$ bosons and the photon. The weak gauge bosons, the $W^\pm$ and $Z$ particles, have masses 80.4 GeV and 91.2 GeV respectively, while the photon is massless. The electroweak interaction may be subdivided into the weak and the electromagnetic interaction, where the former denotes the one mediated by the $W^\pm$ and $Z$ particles and the latter the one mediated by the photon. Intrinsically, the weak and electromagnetic interaction are of the same strength, but the masses of the $W^\pm$ and $Z$ bosons suppresses the weak interaction. This suppression is mostly pronounced in interactions involving momentum transfers of orders much smaller than the masses of the $W^\pm$ and $Z$ bosons. The $W^\pm$ and $Z$ bosons couple to weak isospin, which is carried by all fermions. The weak interaction mediates the decay of unstable particles and may change a quark or lepton of one generation into one of another. For the quark sector, the strength of flavour changing across generations are parametrised in the Cabibbo-Kobayashi-Maskawa matrix \[7, 8\] Furthermore, only the left-handed components of particles take part in the weak interaction (hence the $L$ subscript in $SU(2)_L$). There are left-handed and right-handed particles, where the handedness denotes the chirality of the particle. Chirality is somewhat related to helicity, which is the projection of a particles angular momentum onto its direction of momentum. In the massless limit, chirality and helicity coincide, but the chirality is an intrinsic property whereas helicity is frame dependent. This makes the SM a chiral theory, in that it discriminates between the different chiral states.

The photon couples to electric charge, which is carried by all quarks, by the electron, muon and tau leptons and the $W^\pm$ bosons. Since the photon is massless, the electromagnetic interaction has infinite range, while the massive $W^\pm$ and $Z$ bosons make the weak interaction short ranged.

The theory of the strong interaction is referred to as quantum chromodynamics (QCD). This interaction is mediated by gluons, which like the photons are spin-1 massless bosons. They couple to colour charge (hence the $C$ subscript in $SU(3)_C$), or in short colour, of which there are three, carried by both the quarks and the gluons themselves. There are eight different gluons, all carrying a colour-anticolour charge combination. The quarks (antiquarks) carry one unit of colour (anticolour). The fact that the gluons carry colour makes the strong interaction weaker at short distances, a phenomenon referred to as asymptotic freedom. No coloured particle, e.g. a quark or a gluon, have been directly observed. For example, quarks are only found together with other quarks in “colour-neutral”\(^1\) combinations called hadrons. The QCD potential contains a term proportional to $1/r$ and another term which increases linearly with distance. The strong interaction thus behaves like the electromagnetic interaction at short distances but generates a constant force between objects separated by distances of $\sim 1$ fm or larger. Due to the linear term in the potential, the energy stored in the gluonic field between two coloured objects increases with distance. As two coloured objects move apart, quark-antiquark pairs will eventually be formed at some cut-off distance of order 1 fm. In effect, quarks

\(^1\)I.e. colour singlets, invariant under $SU(3)$ rotations.
are confined within hadrons. This means that the strong interaction, in spite of having a massless mediator, effectively has short range since coloured objects are never found further apart than approximately 1 fm. The confinement property is caused by gluon self-coupling (i.e. the fact the gluons carry colour). Furthermore, this property is responsible for the formation of jets, i.e. sprays of hadrons, as observed in hadron-colliding experiments like the ones at the LHC.

The masses of the charged leptons are known to a high precision, while the masses of the individual quarks are difficult to measure as they are confined within hadrons. A large fraction of the mass of hadrons come from the binding energy stored within them.

The Higgs sector of the SM was confirmed to exist relatively recently with the observation of the Higgs boson in 2012 [9, 10]. The Higgs field is responsible for generating the masses of the elementary particles. This is further detailed in section 2.1.2.

2.1.2 Spontaneous symmetry breaking and the Brout-Englert-Higgs mechanism

The fact that the weak gauge bosons are massive indicates that the $G_{SM}$ is not a symmetry of the vacuum. In the SM, the Brout-Englert-Higgs mechanism is responsible for a spontaneous breaking of the gauge symmetries associated with the electroweak interaction. This leaves a broken $G_{SM}$ in a form which is a good symmetry of the vacuum. The Brout-Englert-Higgs (BEH) mechanism by which this breaking is realised postulates a new Higgs field, a scalar field with a non-zero vacuum expectation value ($vev$). A perturbative expansion around this $vev$ effectively generates the masses of the $W^\pm$ and $Z$ bosons, which evaluate to expressions proportional to the $vev$. In addition, the masses of the fermions are generated through a Yukawa coupling to the Higgs field, and are also proportional to the $vev$. Thus, masses in the SM are generated through interactions with this non-zero $vev$ of the Higgs field.

The Higgs boson, denoted $H$, is the quanta of the Higgs field. By construction, it interacts with all massive particles. The vertex factor for the $H-VV$ interaction is proportional to $vev \cdot g^2 \propto m_V^2 / veev$, where $g$ is the electroweak coupling constant, and $V$ denotes either of the $W^\pm$ or the $Z$ boson. For the fermions, the vertex factor for the $H-\bar{f}f$ interaction is proportional to $m_f / vev$.

2.1.3 Short-comings of the Standard Model

The SM is an effective theory, describing the GeV regime very well. It is however not expected to be a complete theory valid at much higher energies like the Planck scale. Furthermore, the SM cannot explain a number of observed phenomena, and is considered to have inherent problems of theoretical nature. A selected number of

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2The analogy may be done with Newton’s laws of motion, which are valid provided that the involved objects are not too small and moving with non-relativistic speeds.
these phenomena and problems, with some suggested solutions, will be described here.

The SM currently does not incorporate the force of gravity. Because of the vast discrepancy in relative strength between gravity and the other forces, gravity is not easily measured in a particle, small scale experiment. This is a problem for the theories aiming at merging quantum mechanics with gravity (so called quantum gravity models).

Many astrophysical observations suggest the existence of dark matter in and around galaxies, matter that does not interact electromagnetically and thus is not visible (see e.g. Ref [11]). The nature of this dark matter is unknown and many searches are performed in different experiments. There are the direct detection experiments, targeting dark matter particle interactions with a dedicated detector. There are indirect detection experiments, such as telescopes, measuring astrophysical particles to infer annihilation of dark matter particles. Lastly, collider experiments aim at producing dark matter particles and infer its existence from the signature left in the detector (e.g. the ATLAS detector).

The so-called hierarchy problem is a theoretical problem and concerns the apparent smallness of the vacuum expectation value of the Higgs field. Consider for example the Higgs boson mass, to which radiative corrections (i.e. loop diagrams) from other fields contribute. Some contributions will be much larger than the electroweak scale, e.g. contributions from gravity which will become significant at the Planck scale. Because of the large differences in scale, the SM in its current state must contain extremely fine-tuned cancellations of these contributions to agree with the observed Higgs boson mass at the electroweak scale. This is by many considered an undesired feature of the model, and so many theories and have been put forward to solve this problem in a more “natural” way. Perhaps the most popular class of such theories are supersymmetric models. These models postulates a new symmetry between fermions and bosons. This predicts supersymmetric partners for all the particles in the SM. So far, no such supersymmetric particles have been observed, but the topic remains interesting and searches continue.

In the SM, neutrinos are massless. This is in obvious contradiction with the observation of neutrino lepton flavour oscillations, as was awarded the Nobel prize in physics 2015. The exact mechanism through which they acquire mass is not known, neither are their absolute mass values. The latter may be constrained by a combination of cosmological measurements, oscillation experiments and direct detection experiments.
Chapter 3

Experimental facilities

“The science never gets as far as the strangeness. The more sophisticated my equipment, the stranger the worlds it detects.”
— Jeanette Winterson, The Stone Gods

This chapter contains a review of the experimental facilities, i.e. the Large Hadron Collider (LHC) and the ATLAS detector with its subsystems.

3.1 The Large Hadron Collider

The LHC is a circular accelerator located in a tunnel roughly 100 m underground, on the border between Switzerland and France near the CERN site. It accelerates protons and heavy ions up to centre-of-mass energies of $\sqrt{s} = 13$ TeV\(^1\) and $\sqrt{s} = 2.8$ TeV per nucleon respectively, before they are made to collide at the different experiments situated along the ring. In what follows, the proton-proton collisions will be described, as these are the main focus of the ATLAS experiment. The protons are extracted from hydrogen and accelerated in steps in different accelerators, with the LHC being the final one. First, the protons enter the linear accelerator Linac2 and are brought up to an energy of 50 MeV. They are then accelerated by circular accelerators; first the Booster, then the Proton Synchrotron (PS) and finally the Super Proton Synchrotron (SPS) before being injected into the LHC. The energies acquired at the different accelerator are 1.4 GeV, 25 GeV and 450 GeV respectively. It is the PS that sets the bunch spacing to 25 ns. Inside the LHC, the protons are accelerated up to 6.5 TeV per beam using radio-frequency (RF) cavities.

Along the LHC ring, there are 1232 super-conducting NbTi dipole magnets bending the protons, keeping them in orbit. Liquid helium cooling provides an

\(^1\)The design energy of LHC is $\sqrt{s} = 14$ TeV, however it is currently operated at $\sqrt{s} = 13$ TeV.
operating temperature of 1.9 K, enabling a current of 11 kA which generates an 8 T dipole field. Furthermore, 392 quadrupole magnets are responsible for focusing the proton beams.

Down the accelerating chain towards the LHC, the circumference of the different accelerators increases. Therefore, to fill an accelerator with proton bunches, several fills of its preceding accelerator are injected. The exact scheme in which the different accelerators are sequentially filled with proton bunches effectively determines the bunch pattern as finally obtained in the LHC. When the PS is filled it holds 72 proton bunches and 12 empty bunches. Next, an SPS fill consists of two, three or four PS fills. Finally, the LHC consists of 12 of these variable-length SPS fills, holding up to 3564 proton bunches per beam. See fig. 3.2 for a schematic view of how the different accelerator fills are composed. There are different “distances” in time, i.e. number of empty bunches, between the different types of fills. It is important to keep a 3 μs gap in the LHC filling scheme, a so-called abort gap. This time gap is needed for the kicker magnets to ramp up and divert the protons and dump the beam.

The RF cavities provide an oscillating longitudinal electric field, accelerating the protons from 450 GeV to 6.5 TeV. The field oscillates at a frequency of 400 MHz; an integer of the bunch passing frequency 40 MHz. This assures the protons experience an accelerating field inside the cavity. The design causes the bunches to stay compact as they will tend toward certain positions along the circumference as determined by the oscillation frequency. This allows for high luminosity when the beams are collided at the experiments.

The luminosity of a collider is a measure of the number of protons crossing each
other per unit time and area. It characterises the intensity, or brightness, of the collider, and predicts together with the proton-proton cross section the average rate of proton-proton collisions to be expected. It is given by the following expression in the case of uniform bunch population, round beams and equal beam parameters for both beams [14]

\[ \mathcal{L} = \frac{N_b^2 n_b f_r \gamma}{4\pi \epsilon \beta^* F}, \]  

(3.1)

where \( N_b \) is the number of protons per bunch, \( n_b \) the number of colliding bunch pairs, \( f_r \) the revolution frequency, \( \gamma \) the Lorentz factor, \( \epsilon \) the normalised transverse beam emittance, \( \beta^* \) the beta function at the collision point and \( F \) a geometrical factor correcting for the beam-beam crossing angle. The numerator of this expression equals the number of protons crossing each other per unit time, whereas the denominator terms equals the area over which the protons are distributed during collision. A record peak instantaneous luminosity of \( 21.4 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1} \) was delivered in the spring of 2018, a factor 2.14 larger than the design luminosity. If the luminosity is integrated over time, a measure of the total amount of collisions produced is obtained. This number may be multiplied with the cross section for a physical process to infer the expected number of events from that process to be found in the full dataset.

The number of proton collisions in a bunch crossing is denoted \( \mu \). Averaging over multiple bunch crossing yields the average number of collisions, \( \langle \mu \rangle \). Typically
only one of the collisions is interesting, the remaining parasitic collisions are referred to as pile-up.

The first run, denoted Run-1, of the LHC spanned the years 2009–2013, in which the accelerator was operated at a collision energy of 7 TeV and later 8 TeV. During the upgrade phase the energy was ramped up to $\sqrt{s} = 13$ TeV for Run-2 which begun in 2015 and will continue until the end of this year.

3.2 The ATLAS detector

The ATLAS detector, see fig. 3.3, is a large assembly of experimental equipment, weighing some 7000 tonnes and measuring 44 m in length and 25 m in height. It is a cylindrical magnetic spectrometer with forward-backward symmetry, designed as a multi-purpose detector. The different subsystems will be described in this section, which is largely based on Ref. [15].

![Figure 3.3: A cut-away view of the ATLAS detector. Credit: CERN](image)

\footnote{ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the $z$-axis along the beam pipe. The $x$-axis points from the IP to the centre of the LHC ring, and the $y$-axis points upward. Cylindrical coordinates $(R, \phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the $z$-axis. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln \tan(\theta/2)$.}
3.2.1 The inner detector

The inner detector provides measurements of charged particles, used to reconstruct their trajectories (see section 5.2.1). Charged particles traversing the inner detector are bent by a 2 T axial magnetic field provided by a superconducting solenoid magnet, allowing for momentum measurement from the curvature of the track. The inner detector consists of silicon pixel and microstrip detectors and a transition radiation tracker. It is depicted with its subsystem in fig. 3.4. As up to 1000 charged particles may be produced in a collision, the requirements put on precision and performance of this system are strict. In the following three sections the three subsystems will be described, with an emphasis on the pixel detector as it is important for the studies presented in this thesis.

The pixel detector

The pixel detector is a high-granularity silicon detector, segmented in $z$ and $R-\phi$. It consists of four cylindrical layers in the central region and three disks at each end-cap in the forward regions. The innermost layer is positioned at $R = 3.5$ cm, the outermost layer at $R = 12.2$ cm. In total, the detector comprises 1968 sensors and some 80 million readout channels. The position of a measurement in the pixel detector is given in the local coordinate frame, with the local $x$ and $y$ directions for the barrel modules approximately coinciding with the global $R-\phi$ and $z$ directions, respectively.

Figure 3.4: An overview of the ATLAS inner detector and its subsystems. Figure (a) is showing the different subsystems’ location and the overall ID dimensions, Figure (b) is showing the radial placement of the different layers in the barrel region. Image credit: CERN.
The innermost pixel layer (IBL) was inserted for Run-2 of the LHC. By providing an additional measurement closer to the interaction point, it increases the impact parameter resolution of reconstructed tracks. Furthermore, the IBL is required to maintain track reconstruction performance as the performance provided by the other pixel layers alone decreases with increased radiation dose. The pixel dimensions in the IBL are $50 \times 250 \, \mu m$ in the local $x$ and $y$ directions respectively, and $50 \times 600 \, \mu m$ in the other three layers. About 10% of the pixels have longer pitches in the local $y$ direction, namely $400 \, \mu m$ in the IBL and $600 \, \mu m$ in the other three layers. The pixels with longer pitches are located at the edge between modules. The thickness of the silicon sensors are $200 \, \mu m$ for the IBL and $250 \, \mu m$ for the remainder of the pixel detector.

The pixel detector provides a measurement of the charge deposited, corresponding to the energy lost by a particle traversing a silicon sensor. The charge deposited in the detector is collected and amplified by a preamplifier in the front-end chip. Only pixels above a predefined threshold are read out. The recorded time-over-threshold (ToT), i.e. the period of time during which the preamplifier output signal is above this predefined threshold, increases approximately linearly with the deposited charge. The signal is digitised in clock cycles of the readout chip and converted to a charge value at the cluster reconstruction stage using parametrisations derived from calibration data.

The IBL has 4-bit pixel readout, whereas the remainder of the pixel detector has 8-bit pixel readout. The IBL pixel readout saturates at a ToT value of 15 clock cycles, in contrast to the 8-bit readout, saturating at a value of 255 clock cycles. To obtain a uniform response for all pixels, the ToT is tuned such that the average ToT for a charge deposition close to that deposited by a minimum ionising particle is the same for all pixels. A charge deposition of 16 000 (20 000) electrons was tuned to 10 (30) clock cycles for the IBL (the remainder of the pixel detector). The different charge depositions in the IBL and the remainder of the pixel detector are motivated by the different silicon sensor thicknesses.

The SCT detector

Moving radially outwards we find the semiconductor tracker (SCT), which like the pixel detector is based on silicon technology. It consists of silicon micro-strip sensors mounted on four cylindrical layers in the barrel region and nine disks at each end-cap. Strips are mounted on both sides of the sensors with an 80 µm pitch and a 40 mrad stereo angle, running approximately longitudinally (radially) in the barrel (end cap) region. A stereo angle size of $\pi/2$ radians is not optimal due to the high expected occupancy. A space point is built from two strip measurements, one from each side of the sensor. The total number of SCT channels is around six million. In contrast to the other two subsystems the SCT has binary read-out; it does not provide any information about the energy deposited.

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3The impact parameter is the point of closest approach between a track and its associated vertex. See section 5.2.1 for a review of the charged particle reconstruction.
4In practice, for the 8-bit readout, this saturation level is seldom reached.
The TRT

Furthest out in the tracking system is the Transition Radiation Tracker (TRT) which deploys a classical technique for detecting charged particles. It consists of straw tubes filled with a Xe-based gas mixture which is ionised when traversed by charged particles. A voltage causes the freed electrons to drift towards a gold-plated tungsten anode wire in the middle of the tube. The acceleration causes further ionisation to take place near the wire and an avalanche of electrons develops. The electrons are collected on the wire and read out as a signal. The TRT typically supplies some 35 measurements, with roughly 130 µm resolution in the $R-\phi$ plane but practically no information about the $z$ (straw) direction. The straws are interleaved with a plastic material designed to induce transition radiation. When a charged particle crosses a surface between two materials with different dielectric constants, it has a certain probability to emit transition radiation. The amount radiation produced is proportional to the particle’s Lorentz boost factor $E/m$. The transition radiation photons induce further ionisation signals, allowing for discrimination between the relatively lighter electrons with a high Lorentz boost and heavier charged hadrons such as pions.

3.2.2 Calorimetry

As implied by the name, the task of the calorimeters is to measure energy. ATLAS has five calorimeter systems which may be divided into two categories; one electromagnetic (EM) category and one hadronic category, as shown in fig. 3.5. The EM calorimeter is designed to fully contain the showers produced by electrons and photons, whereas hadrons will deposit some energy in the EM calorimeter but not be fully stopped until in the hadronic calorimeter. Both systems are so-called sampling calorimeters in which absorbers, initiating showers, are interleaved with active material measuring the showers.\(^5\) In this section, the five calorimeters subsystems will be described within their respective category.

The electromagnetic calorimeter

The EM calorimeter consist of one barrel and two end cap parts. They all use liquid argon (LAr) as active material and lead as absorber material. The lead is structured in an accordion shape, symmetrical around the $z$ axis, with liquid argon filling the gaps in between. A wedge of the EM barrel calorimeter is shown in fig. 3.6, displaying its three layers with differing cell granularities. The first layer has fine segmentation in $\eta$, allowing for discrimination between prompt photons and photons from $\pi^0$ decays. The accordion structure allows for full $\phi$ coverage without cracks, while simultaneously assuring that particles pass through roughly the same amount of material across the $\phi$ range. As bremsstrahlung and pair production both are proportional to the square of the atomic number $Z$ of the nearby nucleus, the

\(^5\)This is in contrast to homogenous calorimeters in which a single material act both as absorbers and active material.
particle showering will typically be initiated and predominantly develop in the lead. The showers will ionise the liquid argon, where the liberated electrons will drift due to an applied electric field and be read out as a signal. The energy resolution for the EM calorimeter is approximately

\[ \frac{\sigma}{E} \sim \frac{10\%}{\sqrt{E[\text{GeV}]}} \oplus 0.7\%, \]  

(3.2)

where the energy dependent term arises from statistical fluctuations in the showering and the constant term arises from imperfections.

The choice of liquid argon as active material is motivated by requirements on linearity, stability and ability to withstand high radiation doses.

The hadronic calorimeter

The hadronic calorimeter is located directly outside the EM calorimeters and consist of the Tile central barrel, the Tile extended barrel and the hadronic LAr end caps. The Tile calorimeters have iron as absorber material and plastic scintillators as active material. They are paramount to ensure proper identification and measurement of hadronic jets. The Tile Calorimeters are equipped with photo multiplier tubes to measure the light emitted from the scintillators. The hadronic calorimeters have an approximate energy resolution

\[ \frac{\sigma}{E} \sim \frac{50\%}{\sqrt{E[\text{GeV}]}} \oplus 3\%, \]  

(3.3)
Figure 3.6: A wedge of the EM barrel calorimeter. The calorimeter consists of lead absorbers arranged in an accordion structure with liquid argon as active material between the lead plates. There are three layers with different cell size. Image taken from Ref. [15].
The hadronic LAr end caps are similar to the LAr electromagnetic end caps but has copper as absorber material.

**The forward calorimeter**

In the forward region, covering $3.1 < |\eta| < 4.9$, is the LAr based forward calorimeter. It consists of three layers per end cap. The first is made of copper, optimised for electromagnetic showers. The other two are made of tungsten, designed to measure hadronic showers. The detector front face is situated 1.2 m further out with respect to the electromagnetic calorimeter end cap front face, to reduce the neutron albedo in the inner detector cavity. This limits the depth of the detector and it therefore has a high-density design. The forward calorimeter depth amounts to approximately 10 interaction lengths.

### 3.2.3 Muon system

Muons are the most elusive charged particles to be measured by ATLAS as they typically penetrate the inner detector and the calorimeters. To reach the muon system, depicted in fig. 3.7, a muon must have a momentum of more than approximately 3 GeV. This is the largest and the outermost subsystem reaching from approximately $R = 5$ m to $R = 11$ m. It is a spectrometer with its core piece being the magnet system causing the muons to bend and allow for momentum measurement. There are three superconducting toroids, each with eight coils; one in the barrel region and one for each end-cap. The magnetic field has a complicated structure and is mapped by magnetic field sensors to a precision of 0.1 mT. The complexity of the field requires a detailed numerical approximation track model rather than an analytical expression.

The momentum measurements are provided by high-precision tracking chambers, covering $|\eta| < 2.7$, while dedicated trigger chambers provide fast measurements in $|\eta| < 2.4$. The chambers are mounted as three cylindrical layers in the barrel region at radii $R = 5$ m, $R = 7.5$ m and $R = 10$ m. In the forward regions there are four wheels on each side at distances 7.4 m, 10.8 m, 14 m and 21.5 m mounted with chambers. This design provides at least three measurements for a muon passing through the muon system, allowing for the radius of curvature to be measured. The $p_T$ resolution of the muon system is best, $\sim 3\%$, at $p_T = 100$ GeV. Above (below) this transverse momentum the resolution decreases to approximately 10% (6%) at 1000 GeV (4 GeV). It decreases below $p_T = 100$ GeV due to fluctuations in the amount of deposited energy in the material downstream of the muon system. The amount of material between the interaction point and the muon system varies between 100 and 190 radiation lengths depending on pseudorapidity, and consists mostly of calorimeters. A description of the different chambers will now follow.
Figure 3.7: Schematic view of the ATLAS Muon Systems. Credit: CERN.

Monitored drift tube chambers

The monitored drift tube chambers (MDTs) covers $|\eta| < 2.0$ and are used for precision tracking and based on the same classical technology as the TRT. MDT’s are located both in the barrel and in the end-caps. They have aluminium tubes of diameter $\sim 30$ mm filled with an Ar-CO$_2$ gas mixture, and a tungsten wire inside. The tubes are arranged in multi-layers and a muon typically passes through 20 individual tubes on average. The alignment of the MDTs has to be known to a high precision, for which a system of approximately 12000 optical sensors are used to map the sensors’ internal deformations and relative positions.

Cathode strip chambers

In the forward region $|\eta| > 2$ the particle flux is higher than what the MDTs can handle in terms of safe operating counting rate per unit area. To cope the muon system is equipped with cathode strip chambers (CSCs) in the region $2.0 < |\eta| < 2.7$, in the end-caps. There are $2 \times 8$ chambers per end-cap; eight small and eight large chambers on two disks. These are multi-wire proportional chambers with anode wires in the radial direction. As ionisation electrons from the Ar-CO$_2$ gas mixture collect on the wires currents are induced in the cathodes, which are read out (the wire current is not read out). The cathodes are segmented into strips; one with strips oriented in a direction perpendicular to the wire, the other with strips
oriented parallel to the wire. This allows for measurement of the charge distribution in both directions perpendicular to the beam line, yielding a resolution of approximately 60 µm (to be compared with 80 µm for the MDTs).

**Trigger chambers**

The muon trigger system provides fast measurement of muon $p_T$, as well as bunch crossing identification and discrimination against background. In the barrel region ($|\eta| < 1.05$) are the RPCs, in the forward region ($1.05 < |\eta| < 2.4$) are the TGCs. There are three cylindrical layers of RPCs, each with one RPC layer at each end-cap. The RPCs consist of resistive plates with gas in between, the latter being ionised upon a muon traversing. An electron avalanche is built up due to a voltage applied across the plates, which is read out. The TGCs are based on multi-wire proportional technology like the CSCs, and provide finer $\eta$ granularity than the RPCs. This assures the same $p_T$ resolution in the barrel region; the particle momentum increases with $|\eta|$ for a fixed $p_T$, meaning there is less bending power in the forward region.

**3.2.4 Trigger and data acquisition**

The LHC bunch crossing rate corresponds to a 40 MHz rate of events. Recording all those events would require many terabytes of data to be written to disk every second, which is unfeasible. Furthermore, only a fraction of the events will contain interesting physics. To cope with this, ATLAS has a dedicated trigger and data acquisition (TDAQ) system [16], which is designed to reduce the final read-out rate to order 1 kHz. This limit is imposed by the amount of data ATLAS may store. The TDAQ must make a fast decision as to whether an event is worth recording, or not. If an event is discarded by the TDAQ, it is permanently lost.

The trigger chain system consists of two main levels: the first level-1 (L1) and the second high-level-trigger (HLT). The L1 system is hardware based, as it needs to be extremely fast. It uses low-granularity information from calorimeter and muon trigger detector subsystems to find high-$p_T$ objects, namely muons, electrons, photons, jets and hadronically decaying tau leptons. No inner detector information is used at this stage, to reduce the event size. The L1 trigger system needs to reduce the rate to approximately 100 kHz, a limit set by the front-end electronics ability to process information. To achieve this, the L1 reaches a verdict within 2.5 µs.

So-called Regions-of-Interest (RoI) are passed on to the next, software based HLT system. They are $\eta-\phi$ regions in which interesting activity have been detected. In the first step of the HLT, full-granularity information is read out in the RoIs, now including the inner detector track information allowing for matching of calorimeter deposits and tracks. Based on this information the event may be rejected or not. If not rejected, the second step of the HLT follows. The full event information is read out and event building is performed, giving a simplified but full event picture. This allows for using offline reconstruction algorithms to finally decide whether to accept the event or not.
At different levels in the TDAQ pre-scales may be applied to the data. A pre-scale is a number determining the fraction of events to keep from a trigger selection. For example, a pre-scale of five implies that only every fifth event surviving a trigger selection will actually be kept and further processed. This means that events coming from a stream with pre-scaled triggers will effectively be associated with a lower luminosity than the baseline one. Analyses must take this into account, and thus tend to use un-prescaled triggers as much as possible.

Events selected by the TDAQ are sent to full reconstruction at the on-site processing centre known as Tier-0. Once fully reconstructed, the data is distributed world-wide to different computing centres, then available for analysis.
Chapter 4

The High-Granularity Timing Detector as a future luminometer for ATLAS

To everything, there is a season.

— Chris, Catastrophe

In 2026, the High-Luminosity-LHC phase (HL-LHC) will begin, operating at a factor five to seven higher luminosity as compared to its design luminosity of \(10^{34}\) \(\text{cm}^{-2}\text{s}^{-1}\). The goal is to collect a dataset corresponding to 3000 \(\text{fb}^{-1}\) by the end of 2035 (see the ATLAS Phase-II scoping document at Ref. [17]). One of the main goals is precise determination of the properties of the Higgs boson. With the foreseen dataset, the Higgs boson coupling parameters can be measured to percent level precision, putting stringent constraints on BSM physics processes.

At \(\mathcal{L} = 7.5 \cdot 10^{34}\) \(\text{cm}^{-2}\text{s}^{-1}\) the mean number of \(pp\) collisions per beam crossing will be approximately 200. Consequently, the effects of parasitic pile-up interactions will increase as compared to present-day conditions. ATLAS will, among other upgrade projects, build a timing detector called the High-Granularity Timing Detector (HGTD), with the main objective to mitigate the effects of increased pile-up. The Technical Proposal of the project is found at Ref. [18]. The motivation is further outlined in section 4.1, followed by a description of the detector design and technology in section 4.2. The prospects for the HGTD to serve as a luminosity detector is investigated in section 4.4, containing studies to which the author has contributed. Before that, the concept of luminosity and current ATLAS measurement techniques and detectors are presented in section 4.3. Some concluding remarks and outlook to the future are presented in section 4.5.
4.1 Physics motivation for a timing detector

To cope with the increased particle densities at HL-LHC, ATLAS will replace entirely its inner detector with a new all-silicon based tracker with a pseudorapidity coverage of $|\eta| < 4$. The coverage is extended compared to the current inner detector ($|\eta| < 2.5$), providing tracks also in the more forward region $2.5 < |\eta| < 4$. The new tracker’s excellent spatial resolution will be provide a high efficiency for associating tracks to vertices in the central region, $|\eta| < 2.5$. In the forward region however, the longitudinal impact parameter resolution of the inner tracker degrades because of the shallow angle with respect to the $z$ axis along which particles are travelling, see fig. 4.1. At $\langle \mu \rangle = 200$, the resolution in the forward region is lower than the distance between vertices, i.e. the inverse of the interaction density along $z$, the mean of which is 1.8 collisions/mm. As a consequence, multiple vertices are compatible with a track in the forward region, rendering the track-to-vertex association ambiguous. Thus, tracks from pile-up interactions can not be distinguished from tracks from the hard interaction. Track-to-jet association will similarly be degraded in an environment with high vertex density. This in turn degrades the performance of the $b$-jet tagging, which depends on finding tracks displaced with respect to the primary vertex. Furthermore, the efficiency of lepton isolation decreases with increasing probability to have a pile-up track in the vicinity of a lepton. The resolution of $E_T^{\text{miss}}$ will also be degraded. In summary, the harsh pile-up environment in HL-LHC will render forward tracks from the inner tracker difficult to use, negatively affecting the quality of many physics objects.

![Figure 4.1: Longitudinal impact parameter resolution for tracks from the inner tracker (to replace the current inner detector for HL-LHC), as a function of the pseudorapidity. The different curves denote tracks with different transverse momentum. Figure from Ref. [18].](image-url)
To suppress the effects of high pile-up, ATLAS will build and install the HGTD in the forward region, providing a timing resolution of approximately 30 ps for a traversing minimum ionising particle. The motivation for building a timing detector is to exploit the time dimension of the beam spot. Collisions are taking place during the time it takes for the two beams to cross. The time distribution of collisions has a standard deviation of approximately 175 ps. The timing resolution requirements has driven the choice of detector technology, further specified in section 4.2 along with detector requirements and design.

4.2 Detector design and technology

The HGTD consists of two thin disks which will be installed at $z = \pm 3.5$ m in the gap between the inner tracker and the end-cap calorimeters, currently occupied by Minimum Bias Trigger Scintillators. The envelope in $z$ of the full detector is required not to exceed 75 mm. Outside the HGTD, in front of the end-cap calorimeters, 50 mm of moderator material will be inserted to protect the tracker from back-scattered neutrons. Radially, the active area of HGTD is constrained to $120 < R < 640$ mm, due to requirements of cooling and routing services. This corresponds to a coverage in pseudorapidity of $2.4 < |\eta| < 4.0$.

A silicon-based technology simultaneously fulfil the constraints on extension in $z$ and good timing resolution. ATLAS opted for Low Gain Avalanche Detector (LGAD) [19] silicon sensors of thickness 50 $\mu$m, segmented in $1.3 \times 1.3$ mm$^2$ pixels. The pixel size has been optimised to achieve an occupancy of less than 10% at the inner radius. Sensors will be mounted on cooling disks, enabling an operating temperature of $-30^\circ$C. There will be two disks per side (positive and negative $z$) and sensors are mounted on each side of a disk. The sensors are arranged in a pattern having an overlap between sensors on the front and back of a cooling disk of approximately 80% (20%) in the region $R < 320$ mm ($R > 320$ mm). This corresponds to an expected mean number of hits per track of approximately three (two) for the inner (outer) radial region. Due to the degradation of the time resolution caused by radiation, the sensors in the inner radial region will be replaced after half of the HL-LHC program. The sensors have a surface size of 2 mm $\times$ 4 mm and are bump-bonded to custom application-specific integrated circuits (ASICs). Modules consisting of a sensor, ASIC and a flex cable for data transfer will be mounted on support structures on the cooling plate. The ASICs will have the capability to compute the number of hits and transfer at 40 MHz rate. The total number of modules will be around 8000, corresponding a total active area of 6.3 m$^2$ and 3.5 million read-out channels.
4.3 Luminosity measurements

This section will briefly outline the principles and the detectors currently used for luminosity measurements in ATLAS. For a more comprehensive review of luminosity estimation for hadron colliders, see e.g. Ref. [20].

The relation between the luminosity for a single colliding bunch pair, the inelastic $pp$ scattering cross section and the average number of interactions is given by

$$L_b = \frac{R}{\sigma_{inel}} = \frac{\mu f_r}{\sigma_{inel}} = \frac{\mu_{vis} f_r}{\sigma_{inel,vis}}, \quad (4.1)$$

where $R$ is the rate of inelastic collisions and $f_r$ the revolution frequency of the bunch. The total luminosity is obtained by summing over all colliding bunch pairs. In the last equality the principle for luminosity measurement is shown: $\mu_{vis} = \epsilon \mu$ and $\sigma_{inel,vis} = \epsilon \sigma_{inel}$ represents the visible fraction of the number of interactions and the inelastic $pp$ cross section, respectively, seen by a luminometer with a certain acceptance and efficiency, parametrised by $\epsilon$. During running, a luminometer measures $\mu_{vis}$, while $\sigma_{inel,vis}$ has to be determined in special calibration runs. In such runs the luminosity is inferred directly from the beam parameters according to eq. (3.1) (see section 4.3.1 for further explanation).

4.3.1 Calibration

The calibration of a luminosity algorithm amounts to determining $\sigma_{vis,inel}$ in eq. (4.1). This is done in dedicated runs with beam parameters corresponding to collision multiplicities of order 1 or smaller. In these runs, the two beams are scanned across each other in so-called van der Meer scans [21]. In such conditions, the luminosity can be inferred directly from the beam parameters. By simultaneously measuring the luminosity and $\mu_{vis}$, the cross section $\sigma_{vis,inel}$ can be extracted. For beams crossing at half-angle $\alpha$ in the $xz$ plane, the bunch luminosity is given by eq. 13 in Ref. [20] (which is a more general form of eq. (3.1), for a single bunch pair):

$$L_b = f_r N_1 N_2 \cos(\alpha) e^{-\frac{\Delta^2_x}{2\Sigma_x^2} - \frac{\Delta^2_y}{2\Sigma_y^2}}, \quad (4.2)$$

where $N_1$ and $N_2$ are the number of protons in the two respective bunches, $\Delta_x$ ($\Delta_y$) the beam separation in the $x$ ($y$) direction and $\Sigma_x$ ($\Sigma_y$) the so-called convolved beam size in the $x$ ($y$) direction. This is a Gaussian function of the horizontal and vertical beam separations $\Delta_x$ and $\Delta_y$, with standard deviations $\Sigma_x$ and $\Sigma_y$. During scans the beams are separated in steps in the horizontal and vertical directions to map out this Gaussian function. The $\Sigma_x$ and $\Sigma_y$ can then be extracted by evaluating the area under the curve. The motivation for performing the scans at low $\mu$ is that the beam parameters can be better controlled and optimised.
4.3.2 Luminosity detectors and algorithms

ATLAS employs a battery of different detectors and algorithms to measure the luminosity. It is important to have a variety of independent estimates for validation cross-checks and monitoring of the long-term stability. Furthermore, by utilising the different measurements the overall systematic uncertainty on the final total integrated luminosity can be constrained. Luminosity measurements can be classified in two ways. First, as not all bunch pairs in LHC are equal, we distinguish between “per-bunch” and “bunch-integrated” measurements. The former is fast and thus sensitive to the bunch crossing identifier (BCID) while the latter is “BCID-blind” and integrates the luminosity over several bunches. Second, a luminometer may or may not provide its estimate online, i.e. alongside the data taking without need for a dedicated offline analysis.

The different algorithms used to estimate $\mu_{\text{vis}}$ may be coarsely grouped into event-based and rate-based counting algorithms. Event-based algorithms depend on counting the number of events with no signal. “Signal” can be defined in different ways, for example requiring a hit in either single arm of the luminometer, or requiring a double-arm coincidence hit signature, having at least one reconstructed inner detector track or primary vertex, etc. The ratio of this number to the total number of events (with colliding bunches) provides an estimate of $\mu_{\text{vis}}$, by use of the fact that the number of interactions follows Poisson statistics. This event-based counting is also referred to as “zero counting” and works in the regime where $\mu_{\text{vis}}$ is sufficiently small. With increasing $\mu_{\text{vis}}$, the probability to have no signal in the detector decreases and eventually one enters a regime where the algorithm does not work as the fraction of no-signal events approaches zero. This is referred to as saturation.

The two primary luminometers in ATLAS are LUCID (LUminosity measurement using a Cherenkov Integrating Detector) [22] and BCM (Beam Conditions Monitor) [23], which both provide per-bunch, online estimates using event-based algorithms.

LUCID is a Cherenkov detector situated 17 m from the interaction point on either side, at $5.6 < |\eta| < 6.0$. It consists of about 1.5 m long aluminium tubes surrounding the beam pipe, filled with $\text{C}_4\text{F}_{10}$ gas and photo-multiplier tubes (PMTs) attached at the end. As relativistic particles pass through the gas Cherenkov light is emitted with an angle of about three degrees w.r.t. to the particle trajectory, reflected on average three times off the tube walls before being registered by the PMTs. The tube design enables to discriminate against background. Primary particles typically generate more light compared to background sources since they come in approximately parallel to the tube and have a long travel path through the detector. A hit is registered by LUCID if a signal is above a pre-defined threshold. LUCID provides per-bunch luminosity estimates and has its own readout system, separated from the ATLAS data taking. As such, it is not sensitive to trigger dead times and measures the luminosity online.

BCM also measures the luminosity online on a per-bunch basis. The detector is mainly used for monitoring the background rate to trigger a beam dump in
case of severe beam losses which risk damaging ATLAS. It consists of four small diamond sensors placed in a cross pattern at either side of the interaction point at \( z = \pm 184 \text{ cm} \), at \(|\eta| = 4.2\). The two pairs of horizontal and vertical sensors are read out separately for two independent luminosity estimates.

To continue beyond the limit where event-based algorithms saturates, one must move to the rate-based algorithms. These do not count events, but instead measures some observable proportional to the particle-detector interaction rate within each event. Perhaps the simplest example is hit-counting algorithms, measuring the number of hits in a detector, providing per-bunch estimates. Depending on the readout of the detector, it may or may not also provide it online. ATLAS employs one such algorithm measuring the number of pixel clusters in the outermost 3D modules of the IBL. In these modules clusters from primary particles are many pixels long, allowing for separation against background. Similar but more refined versions of hit counting are track-counting and vertex-counting algorithms, which count the number of reconstructed tracks and vertices respectively. While none of these estimates are available online, they are robust, and important e.g. to monitor the long-term drift behaviours of the faster per-bunch devices.

Finally, precise luminosity estimates are obtained by measuring the currents drawn by selected elements in the hadronic and forward calorimeters. These are BCID-blind estimates, however, they are available online and depend linearly on \( \mu \) to sub-per cent accuracy.

### 4.4 Measuring luminosity with the HGTD

The goal of measuring the Higgs boson couplings to per cent level requires the uncertainty on the luminosity to be of the same order or smaller. For comparison, the uncertainty on the total integrated luminosity during 2015 and 2016 Run-2 data taking is above 2%. This motivates the need for upgrading the luminosity capabilities for HL-LHC.

The zero-counting methods used by several current luminometers (see section 4.3) will face severe difficulties at \( \mu \sim 200 \). The fraction of events with no signal will be so small that the running time needed to obtain a precise estimation of \( \langle \mu \rangle \) explodes. One way of coping with this is to reduce the size of the detector to increase the fraction of no-signal events. This would however similarly make the time needed for van der Meer scan calibrations at low \( \mu \) unfeasibly large. LUCID and BCM, both zero-counting luminometers, are currently the only detectors providing per-bunch, online estimates. In summary, the high collision multiplicity environment at HL-LHC requires a luminometer which can operate both at \( \mu \sim 1 \) and at \( \mu \sim 200 \) and scale approximately linearly in between.

The proposed method of measuring the luminosity with the HGTD is straightforward: the luminosity will be proportional to the number of hits in the detector. Given a low enough occupancy, the average number of hits per event should scale linearly with \( \mu \). Based on hit-counting, the estimate thus has the advantage over the current zero-counting based luminometers that it is immune to problems with
saturation. In this section, studies with high-luminosity simulated samples are presented to demonstrate the functionality of HGTD as a luminometer.

For the luminosity measurement, it is proposed to use only the outer radial region $|\eta| < 3.1$ of HGTD, to minimise the probability of a single pixel being traversed by more than one particle. In what follows, the two (positive and negative $z$) innermost cooling disks are considered, counting the sensors on both sides of the disk. For this part of the detector, the average number of hits expected from a single $pp$ collision is 44.6, and approximately 7% of the events have no hits. In fig. 4.2a the average HGTD hit count is shown as a function of $\mu$. The black data points correspond to the standard ATLAS simulation, while the green stars correspond to manually overlaid $\mu = 1$ events. For the black data points in the high-$\mu$ region samples with $\langle \mu \rangle$ ranging between 190-210 are used. The leftmost data point corresponds to $\mu = 1$. Care has been taken to count only one hit even if a pixel is traversed by more than one particle. A linear fit has been made to all data points in the shaded region, and its prediction can be compared to the measured number of hits in high-$\mu$ region. The bottom pad shows the ratio between the data points and the linear fit. A good linearity is observed as well as agreement between the linear prediction and the observed number of hits at high-$\mu$. The green stars in the high-$\mu$ region are compatible with the standard simulation as well as the linear prediction.

![Figure 4.2](image)

**Figure 4.2:** (a) Mean number of HGTD hits in the first layer (front- plus backside of the innermost cooling disk, counting both sides of the interaction point) versus the number of $pp$ interactions per crossing. (b) Relative statistical uncertainty on the $\langle \mu \rangle$ estimate based on HGTD hit counting, as a function of number of interactions. See text for further explanation. Figure from Ref. [18].

The statistical uncertainty on the $\langle \mu \rangle$ estimate has been studied using a toy
method tuned to results from fully simulated data. For each \( \langle \mu \rangle \), a \( \mu \) is sampled from a Poisson with mean \( \langle \mu \rangle \). Then, the number of HGTD hits is sampled from the hit distribution obtained in fully simulated data for the drawn \( \mu \) value. Repeating this procedure 11000 times and taking the average yields the per-bunch \( \langle \mu \rangle \) estimate for a 1 s averaging time, corresponding to a typical online luminosity reporting frequency. The relative statistical uncertainty of this estimate as a function of \( \langle \mu \rangle \) is shown in fig. 4.2b. It is smaller than 1% everywhere except for \( \langle \mu \rangle = 0.01 \). At such low values, corresponding to van der Meer scans, one could use a longer averaging time to reduce the statistical uncertainty. To summarise, the HGTD luminosity estimate is not limited by statistical uncertainties.

The few-ns pulse duration enables the HGTD to report the luminosity per-bunch. This is in contrast to e.g. the calorimeter estimates which are “BCID blind”, i.e. only measure the luminosity in a bunch-integrated manner. A further important capability of the HGTD is the possibility to report the luminosity online, thanks to the trigger-independent readout. Reliable per-bunch online luminosity estimates are crucial during HL-LHC when the luminosity will be levelled. Levelling implies adjusting the beams continuously so that the luminosity is constant during a fill (or during the beginning of a fill), rather than being at its maximum at the beginning of a fill and decreasing as protons are burned off in collisions. One of the motivations for levelling is that the detectors otherwise have difficulties coping with the very large interaction multiplicities at the beginning of a fill.

4.4.1 Background

There are a number of background sources to luminosity measurements that depend on the detector type and location. This may be non-collision background,\(^1\) radiation from activated material or detector noise. Radiation from activated material, often referred to as afterglow, is studied in special runs with several empty bunch pairs following a filled bunch pair.

With the excellent timing resolution of the HGTD the effect of afterglow may be constrained. For each bunch crossing, two hit sums will be read out. One corresponding to the number of hits registered in a few-ns time window covering the time during which particles from the collision are expected. The other corresponds to the number of hits in the sideband, before and after the central time window. In this way, the afterglow can be measured and accounted for in the luminosity estimate, separately for each bunch crossing.

4.5 Conclusion and outlook

The High-Granularity Timing Detector, scheduled to be installed in ATLAS for the high-luminosity phase of the LHC, has been presented. With a 30 ps timing resolution per charged particle track, it provides a handle for suppression of pile-up

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\(^1\)Examples of non-collision backgrounds are showers from cosmic rays or interactions of the beam with residual gas in the beam pipe.
effects in the forward region $2.4 < |\eta| < 4.0$. The detector has unique capabilities to serve as a luminometer, providing per-bunch estimates available online.

The Technical Design Report of the project will be published in the fall of 2018. Continued research and development efforts, e.g. measurement of test sensors at beam facilities, are foreseen during 2018-2020. The construction of the modules and the rest of the detector will take place from 2021 to 2024. In the last two years before the start of the HL-LHC, the detector will be installed and commissioned.
Chapter 5

Event reconstruction and simulation

“Data! Data! Data! I can’t make bricks without clay.”
— Sir Arthur Conan Doyle, The Adventure of the Copper Beeches

This chapter presents a summary of the techniques used to simulate proton collision events, presented in section 5.1. Section 5.2 outlines methods used by ATLAS to reconstruct detector signals into all the physics objects making up an event.

5.1 Event simulation

Successful experimental physics research requires confronting data with theoretical predictions. Generating these predictions is however far from trivial. The final states studied are typically complicated with hundreds of particles, the signals of which are affected non-trivially by the detector acceptance and efficiency. Moreover, the initial state partons must be brought through hadronisation to final state particles, involving the transition from the perturbative to the less well understood non-perturbative regime. The task is tackled by using Monte Carlo event generators, programs which simulate the high-energy pp collisions in the LHC (see e.g. [24] for a review). They rely on factorising the problem in terms of energy scales. For instance, the process in which two gluons fusing to a Higgs boson involves momentum transfers much larger than the scale at which hadronisation occurs. At high-momentum transfers the strong coupling constant is small enough to allow a perturbative treatment, while QCD-inspired phenomenological models are used for e.g. hadron formation.

Consider fig. 5.1 showing a sketch of a pp collision, with the main ingredients to be simulated indicated. These are [25],
The hard interaction; the main high momentum transfer parton-parton sub-process indicated by the red circle. Being in the perturbative regime, the outgoing particles’ properties may be computed through the relevant Feynman diagrams to some fixed order. The computation of higher orders requires a choice of factorisation ($\mu_F$) and renormalisation ($\mu_R$) scales, typically set around $\mu_F = \mu_R \approx 100$ GeV but can depend on the process and vary dynamically for each event. Depending on the generator’s scheme of modelling the hard interactions, parton density functions may or may not be used. If used, probability functions determine for each event which partons from the proton take part in the hard interaction.

Parton showering, in the initial- (blue) and final (red) state. The final state radiation evolves from the final state of the hard process to the point where perturbation theory breaks down and hadronisation begins ($Q \sim 1$ GeV). It thus effectively adds higher-order corrections to the lowest-order calculation for the hard interaction mentioned in the previous bullet.

Hadronisation, i.e. the mechanism responsible for taking coloured partons to colourless hadrons.

Decays of unstable hadrons, i.e. the decays of short-lived hadrons into stable particles (possibly via other unstable hadrons).

The underlying event, i.e. the activity not directly associated with the primary hard interaction. This includes multiple parton-parton interactions (MPIs; softer low-momentum transfer interactions between other partons not involved in the hard interaction) and beam remnants. This activity is mostly found in the forward regions.

At any point in the above, charged particles may radiate photons, indicated in yellow in the figure. Different programs exist, which may simulate the full process or only some particular ingredient out of the ones listed above. For example, **Pythia** [26] and **Sherpa** [27] are multi-purpose event generators, simulating all parts listed above. **MadGraph** [28] is an example of a program used for the hard interaction, which must then be interfaced with some other program for the remaining parts of the simulation.

The output of an event generator is a collection of particles and their respective properties, such as their four-momenta. The next step of the simulation is to feed this collection to the detector simulation.

### 5.1.1 Detector simulation

To obtain a detector view of the particles output of the simulation of a $pp$ collision, they must be propagated through ATLAS in a realistic way. The interaction of the

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The scales only have an influence because processes are evaluated at some truncated order in perturbation theory—if all orders were included, the result would be insensitive to the values of the scales.
Figure 5.1: A sketch of a $pp$ collision and its different steps as simulated by a Monte Carlo event generator (figure from Ref. [29]). The green ellipses with pointing arrows represent the colliding protons. The red filled circle represents the hard scatter interaction. Above it is the final state parton shower in red, while initial state parton shower is shown in blue. In purple is the underlying event, in turquoise beam remnants. The light green ellipses represent hadronisation, the darker green circles are decays. Yellow lines indicate soft photon emissions.
particles with detector material is simulated using the GEANT4 toolkit [30]. The full ATLAS geometry and conditions are simulated and particles are propagated through, taking into account electromagnetic and hadronic interactions. Next, the energy deposits are digitised into a format equal to the one used for real data (output from the detector). In this step, pile-up is simulated by overlaying multiple single-pp collision events simulated with PyTHIA 8, tuned with the A2 parameter set [31]. The reconstruction of physics objects (explained in the next section) then proceeds in the same way for both simulated and real data.

5.2 Particle identification

As particles produced in the pp collisions traverse the ATLAS detector they interact with the different subsystems by depositing energy in them (see section 3.2). This produces raw electrical signals, which are digitised and read out to be used in the event reconstruction. This information must be processed in the appropriate way to form the physics objects which are needed for the physics analyses, such as electrons and muons. This often requires using signals from different subsystems. The detector is designed to deliver a unique signature for each class of particles. For example, all charged particles are expected to leave a track in the inner detector. The magnetic field will cause the particles to bend in a direction depending on the sign of the charge. This allows for reconstructing electrons by combining showers in the electromagnetic calorimeter with a track in the inner detector. For photons, no inner detector track is expected, and as compared to electrons a slightly different shower shape is expected in the electromagnetic calorimeter. Hadrons are expected to leave a small fraction of their energy in the electromagnetic calorimeter and most of their energy in the hadronic calorimeter. The association of an inner detector track allows for discrimination between e.g. protons and neutrons. Collimated sprays of hadrons may be grouped together and be reconstructed as jets. Muons are expected to leave a signal in all the different subsystems of detector and thus information from all of them are combined. Lastly, some particles (like neutrinos) will go undetected and will thus leave an imbalance of momentum and energy in the transverse plane (the xy plane; perpendicular to the beam direction). Thus, the missing transverse momentum in an event may be reconstructed by taking the negative sum of the reconstructed physics objects visible in the event.

In this chapter, the algorithms used to reconstruct some of the most important physics objects will be outlined.

5.2.1 Charged particle reconstruction

Charged particles are reconstructed as tracks using measurements from the ATLAS inner detectors. The ATLAS track reconstruction algorithm [32] realises an inside-out strategy primarily and a complementary outside-in strategy. Here the inside-out strategy will be outlined.
A staged pattern recognition approach is used to first find a set of loose track candidates seeded on combinations of three measurements from the silicon detector layers. Each measurement must come from a unique layer. The IBL and the pixel detector provides clusters, formed from neighbouring pixels grouped together. These measurements map directly into three-dimensional space-points. For the SCT, space-points are formed by combining measurements from pairs of measurements from two strips on a SCT module. There are four possible combinations of space points to make up a seed: all space-points in the pixel detector or all in the SCT, two space-points in the pixel detector and one in the SCT or one space point in the pixel detector and two in the SCT. The fourth category is not used by the seeding algorithm. Using three space points to form a seed maximises the number of combinations while still enabling for a first crude estimate of the momentum. The track parameters are estimated assuming a perfect helical trajectory and uniform magnetic field, with respect to the center of the interaction region. To maximise purity a number of quality cuts are put on the seeds, such as a mini-

\footnote{\label{foot:sharing}Sharing at least one corner.}
mum momentum and a maximum impact parameter requirement\(^3\). Also, usage of the same space points in multiple seeds is carefully controlled, and a fast check is performed to validate that a fourth space point is compatible with the seed.

The track candidates are built from the seeds using a combinatorial Kalman filter [33]. A window search is performed to add to the track candidate additional space points from measurements expected in the remaining layers. The road within which to search is estimated from the propagated track seed parameters. Space points found within the road may be added to the track candidate if they are compatible with the track candidate in its current state. If a space point is successfully added to the track candidate, the track parameters are updated with the new information and then used in the next filter iteration. If multiple space points on the same layer are compatible with the track candidate, multiple track candidates are formed and proceed independently in the subsequent filtering. Each iteration in the filtering takes into account particle-matter interactions and movement through the magnetic field.

Once the set of track candidates is complete, it is the job of the ambiguity solver stage to further filter out tracks which have incorrect space point assignment. The ambiguity solver compares and rates individual tracks based on their quality. Each track is assigned a relative score and tracks with low score are discarded at this stage. The track scoring scheme is based mainly on basic track quality measures. For example, holes\(^4\) get penalised, while a good track fit \(\chi^2\) increases the score. Finally, the tracks surviving the ambiguity solver stage are extended to the TRT. The TRT extension is also performed with a Kalman filtering approach, searching for additional compatible space point measurements to be added to the track. The silicon detector tracks surviving the ambiguity solver stage define the search window.

For a charged particle travelling through a uniform magnetic field, the relation between its momentum component orthogonal to the field direction, the field strength and the bending radius (curvature) \(r\) of its trajectory is given by

\[
p_T = q Br,
\]

where \(q\) is the charge of the particle. For particles travelling through the inner detector, which is inside an axial field of 2 T, the transverse momentum given in units of GeV/c equals \(p_T = 0.6 \cdot r \, [\text{m}]\).

5.2.2 Electrons and photons

Electron and photon reconstruction both uses information from the electromagnetic calorimeter. Calorimeter clusters of cells are seeded on groups of neighbouring cells found by a so-called “sliding window” algorithm searching for local \(E_T\) maxima.

\(^3\)The impact parameter is defined as the distance of closest approach between the track and a reference point, typically the primary vertex.

\(^4\)A hole is the absence of a measurement in the region where one is expected (the intersect between the detector and the track).
The size of the clusters have been optimised to have a high efficiency of reconstructing a typical electromagnetic shower, while at the same time keeping the level of noise contribution low.

For electrons, clusters are then matched to inner detector tracks. A track is required to be consistent with the cluster both in position and in momentum. A multi-variate likelihood is finally built from different shower property variables, track-to-cluster variables and track quality measures. Depending on the value of the likelihood, the algorithm classifies the electron as satisfying either Loose, Medium or Tight identification criteria. By a tighter category is implied a higher purity, but a lower efficiency.

Photon-induced showers are very similar to electron-induced showers, but a few discriminant variables exist and are used to distinguish electrons from photons to some degree. More importantly though, the shower is required not to have an associated track. Photons interacting with material in e.g. the beam pipe may convert to a an electron-positron pair, giving rise to both inner detector tracks and an electromagnetic cluster, mimicking the signature of an electron or a positron. Such conversion pairs may be identified by matching the calorimeter cluster to a pair of inner detector tracks.

5.2.3 Muons

Muons are reconstructed mainly with information from the muon system and the inner detector, and to a lesser extent calorimeter data. Information from the different subsystems may be combined in different ways, leading to four types of muons: Combined muons, formed from a track in the muon system matched to a track in the inner detector; Extrapolated muons, formed from only a track in the muon system and a loose requirement on the compatibility with originating from the interaction point; Segment-Tagged muons, formed from an inner detector track matched to at least one local track segment in the muon system; and Calorimeter-Tagged muons, formed from an inner detector track matched to calorimeter data compatible with coming from a minimum ionising particle. The Extrapolated muons are mainly used to extend the region of acceptance to $2.5 < |\eta| < 2.7$, which is outside the range of the inner detector. Overlap between different types are resolved before the reconstructed muons enter in to physics analyses. When two muons share the same inner detector track, preference is given to Combined muons, followed by Segment-Tagged muons and then Calorimeter-Tagged muons. When two muons share the same muon system track, preference is given to the track with better track quality.

Muon identification aims at reconstructing muons at high efficiency while keeping the rate of fakes, coming mainly from kaons and pions decaying in-flight, low. Similarly to electron identification, there are Loose, Medium, Tight and high-$p_T$ selection criteria. The different criteria applies a set of quality cuts based on the specific features of the muon type, as listed above. The loose identification criteria is optimised for reconstructing the four-lepton final state of Higgs boson candidate events and has a high reconstruction efficiency, using all muon types. The medium identification criteria uses only Extrapolated and Combined muons and
is the default muon selection in ATLAS. Depending on the type, requirements on
the number of hits in the different muon subsystems are applied, together with a
very loose compatibility requirement between the muon system track and the inner
detector track for the Combined muons. The tight identification criteria is designed
to have a high purity and consists only of Combined muons satisfying the medium
criteria with additional quality cuts. Finally, the high-\(p_T\) selection maximises the
momentum resolution for muons with \(p_T > 100\) GeV, using Combined muons satis-
fying the medium identification criteria and applying additional muon system hit
requirements [34]. The Loose and Medium muons have very similar reconstruction
efficiency and is above 98\% (except in a muon system gap at \(|\eta| < 0.1\) for muons
with \(p_T > 10\) GeV. Tight muons have a reconstruction efficiency between 90\% and
98\%. All efficiencies are in good agreement with those predicted by simulation.

5.2.4 Jets

A jet is a spray of hadrons, a commonly emerging product at hadron colliders. The
reconstruction of jets begins with forming topological calorimeter clusters, or topo-
clusters. Topo-clusters are seeded on calorimeter cells with a signal-to-background-
ratio \((S/B)\) larger than four. The \(B\) in this ratio includes expected activity from
pile-up interactions and is thus robust against different pile-up conditions. Neigh-
brouring cells are iteratively added to the cluster if they fulfil \(S/B > 2\). Finally,
neighbours of the neighbouring cells with \(S/B < 2\) are also added to the cluster, but
the iteration procedure stops here. From the collection of resulting topo-clusters,
two topo-clusters are split if found to be compatible with being overlapping. Due
to the sampling nature of the ATLAS calorimeters, the clusters are then calibrated
on a cell-by-cell basis using EM and hadronic calorimeter data. At this stage, the
topo-clusters are input to the jet finding algorithm.

There are many jet finding algorithms, each with its advantages and disadvan-
tages. A desirable feature of a jet algorithm is to be infrared safe, meaning that
it is robust against soft and collinear radiation. The first step in combining the
calibrated topo-clusters, i.e. jet constituents, is to define the \(k_t\) distance measures

\[
d_{ij} = \min\left(k_{t,i}^{2p}, k_{t,j}^{2p}\right) \frac{\Delta_{ij}}{R^2},
\]

\[
d_{iB} = k_{t,i}^{2p}
\]

where \(\Delta_{ij} \equiv (y_i - y_j)^2 + (\phi_i - \phi_j)^2\) and \(k_{t,i}, y_i\) and \(\phi_i\) is the transverse momentum,
rapidity and azimuthal angle of constituent \(i\), and \(d_{iB}\) is the \(k_t\) distance between
constituent \(i\) and the beam. \(R\) and \(p\) are parameters denoting the “radius” (a mea-
sure of the size of the jet) and the relative power of energy versus size, respectively.
Starting with constituent \(i\) and considering all \(k_t\) distances to other constituents, \(i\)
and \(j\) are combined into a new constituent if \(d_{ij} < d_{iB}\). This process is repeated
until no other constituent can be added and the resulting object is then consid-
ered a jet and all its constituents removed from the list of possible constituents for
additional jets.
If \( p = -1 \) the so-called anti-\( k_t \) algorithm is obtained [35], commonly used in ATLAS. Jets reconstructed with the anti-\( k_t \) algorithm are infrared safe. The algorithm is designed so as to let the harder constituents determine the general characteristics of the jet. Softer constituents will tend to cluster with the harder constituents before clustering among themselves. The resulting jets are in general conical in shape with radius equal to \( R \). If two hard constituents have \( \Delta_{ij} \sim R \) the shapes might divert slightly from the conical shape, but always favouring the harder constituent.

The different properties of quarks are utilised to discriminate between jets originating from \( b \) quarks and jets originating light (\( u,d,s \)) quarks. In particular, the lifetime of the \( b \) quark is relatively short, resulting in \( b \)-hadrons with a lifetime of the order 1.5 ps. The average decay length of such hadrons is a few millimetres, long enough to reconstruct a secondary vertex from the decay products. Furthermore, as the decay of quarks is mediated by the weak interaction, soft leptons can be produced in the decay chain. The algorithms developed to classify jets as originating from \( b \) quarks are multivariate and mainly exploit track information and reconstructed secondary vertices. The impact parameter of tracks associated to a \( b \)-jet will tend to be larger than the impact parameter of corresponding light-jet tracks which are associated to the primary vertex. Efficient \( b \)-tagging is important in particular for analyses involving the top quark, as it decays to a \( b \) quark.

### 5.2.5 Missing transverse momentum

The ATLAS detector is designed to infer the existence of particles traversing the whole detector without leaving a trace, such as neutrinos or particles in beyond-the-Standard-Model theories. This is possible through the detection of an imbalance in momentum in the transverse plane. The missing transverse momentum (also denoted missing transverse energy) of an event, \( \vec{E}_T^{\text{miss}} \) with magnitude \( E_T^{\text{miss}} \), is defined as the negative vectorial sum of the transverse momentum of all the other visible objects. It is computed as [36]

\[
\vec{E}_T^{\text{miss}} = (E_x^{\text{miss}}, E_y^{\text{miss}}), \quad E_T^{\text{miss}} = \sqrt{(E_x^{\text{miss}})^2 + (E_y^{\text{miss}})^2}, \quad \phi^{\text{miss}} = \arctan\left(\frac{E_y^{\text{miss}}}{E_x^{\text{miss}}}\right)
\]

where

\[
E_{x(y)}^{\text{miss}} = E_{x(y)}^{\text{miss, } e} + E_{x(y)}^{\text{miss, } \gamma} + E_{x(y)}^{\text{miss, } \tau} + E_{x(y)}^{\text{miss, jets}} + E_{x(y)}^{\text{miss, } \mu} + E_{x(y)}^{\text{miss, soft}}.
\]

The \( e, \gamma, \tau, \) jets and \( \mu \) indices indicate electrons, photons, hadronically decaying tau leptons, jets and muons respectively. The \( E_T^{\text{miss}} \) reconstruction thus requires as input reconstructed, calibrated physics objects and is based mainly on calorimeter data. Object selections will vary between analyses and so will the \( E_T^{\text{miss}} \) accordingly. The “soft” term indicates measured energy not associated to any reconstructed object. It arises from underlying event activity and soft radiation from the objects. The performance of different \( E_T^{\text{miss}} \) reconstruction algorithms have been studied, in particular evaluating alternatives for calculating the soft term.
For Run-2, the primary technique for estimating the soft term utilises track information. As tracks may be associated to a vertex, a track-based soft term is largely independent of the number of pile-up interactions in the event. A $E_T^{\text{miss}}$ variable with its soft term computed with tracks is prefixed with “TST” for “Track-based Soft Term”. Alternatively, with a soft term estimated from calorimeter deposits, but is more sensitive to pile-up. However, such a definition has the advantage of being sensitive also to neutral particles (which do not leave a track in the inner detector) [37]. Missing transverse momentum computed completely from track information is denoted $E_T^{\text{miss, track}}$. This definition is the most robust against pile-up.

5.3 Pile-up reweighting

The pile-up profile of the 2015 and 2016 data is shown in fig. 5.3. The luminosity started out relatively low in 2015 at the beginning of Run-2 to then increase to a mean $\langle \mu \rangle$ of 24.9 for 2016. This profile is not known a priori but depends on the evolution of the accelerator and data taking conditions during the data taking period. Simulated samples being launched before the data taking starts must thus use an estimation for the $\langle \mu \rangle$ profile, bound to not be identical to the profile in data. Any analysis using MC samples (such the one presented later in this thesis) apply weights to the MC to get the same pile-up profile as in the data. This procedure is referred to as pile-up reweighting and is done to account for pile-up dependence.

A “pile-up rescaling” is performed to account for further differences in the modelling between data and simulation which are not corrected by the reweighting procedure alone. A scale factor of $1/1.09$ is applied to the $\mu$ distribution in data before the pile-up reweighting of MC is performed. The number equals the ratio of data to simulation for the visible inelastic cross section [38].

![Figure 5.3](image.png)

**Figure 5.3:** The luminosity weighted distribution of the average number of $pp$ collisions per bunch crossing as recorded online by ATLAS during 2015 and 2016 [39].
Chapter 6

The $H \to WW^* \to e\nu\mu\nu$ analysis

“The more hopeless you were, the further away they hid you.”
— Sylvia Plath, The Bell Jar

This and the following two chapters are devoted to the ATLAS analysis aimed at measuring the gluon–gluon fusion and vector boson fusion Higgs boson production cross sections in the $WW^*$ decay channel. The analysis is carried out by a team consisting of about 20 people of which the author is one. The dataset used, made up of $pp$ collisions at $\sqrt{s} = 13$ TeV, was collected during 2015 and 2016 and corresponds to an integrated luminosity of 36.1 fb$^{-1}$. In this chapter, the analysis strategy and background estimates will be presented, after introducing Higgs boson phenomenology at the LHC and a short review of the Run-1 results on Higgs boson physics. The statistical treatment and results of the analysis will be presented later in chapter 8. Sandwiched in between is chapter 7 covering in detail the main contribution from the author to the analysis: the estimation of background from misidentified leptons. Hereon, the symbol $\ell$ implies an (anti-)electron or a (anti-)muon, unless otherwise stated.

6.1 Higgs boson phenomenology at the LHC

This section will briefly review how the Higgs boson is studied at the LHC by the ATLAS and CMS experiments. For two protons colliding at the Run-2 energy $\sqrt{s} = 13$ TeV, the probability to produce a Higgs boson is approximately $10^{-10}$. At a luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$ this yields a Higgs boson production rate of nearly 2000 per hour. A Higgs boson decays promptly: it is measured via the traces left by its decay products passing through the detector. However, no Higgs boson decay

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1 The particle has a mean lifetime of order $10^{-22}$ s.
signature is free from background.  

In a measurement targeting the Higgs boson, other SM processes without Higgs bosons will enter as background, and must be precisely estimated. The measurement strategies are influenced by the properties of the boson, determining the characteristics of its production and decay modes.

Since the Higgs boson couples more strongly to massive particles, the dominant production modes involve heavy particles. The Feynman diagrams for the leading Higgs boson production modes are shown in fig. 6.1a. They are the gluon–gluon fusion (ggF), vector boson fusion (VBF), associated production with a top-quark pair ($t\bar{t}H$) and Higgs-strahlung ($VH$) processes. By $V$ is implied a $W$ or a $Z$ boson.

In the gluon–gluon fusion mode, the Higgs boson is produced via two gluons fusing through a fermion loop, where the heavy quarks are the main contributors to the loop. This mode makes up approximately 87% of the total cross section. Given that the fermion loop is dominated by the top-quark, analyses probing this production mode is sensitive to the top-quark Yukawa coupling parameter, regardless of the subsequent decay mode studied. In the vector boson fusion mode, a $W$ or $Z$ boson pair fuses to make a Higgs boson. A characteristic of this mode are the two high-energy quarks ($q'$) in the final state, separated by a large rapidity gap. They will hadronise, resulting in a detector signature of two well separated high-energy jets found in the forward regions, with the Higgs boson decay products found in between. Furthermore, there is no colour flow between the quarks, so there will be no or little hadronic activity between the jets. While this mode gives a cleaner detector signature compared to ggF, it is less probable, contributing about 7% to the total cross section. Analyses studying this decay mode are sensitive to the vector boson–Higgs boson coupling parameters. Contributing about 0.5% to the total is $t\bar{t}H$ production, in which the Higgs boson is produced together with a pair of top-quarks. In $VH$ production, contributing approximately 2% to the total cross section, the Higgs boson is radiated from a vector boson. Figure 6.1b shows the production cross section as a function of $\sqrt{s}$, with the Run-1 and Run-2 energies marked with dashed lines. The purple line with the steepest rise in the right plot represents $t\bar{t}H$ production, increasing about a factor of four going from $\sqrt{s} = 8$ TeV to $\sqrt{s} = 13$ TeV. Other modes increased by about a factor of two.

In the decay, the Higgs boson again favours heavy particles. Furthermore, as the particle is electrically neutral, the total net charge of the decay products must sum to zero. Figure 6.2 shows the branching ratios of the different decay modes as a function of the Higgs boson mass. It may be noted all different decay modes are available for the observed mass around 125 GeV (marked with a dashed line). Decay to a $b\bar{b}$-quark pair is the leading mode with a branching ratio of 58%, but it is experimentally challenging due to the large multijet background. It is of particular interest as it is the only channel directly sensitive to the bottom-quark Yukawa coupling. This decay mode is best studied by simultaneously targeting $VH$ production, as tagging a leptonically decaying vector boson provides a handle to suppress multijet backgrounds. Recent results combining Run-2 and Run-1 data have established the observation of this decay mode [41, 42]. The decay mode is

---

2One can not tell on an event-by-event basis whether a Higgs boson has been produced.
Figure 6.1: Production of the Higgs boson at the LHC. (a) Feynman diagrams for the main Higgs boson production modes (ggF, VBF, $t\bar{t}H$ and $VH$). The fermion loop in the $ggF$ production mode can contain any fermion, but as the Higgs couples more strongly to massive particles the contribution from top-quarks is dominating. (b) Cross section for different production modes as a function of the centre-of-mass energy, adapted from Ref. [40]. The dashed lines indicates the Run-1 and Run-2 collision energies. The dominant production mode is ggF, followed by VBF, $VH$ and $t\bar{t}H$.

also included in the recently published measurements demonstrating evidence for the production mode with an associated top-quark pair [43, 44]. The $WW^*$ decay mode, the main topic in this thesis, has the second largest branching ratio at 21%. The relatively large rate makes this channel efficient in probing the Higgs boson production cross sections as well as coupling parameters, in particular the coupling to the $W$ boson. Final states in which either of the $W$ bosons decays hadronically are typically not studied due to overwhelming backgrounds with jets. Instead, the $W \rightarrow \ell\nu$ mode is targeted by requiring an opposite-charge $\ell$ pair and missing transverse momentum. The presence of neutrinos in the final state makes it difficult to reconstruct the invariant mass of the Higgs boson. For that task, the $ZZ^*$ and $\gamma\gamma$ decay channels are better suited.

Both the $\gamma\gamma$ and the $ZZ^*$ decay channels allow for full reconstruction of the invariant mass of the Higgs boson, for $ZZ^*$ by considering $4\ell$ final states. The branching ratios $2.6\% \times (3.4\%)^2 = 0.003\%$ for $ZZ^* \rightarrow 4\ell$ and $0.2\%$ for $\gamma\gamma$ are small relative to the $WW^*$ decay, resulting in smaller datasets. In the clean $ZZ^* \rightarrow 4\ell$ topology there is less background than signal, while the $\gamma\gamma$ channel is characterised by a resonance peak over a large continuum background (signal-to-background ratio of a few per cent).

3The asterisk is not shown in the figure but should be there to emphasise that two $W$ bosons has a mass greater than that of the Higgs, forcing one of the $W$'s to go off-shell in the decay.
The $H \to \tau\tau$ and $H \to \mu\mu$ decay modes are interesting as they directly probe the lepton Yukawa coupling parameters. While the decay to $\tau$ leptons has a fairly large branching ratio (6.3%), the mode is complicated due to the preference of taus to decay hadronically (65%), producing final states drowning in multijet backgrounds. The muon decay mode is clean but has a low branching fraction at 0.02%, due to the low muon mass.

![Figure 6.2: Higgs boson branching ratios as a function of the Higgs boson mass, adapted from Ref. [45]. The dashed line marks 125 GeV. Of particular interest in this thesis is the $WW^*$ decay mode with branching ratio 21%.](image)

6.1.1 Run-1 legacy

During Run-1 of the LHC the Higgs boson was discovered and its properties measured with accuracies possible with the dataset size. The discovery was announced by ATLAS and CMS in July 2012 (the publications came out in September the same year, see Ref. [9, 10]), following the observed excess driven by the $ZZ^* \to 4\ell$, $WW^*$ to leptons and $\gamma\gamma$ decay channels. At the end of Run-1, ATLAS and CMS combined their respective measurements with the full dataset corresponding to about 5 fb$^{-1}$ of 7 TeV data and 20 fb$^{-1}$ of 8 TeV data, per experiment, into joint publications [46, 47]. The ggF and VBF production mechanisms have both been established at more than 5$\sigma$ significance level, as has each of the decay channels $WW^*$, $ZZ^*$, $\gamma\gamma$ and $\tau\tau$. There is also evidence at a lower significance level for the $VH$ and $t\bar{t}H$ production modes and the $b\bar{b}$ and $\mu\mu$ decay channels.

The $ZZ^* \to 4\ell$ and $\gamma\gamma$ channels are used for high-resolution mass measurements, as presented in fig. 6.3a. Combining all measurements (the bottom of the plot) yields a mass of 125.09 ± 0.24 GeV.

Using all available channels and making a combined fit, the Higgs boson coupling parameters have been constrained. Using a framework with “coupling modifiers”, denoted $\kappa$, the production and decay rates are parametrised as $\kappa_j^2 = \sigma_j/\sigma_{j,SM}^2$ for
production process $j$ and correspondingly $\kappa_j^2 = \Gamma_j/\Gamma_j^{SM}$ for decay mode $j$. In fig. 6.3b the couplings to vector bosons and fermions are shown as a function of the mass of the particle. The black points are the combined data, the dashed blue line shows the SM expectation, the solid red line with green and yellow bands shows the best fit with its corresponding uncertainty at 68% and 95% confidence level, respectively. The $y$ axis shows the coupling parameter (for fermions) or the square root of the coupling parameter (for vector bosons). As explained in section 2.1.2 the Higgs boson–vector boson coupling parameter is proportional to $m_V^2$, while the Yukawa coupling is proportional to $m_f$. The data is compatible with the linear expectation from the SM theory.

In the SM, the Higgs boson is a scalar and has positive parity and charge conjugation quantum numbers; $J^{CP} = 0^{++}$. By studying Higgs bosons decaying to diboson pairs, ATLAS and CMS has tested this hypothesis against data [48, 49]. The observation of a $\gamma\gamma$ signal disfavours the spin-1 hypothesis due to the Landau-Yang theorem [50, 51]. Distinguishing between the SM spin-0 and other graviton-like spin-2 or CP-odd spin-0 scenarios is done through studying sensitive variables. Likelihoods are built with e.g. the diphoton transverse momentum in the $\gamma\gamma$ channel, the dilepton invariant mass the $H\rightarrow WW^* \rightarrow e\nu\mu\nu$ channel and production and decay angles of the $Z$ bosons and the leptons in the $ZZ^* \rightarrow 4\ell$ channel. The likelihoods are input to test statistics used to test the compatibility with the different hypotheses. For both ATLAS and CMS the data favours the SM hypothesis and a range of alternative spin-CP models are excluded at more than 99.9% confidence level.

For this plot, the parametrisation assumes there are only SM particles in the ggF and $\gamma\gamma$ loops.
6.2 The Run-2 $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ cross section measurements

In this section we begin covering the main topic of the thesis: the measurement of the ggF and VBF Higgs boson cross sections in the $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ decay mode using using ATLAS data from Run-2. The measurements are published in Ref. [52]; it will here be described in more detail. This first section outlines the analysis strategy and background estimations.\(^5\) The statistical treatment and results are presented later in chapter 8.

The measurement consists of two separate analyses, targeting the ggF and VBF production modes respectively. The ggF analysis considers final states with zero or one jet, the VBF analysis requires at least two jets, tagging the two forward high-energy jets typical of VBF production. A multivariate discriminator is used in the VBF analysis which has a lower expected signal yield, while a more classic cut-based approach is used in the ggF analysis.

Figure 6.4 illustrates the $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ decay. To suppress backgrounds with hadronic activity (which have large cross sections) the measurement is limited to leptonic final states. More specifically, only different-flavour (DF) final states with one (anti-)electron and one (anti-)muon are considered. Due to their preference to decay hadronically, tau leptons are not considered, except the small contribution from $W \rightarrow \tau\nu \rightarrow \ell\nu\bar{\nu}\nu$. In this thesis, “lepton” will be used interchangeably with $\ell$ to denote a final state (anti-)electron or (anti-)muon. To be compatible with a neutral Higgs boson, the two leptons are required to be of opposite electric charge (OC). The same-flavour (SF) channels are not considered due to the low sensitivity caused by the Drell-Yan background. In the figure, the wide arrows show the spin projection on to the respective particles direction of motion, indicated by the small arrows. The leptons from the Higgs boson decay are typically emitted with a small opening angle between them. This is due to the $V-A$ structure of the weak interaction and angular momentum conservation in the decay chain Higgs boson (scalar) $\rightarrow W$ boson (vector) $\rightarrow$ fermions. In contrast, leptons from non-resonant $WW$ production are emitted isotropically.

6.2.1 Simulated samples

Several simulated samples are used for cross validation and to predict background contributions. In table 6.1 the generators used for the different samples are shown. Also listed are the predicted cross sections times branching ratios, and the order of the cross section calculation. For $Z/\gamma^* \rightarrow \ell\ell$ ($Z^*Z^* \rightarrow 2\ell2\nu$) the samples are filtered for $m_{\ell\ell} > 10$ GeV ($m_{\ell\ell} > 4$ GeV). Different programs may be used for the hard interaction generation and the parton shower. For the signal and a few of the background samples, PYTHIA 8 or PYTHIA 6 is used for the parton shower. The dileptonic $t\bar{t}$ is estimated completely with PYTHIA 8. All signal samples and the $Wt$ sample use POWHEG for the hard interaction process. The bulk of the

\(^5\)Except the misidentified lepton backgrounds which will be covered in detail in chapter 7.
Figure 6.4: Illustration of the $H \rightarrow WW^*$ leptonic decay. The small arrows denote the particle direction of motion, the wide arrows the spin projection on to the direction of motion. Due to angular momentum conservation and the chiral structure of the weak interaction the $\ell^- \ell^+$ pair are preferentially emitted with a small opening angle in the laboratory frame.

Table 6.1: Overview of simulation tools used to generate signal and background processes, and to model the parton shower, hadronisation and underlying event (UEPS). The parton distribution functions (PDF) are also summarised. Alternative event generators and configurations used to estimate systematic uncertainties are shown in parentheses. Table from Ref. [52].

6.2.2 Data sample and triggers

The data used for the analysis was collected in 2015 and 2016 at a collision energy $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 36.1 fb$^{-1}$ and passing data quality requirements. The sample is collected with single electron, single muon...
and dilepton $e\mu$ triggers as listed in table 6.2. As the instantaneous luminosity increased over the time of running, the $p_T$ thresholds or quality criteria of the single lepton triggers were raised or tightened to keep the trigger rate under control. As this was done two times, once between 2015 and 2016 data taking, once mid-2016 data taking, the data sample is split in three periods denoted 2015, 2016a and 2016b. To maximise the total trigger efficiency, events are selected using an OR between all the three types of triggers (single electron, single muon and dilepton) and three $p_T$ regions (low-, intermediate- and high). The dilepton trigger have lower $p_T$ thresholds compared to the single lepton triggers, giving a higher efficiency at low $p_T$ and enabling a lowering of the analysis-level (offline) threshold (the lepton $p_T$ selections will be presented in section 6.2.5). By adding this trigger, the trigger efficiency of the signal increased by about 10% with respect to using single lepton triggers only.

<table>
<thead>
<tr>
<th>Period</th>
<th>Lepton</th>
<th>low-$p_T$</th>
<th>intermediate-$p_T$</th>
<th>high-$p_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>$e$</td>
<td>24-Medium</td>
<td>60-Medium</td>
<td>120-Loose</td>
</tr>
<tr>
<td></td>
<td>$\mu$</td>
<td>20-isolation</td>
<td>50</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$e\mu$</td>
<td>17-Loose ($e$), 14 ($\mu$)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2016a</td>
<td>$e$</td>
<td>24-Tight-isolation</td>
<td>60-Medium</td>
<td>140-Loose</td>
</tr>
<tr>
<td></td>
<td>$\mu$</td>
<td>24-isolation</td>
<td>50</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$e\mu$</td>
<td>17-Loose ($e$), 14 ($\mu$)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2016b</td>
<td>$e$</td>
<td>26-Tight-isolation</td>
<td>60-Medium</td>
<td>140-Loose</td>
</tr>
<tr>
<td></td>
<td>$\mu$</td>
<td>26-isolation</td>
<td>50</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$e\mu$</td>
<td>17-Loose ($e$), 14 ($\mu$)</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 6.2: The triggers used to collect the dataset for the $H \to WW^* \to e\nu\mu\nu$ analysis. The numbers stand for $p_T$ threshold in GeV. With increasing luminosity and pileup, thresholds increased over time, explaining the dependence on the three different data taking periods shown in the left column. The Loose, Medium and Tight denote likelihood identification criteria. Events are selected with an OR between the three types of triggers (single-$e/\mu$ and dilepton) and the three $p_T$ regions.

### 6.2.3 Object definitions

As a first level filtering, events are selected which have at least two leptons. At this stage, the leptons are loosely reconstructed and multiple objects may overlap in space. Next, a dedicated overlap removal procedure is performed, selecting which of overlapping objects to keep and which to reject. Once completed, all visible objects have been identified and the $E_T^{miss}$ can be built from them. More stringent cuts are thereafter applied to the leptons. The identification criteria are optimised as a trade-off between wanting a high efficiency to detect muons and electrons (i.e.
minimising signal loss) and keeping contributions from misidentified lepton backgrounds under control. One important tool for suppressing misidentified leptons is to apply isolation requirements. An isolated object has no or little activity in its vicinity. The activity can be computed both with tracks and with calorimeter deposits by measuring the corresponding quantities inside a cone of radius $\Delta R$ surrounding the object. The selection criteria for electrons are shown in table 6.3. Tighter criteria are used for electrons with $p_T \leq 25$ GeV as compared to electrons with $p_T > 25$ GeV, to suppress misidentified electrons which are more numerous in the low-$p_T$ region. In this region, cuts are made on the isolation variables $E_{T, iso}^{cone20}$ and $p_{T, iso}^{\text{varcone40}}$, corresponding to the transverse momentum not associated to the electron, calculated from calorimeter energy deposits and from tracks respectively. The calorimeter based variable measures deposits inside a cone of size $\Delta R = 0.2$ around the electron. The track based variable has $p_T$ dependent cone size according to the formula $\Delta R = 10/p_T$, with $p_T$ given in GeV, however with a maximum cone size to prevent it from blowing up at low transverse momentum. The $p_{T, iso}^{\text{varcone40}}$ variable has a maximum cone size $\Delta R = 0.4$ (used for $p_T \leq 25$ GeV). Electrons with transverse momentum $p_T$ are required to pass $E_{T, iso}^{cone20}/p_T < 0.11$ and $p_{T, iso}^{\text{varcone40}}/p_T < 0.06$. For electrons with transverse momentum above 25 GeV, the so-called “Gradient” isolation is used. Rather than a fixed cut, it has a map of cut values designed to have an overall efficiency increasing with $p_T$. It utilises the variables $E_{T, iso}^{cone20}$ and $p_{T, iso}^{\text{varcone20}}$, both normalised to $p_T$. With this approach, the resulting efficiency increases from 90% at $p_T = 25$ GeV to 99% at $p_T = 60$ GeV. 

For electrons with $p_T \leq 25$ GeV the likelihood discriminator is required to be Tight, while relaxing it to Medium quality above 25 GeV. Furthermore, electrons are required to have “Author” equal to one, indicating that it at reconstruction level passed only as an electron and not simultaneously as a photon. Finally, to reduce the chance of selecting electrons from secondary or pileup interactions, transverse and longitudinal impact parameter requirements are put at $|d_0|/\sigma_{d_0} < 5$ and $|z_0 \cdot \sin \theta| < 0.5$ mm, respectively. They are calculated with the track associated to the electron, with respect to the hard-scatter vertex.

<table>
<thead>
<tr>
<th>Range</th>
<th>Quality</th>
<th>Author</th>
<th>Isolation</th>
<th>Impact parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T \leq 25$ GeV</td>
<td>Tight</td>
<td>1</td>
<td>$\begin{cases} E_{T, iso}^{cone20}/p_T &lt; 0.11 \ p_{T, iso}^{\text{varcone40}}/p_T &lt; 0.06 \end{cases}$</td>
<td>$</td>
</tr>
<tr>
<td>$p_T &gt; 25$ GeV</td>
<td>Medium</td>
<td>1</td>
<td>Gradient</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.3: Selection criteria defining signal electrons in the $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ analysis.

For muon candidates, no significant improvement was found from staggering the selections in $p_T$, like is done for electrons. Muons are required to pass

- the Tight identification criterion,
- $E_{T, iso}^{cone20}/p_T < 0.09$ and $p_{T, iso}^{\text{varcone40}}/p_T < 0.06$,
- $|z_0 \cdot \sin \theta| < 0.5$ mm and $|d_0|/\sigma_{d_0} < 3$.  

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For the calorimeter based isolation criteria, the same variable as for electrons is used. A maximum cone size of $\Delta R = 0.3$ was found to be optimal for defining the track based isolation variable.

The selection criteria outlined above are applied for signal leptons. Looser requirements are used for misidentified leptons (see chapter 7).

To define a jet, additional selections are applied to the baseline jets from the reconstruction (explained in section 5.2.4). A jet is required to have $p_T > 30$ GeV and $|\eta| < 4.5$. Jets with $p_T < 60$ GeV and $|\eta| < 2.4$ are subject to a specific multivariate track based selection to reject jets from pile-up [84]. In the forward region where no tracking information is available, a different calorimeter based variable is used for the same purpose.

Jets originating from decays of $b$-hadrons are identified with a multi-variate $b$-jet tagging algorithm taking as input track- and secondary vertex information (see section 5.2.4). These jets can have a lower transverse momentum compared to the jets explained above, $p_T > 20$ GeV. To make clear the $p_T$ region relevant, we introduce the following notations for the number of $b$-jets in an event: $N_{b\text{-jet}, (p_T > 20\text{GeV})}$, $N_{b\text{-jet}, (p_T > 30\text{GeV})}$ and $N_{b\text{-jet}, (20\text{GeV} < p_T < 30\text{GeV})}$. The working point used has an 85% efficiency to identify jets coming from $b$-quarks, estimated in simulated $t\bar{t}$ events [85]. Correspondingly, the rejection rate for jets originating from a $c$-quark is 33.5.

Missing transverse momentum is naturally present in signal events due to the final state neutrinos escaping detection. In the ggF analysis, a selection requirement is applied to the magnitude of the missing transverse momentum built from tracks, $E_T^{\text{miss, track}}$. Furthermore, variables which require $E_T^{\text{miss}}$ in their construction, such as $m_{\tau\tau}$ and $m_T$, uses the TST $E_T^{\text{miss}}$ as it has proven to give the best resolution for the variables.

### 6.2.4 Common observables

This section defines common observables used in the analysis in some way, e.g. for selection requirements applied to suppress background. The use of the variables will become clear later. The following variables are defined

- $\Delta \phi_{\ell\ell}$ is the azimuthal opening angle between the two signal leptons,
- $m_{\ell\ell}$ is the invariant mass of the dilepton system,
- $p_T^{\ell\ell}$ is the transverse momentum of the dilepton system, with magnitude $p_T^{\ell\ell}$,
- $m_T$ is the transverse mass of the dilepton plus missing transverse energy, computed as
  $$m_T^2 = (E_T^{\ell\ell} + E_T^{\text{miss}})^2 - |p_T^{\ell\ell} + E_T^{\text{miss}}|^2,$$
  where
  $$E_T^{\ell\ell} = \sqrt{(p_T^{\ell\ell})^2 + m_{\ell\ell}^2}.$$

The transverse mass is a measure of the invariant mass reconstructed only in the transverse plane. It is useful in this analysis as the longitudinal component of the missing momentum is unknown.

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$m_T^\ell$ is the transverse mass of a single lepton plus missing transverse energy, computed as

$$m_T^\ell = \sqrt{2p_T^\ell E_T^{\text{miss}}(1 - \cos(\phi^\ell - \phi_E^{\text{miss}}))}$$

A lepton originating from a promptly produced, on-shell $W$ boson typically has a large value of $m_T^\ell$.

$\Delta \phi_{\ell\ell,E_T^{\text{miss}}}$ is the azimuthal angle between the dilepton system and $E_T^{\text{miss}}$. The two are typically back-to-back for signal and most backgrounds. Events in which this angle is close to zero may have mis-measured objects and are therefore rejected.

### 6.2.5 Event selection

Common to both analyses (ggF and VBF) is a set of preselection cuts. They define the final state in terms of objects and electrical charges. The preselection criteria are

- exactly one pair of two opposite charge, different flavour ($e + \mu$) leptons,
- transverse momentum requirements on the leptons; $p_T^{\text{lead}} > 22$ GeV\(^6\) and $p_T^{\text{sublead}} > 15$ GeV, where “lead” denotes the highest-$p_T$ lepton and “sublead” the other one. The rationale for the asymmetric selections is that at least one of the $W$ bosons must be off-shell in the Higgs boson decay, so that one lepton is expected to have a lower energy,
- $m_{\ell\ell} > 10$ GeV, to suppress DY events and low-mass meson resonances.

The second step of the event selection is a jet multiplicity categorisation, aimed at separating the ggF and VBF production modes. The jet multiplicity distribution after the above preselection is shown in fig. 6.5. The dashed lines show the ggF and VBF signal expectations, scaled for visibility. As the VBF production naturally produces two jets, this signal is found predominantly for $N_{\text{jet}} \geq 2$. In contrast, jets in ggF production originates from initial state radiation by the incoming partons. Thus, the ggF signal falls of with jet multiplicity and is concentrated to $N_{\text{jet}} \leq 1$. In the first bin, $N_{\text{jet}} = 0$, the background is dominated by non-resonant $WW$ production, while top-quark backgrounds dominate the $N_{\text{jet}} = 1$ channel (and above). Production of top-quark-antiquark pairs produce the majority of all dilepton events at the LHC, however naturally associated with jets. Different backgrounds have different topology, implying that the total significance can be boosted by categorising the analysis in jet multiplicity, and thereafter apply customised selections. The ggF analysis is therefore divided into zero-jet and one-jet regions, while the VBF analysis requires two or more jets.

In the third and last event selection step custom kinematic selections are applied in each jet multiplicity region, enhancing the signal to background ratio. This step defines the signal regions (SRs) of the analyses.

\(^6\)The single lepton triggers both have $p_T$ thresholds above 22 GeV for the later data periods. Without the dilepton trigger this requirement would have to be increased.
In the next section, a brief overview the background estimation techniques will be described. Then, the ggF and VBF analyses are treated in more detail in section 6.2.7 and section 6.2.8, describing the second and third steps of the event selection and the respective background estimations.

6.2.6 Background estimation

Non-resonant $WW$ production, top-quark (mainly $t\bar{t}$) and Drell-Yan (mostly $Z \rightarrow \tau\tau$, from hereon denoted $Z/\gamma^*$) processes can all produce final states with an opposite-charge $e\mu$ pair, fulfilling the preselection characteristics. These backgrounds are normalised using data (with the exception of $WW$ in the VBF region) by defining dedicated control regions (CRs) enriched in the corresponding process. All CRs are included in the likelihood and the normalisation factors of these three backgrounds are left as free floating parameters in the fit (the fit procedure will be described in detail in chapter 8). One CR, and thus one normalisation factor, per background and jet multiplicity bin is used. The resulting post-fit normalisation factors are presented in table 6.4. The uncertainties are the sum in quadrature of statistic and systematic sources, taking into account nuisance parameter pulls and constraints. In the $N_{\text{jet}} = 0$ region the $Z/\gamma^*$ normalisation factor has a rather low value, found to be affected by misalignment of the inner detector distorting the track impact parameter of leptons coming from tau decays.
### Production of $W$ Bosons

Production of $W$ bosons in association with at least one jet constitutes a potential background if one jet is misidentified as a lepton. In addition, backgrounds from multijet production may also enter the signal regions if two jets are simultaneously misidentified. Such backgrounds with misidentified leptons are estimated with a fully data-driven method; both the shape and the normalisation is extracted from data. They are estimated in almost the same way in the ggF and VBF analysis. A detailed overview of these backgrounds is given in chapter 7.

Excluding $WW$ production, processes with two bosons may also enter the signal regions. For example, a leptonically decaying $WZ$ pair may result in three electrons or muons, which can pass the preselection if one of the leptons from the $Z$ fails to reconstruct (due to inefficiency or being outside acceptance). The photon in $V\gamma$ production can interact with the beam pipe via pair production, possibly giving rise to a reconstructed electron or positron. Such non-$WW$ diboson backgrounds are predicted with simulation both in terms of shape and normalisation, but validated in dedicated validation regions (VRs). The VRs apply the same kinematic selections as the SRs, but require the two leptons to be of the same charge.

6.2.7 Gluon–gluon fusion analyses

The selections applied in the ggF analyses are shown in table 6.5. Apart from the preselection, a fairly soft cut on the $E_T^{\text{miss, track}}$ is applied, mostly rejecting Drell-Yan events. To suppress top quark backgrounds, a veto on $b$-jets with $p_T > 20$ GeV is applied. This requirement is especially important for the $N_{\text{jet}} = 1$ region where top quark backgrounds are relatively large. In the $N_{\text{jet}} = 0$ channel, requirements on $\Delta \phi_{\ell\ell,E_T^{\text{miss}}}$ and $p_T^{\ell\ell}$ are applied. Pathological events (mostly from $Z \rightarrow \tau\tau$) with the missing transverse momentum collinear with the dilepton system are rejected by requiring $\Delta \phi_{\ell\ell,E_T^{\text{miss}}} > \pi/2$. The requirement $p_T^{\ell\ell} > 30$ GeV mainly rejects $Z \rightarrow \tau\tau$ events.

In the $N_{\text{jet}} = 1$ region, to suppress $Z \rightarrow \tau\tau$ events, the requirement $m_{\tau\tau} < m_Z - 25$ GeV is applied. The invariant mass of the ditau system, $m_{\tau\tau}$, is computed in the collinear approximation where it is assumed that the electrons or muons from the decay travel in the direction of the tau leptons [86]. The requirement of a lower bound on the maximum value of $m_T^{\ell\ell}$ rejects $Z/\gamma^* \rightarrow \tau\tau$ and multijet backgrounds.
After applying the background rejection selections, two further requirements are applied in both jet multiplicity regions; \( m_{\ell\ell} < 55 \text{ GeV} \) and \( \Delta \phi_{\ell\ell} < 1.8 \text{ radians} \). These requirements follow the \( H \rightarrow WW^* \rightarrow \ell\nu\ell\nu \) decay characteristics and suppress other backgrounds like \( WW \), top quark and misidentified leptons. The variables are strongly correlated; after applying \( m_{\ell\ell} \) requirement the \( \Delta \phi_{\ell\ell} \) requirement has limited rejection power. Still, some \( WW \) and \( Z \rightarrow \tau\tau \) background is suppressed by this final selection.

<table>
<thead>
<tr>
<th>Category</th>
<th>( N_{\text{jet}} = 0 )</th>
<th>( N_{\text{jet}} = 1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preselection</td>
<td>Two isolated, different flavour leptons (( \ell = e, \mu )) with opposite charge ( p_{\ell}^{\text{leadT}} &gt; 22 \text{ GeV} ), ( p_{\ell}^{\text{subleadT}} &gt; 15 \text{ GeV} ) ( m_{\ell\ell} &gt; 10 \text{ GeV} )</td>
<td></td>
</tr>
<tr>
<td>Background rejection</td>
<td>( E_{\text{T}}^{\text{miss, track}} &gt; 20 \text{ GeV} ) ( N_{b\text{-jet}}(p_T&gt;20\text{ GeV}) = 0 ) ( \Delta \phi(\ell\ell,E_{\text{T}}^{\text{miss}}) &gt; \pi/2 ) ( \max(m_{\ell}^{T}) &gt; 50 \text{ GeV} ) ( m_{\ell\ell} &gt; 30 \text{ GeV} )</td>
<td>( m_{\ell\ell} &lt; 55 \text{ GeV} ) ( \Delta \phi_{\ell\ell} &lt; 1.8 )</td>
</tr>
</tbody>
</table>

**Table 6.5:** Event selection criteria used for the ggF analyses. The first, second and third block denotes the preselection, the background rejection and the topological cuts respectively. The first and last are identical for \( N_{\text{jet}} = 0 \) and \( N_{\text{jet}} = 1 \) regions, while the background rejection cuts differ because of different background composition in the two regions.

Table 6.6 shows the event selection in the ggF \( N_{\text{jet}} = 0 \) analysis, starting from the \( E_{\text{T}}^{\text{miss, track}} \) requirement. The signal and background expectations at each selection requirement are given. The signal to background ratio increases from 0.02 to 0.12 after applying all selections. In the SR, non-resonant \( WW \) production is the dominating background, expected to yield six times as many events as the signal. Top quark and misidentified lepton backgrounds follow, with expected yields similar to that of the signal.

<table>
<thead>
<tr>
<th>Selection</th>
<th>Higgs</th>
<th>WW</th>
<th>VV</th>
<th>( t/Wt )</th>
<th>( Z/\gamma^* )</th>
<th>Mis-Id</th>
<th>( B_{\text{tot}} )</th>
<th>Higgs / ( B_{\text{tot}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_{\text{jet}} = 0 )</td>
<td>818.5 ± 3.2</td>
<td>15891 ± 51</td>
<td>1365 ± 29</td>
<td>7708 ± 38</td>
<td>9289 ± 94</td>
<td>3806 ± 49</td>
<td>38060 ± 130</td>
<td>0.02</td>
</tr>
<tr>
<td>( \Delta \phi(\ell\ell,E_{\text{T}}^{\text{miss}}) &gt; 1.57 )</td>
<td>811.3 ± 3.2</td>
<td>15786 ± 51</td>
<td>1293 ± 29</td>
<td>7509 ± 38</td>
<td>8772 ± 91</td>
<td>3645 ± 48</td>
<td>37010 ± 120</td>
<td>0.02</td>
</tr>
<tr>
<td>( p_{T}^{\ell} &gt; 30 \text{ GeV} )</td>
<td>692.0 ± 2.9</td>
<td>12684 ± 46</td>
<td>888 ± 23</td>
<td>6809 ± 36</td>
<td>1291 ± 42</td>
<td>2389 ± 36</td>
<td>24190 ± 84</td>
<td>0.03</td>
</tr>
<tr>
<td>( m_{\ell\ell} &lt; 55 \text{ GeV} )</td>
<td>577.0 ± 2.7</td>
<td>3052 ± 21</td>
<td>311 ± 13</td>
<td>1076 ± 14</td>
<td>180 ± 13</td>
<td>634 ± 17</td>
<td>5252 ± 36</td>
<td>0.11</td>
</tr>
<tr>
<td>( \Delta \phi_{\ell\ell} &lt; 1.8 )</td>
<td>536.3 ± 2.6</td>
<td>2825 ± 20</td>
<td>289 ± 13</td>
<td>1040 ± 13</td>
<td>250 ± 5.4</td>
<td>524 ± 16</td>
<td>4702 ± 32</td>
<td>0.11</td>
</tr>
<tr>
<td>( N_{b\text{-jet}} = 0 )</td>
<td>521.0 ± 2.6</td>
<td>2766 ± 20</td>
<td>277 ± 12</td>
<td>536 ± 10</td>
<td>25.0 ± 5.4</td>
<td>500 ± 15</td>
<td>4103 ± 30</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Table 6.6: Pre-fit yields for signal and background processes after each selection requirement applied to the \( N_{\text{jet}} = 0 \) ggF SR. Mis-Id denotes misidentified lepton backgrounds, \( B_{\text{tot}} \) denotes the total background. The signal is normalised by its SM prediction (\( \mu = 1 \)). The dashed red line denotes the ggF signal overlaid, scaled for visibility. The uncertainty is statistical only.

In fig. 6.6 the distributions of the selection variables in the \( N_{\text{jet}} = 0 \) analysis are shown, after all selections up to the relevant one have been applied. The ggF signal
is scaled for visibility, demonstrating the different shapes of the background and the signal.

For the \(N_{\text{jet}} = 1\) region, the corresponding signal and background expectations are shown in table 6.7. Having one jet in the final state, backgrounds with top quarks dominate, expected to be 4.5 times the signal expectation after applying all selections. Non-resonant \(WW\) is the second largest background followed by misidentified lepton sources, the latter expected to yield a similar number of events as the signal. The signal to background ratio increases from 0.01 to 0.10.

<table>
<thead>
<tr>
<th>Selection</th>
<th>Higgs</th>
<th>(WW)</th>
<th>(VV)</th>
<th>(t)/Wt</th>
<th>(Z/\gamma^*)</th>
<th>Mis-Id</th>
<th>(B_{\text{tot}})</th>
<th>Higgs / (B_{\text{tot}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(N_{\text{jet}} = 1)</td>
<td>569.9 ± 2.3</td>
<td>7929 ± 36</td>
<td>1217 ± 29</td>
<td>53860 ± 100</td>
<td>6838 ± 83</td>
<td>3207 ± 57</td>
<td>736520 ± 150</td>
<td>0.01</td>
</tr>
<tr>
<td>(N_{\text{b,jet}} = 0)</td>
<td>517.2 ± 2.2</td>
<td>7310 ± 34</td>
<td>1080 ± 27</td>
<td>8528 ± 39</td>
<td>6085 ± 78</td>
<td>2180 ± 41</td>
<td>25180 ± 110</td>
<td>0.02</td>
</tr>
<tr>
<td>(Z \to \tau \tau) veto</td>
<td>358.1 ± 1.9</td>
<td>4899 ± 28</td>
<td>498 ± 16</td>
<td>5608 ± 31</td>
<td>926 ± 28</td>
<td>900 ± 26</td>
<td>12750 ± 59</td>
<td>0.03</td>
</tr>
<tr>
<td>(m_{\ell\ell} &lt; 55) GeV</td>
<td>305.0 ± 1.7</td>
<td>1209 ± 14</td>
<td>214 ± 12</td>
<td>1306 ± 15</td>
<td>337 ± 16</td>
<td>339 ± 14</td>
<td>340 ± 32</td>
<td>0.09</td>
</tr>
<tr>
<td>(\Delta \phi_{\ell\ell} &lt; 1.8)</td>
<td>284.9 ± 1.7</td>
<td>1401 ± 13</td>
<td>188 ± 11</td>
<td>1236 ± 14</td>
<td>70.2 ± 8.2</td>
<td>274 ± 13</td>
<td>2870 ± 27</td>
<td>0.10</td>
</tr>
</tbody>
</table>

### Table 6.7: Pre-fit signal and background yields after each selection requirement applied to the \(N_{\text{jet}} = 1\) ggF SR. Mis-Id denotes misidentified lepton backgrounds, \(B_{\text{tot}}\) denotes the total background. The uncertainty is statistical only.

In fig. 6.7 the corresponding \(N_{\text{jet}} = 1\) selection variable distributions are shown. Each variable is plotted at the level where all selections up to the relevant variable have been applied (in the order as given by table 6.7). The dashed line shows the ggF signal expectation, scaled for visibility. Clear shape differences are observed between the signal and at least one of the backgrounds in each of the plots. The bottom plot shows the discriminant variable \(m_T\) after all selections have been applied.

### Background estimation in the ggF \(N_{\text{jet}} = 0\) analysis

The shapes of the \(WW\), top quark and \(Z/\gamma^*\) contributions are predicted with simulation. The normalisation of these backgrounds are constrained by data by including dedicated CRs, enriched in the corresponding background, in the likelihood fit. The definitions of the CRs are given in table 6.8. They are depleted of signal by inverting one or more of the signal region requirements. In addition, some selections may be loosened or removed to increase the statistical precision.

In the following sections, the modelling in the CRs will be shown before the fit, with pre-fit normalisation factors applied. These normalisation factors are obtained by scaling the relevant background yield to obtain the best data to background ratio in the CR. They need not be equal to the normalisation factors obtained from the fit.

The \(WW\) CR is defined by, in addition to the preselection and \(E_T^{\text{miss}}\), track requirements, considering the high \(m_{\ell\ell}\) region and loosening the \(\Delta \phi_{\ell\ell}\) requirement. To gain statistical precision, the \(p_T^{\ell\ell}\) and \(\Delta \phi(\ell\ell, E_T^{\text{miss}})\) selections are dropped. Its purity is approximately 68%. In fig. 6.8 the modelling of some important variables are shown for this CR. The pre-fit normalisation factors are applied, which for \(WW\) was measured to be 1.13±0.03 (stat). The bottom pad shows the ratio of data
Figure 6.6: Signal and background predictions of the selection variables in the ggF $N_{\text{jet}} = 0$ signal region. Each variable is plotted before applying its associated requirement, with the order of the selections given in table 6.6. The bottom right plot shows the discriminant variable $m_T$ after all selections have been applied. The red dashed line shows the ggF signal overlaid, scaled for visibility. The hatched region denotes the statistical uncertainty.
Figure 6.7: Signal and background predictions of the selection variables in the ggF $N_{\text{jet}} = 1$ signal region. Each variable is plotted right before applying its associated requirement, with the order of the selections as given in table 6.7. The bottom plot shows the discriminant variable $m_T$ after all selections have been applied. The red dashed line shows the ggF signal overlaid, scaled for visibility. The hatched region denotes the statistical uncertainty.

to the SM prediction. The uncertainty band is computed as the sum in quadrature of the statistical and the main sources of experimental systematic uncertainties. A
Table 6.8: Selection criteria defining the control regions in the ggF analyses. The selections are applied in addition to the preselection criteria. The control regions are used in the fit to constrain the normalisation, floated in the fit, of the corresponding backgrounds. Backgrounds not listed are either normalised to their cross section prediction and validated in a validation region, or estimated in a data-driven way.

| CR       | $N_{\text{jet}} = 0$                                                                  | $N_{\text{jet}} = 1$                                      | $E_{\text{T miss, track}} > 20$ GeV | $m_{\ell\ell} > 80$ GeV | $|m_{\tau\tau} - m_Z| > 25$ GeV | $N_{b\text{-jet.}(p_T>20)} = 0$ | $\max(m_{T_{\ell\ell}}) > 50$ GeV |
|----------|----------------------------------------------------------------------------------------|----------------------------------------------------------|-----------------------------------|-----------------------|---------------------------------|--------------------------------|-------------------------------|
| WW       | 55 < $m_{\ell\ell}$ < 110 GeV                                                         | $\Delta\phi_{\ell\ell} < 2.6$                           |                                  |                       |                                |                                |                               |
|          | $\Delta\phi_{\ell\ell},(20 GeV < p_T < 30 GeV) = 0$                                   |                                                          |                                  |                       |                                |                                |                               |
| top quark| $N_{b\text{-jet.}(p_T>30)} = 1$                                                         | $N_{b\text{-jet.}(p_T>20)} = 0$                          | $\Delta\phi_{\ell\ell} > \pi/2$ | $m_{\tau\tau} = m_Z - 25$ GeV |                                |                                |                               |
|          | $\Delta\phi(\ell\ell, E_{\text{T miss}}^\ell) > \pi/2$                              |                                                          |                                  |                       |                                |                                |                               |
|          | $p_{T_{\ell\ell}} > 30$ GeV                                                            |                                                          |                                  |                       |                                |                                |                               |
|          | $\Delta\phi_{\ell\ell} < 2.8$                                                         |                                                          |                                  |                       |                                |                                |                               |
| Z → ττ  | $\Delta\phi_{\ell\ell} > 2.8$                                                         | $m_{\tau\tau} > m_Z - 25$ GeV                           |                                  |                       |                                |                                |                               |
|          | $N_{b\text{-jet.}(p_T>20)} = 0$                                                         |                                                          |                                  |                       |                                |                                |                               |
|          | $\max(m_{T_{\ell\ell}}) > 50$ GeV                                                      |                                                          |                                  |                       |                                |                                |                               |

Events with $Z \rightarrow \tau\tau$ processes enter the signal region when the $\tau$ leptons decay leptonically. The final state electron and muon are expected to be back-to-back. The $Z/\gamma^*$ CR is defined by applying the preselection requirements, $\Delta\phi_{\ell\ell} > 2.8$, loosening the $m_{\ell\ell}$ requirement to 80 GeV and the $b$-jet veto. No $E_{T_{\text{miss, track}}}$ cut is applied. The resulting purity is 90%. In fig. 6.10 some kinematic variables are shown for this CR, with the pre-fit normalisation factors applied, measured to be good modelling is observed for all variables.

Background processes with top quarks, consisting of $t\bar{t}$ and $Wt$ production, may enter the SR since the top quark decays via a $W$ boson. They are however expected to be associated with one or more $b$-jets in the final state. The $b$-jet veto helps to suppress these backgrounds, but due to inefficiency of the identification algorithm and the large cross section some residual background enters the $N_{\text{jet}} = 0$ SR. A CR is constructed by requiring one $b$-jet with $20 < p_T < 30$ GeV, and loosening the $\Delta\phi_{\ell\ell}$ requirement to 2.8 radians. The $\Delta\phi(\ell\ell, E_{T_{\text{miss}}})$ and $p_{T_{\ell\ell}}$ selections are the same as in the SR. The purity of the top quark CR is 87%, and the top quark pre-fit normalisation factor applied was measured to 1.01 ± 0.02. Kinematic distributions for the top quark CR, with the pre-fit normalisation factors applied, are shown in fig. 6.9. The uncertainty band is computed as the sum in quadrature of the statistical and the main sources of experimental systematic uncertainties. The data is modelled well by simulation in all variables.
Figure 6.8: Kinematic distributions in the WW control region for the $N_{\text{jet}} = 0$ ggF analysis. The pre-fit normalisation factors are applied. The uncertainty band represents the sum in quadrature of the statistical uncertainty and experimental systematic rate uncertainties on the signal and backgrounds.

$0.88 \pm 0.01$ for $Z/\gamma^*$. The uncertainty band is computed as the sum in quadrature of the statistical and the main sources of experimental systematic uncertainties. The normalisation factor deviates significantly from one due to mismodelling of the $d_0$ variable of electrons and muons from $\tau$ decay, caused by inner detector misalignment. The same effect has been observed by other ATLAS analyses. After applying the normalisation factors, a good modelling is observed.

The non-WW diboson backgrounds are predicted by simulation, both in terms of shape and normalisation, and validated in the same-charge region. The VR
applies the same kinematic selections as the SR, but require the leptons to be of the same electrical charge. This requirement suppresses contributions from signal, $WW$, top quark and $Z/\gamma^*$ processes. The non-$WW$ backgrounds consist of $W\gamma$, $W\gamma^*$, $WZ$ and $ZZ$ production. The former three all have equal probability to produce a second lepton of either charge with respect to the charge of the lepton from the $W$. Production of $ZZ$ is not completely symmetric as the two leptons may come from one of the tau leptons in a $Z \to \tau\tau$ decay. However, the relative contribution from $ZZ$ is only 1.5% in the CR and 0.2% in the SR. In fig. 6.11 some kinematic distributions are shown for the same-charge validation region. A
Figure 6.10: Kinematic distributions in the $Z/\gamma^* \ell\ell$ control region in the ggF $N_{\text{jet}} = 0$ analysis. The pre-fit normalisation factors are applied. The uncertainty band represents the sum in quadrature of the statistical uncertainty and experimental systematic rate uncertainties on the signal and backgrounds.

A fairly good modelling of the data is observed. A significant fraction of the events originate from misidentified lepton backgrounds.

**Background estimation in the ggF $N_{\text{jet}} = 1$ analysis**

The background estimation in the $N_{\text{jet}} = 1$ channel follows the $N_{\text{jet}} = 0$ procedure but with control regions defined differently.

In addition to the preselection and $E_T^{\text{miss}}$, track cut, the $WW$ CR is defined by requirements on $m_{\ell\ell}$ and $\max(m_{\ell\ell})$ and applying $Z \to \tau\tau$ and $b$-jet vetoes, according to table 6.8. The resulting purity is relatively low at 39%, due to a large
Figure 6.11: Validation region for the non-\(WW\) diboson backgrounds in the ggF \(N_{\text{jet}} = 0\) analysis. The same selections as in the SR are applied, except that the leptons are required to have the same electrical charge. The uncertainty band represents the sum in quadrature of the statistical uncertainty and experimental systematic rate uncertainties on the signal and backgrounds.

contribution from top quark events of about 50%. The pre-fit normalisation factor equals \(1.01 \pm 0.04\) (stat). A good modelling is observed for all variables.

The top quark control region requires the jet to be identified as a \(b\)-jet, while vetoing sub-threshold \(b\)-jets \((N_{b\text{-jet}}(20\text{GeV},p_T<30\text{GeV}) = 0)\). All other SR cuts are applied. The resulting purity is 96%. Figure 6.13 shows a few distributions in the top quark CR, with the pre-fit normalisation factor, measured to be \(1.03 \pm 0.01\) (stat.), applied. A good modelling is observed.

The \(Z/\gamma^*\) \(N_{\text{jet}} = 1\) CR does not apply the \(E_T^{\text{miss}}\), track cut, and requires \(m_{\ell\ell} >\)
Figure 6.12: The $WW$ control region in the ggF $N_{jet} = 1$ analysis. Due to the jet, this region suffers from large contamination of top quark processes. The pre-fit normalisation factors have been applied. The uncertainty band represents the sum in quadrature of the statistical uncertainty and experimental systematic rate uncertainties on the signal and backgrounds.

80 GeV. Like in the SR, events with $b$-jets are rejected and the requirement on $\max(m_T^\ell) > 50$ GeV is applied. Lastly, the di-$\tau$ invariant mass requirement is inverted with respect to the signal region. The resulting purity is 73%. The pre-fit normalisation factor equals 0.87 ± 0.02 (stat). In fig. 6.14 some characteristics of the CR is shown, with the pre-fit normalisation factors applied. In all variables the data is well modelled by simulation.

The non-$WW$ diboson backgrounds are validated in a region with all SR requirements, except replacing the opposite-charge requirement by a same-charge
Figure 6.13: Top quark control region in the ggF $N_{\text{jet}} = 1$ analysis. The purity is about 96%. Pre-fit normalisation factors are applied. The uncertainty band represents the sum in quadrature of the statistical uncertainty and experimental systematic rate uncertainties on the signal and backgrounds.

one. In fig. 6.15 some kinematic distributions are shown for the $N_{\text{jet}} = 1$ VR. The limited yield makes it difficult to draw clear-cut conclusions, but the background prediction appears to agree reasonably well with the data. In the measurement of misidentified leptons in the $Z$+jets process (to be presented in chapter 7) it was found that the normalisation of the $WZ$ background is underestimated by MC by a factor of 1.15 (for POWHEG). Similar modelling issues has been reported in a $WZ$ production cross section measurement [87]. This effect is not corrected for in any of the ggF $N_{\text{jet}} = 0$, $N_{\text{jet}} = 1$ and VBF SRs, given it is a small background.
Figure 6.14: $Z/\gamma^*$ control region in the ggF $N_{jet} = 1$ analysis. Pre-fit normalisation factors are applied. The uncertainty band represents the sum in quadrature of the statistical uncertainty and experimental systematic rate uncertainties on the signal and backgrounds.

Signal extraction

After applying all selections, the signal extraction is done by making combined fit with normalisation factors for signal background processes ($WW$, top quark and $Z/\gamma^*$) floating. The ggF analyses uses $m_T$ as the discriminant variable. The fit regions and statistical procedure, followed by the results, is presented in chapter 8.
Figure 6.15: Validation region for the non-\(WW\) diboson backgrounds in the \(ggF\) \(N_{\text{jet}} = 1\) analysis. The same selections as in the SR are applied, except that the leptons are required to have the same electrical charge. The uncertainty band represents the sum in quadrature of the statistical uncertainty and experimental systematic rate uncertainties on the signal and backgrounds.

6.2.8 Vector boson fusion analysis

The VBF region requires two or more jets. The two jets with highest transverse momentum are identified as the ones originating from the quarks radiating the vector bosons \(q'\) in fig. 6.1a), referred to as the “VBF-induced jets”. In addition to the preselection, the following selection criteria are applied,

- \(b\)-jet veto; \(N_{b,\text{jet},(p_T>20\text{GeV})} = 0\),
• Central jet veto; reject events with a jet with $p_T > 20$ GeV in between the VBF-induced jets’ rapidity gap [88],

• Outside lepton veto; accept only events where the two leptons are inside rapidity gap of the VBF-induced jets [88],

• $Z \rightarrow \tau \tau$ veto; $m_{\tau \tau} < m_Z - 25$ GeV.

<table>
<thead>
<tr>
<th>Selection</th>
<th>SR</th>
<th>Top quark CR</th>
<th>$Z/\gamma^*$ CR</th>
<th>WW VR</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF topology</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Outside lepton veto</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>$N_{b\text{-jet,}(p_T&gt;20\text{GeV})} = 0$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transverse mass</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>$Z \rightarrow \tau \tau$</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>$m_{\ell \ell} &lt; 80$ GeV</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td></td>
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<tr>
<td>$m_{\ell \ell} &lt; 80$ GeV</td>
<td>–</td>
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<td>$m_{\ell \ell} &lt; 80$ GeV</td>
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</tr>
<tr>
<td>$m_{\ell \ell} &lt; 80$ GeV</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.9: Selection criteria defining the signal region (SR), top quark and $Z/\gamma^*$ control regions (CRs) and the $WW$ validation region (VR) in the VBF analysis. The control regions are used in the fit to constrain the normalisation of the corresponding backgrounds. Backgrounds not listed here are either normalised to their cross section predictions and validated in a validation region, or estimated in a data-driven way.

The signal region selection criteria are summarised in the left of table 6.9. The rightmost columns show the criteria used for the control and validation regions of the most important backgrounds. In table 6.10 the event yields for signal and background in the VBF signal region are reported. The $b$-jet veto is approximately 95% efficient in suppressing top quark backgrounds. The central jet veto rejects the different background processes at an efficiency of about 30%. The outside lepton veto rejects approximately 80% of the backgrounds while retaining almost 80% of the VBF signal. The $Z \rightarrow \tau \tau$ veto rejects about two thirds of the $Z/\gamma^*$ backgrounds. After the $Z \rightarrow \tau \tau$ veto, the VBF signal to background ratio is 0.02. Processes with top quarks dominate the background, followed by $WW$ production. The expected yield of ggF Higgs bosons is approximately the same as the expected VBF signal yield.

In fig. 6.16 the distributions of the selection variables in the SR are shown, with all selections up to the relevant criterium applied. The dashed red line shows the VBF signal overlaid (scaled for visibility), demonstrating the difference in shape with respect to the background.

Multi-variate discriminant

Given the low expected VBF signal yield compared to ggF production, the VBF analysis employs a multivariate technique to extract the most out of the statistically limited dataset. A boosted decision tree (BDT) [89] is trained after the $b$-jet veto requirement. Applying further selections leads to a too small training sample size. The training is performed with simulated samples as listed in table 6.11, where the corresponding number of events is listed. The ggF Higgs boson production
Table 6.10: Pre-fit event yields for signal and background processes in the VBF signal region. The selections are applied after applying the preselection criteria (see section 6.2.5). The bottom half of the table shows the yields in the four different BDT bins, with increasing signal purity. Uncertainties are statistical only.

<table>
<thead>
<tr>
<th>Selection</th>
<th>VBF</th>
<th>ggF</th>
<th>WW</th>
<th>VV</th>
<th>$t/Wt$</th>
<th>$Z/\gamma$*</th>
<th>Mis-Id</th>
<th>$B_{\text{tot}}$</th>
<th>VBF/$B_{\text{tot}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{b\text{-jet}} = 2$</td>
<td>97.5 ± 0.4</td>
<td>270.0 ± 1.6</td>
<td>6125 ± 17</td>
<td>1158 ± 28</td>
<td>241740 ± 220</td>
<td>7400 ± 70</td>
<td>5790 ± 90</td>
<td>262210 ± 250</td>
<td>0.00</td>
</tr>
<tr>
<td>$N_{b\text{-jet}} = 0$</td>
<td>84.2 ± 0.4</td>
<td>223.2 ± 1.5</td>
<td>5160 ± 16</td>
<td>923 ± 25</td>
<td>13760 ± 50</td>
<td>5940 ± 60</td>
<td>1280 ± 40</td>
<td>27010 ± 90</td>
<td>0.00</td>
</tr>
<tr>
<td>Central jet veto</td>
<td>64.6 ± 0.3</td>
<td>164.4 ± 1.3</td>
<td>3649 ± 14</td>
<td>621 ± 20</td>
<td>9190 ± 40</td>
<td>4360 ± 50</td>
<td>940 ± 30</td>
<td>18750 ± 80</td>
<td>0.00</td>
</tr>
<tr>
<td>Outside lepton veto</td>
<td>50.1 ± 0.3</td>
<td>43.2 ± 0.6</td>
<td>633 ± 6</td>
<td>134 ± 10</td>
<td>1973 ± 19</td>
<td>905 ± 26</td>
<td>205 ± 16</td>
<td>3870 ± 40</td>
<td>0.01</td>
</tr>
<tr>
<td>$Z \rightarrow \tau\tau$ veto</td>
<td>43.2 ± 0.3</td>
<td>38.4 ± 0.6</td>
<td>393 ± 5</td>
<td>76 ± 9</td>
<td>1281 ± 15</td>
<td>318 ± 17</td>
<td>113 ± 11</td>
<td>2181 ± 27</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Figure 6.16: Signal and background predictions of the selection variables in the VBF analysis. Each variable is plotted before applying its associated requirement, with the order as given in table 6.10. The VBF signal is scaled for visibility. The hashed band represents the statistical uncertainty.

(a) $N_{b\text{-jet}}$ after $N_{\text{jet}} = 2$
(b) $N_{\text{jet}}$ in rapidity gap after $b\text{-jet}$ veto
(c) Leptons-inside-gap boolean after central jet veto
(d) $m_{\tau\tau}$ after outside lepton veto

is classified as a background. Backgrounds with misidentified leptons is not used
in the training due to limited statistics. As these backgrounds are sub-dominant, training without them does not significantly degrade the performance.

<table>
<thead>
<tr>
<th>Process</th>
<th>Events for training</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBF</td>
<td>7632</td>
</tr>
<tr>
<td>ggF</td>
<td>9448</td>
</tr>
<tr>
<td>(tt)</td>
<td>99788</td>
</tr>
<tr>
<td>(Wt)</td>
<td>4375</td>
</tr>
<tr>
<td>(WW)</td>
<td>99836</td>
</tr>
<tr>
<td>(Z\rightarrow\tau\tau)</td>
<td>54269</td>
</tr>
</tbody>
</table>

Table 6.11: Processes and corresponding MC statistics available for training of the BDT classifier used in the VBF analysis. An independent set of samples of similar size is used for cross-validation and tests for overtraining.

Eight variables sensitive to differences between signal and background are used; \(\Delta \phi_{\ell \ell}, m_{\ell \ell}, m_T, \Delta y_{jj}, m_{jj}, p_T^{\text{tot}}, \sum_{\ell,j} m_{\ell j} \) and \(\sum_{\ell} C_{\ell} \). The first three were described in section 6.2.4, the remaining are

\[ \Delta y_{jj} \] is the rapidity gap between the two VBF-induced jets in the event,

\[ m_{jj} \] is the invariant mass of the two leading jets in the event,

\[ p_T^{\text{tot}} \] is the magnitude of the vectorial sum

\[ \vec{p}_T^{\text{lead}} + \vec{p}_T^{\text{sublead}} + \vec{E}_T^{\text{miss}} + \sum_{\text{jets}} \vec{p}_T^{\text{jet}}, \]

where the sum runs over all jets passing the jet defining criteria.

\( \sum_{\ell,j} m_{\ell j} \) is the sum of the invariant masses of all four possible lepton-jet pairs.

\( \sum_{\ell} C_{\ell} \) denotes the “\( \eta \) centrality” of the di-lepton system, measuring how central the leptons are with respect to the two VBF-induced jets:

\[ C_{\ell} = \left| \left( \eta_{\ell} - \frac{\sum \eta_{j}}{2} \right) / \frac{\Delta \eta_{jj}}{2} \right|, \]

where the sum runs over the two VBF-induced jets and \( \Delta \eta_{jj} \) denotes the difference in rapidity between them.

The relative importance of the variables have been ranked and reaches from 19% for the most highly ranked \( m_{jj} \) to 7% for the least important \( p_T^{\text{tot}} \). The distributions of the four highest ranked variables are shown in fig. 6.17, plotted after the \( b \)-jet veto criterium at which level the BDT is trained. The VBF signal is scaled by 300 for visibility.
The BDT is implemented using the scikit-learn interface \cite{90}. A grid scan was performed to determine the optimal hyperparameters.

The output score of the BDT ranges from −1 to 1 and is binned in four bins as \([-1,0.26,0.61,0.86,1]\). The binning was optimised by a significance scan procedure using the formula \cite{91}

\[
\text{significance} = \frac{N_S}{\sqrt{N_S + N_B + \Delta N_B^2}},
\]

where \(N_S\) is the number of signal events, \(N_B\) the number of background events and \(\Delta N_B\) the sum of statistical uncertainties on the backgrounds. This definition makes the scan robust against statistical fluctuations, and results in smaller bins at the high-score end where most of the signal is expected. The procedure is iterative, scanning the BDT output for the boundary providing the best significance. This process is repeated starting from the first boundary to obtain a second one; iterating until the significance no longer improves. The resulting expected VBF signal to
background ratio in the last bin is 0.62 (see table 6.10), with an expected VBF signal yield of $24.7 \pm 0.2$.

A BDT has the potential to be “overtrained”, meaning that it is taught to recognise the statistical fluctuations of the training sample. To avoid this, cross-validation is performed by training two sets of BDTs on two independent halves of the initial training dataset. In fig. 6.18 the BDT outputs are shown, signal in red and background in blue. The left hand plot has been trained with one half of the sample (histogram), and validated with the other half (data points). In the right hand side the training and validation samples are swapped. No significant overtraining problems are observed.

![Figure 6.18: Cross-validation of the BDT training. The histograms show the BDT scores for the signal (red) and background (blue) for two statistically independent samples. The left hand side is trained with one half and validated with the other, in the right hand plot the training and validation samples are swapped.](image)

**Background estimation in the VBF analysis**

Contrary to the ggF analysis, no $WW$ CR is used in the VBF analysis. Instead the $WW$ is estimated with simulation and validated in a validation region. The misidentified lepton backgrounds includes a correction for multijet backgrounds, see chapter 7. For all other backgrounds, the estimation follows the ggF procedure.

The top quark CR is applies all SR selection requirements (up to and including the $Z \to \tau\tau$ veto) except inverting the $b$-jet criterium to require exactly one $b$-jet, see table 6.9. Requiring exactly one rather than having an inclusive selection makes the jet flavour composition of the VBF-induced jets more similar to the composition in the SR. In fig. 6.19 the distribution of the four most important training variables are shown for the top quark CR. The purity is approximately 96%, and the pre-fit normalisation factor is measured to be $1.02 \pm 0.01$ (stat.). A good modelling is observed in all variables.
The $Z/\gamma^*$ control region is defined as listed in table 6.9. The central jet- and outside lepton vetoes are applied like in the SR. Instead of the $Z \rightarrow \tau\tau$ veto the di-tau lepton invariant mass is required to be inside the $Z$ boson mass window; $|m_{\tau\tau} - m_Z| < 25$ GeV. Lastly, the di-lepton invariant mass requirement $m_{\ell\ell} < 80$ GeV is applied. The resulting purity is about 74%, and the pre-fit normalisation factor is measured to $0.97 \pm 0.07$ (stat.). In fig. 6.20 the distributions of the four most important BDT training variables are shown for the $Z/\gamma^*$ CR, with the top quark and $Z/\gamma^*$ pre-fit normalisation factors applied. The yields are statistically limited,
but a fairly good modelling is observed.

**Figure 6.20:** $Z \rightarrow \tau\tau$ control region in the VBF analysis. The four most important BDT training variables are shown. Top quark and $Z/\gamma^*$ pre-fit normalisation factors are applied. The uncertainty band represents the sum in quadrature of the statistical uncertainty and experimental systematic rate uncertainties on the signal and backgrounds.

Defining a region pure in the $WW$ background is very difficult for the $N_{\text{jet}} \geq 2$ final state due to contamination from $tt$ events. No gain in significance was observed when using a CR in the fit. Instead, the $WW$ background is validated in a VR, defined using the $m_{T2}$ variable [92],

$$m_{T2} = \min_{\not{p}_1 + \not{p}_2 = \not{p}_T} \left[ \max\{ m_{T}^2(p_{T}^{\text{vis1}}, \not{p}_1), m_{T}^2(p_{T}^{\text{vis2}}, \not{p}_2) \} \right],$$

where vis1 and vis2 denote the two visible decay parts of the top quark and the top anti-quark, $\not{p}_1, \not{p}_2$ the invisible parts. Only the leading jet and either of the leptons
are used in the computation of the visible part. While $WW$ production does not have an upper bound in $m_{T2}$, $t\bar{t}$ production does since the $W$ bosons originate from a top (anti-)quark decay. The $m_{T2}$ variable represents a lower bound on the parent particle’s mass, meaning that for $t\bar{t}$ the $m_{T2}$ spectrum will fall off at an edge around the top quark mass. The validation region is defined by requiring transverse mass requirements in addition to the preselection and central jet veto requirements, see table 6.9. Events are required to pass $m_T > 130$ GeV and $m_{T2} > 160$ GeV. The resulting region has a $WW$ purity of about 42%. In fig. 6.21 the distributions of the four most important training variables are shown. Decent modelling of the data is observed.

The contribution from ggF Higgs boson production is comparable to the VBF signal and thus constitutes an important background. Its normalisation is largely constrained by the ggF analyses in the simultaneous fit (see chapter 8).

**Signal extraction**

The VBF analysis uses the BDT score as the discriminant variable. The combined fit and the results are explained in detail in chapter 8.
Figure 6.21: Distributions of the four most important BDT training variables in the $W W$ validation region in the VBF analysis. Top quark and $Z/\gamma^*$ pre-fit normalisation factors are applied. The uncertainty band represents the sum in quadrature of the statistical uncertainty and experimental systematic rate uncertainties on the signal and backgrounds.
Chapter 7

Misidentified lepton background estimation

"Have you seen my lookalike? Have you seen he’s got my eyes?"
— Sahara Hotnights

This chapter presents a detailed overview of the misidentified lepton background estimates in the \( H \rightarrow W W^* \rightarrow e\nu\mu\nu \) analysis presented in the preceding chapter. This is the author’s main contribution to the analysis.

7.1 Introduction

The signature for \( H \rightarrow W W^* \rightarrow \ell\nu\ell\nu \) is two collimated, isolated, leptons plus missing transverse momentum. Processes with a leptonically decaying \( W \) boson may enter as background when an associated object is misidentified as a lepton. A misidentified lepton is also denoted a fake lepton; an object identified as a lepton but not originating from the decay of a promptly produced \( W \) or \( Z \) boson. Together with the neutrino from the \( W \) boson decay, giving rise to missing transverse momentum, the misidentification mechanism allows the \( W \)+jets process to mimic all signal characteristics and contaminate the signal region. Furthermore, multi-jet processes may also contribute, if artificial \( E_T^{\text{miss}} \) is measured and two objects simultaneously misidentify as leptons.

There are several sources of misidentified leptons. It may be a real lepton from leptonic or semi-leptonic decays of hadrons made of heavy flavour quarks (\( b-, c- \) or \( s \) quarks). For example, a kaon may decay in-flight within the detector volume to a final state with a muon, then traversing the muon system. Alternatively, they may be of jet-like nature, such as a jet with a high-energy \( \pi^0 \) decaying to two...
photons. Two collimated photons (matched to an inner detector track) have a similar detector signature to that of an electron.

The misidentification is a rare phenomenon; depending on the lepton flavour, the topology considered and the lepton identification criteria used, the probability for a jet to misidentify as a lepton lies somewhere in the regime $10^{-5} - 10^{-4}$. Nonetheless, $W$+jets constitutes a non-negligible background owing to its much larger cross section compared to Higgs boson processes. Processes with a $W$ boson are more than three orders of magnitude more probable than Higgs boson production, see fig. 7.1. The relative strength of $W$+jets compared to Higgs boson production is further increased when factoring in the branching ratio for the $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ decay mode.

![Standard Model Total Production Cross Section Measurements](image)

**Figure 7.1:** Production cross sections of different SM processes as measured by ATLAS, along with theoretical predictions. In purple at the values at $\sqrt{s} = 13$ TeV. Theoretical predictions, calculated at NLO or higher, are shown in grey. Figure from Ref. [93].

Because the misidentification rate is low, it is difficult to accurately predict in simulation. Therefore, the fake lepton background is estimated with a data-driven technique. Both the normalisation and the shape is taken from fake-enriched data samples, after correcting for real lepton “contamination” using MC simulation. The method used is denoted the *fake factor* method and will be outlined in the next section.
Misidentified lepton backgrounds may be separated into the two components “single-fake” and “double-fake”, denoting contributions from $W$+jets (one fake lepton) and multijet (two fake leptons) processes, respectively. Consider the following expression for the number of events in the signal region, containing two id leptons, separating in prompt and fake parts,

$$N_{\text{id+id}}^{\text{id+id}} = N_{\text{id+id}}^{\text{prompt}} + N_{\text{id+id}}^{\text{Misid}} = N_{\text{id+id}}^{\text{prompt}} + N_{\text{id+id}}^{W+\text{jets}} + N_{\text{id+id}}^{\text{multijet}},$$

where the $N_{\text{id+id}}^{\text{prompt}}$ term denotes all processes with two prompt leptons (including signal processes), $N_{\text{id+id}}^{\text{Misid}}$ denotes the yield from sources with misidentified leptons, which is the sum of $W$+jets single-fake and multijet double-fake contributions ($N_{\text{id+id}}^{W+\text{jets}}$ and $N_{\text{id+id}}^{\text{multijet}}$, respectively). The rate of double-fake processes is smaller than that of single-fake processes, as both the electron and the muon must be simultaneously misidentified. Therefore, the $W$+jets process is the main background of interest and the primary focus of this chapter. The multijet background treatment is further outlined in section 7.7.

### 7.2 The fake factor method

The fake factor method for estimating misidentified lepton backgrounds has two main ingredients,

- the **control sample**, designed to be rich in misidentified objects, from which the kinematic shape is extracted,

- the **extrapolation factor**, used to transfer the control sample yields to the signal region and thereby fixing the normalisation of the estimate.

The control sample is defined by the same kinematic selections as the signal sample, but requiring one of the two leptons to fail the identification criteria (see section 6.2.3), and instead satisfy a less restrictive set of selections. A lepton passing these requirements is said to be **anti-identified** (anti-id). To understand why this definition yields a fake-enriched sample, consider misidentified muons. They originate almost exclusively from semi-leptonic decays of heavy quarks (this will be shown in section 7.5). Muons from such decays are likely accompanied by nearby hadrons. By inverting the isolation criteria (i.e. requiring the muon not to be isolated) we thus enrich the selected muon sample with non-prompt muons. The number of events in the control sample may then be written as

$$N_{\text{id+id}}^{\text{anti-id}} = N_{\text{id+id}}^{W+\text{jets}} + N_{\text{id+id}}^{\text{multijet}} + N_{\text{id+id}}^{\text{prompt}},$$

where the strike-through denotes anti-id. The yield of events with misidentified leptons is obtained by subtracting the prompt lepton background contribution from the observed data yield, using MC. When the contribution from multijet processes is small enough to be neglected, the resulting yield is interpreted as coming from $W$+jets processes alone. The validity of this approximation is investigated in ??.
The multijet contribution is found to be substantial in the VBF region, calling for a proper treatment. With that exception, the multijet contribution is assumed to be negligible in what follows.

To extrapolate from the control sample to the signal region an extrapolation factor is applied. The extrapolation factor is denoted “fake factor”, hence the name of the method. It is measured separately for fake muons and fake electrons, as a function of $p_T$ and $|\eta|$, according to

$$FF(p_T, |\eta|) = \frac{N_{\text{id}}}{N_{\text{id}^\text{anti}}}(p_T, |\eta|)$$  (7.2)

where $FF$ stands for fake factor and $N_{\text{id}}$ ($N_{\text{id}^\text{anti}}$) is the number of id (anti-id) leptons. It may be evaluated in any sample enriched in fake objects. In this estimation a $Z$+jets sample is used primarily (see section 7.3) and a multijet sample secondarily (see section 7.4). Putting the two ingredients together, the fake lepton background estimation in the signal region is obtained to first order accuracy as

$$N_{\text{id},\text{id}}^{W+jets} = FF \times N_{\text{id},\text{id}}^{W+jets} = FF \times (N_{\text{id},\text{id}^\text{anti}} - N_{\text{id},\text{id}^\text{anti}}^{\text{prompt}})$$  (7.3)

This estimate is refined by including a correction factor ($CF$), estimated using simulation, accounting for differences in fake sample composition between the $W$+jets process and the $Z$+jets process,

$$N_{\text{id},\text{id}}^{W+jets} = FF^{W+jets} \times N_{\text{id},\text{id}^\text{anti}}^{W+jets} = FF^{Z+jets} \times \frac{FF^{W+jets}}{FF^{Z+jets}} \times N_{\text{id},\text{id}^\text{anti}}^{W+jets} = FF^{Z+jets} \times CF \times (N_{\text{id},\text{id}^\text{anti}} - N_{\text{id},\text{id}^\text{anti}}^{\text{prompt}})$$  (7.4)

where in the last equality we have defined the $CF$ as the ratio between the $W$+jets and the $Z$+jets fake factors. The correction factor measurements are presented in section 7.5.

The fake lepton background estimation mainly aims at estimating $W$+jets processes. It however by construction includes any process with one real lepton and one misidentified lepton, such as $t\bar{t}$ production with one leptonically decaying $W$ boson in the subsequent decay chain.

The anti-identified electron (muon) definitions are shown in table 7.1 (table 7.2), along with the corresponding id definitions for comparison. Electrons are anti-identified by failing the likelihood quality requirement and/or the isolation criteria. Muons are anti-identified by failing either the $d_0$ significance requirement, the quality criteria or the isolation criteria, or any combination of the three.

### 7.3 $Z$+jets fake factor measurements

The fake factor measurement benefits from measuring the fake factors in a sample as similar as possible to the process one wants to estimate, in terms of composition
<table>
<thead>
<tr>
<th>Selection</th>
<th>id</th>
<th>anti-id</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common</td>
<td>$p_T &gt; 15 \text{ GeV}$</td>
<td>$</td>
</tr>
<tr>
<td></td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td></td>
<td>$</td>
<td>z_0 \sin \theta</td>
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<tr>
<td></td>
<td>$</td>
<td>d_0</td>
</tr>
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<td>Author = 1</td>
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</tr>
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<td>Quality</td>
<td>Tight if $p_T \leq 25 \text{ GeV}$</td>
<td>Medium if $p_T &gt; 25 \text{ GeV}$</td>
</tr>
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<td>Isolation</td>
<td>$E_{T, \text{iso}}^{\text{cone20}}/p_T &lt; 0.11$ if $p_T \leq 25 \text{GeV}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$p_T/\sigma(p_T) &lt; 0.06$ if $p_T &gt; 25 \text{GeV}$</td>
<td></td>
</tr>
<tr>
<td>Id veto</td>
<td>–</td>
<td>Veto against identified electron</td>
</tr>
</tbody>
</table>

**Table 7.1:** The requirements for identified and anti-identified electrons. The identified selections define electrons in the SR, the anti-identified selections are used to define the misidentified electron control sample.

<table>
<thead>
<tr>
<th>Selection</th>
<th>id</th>
<th>anti-id</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common</td>
<td>$p_T &gt; 15 \text{ GeV}$</td>
<td>$</td>
</tr>
<tr>
<td></td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td></td>
<td>$</td>
<td>z_0 \sin \theta</td>
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<tr>
<td>Quality</td>
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<td>Medium</td>
</tr>
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<td>Transverse impact parameter</td>
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<td>d_0</td>
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<tr>
<td>Isolation</td>
<td>$E_{T, \text{iso}}^{\text{cone20}}/p_T &lt; 0.09$, $p_T/\sigma(p_T) &lt; 0.06$</td>
<td>–</td>
</tr>
<tr>
<td>Id veto</td>
<td>–</td>
<td>Veto against identified muon</td>
</tr>
</tbody>
</table>

**Table 7.2:** The requirements for identified and anti-identified muons. The identified selections define muons in the SR, the anti-identified selections are used to define the misidentified muon control sample.
of the type of fake objects. A priori one expects fake objects produced in association with $Z$ bosons to have a similar composition compared to fakes in $W$+jets. Based on this assumption, fake factors should preferably be extracted from $Z$+fake processes over say a jet-enriched sample. In fig. 7.2 the leading order Feynman diagrams for $Z$ and $W$ boson production in association with a quark or gluon are shown.

![Feynman Diagrams](image)

**Figure 7.2:** Leading order Feynman diagrams for vector boson plus gluon (left) or quark (right) production in $pp$ collisions.

A data sample enriched in the $Z$+fake topology is selected, containing a fake candidate lepton recoiling off a leptonically decaying $Z$ boson. The dataset used was collected during 2015 and 2016, corresponding to an integrated luminosity of 36.1 fb$^{-1}$, with the single lepton triggers listed in table 6.2. In table 7.3 the event selection is shown with the corresponding yields in data and MC. The latter is used to estimate contributions from processes with prompt leptons; the fake contribution is obtained by subtracting the sum of prompt lepton contributions from the data. For comparison, the yield of $Z$+jets fakes as predicted by MC (using Alpgen) is also shown. In “Other prompt” the relatively small contributions from $W\gamma$, top quark ($tt$, $ttV$, $Wt$) and triboson processes have been grouped together. In this section, since misidentified leptons are considered to be signal, “background” denotes processes with prompt leptons.

The upper part of the table shows the inclusive $Z$+fake selection, before separating into fake electron and fake muon categories. Exactly three leptons are required, each with $p_T > 15$ GeV. The $Z$ boson is tagged by requiring a same flavour, opposite-charge (SFOC) electron or muon pair fulfilling the same identification requirements as used in the analysis (see table 6.3 and section 6.2.3), with invariant mass within the $Z$ boson mass window. At least one of the $Z$ boson candidate leptons must be matched to one of the single lepton triggers listed in table 6.2. The third remaining lepton is the fake candidate object. The $Z$ boson mass window is set to $70(80) < m_{\ell\ell} < 110$ GeV for events with fake muons (electrons). The tighter window requirement for events with fake electrons is used to suppress $Z\gamma$ background. In $Z\gamma$ production the photon may be misidentified as an electron and wrongly tagged as coming from the $Z$, causing an invariant mass tail on the $m_{\ell\ell} < m_Z$ side. If more than one lepton pair pass the $Z$ boson mass window requirement (relevant for events with three electrons or three muons), the pair with invariant mass closest to the $Z$ boson mass is chosen. In fig. 7.3a the invariant mass distribution of the two $Z$ boson candidate leptons is shown, made
after the $Z$ boson tagging requirement. The blue data points represent the fake lepton contribution, obtained as the difference between the data in black and the prompt lepton background contributions in the histograms. Overlaid in the green dashed line is the prediction for the fake contribution from MC (using ALPGEN). The plots are inclusive in flavour of the fake lepton, i.e. made before separating in electron and muon fake candidate populations. The $Z$ boson peak is clearly visible. The kink at $m_{\ell\ell} = 80$ GeV is explained by the different $Z$ boson mass window requirements used in the fake electron and the fake muon selections.

The numerator of the fake factor contains three identified leptons and is naturally contaminated with prompt lepton backgrounds, in particular from $ZZ$ and $WZ$ diboson production. The $ZZ$ background is suppressed by vetoing events with more than three leptons. Production of $WZ$ bosons is the main background, suppressed by making a cut on the transverse mass of the fake candidate lepton, $m_W^{T} = \sqrt{2p_T^{\text{fake}}E_T^{\text{miss}}(1 - \cos \Delta \phi)} > 50$ GeV. The cosine is evaluated for the azimuthal angle between the fake candidate and the missing transverse momentum. The distribution of this variable is shown in fig. 7.3b, plotted after the $Z$ boson tagging requirement. Background contributions from $WZ$ production dominates the tail, while the fake lepton contribution is concentrated to lower values. The $WZ$ veto removes about two thirds of the $WZ$ background while retaining more than 90% of the $Z+\text{jets}$ fake lepton yield. Because this background is the most important, the $m_W^{T}$ tail is used as a dedicated control region to normalise it to data, see section 7.3.1. The resulting normalisation factor 1.15 is applied to the $WZ$ yield in the table and in fig. 7.3.

The middle and bottom part of the table show the fake electron and fake muon categories, respectively. For both electrons and muons, the anti-id category is rich in fakes with a purity above 80%. The id category suffers more from prompt lepton contamination, with a purity of 19% (26%) for muons (electrons).

In figs. 7.4 and 7.5 the $p_T$ and $\eta$ distributions of the numerator and denominator populations are shown, for electrons and muons respectively. The $Z+\text{jets}$ fake lepton prediction from ALPGEN is overlaid for comparison. For electrons, the kink at $p_T = 25$ GeV arises due to the different electron quality and isolation requirements for $p_T \leq 25$ GeV and $p_T > 25$ GeV (see table 6.3). In the $\eta$ distribution, which is mostly flat, the dips at $|\eta| \sim 1.4$ is due to the calorimeter crack region. The prompt lepton contamination increases with $p_T$ of the fake lepton, especially for muons. There are hardly any id muon fakes above $p_T = 30$ GeV.

Figure 7.6 shows a summary of the fake lepton $p_T$ distributions, published as auxiliary material in [52]. All prompt lepton background contributions have been combined into a single histogram. The hashed band denotes the sum in quadrature of the statistical uncertainty and the systematic uncertainty on the prompt lepton backgrounds. The estimation of the latter is presented in section 7.9.1.

Finally, the fake factor is computed as the ratio between the numerator and denominator, binned in $p_T$ and $|\eta|$. The binning is a trade-off between wanting as good granularity as possible and keeping statistical uncertainties under control. For electrons, the fake factor is binned as $p_T : [15, 20, 25, 35, 1000]$ GeV and...
Table 7.3: Event yield selection table for the $Z$+jets fake factor estimation. The upper part shows the inclusive selection, the middle and bottom parts show the fake electron and fake muon regions, respectively. The MC prediction for $Z$+jets fakes, estimated with Alpgen, is shown for comparison. Background from $WZ$ production is normalised according to the procedure presented in Section 7.3.1. The $Z$+jets fake contribution is taken as the data minus the contributions from processes with prompt leptons. The rightmost column shows the fake purity, taken as the fake yield divided by the data yield. Uncertainties are statistical only.

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<th>$ZZ$</th>
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<td>31860 ± 120</td>
<td>11411 ± 53</td>
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<td>\eta</td>
<td>&lt;2.5$</td>
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<td>\eta</td>
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<td>2890 ± 110</td>
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<tr>
<td>$</td>
<td>\eta</td>
<td>&lt;2.5$</td>
<td>2890 ± 110</td>
</tr>
</tbody>
</table>
Figure 7.3: Distributions of the dilepton system invariant mass (a) and the fake candidate transverse mass (b) in the Z+jets fake factor estimation. The plots are made after the Z boson tagging selection requirement (see table 7.3). The fake contribution in blue data points is obtained by subtracting processes with prompt leptons, shown in histograms, from the data. The normalisation factor is applied to the WZ background. The hashed uncertainty band represents the statistical uncertainty.

$|\eta|: [0., 1.37], [1.52, 2.5]$. Fewer bins are used for the muon fake factor, due to the comparatively lower event yield in the numerator population. As no significant differences are observed in the low- and high-$|\eta|$ regions, the muon fake factor is integrated in $|\eta|$, while binned in $p_T$ as $[15, 20, 25, 100]$ GeV. In fig. 7.7 the fake factors obtained in data are shown as black data points. Also plotted are the fake factors obtained in MC for different generators. For muons, the MC expectation agrees fairly well with fake factors derived in data. For electrons, the MC predicts a lower fake factor compared to the data for the high-$p_T$ region. This demonstrates the difficulty in using simulation for predicting misidentified lepton contributions.

7.3.1 WZ normalisation

To normalise the WZ contribution, the largest background in the Z+jets fake factor analysis, an enriched control sample is constructed. The event selection follows the Z+jets fake factor selection for identified leptons, but inverts the $m_W^T$ requirement. The control sample is thus defined by selecting the $m_W^T > 50$ GeV region of the distribution in fig. 7.3b and applying the identified selection on the fake candidate lepton. Since a lepton in this tail is likely prompt, it is denoted W-tagged.

In table 7.4 the predicted yields for WZ and additional processes in this control sample are listed along with their respective statistical uncertainties. The sample purity in WZ is 76%. A $\chi^2$ fit to the data is performed in the transverse mass distribution, with a global normalisation on WZ allowed to float while all other processes are fixed to their MC prediction. The fit returns a normalisation factor $\alpha = 1.15 \pm 0.02$ (stat.) $\pm 0.07$ (sys.), with $\chi^2/N_{dof} = 8.9/11$. Figure 7.8 shows
Figure 7.4: Transverse momentum (left) and $\eta$ (right) distributions for id (top) and anti-id (bottom) electrons in the $Z+$jets fake factor estimation. The black points are the data, the coloured histograms the prompt lepton background; the blue points the resulting fake lepton contribution obtained by subtracting the histograms from the data. The green dashed line shows the $Z+$jets fake contribution as predicted by ALPGEN, for comparison. The $WZ$ normalisation factor is applied. Uncertainties are statistical only.

The transverse mass distribution before (a) and after (b) the fit. The bottom pad shows the ratio between the data and the prompt lepton backgrounds, which clearly demonstrates the improvement obtained by applying the normalisation. In fig. 7.9 the $W$-tagged lepton $p_T$ distribution is shown in the $WZ$ control sample, with the normalisation factor applied. A small slope is observed in the ratio of data to simulation in the low-$p_T$ end of the spectrum.

The systematic uncertainty on $\alpha$ has three sources. Firstly, a component is included to cover the uncertainty on the $Z+$jets fake contribution. The fake factors of the data and the fake factors of the ALPGEN prediction as seen in fig. 7.7 are different by at most a factor of two. Consequently, the $Z+$jets uncertainty is evaluated by varying the normalisation of the ALPGEN prediction by a factor of two and one half, resulting in an uncertainty on the $WZ$ normalisation factor.

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Figure 7.5: Transverse momentum (left) and $\eta$ (right) distributions for id (top) and anti-id (bottom) muons in the $Z$+jets fake factor estimation. The black points are the data, the coloured histograms the prompt lepton backgrounds; the blue points the resulting fake contribution obtained by subtracting the histograms from the data. The dashed green line is the $Z$+jets fake contribution as predicted by ALPGEN, for comparison. The $WZ$ background has the normalisation factor applied. Uncertainties are statistical only.

of 0.01. Secondly, an uncertainty on the extrapolation of the normalisation factor across the boundary $m_T^W = 50$ GeV is assigned. By studying the dependence of both theoretical and experimental sources of uncertainty on $m_T^W$, an uncertainty of 0.01 was assigned. The theoretical uncertainties comprise PDF, choice of hard interaction generator and QCD scale dependence, the experimental uncertainties are systematic uncertainties on different objects and pileup reweighting. Each source of systematic uncertainty is evaluated by monitoring its effect on the ratio $N_{WZ}(m_T^W \leq 50$ GeV)/$N_{WZ}(m_T^W > 50$ GeV). The envelope of the theoretical and experimental uncertainties has an impact on the $WZ$ normalisation factor of approximately 5%.

Finally, to be conservative, an uncertainty component is added to cover for the mismodelling observed in the low-$p_T$ region of the $W$-tagged lepton transverse
**Figure 7.6:** Fake candidate $p_T$ distributions in the $Z$+jets sample, for electrons (left) and muons (right) in the id (top) and anti-id (bottom) populations. The data is in black points, the background subtractions have been added together in the histogram. The hashed band denotes the sum in quadrature of statistical and systematic uncertainties. Figure from [52].

<table>
<thead>
<tr>
<th>Process</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>4587</td>
</tr>
<tr>
<td>$WZ$</td>
<td>$3492 \pm 27$</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>$289 \pm 12$</td>
</tr>
<tr>
<td>$Z$+jets</td>
<td>$72 \pm 17$</td>
</tr>
<tr>
<td>$Z + \gamma$</td>
<td>$25 \pm 3$</td>
</tr>
<tr>
<td>Other prompt</td>
<td>$212 \pm 3$</td>
</tr>
<tr>
<td><strong>Total MC</strong></td>
<td>$4090 \pm 30$</td>
</tr>
</tbody>
</table>

**Table 7.4:** Event yields in the $WZ$ control sample, before applying the $WZ$ normalisation. Only the MC statistics is considered in the uncertainty.

momentum distribution as seen in fig. 7.9. It is evaluated by performing the fit separately for three regions of $p_T$: [15–35], [35–50] and $> 50$ GeV. The respective resulting normalisation factors are 1.08, 1.21 and 1.16, the standard deviation of which equals 0.066. Adding the three contributions in quadrature yields a total uncertainty of 0.088, corresponding to 7.7%. 

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7.4 Trigger bias and multijet fake factor measurements

Primarily, $Z$+jets fake factors are used for the fake lepton estimates. Fake factors have also been derived in a fake enriched multijet sample. Two types of fake factors are derived: “triggered” and “nominal”, used for two different purposes. For events in the $W$+jets control sample triggered solely by a single lepton trigger matched to the anti-id object, there is a bias since the trigger selections are tighter than the anti-id selections.\footnote{If the di-lepton trigger fires, no trigger bias exists since the di-lepton trigger selections are as loose or looser than the anti-id selections.} For example, all low-$p_T$ threshold single muon triggers have an isolation requirement, while the anti-id selection does not (see tables 6.2 and 7.2). To compensate this bias, such events are weighted with fake factors derived in a
Figure 7.8: Distribution of the transverse mass in the $WZ$ control sample. The variable is computed with the $W$-tagged lepton and the missing transverse momentum. The normalisation of $WZ$ is fit to the data with $\chi^2$ minimisation; (a) shows the pre-fit expectation, (b) shows the post-fit expectation.

Figure 7.9: Transverse momentum distribution of the $W$-tagged lepton in the $WZ$ control sample. The bottom pad shows the ratio of data to simulation. Uncertainties are statistical only.
sample in which both the numerator and denominator are collected with the same single lepton trigger expression as was firing the event (corresponding to one of the single lepton trigger rows in table 6.2). These are the triggered fake factors. Because the triggers differ depending on data taking period, three sets of triggered fake factors are derived, corresponding to periods 2015, 2016a and 2016b. The triggered fake factors are derived in a multijet sample because the Z+jets sample lacks sufficient statistics.

The nominal (unbiased, non-triggered) fake factors are derived in a sample collected with triggers having selections looser than the anti-id selections. They are used for comparisons with the Z+jets fake factors, and for estimating the multijet background in the VBF analysis. The triggers used to collect the data sample for the nominal fake factors are listed in table 7.5. They are chosen to have $p_T$ thresholds lower than the analysis subleading lepton $p_T$ criteria of 15 GeV. Due to the low thresholds, these triggers are subject to a prescale. The prescales are approximately equal to 7000 (1400) for the electron (muon) trigger, but vary over time (both within a run and over longer time scales). As a result, the sample may have a different pile-up profile than that of the not prescaled data used in the analysis. To compensate any bias, the data in the multijet sample is weighted with the prescale values.

<table>
<thead>
<tr>
<th>Fake lepton</th>
<th>$p_T$ threshold [GeV]</th>
<th>Quality criteria</th>
<th>Approximate prescale</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron</td>
<td>12</td>
<td>Very Loose</td>
<td>7000</td>
</tr>
<tr>
<td>muon</td>
<td>14</td>
<td>–</td>
<td>1400</td>
</tr>
</tbody>
</table>

Table 7.5: Triggers used to collect the single lepton sample used for the nominal multijet fake factor estimate.

### 7.4.1 Multijet fake factor measurements

To enrich the data sample in multijet processes and suppress background contributions from electroweak processes with real leptons the following selections are applied:

- Exactly one electron or muon (the fake candidate object),
- $N_{\text{jet}} > 0$,
- $p_T^{\text{lead jet}}, p_T^{\text{sublead jet}} > 25$ GeV, any other jets $p_T^{\text{jet}} > 20$ GeV
- $p_T^{\text{fake}} > 15$ GeV, $|\eta^{\text{fake}}| < 2.5$ (excluding crack region $1.37 < |\eta| < 1.52$ for electrons),
- $W$ veto; $m_T + E_{T}^{\text{miss,track}} < 50$ GeV,
where $m_T$ is computed with the fake candidate lepton and the missing transverse momentum. Background contributions with prompt leptons from $W$, $Z/\gamma^*$, top quark processes or processes with prompt photons are estimated with MC and subtracted. The latter is relevant only for fake electrons. In tables 7.6 and 7.7 the event yields are shown for the nominal selection for fake electrons and fake muons, respectively, in units of million events. The contribution from top quark processes is negligible and thus not listed explicitly. The respective trigger’s prescale value is applied to the data as a weight. In the outermost right column the fake purity is shown, revealing a high overall purity above 98% in the anti-id population. The id population has a purity of 70-80%, contaminated mainly by real leptons from $W \to (e/\mu)\nu$ processes. This process is suppressed by applying a requirement on the $m_T + E^{\text{miss}}_T$ variable. Figure 7.10 shows the distribution of this variable before applying the requirement, for the id fake electron (a) and id fake muon (b) categories. The data is shown in black points and the prompt lepton background processes to be subtracted in the coloured histograms. The resulting difference constitutes the fake lepton contribution, shown in blue data points.

### Table 7.6: Event yield selection table for the multijet nominal fake factor measurement for electrons, in units of million events. The fake candidate electron is matched to the trigger listed in table 7.5. To correct for the prescale on the trigger, the data yield has been weighted (see text for further description). The fake contribution is obtained as the difference between the data and the total background contribution, $B_{\text{tot}}$. Uncertainties are statistical only.

<table>
<thead>
<tr>
<th>Selection</th>
<th>$W$</th>
<th>$Z/\gamma^*$</th>
<th>$\gamma$</th>
<th>$B_{\text{tot}}$</th>
<th>Data</th>
<th>Fakes</th>
<th>Fake purity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>One triggered electron</td>
<td>78.10 ± 0.12</td>
<td>19.97 ± 0.05</td>
<td>248.9 ± 1.2</td>
<td>350.6 ± 1.2</td>
<td>5499.6 ± 6.5</td>
<td>5059.0 ± 6.7</td>
<td>94</td>
</tr>
<tr>
<td>$N_{\text{jet}} &gt; 0$</td>
<td>55.94 ± 0.10</td>
<td>17.93 ± 0.04</td>
<td>220.5 ± 1.1</td>
<td>297.9 ± 1.1</td>
<td>4797.2 ± 6.1</td>
<td>4499.3 ± 6.2</td>
<td>94</td>
</tr>
<tr>
<td>Fake $p_T$ and $</td>
<td>\eta</td>
<td>$ cuts</td>
<td>51.41 ± 0.10</td>
<td>15.96 ± 0.04</td>
<td>190.3 ± 1.0</td>
<td>261.0 ± 1.0</td>
<td>2744.5 ± 4.7</td>
</tr>
<tr>
<td>$W$ veto</td>
<td>6.86 ± 0.03</td>
<td>7.85 ± 0.03</td>
<td>97.96 ± 0.77</td>
<td>112.97 ± 0.78</td>
<td>1837.1 ± 3.8</td>
<td>1724.1 ± 3.9</td>
<td>94</td>
</tr>
<tr>
<td>Fake is id</td>
<td>5.30 ± 0.03</td>
<td>6.21 ± 0.03</td>
<td>2.56 ± 0.12</td>
<td>14.30 ± 0.13</td>
<td>72.72 ± 0.76</td>
<td>58.41 ± 0.77</td>
<td>80</td>
</tr>
<tr>
<td>Fake is anti-id</td>
<td>1.25 ± 0.01</td>
<td>1.30 ± 0.01</td>
<td>10.35 ± 0.27</td>
<td>12.95 ± 0.27</td>
<td>72.26 ± 2.4</td>
<td>58.41 ± 2.4</td>
<td>98</td>
</tr>
</tbody>
</table>

### Table 7.7: Event yield selection table for the multijet nominal fake factor measurement for muons, in units of million events. The fake candidate muon is matched to the trigger listed in table 7.5. To correct for the prescale on the trigger, the data yield has been weighted (see text for further description). The fake contribution is obtained as the difference between the data and the total contribution from processes with prompt leptons, $B_{\text{tot}}$. Uncertainties are statistical only.

<table>
<thead>
<tr>
<th>Selection</th>
<th>$W$</th>
<th>$Z/\gamma^* / \gamma$</th>
<th>$B_{\text{tot}}$</th>
<th>Data</th>
<th>Fakes</th>
<th>Fake purity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>One triggered muon</td>
<td>69.19 ± 0.11</td>
<td>9.91 ± 0.12</td>
<td>82.08 ± 0.16</td>
<td>1083.5 ± 1.3</td>
<td>1001.5 ± 1.3</td>
<td>92</td>
</tr>
<tr>
<td>$N_{\text{jet}} &gt; 0$</td>
<td>51.22 ± 0.09</td>
<td>7.92 ± 0.09</td>
<td>63.11 ± 0.13</td>
<td>982.3 ± 1.3</td>
<td>920.2 ± 1.3</td>
<td>94</td>
</tr>
<tr>
<td>Fake $p_T$ and $</td>
<td>\eta</td>
<td>$ cuts</td>
<td>50.22 ± 0.09</td>
<td>7.21 ± 0.08</td>
<td>60.34 ± 0.12</td>
<td>707.5 ± 1.1</td>
</tr>
<tr>
<td>$W$ veto</td>
<td>7.30 ± 0.04</td>
<td>3.17 ± 0.06</td>
<td>10.75 ± 0.07</td>
<td>514.04 ± 0.90</td>
<td>503.29 ± 0.91</td>
<td>98</td>
</tr>
<tr>
<td>Fake is id</td>
<td>5.96 ± 0.03</td>
<td>2.07 ± 0.02</td>
<td>8.26 ± 0.04</td>
<td>61.27 ± 0.31</td>
<td>53.01 ± 0.31</td>
<td>87</td>
</tr>
<tr>
<td>Fake is anti-id</td>
<td>1.32 ± 0.02</td>
<td>1.10 ± 0.05</td>
<td>2.47 ± 0.06</td>
<td>446.17 ± 0.84</td>
<td>443.70 ± 0.84</td>
<td>99</td>
</tr>
</tbody>
</table>

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Figure 7.10: Distribution of $m_T + E^{\text{miss, track}}$ for the identified fake candidate electron (a) and muon (b) in the multijet nominal fake factor measurement. The data is shown in black and the blue data points represent the fake lepton contribution, equal to the data minus prompt lepton contributions in the histograms. The hashed uncertainty band represents the statistical uncertainty.

After the last selection requirement the sample is separated into the id (numerator) and anti-id (denominator) categories. The transverse momentum distribution of the fake lepton candidates are shown in fig. 7.11. For identified electrons the kink at $p_T = 25 \text{ GeV}$ is due to the change in the id selection at this boundary (see table 6.3). With increasing $p_T$ the id populations ((b) and (d)) are increasingly contaminated with real leptons. In fig. 7.12 the $\eta$ distributions of the fake candidate leptons are shown. After subtracting the prompt lepton background, the fake factor is evaluated as the binned ratio of the two populations, as a function of $p_T$ and $|\eta|$ of the fake candidate. The nominal multijet fake factors are shown in fig. 7.13 along with the $Z$+jets fake factors for comparison. Despite potential differences in sample composition, the fake factors agree within certainties.

There are three sets of triggered fake factors, one for each trigger period. The samples are derived with the same selection requirements as the nominal fake factors, except that the triggers used correspond to the analysis single lepton triggers instead of the prescaled triggers. In tables 7.8 and 7.9 the event yields in units of thousand events are shown for the fake electron and fake muon categories, respectively, for the data period 2016a. For brevity, the yields are shown only for this period; the resulting fake factors for all periods will be presented later. Contributions from top quark events are not shown explicitly in the table for fake electrons, since they are negligible. The purity is around 60% for id and 94% for anti-id, for both electrons and muons. Compared to the nominal selection, the purity is lower in the id sample due to the $p_T$ threshold of the trigger, removing the low-$p_T$ region which is richer in fakes compared to the high-$p_T$ tail. In addition to the $p_T$ threshold, the purity of the anti-id category is also affected by the quality criteria of the triggers which are tighter than the anti-id selections.
Figure 7.11: Transverse momentum distributions of the anti-identified (a,c) and identified (b,d) electrons and muons in the multijet sample used for the nominal fake factor measurement. The data is shown in black, while the blue data points represent fakes (equal to the data minus the prompt lepton contribution in the histograms). The hashed region denotes the statistical uncertainty.

Table 7.8: Event yield selection table for the multijet triggered fake factor measurement for electrons, corresponding to data period 2016a, in units of thousand events. The fake candidate electron is matched to at least one of the single electron triggers in the 2016a period, listed in table 6.2. The fake contribution is obtained as the difference between the data and the total contribution from processes with real leptons, $B_{tot}$. Uncertainties are statistical only.
**Figure 7.12:** Pseudorapidity distributions of the anti-identified (a,c) and identified (b,d) electrons and muons in the multijet sample used to measure the nominal fake factor. The data is shown in black, while the blue data points represent fake leptons (equal to the data minus the prompt lepton contribution in the histograms). The hashed region denotes the statistical uncertainty.

<table>
<thead>
<tr>
<th>Selection</th>
<th>W</th>
<th>Z/\gamma^*/\gamma</th>
<th>tt/WW</th>
<th>B_{tot}</th>
<th>Data</th>
<th>Fakes</th>
<th>Fake purity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>One triggered muon</td>
<td>8268 ± 32</td>
<td>791 ± 11</td>
<td>384.6 ± 1.0</td>
<td>9384 ± 34</td>
<td>13921 ± 3.7</td>
<td>4537 ± 34</td>
<td>33</td>
</tr>
<tr>
<td>N_{jet} &gt; 0</td>
<td>6361 ± 28</td>
<td>675 ± 10</td>
<td>384.5 ± 1.0</td>
<td>7420 ± 30</td>
<td>12462 ± 3.5</td>
<td>5042 ± 30</td>
<td>40</td>
</tr>
<tr>
<td>Fake p_{T} and</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W veto</td>
<td>6361 ± 28</td>
<td>675 ± 10</td>
<td>384.5 ± 1.0</td>
<td>7420 ± 30</td>
<td>12462 ± 3.5</td>
<td>5042 ± 30</td>
<td>40</td>
</tr>
<tr>
<td>Fake is id</td>
<td>578.0 ± 8.4</td>
<td>175.2 ± 4.9</td>
<td>28.06 ± 0.27</td>
<td>781.3 ± 9.8</td>
<td>1838.6 ± 1.4</td>
<td>1057.4 ± 9.9</td>
<td>58</td>
</tr>
<tr>
<td>Fake is anti-id</td>
<td>603.3 ± 2.7</td>
<td>28.4 ± 1.7</td>
<td>3.06 ± 0.09</td>
<td>91.8 ± 3.2</td>
<td>1549.1 ± 1.2</td>
<td>1457.2 ± 3.4</td>
<td>94</td>
</tr>
</tbody>
</table>

**Table 7.9:** Event yield selection table for the multijet triggered fake factor measurement for muons, corresponding to data period 2016a, in units of thousand events. The fake candidate muon is matched to at least one of the single muon triggers in the 2016a period, listed in table 6.2. The fake contribution is obtained as the difference between the data and the total contribution from processes with real leptons, B_{tot}. Uncertainties are statistical only.
Figure 7.13: Comparison between the electron (a,b) and muon (c) fake factors derived in the multijet sample (red points) and the Z+jets sample (black points).
In fig. 7.14 and fig. 7.15 the $p_T$ and $\eta$ distributions of anti-id and id fake candidate objects are shown for the 2016a dataset. The corresponding distributions in the 2015 and 2016b datasets are not shown as all three are qualitatively very similar. For the anti-id, the high fake purity is clearly visible. The purity of the id population is fairly high in the low-$p_T$ region but decreases with increasing $p_T$, due to contamination from prompt leptons from $W$ bosons. In summary, the multijet samples are more pure in fakes than the $Z$+jets sample.

Figure 7.14: Transverse momentum distributions of the anti-identified (a,c) and identified (b,d) electrons and muons in the multijet sample used for the triggered fake factor measurement in the 2016a dataset. The data is shown in black points, while the blue points represent fake leptons, equal to the data minus the prompt lepton contributions in the histograms. The hashed band denotes the statistical uncertainty.

Given the larger statistics compared to the $Z$+jets sample, the triggered multijet fake factor allows for finer binning. For fake electrons, the fake factors are binned in $p_T$ as $[15, 20, 25, 30, 35, 45, 1000]$ GeV and in $|\eta|$ as $[[0, 1.37], [1.52, 2.5]]$. For muon fakes, the corresponding bin edges are $[15, 20, 25, 30, 40, 1000]$ GeV and $[0, 1.05, 2.5]$. One exception is made for muons in the 2015 data, where the last $p_T$ bin instead starts from 30 GeV, to avoid a large statistical uncertainty.
Figure 7.15: Pseudorapidity distributions of the ant-identified (a,c) and identified (b,d) electrons and muons in the multijet sample used to measure the triggered fake factor in 2016a data. The data is shown in black points, while the blue points represent fakes, equal to the data minus the prompt lepton contribution in the histograms. The hashed band denotes the statistical uncertainty.
The triggered fake factors are shown in fig. 7.16, for electrons (a,b) and muons (c, d). When requiring the anti-id object to be matched to an analysis single lepton trigger, the anti-id definition is effectively modified to one with tighter criteria. This results in a shrinking denominator population and a larger fake factor relative to the nominal fake factor measurement. The increase in trigger quality selections between the 2015 and 2016 dataset explains why the 2015 data is associated with a smaller fake factor compared to the 2016 period. Since the trigger thresholds are around $p_T = 25$ GeV, some bins are empty.

Figure 7.16: Electron (a,b) and muon (c,d) triggered fake factors versus $|\eta|$ and $p_T$, derived from a multijet sample. They are derived separately for each data period associated to a certain set of triggers. The triggered fake factors are applied to events in the $W$+jets control sample in which the anti-id lepton is triggered and the id lepton is not triggered. The error bars denote the statistical uncertainty.
7.4.2 Triggered fakes

In fig. 7.17 the composition in terms of triggered and non-triggered fakes is presented. The two contributions are plotted as a function of anti-id \( p_T \), with their corresponding ratio to the total yield in the bottom pads. The distributions are made for the \( W + \text{jets} \) control sample with one id lepton and one anti-id lepton, with kinematic selections of the ggF \( N_{\text{jet}} = 0 \) (top panel), ggF \( N_{\text{jet}} = 1 \) (middle panel) and VBF \( N_{\text{jet}} \geq 2 \) regions. No fake or correction factors are applied. Processes with real leptons have been subtracted from the data to yield the resulting fake contribution. The red histogram represents events without trigger bias, to be extrapolated with nominal \( Z + \text{jets} \) fake factors. In contrast, the blue histogram represent events where the anti-id lepton solely triggers the event, to be extrapolated with triggered multijet fake factors. Fake leptons with transverse momentum below 25 GeV are almost exclusively non-triggered, as expected since they are below the single lepton trigger thresholds. At higher \( p_T \) the contribution from triggered fakes increases, but is generally below 20%.

The VBF analysis also considers events with two anti-id objects to correct for contributions from multijet processes (see section 7.7). If either of the anti-id leptons are the sole object triggering the event, it will be associated with a triggered fake factor for its extrapolation. Otherwise, \( Z + \text{jets} \) fake factors are used. After the \( Z \rightarrow \tau \tau \) veto requirement, 12\% of the events in the \( W + \text{jets} \) control sample have a trigger bias.

7.5 Sample composition and correction factors

As explained in the introduction to this chapter, misidentified leptons may originate from different sources. The relative abundance of different origins of misidentified leptons in a sample depends on which process(es) contributes to the topology considered. For example, a single-lepton sample is likely to have contributions of misidentified leptons from multijet processes. Misidentified leptons in a dilepton sample will mainly originate from \( W + \text{jets} \) processes. Furthermore, in a multi-lepton sample, the charge and flavour configurations of leptons will influence the composition of different origins. A correction factor is applied in the fake factor estimate (see eq. (7.4)) to account for the differences in fake origin composition in (a) the trilepton \( Z + \text{jets} \) topology, in which the fake factor is derived, and (b) the dilepton, opposite-charge \( W + \text{jets} \) topology, representing the process we want to estimate. This section investigates the fake lepton origin for fake leptons produced in these processes. This is primarily done using two sets of simulated samples, using \textsc{Powheg} (\textsc{Alpgen}) for the hard interaction generation and \textsc{Pythia} 8 (\textsc{Pythia} 6) for the parton shower. In what follows, they will be abbreviated using the generator name only. In section 7.5.1 the MC predictions are tested in data. Section 7.5.2 outlines the derivation of the correction factors.
Figure 7.17: Electron (a,c,e) and muon (b,d,f) fake composition in the $W+$jets control sample (one id and one anti-id lepton) as a function of $p_T$ of the anti-id lepton in the ggF $N_{\text{jet}} = 0$ (a,b), ggF $N_{\text{jet}} = 1$ (c,d) and VBF $N_{\text{jet}} \geq 2$ (e,f) channel. All SR selection requirements are applied. No fake or correction factors are applied. The red histogram represents the non-triggered contribution, the blue histogram represents the triggered contribution. The hashed band represents the statistical uncertainty.
A simplified version of the analysis event selection is used to filter the MC $W$+jets samples. Two leptons are required, passing the same $p_T$ and $\eta$ selections as used in the analysis. They required to be of opposite charge and to pass $m_{\ell\ell} > 10$ GeV. The prompt lepton is required to pass the lepton id requirements. No $E_T^{\text{miss,track}}$ or $N_{\text{jet}}$ requirements are applied. Similarly, for studying fake leptons in simulated $Z$+jets samples, a simplified version of the $Z$+jets fake factor analysis is used (see section 7.3). Events with exactly three leptons are selected, with two of them being prompt leptons originating from the $Z$ boson. Lepton $p_T$ and $\eta$ requirements and the $Z$ boson tagging procedure follows what is done in the $Z$+jets fake factor measurement. After applying the event selection, each sample is separated in two parts, in which the fake lepton is id or anti-id.

Fake leptons are classified into different categories, or types, according to the following scheme. A fake lepton may come from a real lepton produced in decay or in interactions with the detector material. If a real lepton is found within $\Delta R < 0.03$ of the fake lepton, it is classified as “leptonic”. Otherwise it is assumed to originate from hadronic activity, denoted “hadronic”. To classify whether a fake lepton originates from a quark of a certain flavour, a matching scheme is applied starting from heavier and moving to lighter quarks. A fake lepton is classified as type “Bottom” if a bottom-type quark is found within $\Delta R < 0.4$ of the fake lepton. If no bottom-type quark is found, the test is repeated for charm-, strange- and light-type ($u$ and $d$) quarks, in that order. If the fake object can not be matched to any of the quark categories, it is classified as “Other”. It has been found that electrons of type Other are mainly originating from photons, either from Bremsstrahlung, $\pi^0$ decays or final state radiation. The origin of fake muons in of type Other is not completely known, however a significant fraction come from pileup. It was not studied in further detail as the fraction of Other is very low for fake muons.

In table 7.10 the fake factors for different fake types are shown for the POWHEG samples. Within statistical uncertainties, the fake factor for each type is compatible between $W$+jets and $Z$+jets. This is reassuring; a fake object of a certain origin should have the same properties regardless of in what physics process it was produced. Furthermore, the fake factors are significantly different between the different types. For example, type Other electrons stands out with a larger fake factor relative to the other types. This is expected; isolation criteria are used to define id and anti-id, and a fake lepton of photon origin is expected to be more isolated than fake leptons of other origins. This brings confidence to the classification algorithm. The differences in fake factors motivate the need for assessing the type composition differences between samples.

In fig. 7.18 the fake electron type composition is shown for $W$+jets (a,b) and $Z$+jets (c,d) as a function of $p_T$ of the fake candidate. The different fake types are stacked. Anti-id electrons (a,c) are predominantly of charm and light origin, in approximately equal fractions. The light fraction is in turn made up of approximately equal proportions of the hadronic and leptonic categories. Type Other is more abundant in the id (b,d) than in the anti-id population. In $W$+jets a larger fraction of charm relative to $Z$+jets is observed, the latter instead has a signifi-
Table 7.10: Electron and muon fake factors by type, as predicted by POWHEG, for fake leptons in $W$+jets and $Z$+jets. The numbers are integrated in $p_T$ and $\eta$.

<table>
<thead>
<tr>
<th>Lepton</th>
<th>Sample</th>
<th>Bottom</th>
<th>Charm</th>
<th>Strange</th>
<th>Light</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e$</td>
<td>$W$+jets</td>
<td>0.129±0.044</td>
<td>0.002±0.009</td>
<td>0.056±0.018</td>
<td>0.081±0.009</td>
<td>0.302±0.060</td>
</tr>
<tr>
<td></td>
<td>$Z$+jets</td>
<td>0.094±0.013</td>
<td>0.000±0.015</td>
<td>0.042±0.009</td>
<td>0.069±0.007</td>
<td>0.412±0.060</td>
</tr>
<tr>
<td>$\mu$</td>
<td>$W$+jets</td>
<td>0.102±0.033</td>
<td>0.191±0.018</td>
<td>0.103±0.035</td>
<td>0.198±0.054</td>
<td>0.172±0.079</td>
</tr>
<tr>
<td></td>
<td>$Z$+jets</td>
<td>0.115±0.011</td>
<td>0.163±0.018</td>
<td>0.050±0.018</td>
<td>0.128±0.033</td>
<td>0.270±0.098</td>
</tr>
</tbody>
</table>

Table 7.11: Relative abundance, in percent, of the different fake lepton types in the anti-id and id electron populations, for the $W$+jets sample and the $Z$+jets sample, simulated with POWHEG. Each row sums to 100%. The uncertainties are statistical only.

<table>
<thead>
<tr>
<th>Fake electron</th>
<th>Sample</th>
<th>Bottom</th>
<th>Charm</th>
<th>Strange</th>
<th>Light</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>anti-id</td>
<td>$W$+jets</td>
<td>1.9±0.2</td>
<td>43.1±1.5</td>
<td>9.4±0.6</td>
<td>39.6±1.3</td>
<td>5.9±0.5</td>
</tr>
<tr>
<td></td>
<td>$Z$+jets</td>
<td>22.3±0.9</td>
<td>18.3±0.7</td>
<td>13.0±0.7</td>
<td>41.8±1.3</td>
<td>4.6±0.4</td>
</tr>
<tr>
<td>id</td>
<td>$W$+jets</td>
<td>2.5±0.8</td>
<td>36.5±4.6</td>
<td>5.5±1.7</td>
<td>33.2±4.1</td>
<td>22.3±3.5</td>
</tr>
<tr>
<td></td>
<td>$Z$+jets</td>
<td>24.7±3.2</td>
<td>17.1±2.8</td>
<td>5.5±1.2</td>
<td>31.9±3.4</td>
<td>20.8±2.6</td>
</tr>
</tbody>
</table>

Table 7.12: Relative abundance, in percent, of the different fake lepton types in the anti-id and id muon populations, for the $W$+jets sample and the $Z$+jets sample, simulated with POWHEG. Each row sums to 100%. The uncertainties are statistical only.

<table>
<thead>
<tr>
<th>Fake muon</th>
<th>Sample</th>
<th>Bottom</th>
<th>Charm</th>
<th>Strange</th>
<th>Light</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>anti-id</td>
<td>$W$+jets</td>
<td>7.7±1.1</td>
<td>77.2±3.6</td>
<td>6.5±0.7</td>
<td>6.0±0.8</td>
<td>2.7±0.6</td>
</tr>
<tr>
<td></td>
<td>$Z$+jets</td>
<td>65.4±2.5</td>
<td>22.6±1.1</td>
<td>5.5±0.5</td>
<td>4.7±0.5</td>
<td>1.8±0.4</td>
</tr>
<tr>
<td>id</td>
<td>$W$+jets</td>
<td>4.4±1.3</td>
<td>82.6±9.6</td>
<td>3.8±1.2</td>
<td>6.7±1.7</td>
<td>2.6±1.0</td>
</tr>
<tr>
<td></td>
<td>$Z$+jets</td>
<td>59.9±6.1</td>
<td>28.9±3.3</td>
<td>2.3±0.7</td>
<td>4.7±1.1</td>
<td>4.3±1.2</td>
</tr>
</tbody>
</table>

The significant fraction of electron fakes from $b$-quarks (leptonic). This is expected as there is a $W$+jets process which naturally produces an opposite-charge final state, see fig. 7.19. In table 7.11 the relative abundance of the different types observed in the anti-id and id samples are quantified. To gain statistical precision, the numbers are integrated in $p_T$ and $\eta$.

In fig. 7.20 the corresponding $p_T$ distributions for fake muons are shown, with the different fake types stacked. Fake muons originate mainly from decays of heavy quarks; $W$+jets is dominated by fakes from $c$ quarks while $Z$+jets is dominated by fakes from $b$ quarks. Only a small fraction of the fake muons originate from the Strange, Light and Other types. The denominator and numerator populations are very similar in terms of composition, the latter however suffer from a large statistical uncertainties. The fractions obtained upon integrating in $p_T$ and $\eta$ are shown in table 7.12.

<table>
<thead>
<tr>
<th>Fake muon</th>
<th>Sample</th>
<th>Bottom</th>
<th>Charm</th>
<th>Strange</th>
<th>Light</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>anti-id</td>
<td>$W$+jets</td>
<td>7.7±1.1</td>
<td>77.2±3.6</td>
<td>6.5±0.7</td>
<td>6.0±0.8</td>
<td>2.7±0.6</td>
</tr>
<tr>
<td></td>
<td>$Z$+jets</td>
<td>65.4±2.5</td>
<td>22.6±1.1</td>
<td>5.5±0.5</td>
<td>4.7±0.5</td>
<td>1.8±0.4</td>
</tr>
<tr>
<td>id</td>
<td>$W$+jets</td>
<td>4.4±1.3</td>
<td>82.6±9.6</td>
<td>3.8±1.2</td>
<td>6.7±1.7</td>
<td>2.6±1.0</td>
</tr>
<tr>
<td></td>
<td>$Z$+jets</td>
<td>59.9±6.1</td>
<td>28.9±3.3</td>
<td>2.3±0.7</td>
<td>4.7±1.1</td>
<td>4.3±1.2</td>
</tr>
</tbody>
</table>

Table 7.12: Relative abundance, in percent, of the different fake lepton types in the anti-id and id muon populations, for the $W$+jets sample and the $Z$+jets sample, simulated with POWHEG. Each row sums to 100%. The uncertainties are statistical only.
Figure 7.18: Fake type composition for anti-identified (a,c) and identified (b,d) electrons in Powheg MC. The composition is shown for fake leptons in W+jets (a,b) and Z+jets (c,d) samples, corresponding to final states similar to the analysis SR and Z+jets fake factor sample, respectively.

Figure 7.19: Leading order Feynman diagram for W+charm production in a pp collision. If both the prompt W boson and the W boson from the decay of the charm quark decays leptonically, the process has a final state of with two leptons of opposite electrical charge.
Figure 7.20: Origin composition for anti-identified (a,c) and identified (b,d) misidentified muons in POWHEG MC. The composition is shown for fake leptons in W+jets (a,b) and Z+jets (c,d) samples, corresponding to final states similar to the analysis SR and Z+jets fake factor sample, respectively. The hashed band denotes the statistical uncertainty.
7.5.1 Flavour template fits

The MC predictions of the previous section are tested in data by performing template fits of the transverse impact parameter significance. This variable is expected to have a different shape for fake leptons from heavy quark decays and fake leptons from light quark origin. As explained in section 5.2.4, hadrons containing b quarks travel a short distance (of order 1 mm) in the detector before decaying, giving rise to a displaced vertex and larger impact parameters for the resulting jets’ associated tracks. In fig. 7.21 the transverse impact parameter significance, $|d_0/\sigma(d_0)|$, is shown for anti-id electrons (a,c) and muons (b,d) in the Z+jets sample, for POWHEG (a,b) and ALPGEN (c,d). Two templates are formed; the “Heavy” template made up by combining all Bottom and Charm categories, and the “Light” template from combining all remaining categories. A similar behaviour is observed with both generators. For fake muons, a clear shape difference is observed for the two templates. For fake electrons, the difference is smaller. In fig. 7.22 the same distributions are shown for fakes from W+jets. They demonstrate similar trends compared to the Z+jets sample.

Two data samples are collected, to which the W+jets and Z+jets templates are fit. The first corresponds to the W+jets control sample in the analysis, at the preselection level, inclusive in jet multiplicity. The second corresponds to the sample used in the Z+jets fake factor measurement, with the anti-id selection applied to the fake candidate lepton (see section 7.3). A fit of the $|d_0/\sigma(d_0)|$ distribution of the anti-id object is performed using TFRACTIONFITTER, part of the ROOT framework [94]. The fraction of the Light ($\alpha_L$) and Heavy ($\alpha_H$) components are allowed to float, while enforcing the condition $\alpha_L + \alpha_H = 1$.

Fake electrons

In table 7.13 the template fit results for fake electrons are summarised. As a sanity check, a fit is performed to the MC prediction, to verify that the MC predicted fractions of Light and Heavy are recovered. This is indeed observed.

For POWHEG, the fit to data yields a larger Heavy fraction (67%) and a lower Light fraction (33%) compared to the MC prediction (39% and 61% respectively). The chi-square sum divided by degrees of freedom, $\chi^2/N_{dof}$, is 8.2/6, indicating a well behaved fit. For the W+jets the goodness-of-fit is weaker with $\chi^2/N_{dof} = 50/6$. The same trend as for Z+jets is observed with a larger $\alpha_H$ and lower $\alpha_L$ as compared to the MC prediction. The Light and Heavy proportions observed in data are compatible between W+jets and Z+jets, both for data and MC. Comparing with ALPGEN, for Z+jets the resulting Heavy proportion (46%) is a bit lower than POWHEG, but still larger than the MC prediction (37%). The ALPGEN templates have difficulties reproducing as hard spectrum as observed in the data, reflected in the poor $\chi^2/N_{dof} = 68/6$. Also for W+jets, the ALPGEN performs poorly with a fit returning $\alpha_H = 1$ and $\chi^2/N_{dof} = 72/6$. Figure 7.23 displays the post-fit impact parameter significance distributions for the data fits.
Figure 7.21: Distributions of the transverse impact parameter significance for anti-id fake electrons (a,c) and muons (b,d) in Z+jets, simulated with POWHEG (a,b) and ALPGEN. Fake leptons have been classified according to their type and grouped in to a Heavy and a Light template. The error bars denote the statistical uncertainty.
Figure 7.22: Distributions of the transverse impact parameter significance for anti-id fake electrons (a,c) and muons (b,d) in $W$+jets, simulated with POWHEG (a,b) and ALPGEN (c,d). Fake leptons have been classified according to their type and grouped into a Heavy and a Light template. The error bars denote the statistical uncertainty.
Concluding for fake electrons, it is difficult to extract precise fractions of Heavy and Light proportions, especially in the $W$+jets data. For $Z$+jets data, ALPGEN predicts a slightly lower (larger) Heavy (Light) fraction than POWHEG.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Result</th>
<th>$\alpha_H$ [%]</th>
<th>$\alpha_L$ [%]</th>
<th>$\chi^2/N_{dof}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>POWHEG</strong></td>
<td>Data fit</td>
<td>66.9 ± 7.5</td>
<td>33.1 ± 7.5</td>
<td>8.2 / 6</td>
</tr>
<tr>
<td>$Z$+jets</td>
<td>MC fit</td>
<td>39.3 ± 6.5</td>
<td>60.8 ± 6.6</td>
<td>0.0 / 6</td>
</tr>
<tr>
<td></td>
<td>MC expectation</td>
<td>39.3 ± 0.8</td>
<td>60.7 ± 1.0</td>
<td>–</td>
</tr>
<tr>
<td><strong>POWHEG</strong></td>
<td>Data fit</td>
<td>60.7 ± 2.2</td>
<td>39.3 ± 2.2</td>
<td>50 / 6</td>
</tr>
<tr>
<td>$W$+jets</td>
<td>MC fit</td>
<td>42.4 ± 2.2</td>
<td>57.6 ± 2.2</td>
<td>0.0 / 6</td>
</tr>
<tr>
<td></td>
<td>MC expectation</td>
<td>42.4 ± 0.9</td>
<td>57.6 ± 1.0</td>
<td>–</td>
</tr>
<tr>
<td><strong>ALPGEN</strong></td>
<td>Data fit</td>
<td>45.7 ± 7.8</td>
<td>54.3 ± 7.8</td>
<td>68 / 6</td>
</tr>
<tr>
<td>$Z$+jets</td>
<td>MC fit</td>
<td>37.0 ± 5.5</td>
<td>63.0 ± 5.5</td>
<td>0.0 / 6</td>
</tr>
<tr>
<td></td>
<td>MC expectation</td>
<td>37.0 ± 1.6</td>
<td>63.0 ± 1.4</td>
<td>–</td>
</tr>
<tr>
<td><strong>ALPGEN</strong></td>
<td>Data fit</td>
<td>99.8 ± 0.9</td>
<td>0.2 ± 0.8</td>
<td>72 / 6</td>
</tr>
<tr>
<td>$W$+jets</td>
<td>MC fit</td>
<td>35.5 ± 2.8</td>
<td>64.5 ± 2.8</td>
<td>0.0 / 6</td>
</tr>
<tr>
<td></td>
<td>MC expectation</td>
<td>35.5 ± 1.1</td>
<td>64.5 ± 1.2</td>
<td>–</td>
</tr>
</tbody>
</table>

Table 7.13: Results of the flavour template fits for fake electrons, compared to the MC predictions, for POWHEG (top) and ALPGEN (bottom). The fits are made to the transverse impact parameter significance distribution, for misidentified leptons in a $W$+jets sample and a $Z$+jets sample.

Fake muons

For fake muons, the fit results are summarised in table 7.14 and the corresponding post-fit distributions are shown in fig. 7.24. For POWHEG, in both in $Z$+jets and $W$+jets the Heavy fraction is measured to 95% and the Light fraction to 5%. The $W$+jets fit however has a large $\chi^2/N_{dof} = 250/6$. The Heavy/Light ratio is approximately two (three) standard deviations larger in data as compared to the MC prediction for $Z$+jets ($W$+jets). Like the fake electron case, the Heavy and Light proportions are compatible between $Z$+jets and $W$+jets. ALPGEN again prefers $\alpha_H = 1$ for $W$+jets, but the MC clearly has problems reproducing the hard spectrum observed in data. For $Z$+jets the ALPGEN fit also results in $\alpha_H = 1$, but with a very large uncertainty. The MC predictions prefer a larger Heavy fraction in $Z$+jets (84.5%) compared to $W$+jets (71.3%).

Summary

It is not possible to extract precise information on the Light and Heavy fractions of fake electrons in data. Their corresponding templates do not have a significantly
Figure 7.23: Post-fit transverse impact parameter distributions in the POWHEG(a,c) and ALPGEN (b,d) samples, for fake electrons in $Z$+jets (a,b) and $W$+jets (c,d) samples.
Figure 7.24: Post-fit transverse impact parameter distributions in the Powheg (a,c) and Alpgen (b,d) samples, for fake muons in $Z$+jets (a,b) and $W$+jets (c,d) samples.
Table 7.14: Fake muon flavour template fit results using Powheg (top) and Alpgen (bottom), in the $W$+jets and $Z$+jets samples. The fits are made to the transverse impact parameter significance distribution, for fakes in a $W$+jets sample and a $Z$+jets sample.

different shape. For fake muons however, the data can be explained by a large fraction of the Heavy component (everywhere above 80%), indicating that the leptons originate from heavy quark decays. The MC does a fairly good job in predicting the fractions obtained from the fit. The Powheg generator does better than Alpgen in modelling the data, which is one reason why it is chosen as the nominal in computing the correction factors (see section 7.5.2). Secondly, it has better statistical precision.

7.5.2 Correction factors

Given the results presented in previous section, the Powheg sample is chosen as the preferred generator for computing the correction factors (which were introduced in section 7.2). In fig. 7.25 the electron (a) and muon (b) fake factors for $W$+jets and $Z$+jets are shown. Figures 7.25c and 7.25d show the resulting correction factors, centered around zero, obtained as the ratio of the $W$+jets $FF$ to the $Z$+jets $FF$. For reference, the yellow band denotes ±0.3. Like for muons, the electron numbers have been integrated in pseudorapidity to gain statistical precision. Both the fake factors and correction factors suffer from large statistical uncertainties. This is caused by the tight lepton selections used for the id, exhausting this population of events. The values for the correction factors are given in table 7.15 for electrons (top) and muons (bottom), where the Alpgen prediction is also listed.

To cope with the poor statistical precision, the correction factors are further integrated in $p_T$. A two-bin correction factors is used; $p_T \leq 25$ GeV and $p_T > 25$ GeV.
Figure 7.25: Fake factors (a,b) and correction factors (c,d) for fake electrons (a,c) and muons (b,d) in $Z$+jets and $W$+jets. The numbers are evaluated with POWHEG. By subtracting one, the correction factors are centered around zero. The yellow band denotes $\pm 0.3$ for reference.

<table>
<thead>
<tr>
<th>Lepton</th>
<th>$p_T$ region [GeV]</th>
<th>ALPGEN</th>
<th>POWHEG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>$15 - 20$</td>
<td>$1.19 \pm 0.32$</td>
<td>$1.03 \pm 0.16$</td>
</tr>
<tr>
<td></td>
<td>$20 - 25$</td>
<td>$1.16 \pm 0.43$</td>
<td>$0.80 \pm 0.19$</td>
</tr>
<tr>
<td></td>
<td>$25 - 35$</td>
<td>$0.92 \pm 0.21$</td>
<td>$1.08 \pm 0.20$</td>
</tr>
<tr>
<td></td>
<td>$&gt; 35$</td>
<td>$1.28 \pm 0.23$</td>
<td>$1.24 \pm 0.22$</td>
</tr>
<tr>
<td></td>
<td>average</td>
<td>$1.11 \pm 0.13$</td>
<td>$1.02 \pm 0.09$</td>
</tr>
<tr>
<td>Muon</td>
<td>$15 - 20$</td>
<td>$0.99 \pm 0.22$</td>
<td>$1.49 \pm 0.21$</td>
</tr>
<tr>
<td></td>
<td>$20 - 25$</td>
<td>$1.31 \pm 0.48$</td>
<td>$0.85 \pm 0.20$</td>
</tr>
<tr>
<td></td>
<td>$&gt; 25$</td>
<td>$1.63 \pm 0.53$</td>
<td>$1.83 \pm 0.38$</td>
</tr>
<tr>
<td></td>
<td>average</td>
<td>$1.12 \pm 0.18$</td>
<td>$1.24 \pm 0.14$</td>
</tr>
</tbody>
</table>

Table 7.15: Correction factors for electrons (top) and muons (bottom) in $W$+jets, evaluated with two different MC programs. The average is computed as the uncertainty weighted sum of the different $p_T$ regions.
Their values, applied in the analysis, are shown in table 7.16 along with their corresponding statistical and systematic uncertainties. The systematical uncertainty is evaluated by taking the difference with respect to the corresponding correction factors evaluated with ALPGEN. The motivation for evaluating the systematic uncertainty in this way is that the choice of generator is somewhat arbitrary. However, it should be considered a conservative estimate, given the large statistical uncertainties; the statistical uncertainty is likely double-counted by this method.

<table>
<thead>
<tr>
<th>lepton</th>
<th>$p_T \leq 25$ GeV</th>
<th>$p_T &gt; 25$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron</td>
<td>$0.96 \pm 0.13$(stat) $\pm 0.28$(syst)</td>
<td>$1.15 \pm 0.15$(stat) $\pm 0.02$(syst)</td>
</tr>
<tr>
<td>muon</td>
<td>$1.34 \pm 0.17$(stat) $\pm 0.25$(syst)</td>
<td>$1.83 \pm 0.38$(stat) $\pm 0.20$(syst)</td>
</tr>
</tbody>
</table>

Table 7.16: Corrections factors with uncertainties applied to the misidentified lepton fake factor estimates in the analysis. POWHEG is used to derive the central values, while the systematic uncertainty is evaluated by comparing with ALPGEN.

### 7.6 $W$+jets control sample

The $W$+jets control sample determines the shape of the single-fake lepton background estimates. In fig. 7.26 the $m_T$ distribution is shown for misidentified electrons (a,c,e) and misidentified muons (b,d,f), for the three different signal regions. The plots in the bottom for the VBF region are made after the $Z \rightarrow \tau\tau$ veto requirement. No fake factors or correction factors are applied. The blue data points represent the fake contribution, obtained by subtracting the real lepton contributions in the histograms from the data (black points). For the VBF region, the misidentified lepton estimate incorporates also the double-anti-id region, presented in section 7.7.

In fig. 7.27 the $m_T$ distribution for the fake lepton estimate is shown for the signal region, where the fake factors and correction factors have been applied. For comparison, the $W$+jets prediction from POWHEG is overlaid in the red dashed line. Note that there is no multijet prediction from simulation included, while it by construction is present in the data-driven estimates (and corrected for in the case of the VBF analysis, see section 7.7). The data-driven estimates are larger than the MC prediction in all regions, and more so with increasing jet multiplicity.

### 7.7 Multijet background

In the fake factor method outlined so far, the multijet contribution is double counted if not explicitly subtracted from the $W$+jets control sample. This is illustrated in
Figure 7.26: Transverse mass distribution in the $W$+jets control sample with misidentified electrons (a,c,e) and misidentified muons (b,d,f). The distributions are made in the ggF $N_{\text{jet}} = 0$ region (a,b), the ggF $N_{\text{jet}} = 1$ region (c,d) and the VBF $N_{\text{jet}} \geq 2$ region (e,f). No fake factors or correction factors are applied. The blue data points represent the fake contribution, obtained by subtracting the prompt lepton contributions in the histograms from the data. Uncertainties are statistical only.
Figure 7.27: Transverse mass distribution of the data-driven misidentified lepton estimates in the ggF (a,b) and VBF (c,d) signal regions. For comparison, the $W$+jets prediction from POWHEG is overlaid in the red dashed line. The hashed band denotes the statistical uncertainty.
where the fake lepton estimate is expanded,

\[
N_{\text{FF estimate}}^{\text{id+id}} = N_{\text{e-fake}} + N_{\mu\text{-fake}} = \\
= FF_{e}^{Z} \cdot (N_{\text{data}}^{\mu,\text{id}} - N_{\text{prompt, MC}}^{\mu,\text{id}}) + FF_{\mu}^{Z} \cdot (N_{\text{data}}^{e,\text{id}} - N_{\text{prompt, MC}}^{e,\text{id}}) = \\
= FF_{e}^{Z} \cdot (N_{W^{\text{jet}}}^{\mu,\text{id}} + N_{\text{multijet}}^{\mu,\text{id}}) + FF_{\mu}^{Z} \cdot (N_{W^{\text{jet}}}^{e,\text{id}} + N_{\text{multijet}}^{e,\text{id}}) = \\
= FF_{e}^{Z} \cdot N_{W^{\text{jet}}}^{\mu,\text{id}} + FF_{\mu}^{Z} \cdot N_{W^{\text{jet}}}^{e,\text{id}} + N_{\text{multijet}}^{\mu,\text{id}} + N_{\text{multijet}}^{e,\text{id}} \\
(7.5)
\]

where \(FF_{e}^{Z}\) and \(FF_{\mu}^{Z}\) denote the \(Z+\text{jets}\) electron and muon fake factors respectively, and \(FF_{e}^{j}\) and \(FF_{\mu}^{j}\) denote the multijet fake factors. For brevity, the correction factors are suppressed in the above expression (but implicitly each \(FF_{\text{Z}}\) is multiplied by an associated \(CF\)). In the last equality, the multijet estimate in the \(\text{id}+\text{anti-id}\) region has been expanded with the fake factor method. In the final expression, there are two terms with the multijet estimate in the \(\text{anti-id}+\text{anti-id}\) region, extrapolated with a fake factor product. This is the source of the double-counting. Note however that the double-counting is approximate – it becomes exact under the assumption that the multijet fake factors and the \(Z+\text{jets}\) fake factors are the same. The correct multijet estimate is obtained by extrapolating from the \(\text{anti-id}+\text{anti-id}\) region with the multijet fake factors. The full fake lepton estimate is thus obtained by adding together such a multijet estimate and a \(W^{\text{jet}}\) estimate, where for the latter the multijet contribution is subtracted from the \(\text{anti-id}+\text{id}\) control sample. This can be accomplished by adding to the standard \(\text{anti-id}+\text{id}\) estimation \(N_{\text{FF estimate}}^{\text{id+id}}\) a correction based on the \(\text{anti-id}+\text{anti-id}\) region, according to eq. (7.6).

\[
N_{\text{id, id}}^{\text{multijet corr.}} = N_{\text{id, id}}^{\text{multijet}} \cdot FF_{\text{multijet corr.}} = \\
= (N_{\text{data}}^{\mu,\text{id}} - N_{\text{prompt, MC}}^{\mu,\text{id}}) \cdot (FF_{e}^{j} FF_{\mu}^{j} - FF_{e}^{Z} FF_{\mu}^{Z} - FF_{\mu}^{Z} FF_{e}^{j}) \\
(7.6)
\]

where \(N_{\text{id, id}}^{\text{prompt, MC}}\) is the contamination from all processes with at least one real lepton. The combined fake factor weight expression \(FF_{\text{multijet corr.}}\) will be a negative number.

In table 7.17 the different fake lepton yields are given along with the overestimation due to the double-counting, for the ggF and VBF analyses. The overestimation is computed as \(N_{\text{id+id}}^{\text{FF estimate}} / (N_{\text{id+id}}^{\text{FF estimate}} + N_{\text{id, id}}^{\text{multijet corr.}})\). For the ggF, it evaluates to at most 7.3% in the \(N_{\text{jet}} = 1\) region. This is a small bias considering the comparatively large uncertainties on the full fake lepton estimate. It is considered negligible, and no multijet correction is applied in the ggF analyses. For the VBF analysis, it is larger than 20% and therefore the multijet correction is applied. The multijet contribution increases with jet multiplicity, presumably due to combinatorics; the more number of jets, the more number of ways to combine pairs to be misidentified as leptons.
Table 7.17: Fake lepton background yields in the ggF and VBF analyses, split in the 
$e\mu$ and $\mu e$ channels. The standard $e$-fake and $\mu$-fake yields, the multijet correction term 
(defined as outlined in the text) and the resulting corrected “Misid” yields are shown. 
The overestimation (in percent) is given, computed as $(e$-fake $+ \mu$-fake)/Misid. The VBF 
rows denote yields after the $Z \rightarrow \tau\tau$ veto (but before BDT application).

<table>
<thead>
<tr>
<th>Signal region</th>
<th>$e$ $W$+jets</th>
<th>$\mu$ $W$+jets</th>
<th>Multijet</th>
<th>Overest. (%)</th>
<th>$W$+jets $e+\mu$</th>
<th>Misid. (corr.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggF $N_{\text{jet}} = 0$ $(e\mu)$</td>
<td>130 ± 10</td>
<td>193 ± 7</td>
<td>-14.0 ± 2.3</td>
<td>4.5 ± 0.8</td>
<td>323 ± 13</td>
<td>309 ± 13</td>
</tr>
<tr>
<td>ggF $N_{\text{jet}} = 0$ $(\mu e)$</td>
<td>130 ± 7</td>
<td>48 ± 6</td>
<td>-4.7 ± 1.9</td>
<td>2.7 ± 1.1</td>
<td>178 ± 9</td>
<td>173 ± 9</td>
</tr>
<tr>
<td>ggF $N_{\text{jet}} = 1$ $(e\mu)$</td>
<td>70 ± 8</td>
<td>96 ± 6</td>
<td>-11.3 ± 2.0</td>
<td>7.3 ± 1.4</td>
<td>166 ± 10</td>
<td>155 ± 10</td>
</tr>
<tr>
<td>ggF $N_{\text{jet}} = 1$ $(\mu e)$</td>
<td>73 ± 6</td>
<td>35 ± 6</td>
<td>-6.0 ± 0.8</td>
<td>5.8 ± 0.9</td>
<td>108 ± 8</td>
<td>102 ± 8</td>
</tr>
<tr>
<td>VBF $N_{\text{jet}} \geq 2$ $(e\mu)$</td>
<td>36 ± 6</td>
<td>51 ± 5</td>
<td>-18.6 ± 1.7</td>
<td>27 ± 4</td>
<td>87 ± 8</td>
<td>69 ± 8</td>
</tr>
<tr>
<td>VBF $N_{\text{jet}} \geq 2$ $(\mu e)$</td>
<td>32 ± 5</td>
<td>19 ± 5</td>
<td>-7.9 ± 1.0</td>
<td>18 ± 4</td>
<td>51 ± 7</td>
<td>43 ± 7</td>
</tr>
</tbody>
</table>

In the anti-id+anti-id control sample, the triggered fake factors are used for 
anti-id objects in events where this object is the only object triggering the event. If 
the di-lepton trigger fires, there is no trigger bias and the nominal (non-triggered) 
fake factors are used. This procedure is the same as for the single-fakes in the 
id+anti-id region.

Figure 7.28 show the $m_T$ and $E_T^{\text{miss}}$ distributions in the anti-id+anti-id control 
sample, from which the shape of the multijet correction is taken. It is extrapolated 
to the SR with the combined fake factor weight expression $F F^{\text{multijet}}$ as given in 
eqq. (7.6). The region is more than 90% pure in fake leptons. As multijet processes 
have little natural $E_T^{\text{miss}}$, the resulting $m_T$ distribution peaks at lower values as 
compared to the $W$+jets process (see fig. 7.26).

7.8 Fake lepton electrical charge asymmetry

In $pp$ collisions the cross section for producing a $W^+$ is a factor 1.3 larger than producing a $W^-$ [95], thanks to the relatively larger abundance of up quarks compared 
to down quarks in the colliding protons. To first order approximation, assuming 
$W$ boson production through valence quarks, this asymmetry should be reflected 
in the charge of the fake and prompt leptons in the $W$+jets background.

In fig. 7.29 the charge of the prompt lepton candidate lepton is shown in the 
$W$+jets control sample, i.e. the charge of the identified lepton. As we consider 
opposite-charge final states, the $x$ axis may also be interpreted as minus the charge 
of the anti-identified lepton. The plots are made after all SR selection requirements, 
separated in the ggF $N_{\text{jet}} = 0$ (a,b), ggF $N_{\text{jet}} = 1$ (c,d) and VBF $N_{\text{jet}} \geq 2$ regions 
(e,f), showing fake electrons (a,c,e) and muons (b,d,f). For the fake muon case, 
no significant charge asymmetry is observed. In section 7.5 it was shown that 
MC predicts large fraction of charm origin for fakes in $W$+jets (around 80%) .

Given that the leading order Feynman diagram for $W$+charm quark has an initial
state $s$ quark from the sea, we don’t expect a charge asymmetry for this particular process.

For the fake electron case, a charge asymmetry, defined as the ratio of the yield of positively charged prompt leptons to negatively charged prompt leptons, is observed. It is equal to $1.35 \pm 0.04$ for $N_{\text{jet}} = 0$, $1.23 \pm 0.10$ for $N_{\text{jet}} = 1$ and $1.19 \pm 0.18$ for the VBF $N_{\text{jet}} \geq 2$ region. An asymmetry is expected, given that a significant fraction of fake electrons are of light quark origin. The associated processes involve initial state valence quarks.

In fig. 7.30 the prompt lepton charge is shown for $W+\text{jets}$, predicted by POWHEG (a,b) and ALPGEN (c,d). The left (right) hand side plots shows the prompt muon (electron) charge in the sample with anti-id fake electrons (muons). These plots are inclusive in jet multiplicity to retain statistics. For muons, no asymmetry is observed; as expected the green histograms representing charm quark origin are of equal height in both bins. For electrons, POWHEG predicts an asymmetry of $(11 \pm 4)\%$, ALPGEN predicts $(17 \pm 4)\%$. The asymmetry is found to originate from the yellow histograms, representing processes with fake leptons of light quark origin.

In conclusion, neither the data nor the MC predicts any asymmetry for the muon fakes. For fake electrons, MC predicts a slightly smaller asymmetry than what is observed in data.

### 7.9 Systematic uncertainties

The fake lepton estimate is subject to systematic uncertainties, coming from uncertainties on the fake factors. No uncertainties on the $W+\text{jets}$ control sample...
Figure 7.29: Electric charge of the identified lepton in the $W+\text{jets}$ control sample for fake electrons (a,c,e) and fake muons (b,d,f). All signal region selection requirements are applied. No fake factor or correction factor is applied. The uncertainties are statistical only.
Figure 7.30: Charge of the prompt lepton for Powheg (a,b) and Alpgen (c,d) for $W$+jets. The left panel show the prompt muon charge in the sample with anti-identified fake electrons, the right show the prompt electron charge in the sample with anti-identified muons. The uncertainties are statistical only.
apart from its statistical uncertainty are applied. There are two systematic uncertainties applied; the prompt lepton background subtraction uncertainty, and the sample composition uncertainty. The total uncertainty is obtained by adding the two sources of systematic uncertainty, and the statistical uncertainty, in quadrature. The sample composition uncertainty is implemented as an uncertainty on the correction factor as explained in section 7.5.2. It is evaluated as the difference between the nominal POWHEG prediction and the ALPGEN prediction.

In section 7.9.1 the estimation of the prompt lepton background subtraction uncertainty is detailed. The section concludes with a summary of the uncertainties applied to the misidentified lepton background estimate.

7.9.1 Prompt lepton background subtraction uncertainty

The numerator (id) population of the Z+jets fake factor measurement is suffering from large contamination of prompt leptons. This is especially true for the muon fakes. To obtain a sample of fake muons only, the prediction of prompt leptons as obtained from MC is subtracted from the data. Production of WZ bosons is the main background, followed by ZZ production, each subject to uncertainties. A systematic uncertainty is assigned to the fake factors to account for the uncertainty in the subtracted backgrounds. The uncertainty on the Z+jets fake factors are obtained by comparing their nominal values to the ones obtained upon varying the prompt lepton MC predictions by their respective uncertainty. This is done in a fully correlated way, i.e. all background processes are varied simultaneously, in the same direction. In fig. 7.31 the resulting relative uncertainties on the fake factors are shown. For comparison, the statistical uncertainties are shown as well. Electron fake factors are integrated in $|\eta|$ to gain statistical precision (the muon fake factors are already integrated in $|\eta|$). The uncertainty on the electron fake factors due to the prompt lepton background subtraction reaches from 13% in the first $p_T$ bin to 33% in the highest-$p_T$ bin. For muon fake factors, the uncertainty is 9%, 17% and 143% in the first, intermediate and last $p_T$ bin respectively. As the region $p_T > 25$ GeV has a low fake purity, the fake factor is very sensitive to changes in the subtraction. The effect of the uncertainty in the high-$p_T$ bin of the muon fake factor on the significance of the analysis has been evaluated. It was found to be small; artificially reducing the uncertainty to 30% caused an increase of the significance of the order 0.01. In the highest-$p_T$ bin for the muon fake factor, an upward variation of the prompt lepton background causes the fake factor to be negative. The fake factor is forced to be zero in this bin.

7.9.2 Summary and final fake factors

The Z+jets fake factors applied in the analysis are shown in fig. 7.32. The different sources of uncertainty are shown as bands, added in quadrature. For brevity, the electron fake factors are integrated in $|\eta|$ in the figure. In the $p_T > 25$ GeV region, the muon fake factors suffer from a large prompt lepton background subtraction uncertainty, due to the large WZ background. Uncertainties on electron fake factors
Figure 7.31: Systematic uncertainty due to uncertainty in the prompt lepton background subtraction on the $Z$+jets electron (a) and muon (b) fake factors. The statistical uncertainties are shown in red for comparison.

are generally dominated by sample composition in the region $p_T < 25$ GeV, while statistical and prompt background subtraction uncertainties are larger for the $p_T > 25$ GeV region. A breakdown of the uncertainty on the electron and muon $Z$+jets fake factors are shown in tables 7.18 and 7.19, respectively. For electrons, the total uncertainty is around 40% for all bins. For $p_T < 25$ GeV, the sample composition uncertainty is generally the dominating component. Above 25 GeV, the prompt lepton background uncertainty and the statistical uncertainty are approximately the same size. For muons, the uncertainty is largely $p_T$ dependent.

Regarding the triggered and the nominal multijet fake factors, only the statistical uncertainty is considered. It is small enough to be pruned away in the likelihood fit.

Figure 7.32: $Z$+jets fake factors applied in the analysis, including all sources of uncertainty. The electron fake factors are in reality split in two bins in pseudorapidity but have here been integrated for simplicity. Figures taken from [52].
| $|\eta|$ | $p_T$ [GeV] | Statistical | Prompt lepton subtraction | Sample composition | Total |
|------|------------|-------------|--------------------------|-------------------|-------|
| $|\eta| < 1.37$ | 15 – 20 | 27 | 13 | 32 | 44 |
| | 20 – 25 | 25 | 16 | 32 | 44 |
| | 25 – 35 | 23 | 16 | 13 | 31 |
| | 35 – 1000 | 26 | 33 | 13 | 44 |
| $1.52 < |\eta| < 2.50$ | 15 – 20 | 26 | 13 | 32 | 43 |
| | 20 – 25 | 54 | 16 | 32 | 65 |
| | 25 – 35 | 27 | 16 | 13 | 34 |
| | 35 – 1000 | 32 | 33 | 13 | 47 |

Table 7.18: Summary of uncertainties (quoted as percentages) on the $Z$+jets electron fake factors. In the rightmost column the individual components have been added in quadrature.

<table>
<thead>
<tr>
<th>$p_T$ [GeV]</th>
<th>Statistical</th>
<th>Prompt lepton subtraction</th>
<th>Sample composition</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 – 20</td>
<td>11</td>
<td>9</td>
<td>23</td>
<td>27</td>
</tr>
<tr>
<td>20 – 25</td>
<td>24</td>
<td>17</td>
<td>23</td>
<td>37</td>
</tr>
<tr>
<td>25 – 1000</td>
<td>76</td>
<td>143</td>
<td>23</td>
<td>163</td>
</tr>
</tbody>
</table>

Table 7.19: Summary of uncertainties (quoted as percentages) on the $Z$+jets muon fake factors. In the rightmost column the individual components have been added in quadrature.

7.10 Outlook

By adding the data collected in 2017 and 2018, the measurement will be updated to contain the full Run-2 dataset, corresponding to about 150 fb$^{-1}$. On average, there is more pile-up in the 2017 and 2018 data relative to the current dataset. Consequently, the measurement might be subject to larger backgrounds from misidentified leptons, and would thus benefit from a more precise estimate.

The misidentified lepton estimate has the potential to improve in different ways. Preliminary studies indicate that the suppression of prompt lepton backgrounds in the $Z$+jets fake factor estimate can improve by optimising the selections. This would improve the statistical precision on the fake factors and reduce systematic uncertainty related to the prompt lepton background subtraction. A different way of countering the large uncertainties at high $p_T$ is to extend the use of multijet fake factors, which are more pure in misidentified leptons.

For the low-$p_T$ region, the sample composition uncertainty is substantial. If larger MC samples are produced, the correction factors can be constrained with
greater precision, resulting in a smaller uncertainty. Additional insights may be obtained by studying the sample composition of misidentified leptons in the multijet sample. A different approach is to search for a $W$+jets-enriched region, orthogonal to the SR, in which to evaluate the fake factor.

Lastly, given the more harsh pileup conditions, it is possible that the lepton id selections need to be re-optimised. Considering the large uncertainties on the misidentified lepton estimate of order 40%, tighter selections can potentially improve the significance of the analysis.
Chapter 8

$H \rightarrow WW^* \rightarrow e\nu\mu\nu$ statistical interpretation and results

“Sometimes science is more art than science.”
— Rick Sanchez

The goal of the analysis described in the two preceding chapters is to measure the ggF and VBF Higgs boson production cross sections times branching ratio for the $H \rightarrow WW^*$ decay. To extract the yield of Higgs boson events observed in data, a likelihood analysis is performed. The likelihood function expresses how likely a set of model parameters are, given an observed dataset. It is a product of probability functions and terms accounting for the systematic uncertainties, and it describes the full background plus signal model. It is maximised to obtain the values of the model parameters which best describe the data. Here, the parameters of interest (POIs) targeted for measurement are the ggF and VBF signal strengths, defined as

$$
\mu_{ggF} = \frac{\sigma_{obs}^{ggF}}{\sigma_{SM}^{ggF}}, \quad \mu_{VBF} = \frac{\sigma_{obs}^{VBF}}{\sigma_{SM}^{VBF}}.
$$

A signal strength compatible with one corresponds to agreement with the SM (including the Higgs boson), while $\mu = 0$ corresponds to a background-only (no Higgs boson) scenario. A profile likelihood method is used to test the two hypotheses. Note that the parametrisations are only with respect to the production cross sections. The SM prediction is assumed for the branching ratios of the decays to the final state; $\mathcal{B}(H \rightarrow WW^*) \times \mathcal{B}(WW^* \rightarrow e\nu\mu\nu) = 0.2137 \times 2 \cdot 0.107 \cdot 0.106$.

The likelihood formalism is explained in section 8.1, followed by a listing of the systematic uncertainties in section 8.3. In section 8.4 the results are presented, with figures and tables from Ref. [52].
8.1 Likelihood formalism

Before building the full likelihood used in this measurement, consider the simplest form of it, describing a single-bin Poisson counting experiment. With a signal region (SR) expected to contain $B_{SR}$ events from a background process, and possibly events from a signal process, the likelihood is equal to

$$L(\mu; N_{SR}) = P(N_{SR} | \mu s_{SR} + B_{SR}),$$

where $P$ denotes Poisson probability, $N_{SR}$ the number of observed events, $\mu$ is the signal strength and $s_{SR}$ the predicted number of signal events for $\mu = 1$. The signal strength is the POI, scaling the signal yield, with $\mu = 1$ corresponding to the expected rate (in our case, the SM rate). By maximising with respect to $\mu$ the value best describing the data is obtained. This example assumes that the background prediction is perfectly known, which is rarely the case. If a sideband (control) region enriched in the background process is included in the measurement, we can instead introduce another parameter; the background normalisation factor $\beta$ (“background strength”), defined by $b = \beta B$. Like $\mu$, $\beta$ is floating in the fit, and will be constrained by the sideband measurement. The likelihood is modified accordingly by multiplying with another Poisson term,

$$L(\mu, \beta; N_{SR}, N_{CR}) = P(N_{SR} | \mu s_{SR} + \beta b_{SR}) \times P(N_{CR} | \mu s_{CR} + \beta b_{CR}),$$

where CR stands for control region. The normalisation parameter $\beta$ is an example of a nuisance parameter (NP); something the experiment is sensitive to but does not target for measurement. NPs may be introduced to model the impact of systematic uncertainties on the signal and background predictions. In our case, an example is the uncertainty in the jet energy scale, affecting the number of events falling into each jet bin category. The effect of a NP $\theta$ is accounted for by including the dependence on $\theta$ for the signal and background predictions $s$ and $b$, and adding a constraint term, containing information on the expected value and uncertainty of $\theta$, to the likelihood. A constraint term functions to constrain its associated NP within given bounds, and represents a simplified version of a subsidiary calibration measurement (it should not be mistaken for a pdf of the NP). By including NPs in the model, the likelihood as a function of $\mu$ broadens compared to the case of fixed NPs, representing the loss of information on $\mu$ due to systematic uncertainties.

The full likelihood including all signal and control regions and constraint terms for nuisance parameters is given in eq. (8.1). The two signal strengths are collectively denoted $\mu$. The product of Poisson terms runs over indices $j$ and $i$, where $j$ is short for $N_{jet}$ and $i$ denotes signal and control region bins inside an $N_{jet}$ multiplicity bin. The sum runs over index $k$, denoting the different background processes, with associated normalisations $\beta_{kj}$. For the backgrounds with normalisations constrained in a control region, the $\beta_{kj}$ are floating in the fit, with resulting values given in table 6.4. For the other backgrounds the $\beta_{kj}$ are fixed to unity. For each region $ij$, the signal and background expectations are denoted $s_{ij}$ and $b_{ij}$ respectively, and $N_{ij}$ denotes the number of observed events. The collection of NPs, not counting
the background normalisation factors, are denoted by $\theta$. The constraint terms are most often Gaussian, but Poisson terms are used for statistical uncertainties on the background predictions. The likelihood is maximised with respect to all parameters to obtain the best-fit values of the POIs. In the fit, a NP may be pulled, meaning that its best-fit value deviates relative to its nominal (pre-fit) value. If the uncertainty of a NP as computed by the fit is constrained to a smaller value relative to the nominal one, it is said to be over-constrained.

$$L(\mu, \theta; N) = \prod_{j} L_j(\mu, \theta; N_j)$$

$$= \prod_{j} \prod_{i} P\left(N_{ij} \mid \mu_{ggF} \cdot s_{ij}^{ggF}(\theta) + \mu_{VBF} \cdot s_{ij}^{VBF}(\theta) + \sum_{k} \beta_{j}^{k} \cdot b_{ij}^{k}(\theta) \right) \prod_{\theta \in \theta} C(\theta) \quad (8.1)$$

To facilitate interpretation, the likelihood is input to a test statistic, as explained in the next section. The definition of the regions $i$ will be presented in sections 8.2.1 and 8.2.2.

### 8.2 Test statistic and interpretation

To evaluate the compatibility between the observed data and the prediction, and to compute the confidence intervals for the observed signal strengths, a test statistic is used. The choice follows [96] and first requires the construction of the profile likelihood ratio shown in eq. (8.2). The denominator is the global maximum of the likelihood obtained by minimising with respect to all parameters simultaneously; the POIs and NPs are equal to their unconditional maximum likelihood estimates. In the numerator is a profile likelihood with the NPs profiled at some given values of the POIs. Profiling the nuisance parameters implies that they are written as functions of the POIs. More specifically, each NP is equal to its conditional maximum likelihood estimator for a fixed $\mu$, denoted $\hat{\theta}(\mu)$. Thus, the profile likelihood ratio is effectively only parametrised by the POIs.

$$\lambda(\mu) = \frac{L(\mu, \hat{\theta}(\mu))}{L(\mu, \theta)} \quad (8.2)$$

The test statistic is defined as twice the negative logarithm of $\lambda(\mu)$,
Increasing values of $t_\mu$ corresponds to decreasing compatibility between the data and $\mu$. The compatibility between the data and the no-signal ($\mu = 0$) hypothesis, where $\mu$ is either $\mu_{ggF}$ or $\mu_{VBF}$, is evaluated through the $p$-value,

$$p_0 = \int_{t_{0,\text{obs}}}^{\infty} f(t_0|\hat{\theta}(\mu = 0)) \, dt_0,$$

where $f$ denotes pdf of $t_0$, which is the test statistic for $\mu = 0$. The $p$-value is the probability that the background fluctuated to the observed (or a more extreme) value. Ref. [96] gives formulas to approximate $f$, valid in the large sample limit.

One finds that the observed significance of the signal, expressed as number of Gaussian standard deviations $Z_0$, is equal to $\sqrt{t_{0,\text{obs}}}$. When the significance of the ggF signal is evaluated, the VBF production is profiled, and vice versa. The observed significance may be compared to the expected, also referred to as sensitivity, corresponding to the $p$-value for the signal (simulated with $\mu = 1$) and background expectations.

The two-sided confidence interval of $\mu$ is obtained by scanning the test statistic of $\mu$, where for each point a fit is made with $\mu$ fixed. The points where the test statistic is one (two) unit(s) above minimum corresponds to a 68% (95%) confidence level interval.

### 8.2.1 Gluon–gluon fusion analysis

This section describes the signal and control regions $i$ (see eq. (8.1)) of the ggF analysis, i.e. for $j = 0$ and $j = 1$. In addition to the $N_{\text{jet}}$ separation, the SR is categorised based on flavour of the $p_T$-leading lepton ($e\mu/\mu e$, where the first letter denotes the flavour of the leading lepton), $m_{\ell\ell}$, subleading lepton $p_T$ and transverse mass, according to table 8.1. The $p_T^{\text{sublead}}$ categorisation is motivated by the fact that the misidentified lepton contributions are concentrated to the low-$p_T$ regime. Similarly the $e\mu/\mu e$ categorisation increases the sensitivity as the identification and trigger efficiencies are different for electrons and muon, resulting in slightly different background composition in the $e\mu$ and $\mu e$ regions. The $m_{\ell\ell}$ categorisation separates the SR into halves with less and more non-$WW$ diboson background. Finally, the transverse mass is used as discriminant variable. For the $N_{\text{jet}} = 0$ ($N_{\text{jet}} = 1$) region, eight (six) bins in $m_T$ are used. The bin boundaries, shown in fig. 8.1, are optimised to make the signal distribution approximately flat (i.e., each bin should have about the same number of signal events).

The fine granularity used for the SRs as described above is not used for the CRs, which are designed to be pure in a single background process. For the $WW$, top quark and $Z+\text{jets}$ backgrounds, two normalisation factors each are used, corresponding to the normalisations in the $N_{\text{jet}} = 0$ and $N_{\text{jet}} = 1$ regions.

---

$1$The $p$-value is equal to $1 - \Phi(Z_0)$ where $\Phi$ denotes the cumulative distribution function of the Gaussian distribution.
<table>
<thead>
<tr>
<th>$N_{\text{jet}}$</th>
<th>$m_{\ell\ell}$ [GeV]</th>
<th>$p_{T}^{\text{sublead}}$ [GeV]</th>
<th>$e\mu/\mu e$-channel</th>
<th>$m_{T}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[0, 1]</td>
<td>[10–30, 30–55]</td>
<td>[15–20, 20–∞]</td>
<td>$e\mu, \mu e$</td>
<td>see fig. 8.1</td>
</tr>
</tbody>
</table>

**Table 8.1:** Signal region categories of the ggF analysis.

**Figure 8.1:** Transverse mass bin boundaries of histograms used in ggF signal regions, in GeV. The $N_{\text{jet}} = 0$ regions is segmented in eight $m_{T}$ bins, the $N_{\text{jet}} = 1$ region in six bins.
Vector boson fusion analysis

The regions $i$ for $j \geq 2$ (see eq. (8.1)) correspond to the signal and control regions in the VBF analysis. The BDT score is used as discriminant variable, with its four bins (see section 6.2.8) serving as signal regions. Like in the ggF case, no further categorisation is done for the top quark and $Z/\gamma^*$ control regions; one normalisation factor per background is used.

Systematic uncertainties

Systematic uncertainties can coarsely be grouped into two categories; experimental and theoretical. The former concerns trigger and object identification, luminosity, $b$-jet tagging, pileup reweighting and the scale and resolution of energy and momentum. The latter concerns uncertainties in shape and/or normalisations of MC predictions of signal and background processes, related to uncertainties in the simulation.

Experimental uncertainties

Experimental uncertainties are either an uncertainty on the four-momentum of an object, or on the weights applied to objects or events in MC. The former is denoted $P_4$ systematics and the latter is denoted scale factor (SF) systematics.

The $P_4$ systematic uncertainties from energy and momentum scale and resolution is obtained by shifting the energy or momentum on the corresponding object (electron, muon or jet) before selecting events. In the shifting, the overlap removal procedure and the building of transverse missing energy are updated. The result of $P_4$ systematic variations is that some events will migrate out of the phase space and others will migrate in.

Two nuisance parameters are considered for muon track-to-vertex association uncertainties, affecting the impact parameter requirements.

Uncertainties on the jet energy scale and resolution are modelled with 11 nuisance parameters. One of these accounts for the resolution, which is varied only in one direction (towards poorer resolution).

Uncertainty due to flavour tagging affects mainly the top quark control regions and thus the top quark background normalisations. Out of the four nuisance parameters included, the one related to $b$-jet tagging is the most relevant for this analysis.

The total uncertainty on the integrated luminosity is 2.1% for the 2015 dataset and 2.2% for the 2016 dataset. This uncertainty affects the signal strengths to be measured as well as the normalisation of the backgrounds normalised to their theoretical predictions (i.e. which do not use a control region).

The pileup reweighting carries an uncertainty on its data rescaling factor (see section 5.3). Additionally, four nuisance parameters are included to model the uncertainty on the efficiency of the pileup jet rejection tool.
In total, 94 nuisance parameters are used for experimental uncertainties.

8.3.2 Theoretical uncertainties

The theoretical uncertainties concern the rate (normalisation) and shape of the MC predictions of signal and background processes. In general, four sources of uncertainty are considered, related to different steps in the simulation as presented in section 5.1,

1. QCD scale uncertainty, i.e. uncertainty on the factorisation and renormalisation scales,
2. uncertainty in the PDFs,
3. underlying event and parton shower uncertainties (UEPS),
4. uncertainties on the generation of the hard interaction.

The background processes normalised in a CR are not directly sensitive to uncertainties affecting the overall rate. However, the theoretical uncertainties may affect the rate differently in the CR and the SR. In this case, an uncertainty is assigned to the extrapolation of the normalisation factor from the CR to the SR. The uncertainties are often evaluated by use of comparisons between alternative samples and the nominal, as indicated by table 6.1.

Gluon–gluon fusion Higgs boson production

Extra care must be taken when evaluating the uncertainty on the ggF process, due to the jet multiplicity categorisation. The presence of a jet implies that the QCD scale for the process is different, as compared to the no-jet case. Thus, QCD scale uncertainties accounting for jet bin migrations are evaluated for the $N_{\text{jet}}$-exclusive cross sections, following the LHC Higgs Cross Section Working Group scheme [40, 97]. Also included in this scheme are uncertainties related to the transverse momentum of the Higgs boson and to the mass of the top quark. The resulting uncertainties are around 5% in the $N_{\text{jet}}=0$ SR and around 10% in the $N_{\text{jet}}=1$ SR. Additionally, the above four uncertainties are evaluated in each $N_{\text{jet}}$ bin. For the generator uncertainty, the nominal sample with hard interaction modelled by POWHEG+PYTHIA 8 is compared to the alternative using MG5_AMC+PYTHIA 8, both with the same UEPS model (PYTHIA 8). The comparison is done at the NLO level, as this is the precision of the alternative sample. Within the nominal sample, the NLO prediction is given as a weight. The UEPS uncertainty is evaluated by comparing the nominal sample to an alternative one using the same program for the hard interaction but HERWIG 7 (tuned with UEEE5) for UEPS. Uncertainties due to the choice of PDF parameter set is evaluated by adding the uncertainty given in Ref. [53] in quadrature with the differences obtained by comparing the nominal with the alternative PDF sets NNPDF3.0NNLO and CT10. Lastly, the QCD scale uncertainty is evaluated by varying the factorisation and renormalisation scales
within the nominal sample. In the variations the nominal values of the two scales are multiplied by a factor of two or one half, and the uncertainty evaluated from the variation giving the largest difference with respect to the nominal. In summary, the $N_{\text{jet}}$-exclusive uncertainty dominates.

For the VBF analysis, the QCD scale uncertainty on the ggF process is evaluated with the Stewart-Tackmann method [98]. The estimate includes an uncertainty on the normalisation and on the shape of the BDT distribution. The normalisation uncertainty is about 22%, the shape uncertainty is between 1% and 2% in the last two BDT bins. In addition to the QCD scale component, uncertainty in the acceptance due to choice of hard interaction generator, PDF and UEPS uncertainties are evaluated by comparing alternative programs to the nominal. While the latter is found to be the largest of the three (equal to 8.6%), the QCD scale uncertainty dominates.

**Vector boson fusion Higgs boson production**

The uncertainties on the VBF Higgs boson production are evaluated both in terms of normalisation and in terms of shape of the BDT distribution. The uncertainty due to QCD scale uncertainties is evaluated using the same procedure of varying the renormalisation and factorisation scales as described above. Uncertainty related to the choice of generator is estimated by comparing the alternative sample MG5\_AMC@NLO to the nominal POWHEG-Box v2. Like for the ggF process, the UEPS uncertainty is evaluated by comparing the nominal sample to one with parton shower modelled with HERWIG 7 (tuned to UEE5). For PDF uncertainties, the same procedure as for ggF is used. Out of the four sources of uncertainty, the UEPS is largest at 6% normalisation uncertainty.

**WW production**

The non-resonant $WW$ production is normalised in control regions for the ggF $N_{\text{jet}} = 0$ and $N_{\text{jet}} = 1$ analyses. Thus, uncertainties affecting the rate are assigned to the extrapolation from the WW CR to other regions (e.g. the SR or the top quark CR), rather than to the normalisation itself. The effect of the uncertainties on the shape of $m_T$ (BDT) distribution is evaluated for the ggF (VBF) analysis. First, the uncertainty on the production of $WW$ via quarks, constituting about 90% of the total $WW$ yield, is presented. Uncertainties on $qq \rightarrow WW$ due to choice of QCD scales are evaluated by varying the renormalisation and factorisation scales, analogously with the signal processes. For the VBF analysis, a comparison is made between the nominal SHERPA 2.2.2. and MG5\_AMC@NLO. As SHERPA models parton showering as well as the hard interaction, both of these components differ in the comparison, and the resulting difference is assumed to cover both sources (generator choice and UEPS) of uncertainty. For the ggF analysis, the comparison is instead done between two alternative samples using POWHEG-Box v2 for the hard interaction and PYTHIA 8 or HERWIG++ for UEPS modelling. The uncertainty related to PDFs is estimated from the variance of the 100 PDF
sets given in NNPDF3.0NNLO. Finally, an uncertainty from the choice of shower parameters in Sherpa, governing e.g. the matching of matrix element objects to parton shower objects, is assigned for both the ggF analysis and the VBF analysis. The envelope of the extrapolation uncertainties is about 1% (2%) on average in the $N_{\text{jet}}=0$ signal regions. For the acceptance, the uncertainty due to UEPS is largest, reaching 2.6% in the low-$m_{t\bar{t}}$, high-$p_T^{\text{sublead}}$, $N_{\text{jet}}=0$ regions and 12% in the high-$m_{t\bar{t}}$, low-$p_T^{\text{sublead}}$, $N_{\text{jet}}=1$ bins. In the VBF region, the uncertainty related to QCD scale is largest, equal to about 13% on the normalisation and 19% for the shape uncertainty in the last BDT bin.

For the uncertainty on the $gg \to WW$ component, only the normalisation is considered. Because the difference in impact of systematic uncertainties on the $gg$ production between the SR and CR is unknown, the normalisation uncertainties are assigned to the full $gg \to WW$ component rather than to its extrapolation (no cancellation between the SR and CR is allowed for). The uncertainty on the NLO cross section is evaluated for $\sqrt{s}=8$ TeV and $\sqrt{s}=14$ TeV in Ref. [99], using a kinematic selection very similar to the SR selections used in this analysis. The largest of the two uncertainties reported are used here, equal to 26% (39%) for $N_{\text{jet}}=0$ ($N_{\text{jet}}=1$) region.

**Top quark production**

Top quark processes consist of $t\bar{t}$ and $Wt$ production, which are normalised in control regions in both the ggF and VBF analyses. Thus, the uncertainties are assigned to the extrapolation and to the shape of the $m_T$ (BDT) distribution for the ggF (VBF) analysis. Due to limited statistical precision of the samples, the uncertainty is assigned inclusively to each jet bin category. Uncertainties due to the choice of QCD scales are evaluated with the same variation procedure as done for other processes. For the UEPS uncertainty, the prediction of the nominal sample is compared to that of sample with an alternative UEPS model; Pythia 8 versus Herwig 7 for $t\bar{t}$, Pythia 6 versus Herwig++ for $Wt$. The uncertainty due to choice of generator is evaluated by comparing the nominal Powheg sample to the alternative Sherpa 2.2.1 (MG5_AMC@NLO) for $t\bar{t}$ ($Wt$). The PDF uncertainties are estimated analogously to the WW background. Lastly, an uncertainty from the interference between $t\bar{t}$ and $Wt$ is assigned, evaluated by comparing two different schemes for removing overlapping diagrams. Due to limited statistical precision, all uncertainties are evaluated inclusively for the $N_{\text{jet}}=0$ and $N_{\text{jet}}=1$ regions. In the $N_{\text{jet}}=0$ ($N_{\text{jet}}=1$) region the envelope of the extrapolation uncertainties on $t\bar{t}$ is approximately equal to 25% (7%), dominated by the contribution from choice of generator (UEPS). The extrapolation uncertainty on $Wt$ is smaller than 8% for both $N_{\text{jet}}$ regions. In the VBF region, the extrapolation uncertainty is about 12% (9%) for $t\bar{t}$ ($Wt$). The acceptance uncertainties are equal to 18% (7%) for $t\bar{t}$ in the $N_{\text{jet}}=0$ ($N_{\text{jet}}=1$) SR, while a few unit percent larger for $Wt$. For the VBF region, the envelope of the acceptance uncertainties on $t\bar{t}$ equals 10% in the SR and 4% in the top quark CR, while the corresponding numbers for $Wt$ are 9% and 14%.
Non-WW diboson production

Out of the four non-WW processes, \(ZZ, Z\gamma, W\gamma\) and \(WZ/\gamma^*\), the former two are negligible; only the latter two have theoretical systematic uncertainties assigned to them. Analogously with the other backgrounds, the uncertainty from QCD scale is estimated in the same way for both processes. For \(WZ/\gamma^*\), the uncertainty related to the hard interaction generation is estimated by varying parameters governing the matching of objects produced in the hard interaction to objects generated in the parton shower. The uncertainty due to UEPS modelling is estimated by comparing the nominal tune of the parton shower to an alternative one. Like for the top quark backgrounds, the uncertainties are evaluated inclusively in each jet multiplicity region to retain statistical precision. The envelope of the uncertainties on \(WZ/\gamma^*\) in the \(N_{\text{jet}} = 0\) (\(N_{\text{jet}} = 1\)) signal region equals 9% (17%).

For production of \(W\gamma\), a combined generator choice and UEPS uncertainty is assigned to its normalisation by comparing the nominal sample using Sherpa 2.2.2 with the alternative using MG5\_AMC@NLO for the hard interaction and a CSS variation for UEPS modelling. The uncertainty related to PDFs are derived analogously to the top quark and WW estimates. The uncertainties are derived inclusively for the \(N_{\text{jet}} = 0\) and \(N_{\text{jet}} = 1\) categories. The dominating component is the combined generator/UEPS uncertainty, equal to 8% for the \(N_{\text{jet}} = 0\) region and 12% for the \(N_{\text{jet}} = 1\) region.

\(Z/\gamma^*\) production

The theoretical systematic uncertainties on \(Z/\gamma^*\) are derived in the same way as the uncertainties on \(WZ/\gamma^*\). The size of the envelope of uncertainties is 25% in the \(N_{\text{jet}} = 0\) region and 10% in the \(N_{\text{jet}} = 1\) region.

8.4 Results

In table 8.2 the observed data yield and the post-fit background and signal expectations are shown for all three SRs. For the VBF SR, the yields in the highest-score BDT bin are also shown. The yields and uncertainties account for pulls and constraints of the nuisance parameters. The uncertainty on the total signal plus background prediction (given in the bottom) is smaller than the sum of uncertainties from individual contributions due to (anti-)correlations between different data regions and background processes with associated nuisance parameters. For example, a change in the \(b\)-jet tagging efficiency causing an increase in the yield of top quark events in the SR will simultaneously cause a decrease of the WW yield. The fit imposes this behaviour to best constrain the total signal plus background yield to the data. Thus, a certain systematic uncertainty may have a large impact on the yield of an individual process but a small impact on the yield of the sum of processes.

Approximately one thousand Higgs boson events are observed in total. For the inclusive VBF SR, the post-fit expectation of VBF signal events is \(28 \pm 16\),
Process $N_{\text{jet}} = 0$ ggF $N_{\text{jet}} = 1$ ggF $N_{\text{jet}} \geq 2$ VBF Inclusive BDT: [0.86, 1.0]

<table>
<thead>
<tr>
<th>Process</th>
<th>$H_{\text{ggF}}$</th>
<th>$H_{\text{VBF}}$</th>
<th>$WW$</th>
<th>$VV$</th>
<th>$t\bar{t}/Wt$</th>
<th>Mis-Id</th>
<th>$Z/\gamma^*$</th>
<th>Total</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_{\text{ggF}}$</td>
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<td>300 ± 50</td>
<td>45 ± 18</td>
<td>6.4 ± 2.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$H_{\text{VBF}}$</td>
<td>7 ± 1</td>
<td>30 ± 2</td>
<td>28 ± 16</td>
<td>15.9 ± 4.1</td>
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<td>$WW$</td>
<td>2960 ± 200</td>
<td>1020 ± 210</td>
<td>370 ± 60</td>
<td>10.2 ± 3.2</td>
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<td></td>
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<tr>
<td>$VV$</td>
<td>320 ± 30</td>
<td>200 ± 30</td>
<td>70 ± 12</td>
<td>2.6 ± 1.6</td>
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<tr>
<td>$t\bar{t}/Wt$</td>
<td>580 ± 130</td>
<td>1400 ± 180</td>
<td>1270 ± 80</td>
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<tr>
<td>Mis-Id</td>
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<td>250 ± 50</td>
<td>96 ± 30</td>
<td>6.7 ± 2.7</td>
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<td>$Z/\gamma^*$</td>
<td>27 ± 10</td>
<td>76 ± 22</td>
<td>280 ± 40</td>
<td>4.2 ± 2.1</td>
<td></td>
<td></td>
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<tr>
<td>Total</td>
<td>5060 ± 70</td>
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<td>60</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Table 8.2: Post-fit data and MC yields in the ggF and VBF SRs. All systematic and statistical uncertainties are included, with pulls and constraints on nuisance parameters taken into account. The sum of individual contributions may differ from the total value due to rounding. Table from Ref. [52].

The yield of ggF Higgs boson events is $680 \pm 110$ in the $N_{\text{jet}} = 0$ region and $303 \pm 52$ in the $N_{\text{jet}} = 1$ region. The resulting ggF and VBF cross sections times branching ratios are simultaneously measured to be

$$\sigma_{\text{ggF}} \cdot B_{H \to WW^*} = 12.6 \pm 1.0(\text{stat.}) \pm 1.1(\text{th sys.})^{+1.6}_{-1.5}(\text{exp sys.}) \text{ pb} = 12.6_{-2.1}^{+2.3} \text{ pb}$$

$$\sigma_{\text{VBF}} \cdot B_{H \to WW^*} = 0.50_{-0.23}^{+0.24}(\text{stat.}) \pm 0.11(\text{th sys.}) \pm 0.13(\text{exp sys.}) \text{ pb} = 0.50_{-0.29}^{+0.30} \text{ pb}.$$

The corresponding predicted values are $10.4 \pm 0.6$ pb and $0.81 \pm 0.02$ for the ggF and VBF processes, respectively. In fig. 8.2 the cross sections times branching ratios are shown in a two-dimensional scan, with contours indicating 68% and 95% confidence levels. The measured value is shown as a black star and the SM prediction as a red point.

The ggF and VBF signal strength parameters are measured to be

$$\mu_{\text{ggF}} = 1.21 \pm 0.10(\text{stat.})^{+0.13}_{-0.12}(\text{th sys.}) \pm 0.15(\text{exp sys.}) = 1.21_{-0.21}^{+0.22}$$

$$\mu_{\text{VBF}} = 0.62^{+0.30}_{-0.28}(\text{stat.}) \pm 0.13(\text{th sys.}) \pm 0.16(\text{exp sys.}) = 0.62_{-0.36}^{+0.37}.$$

The measurements are compatible with the SM expectations within one standard deviation.

The observed (expected) significances are evaluated to 6.3 (5.2) standard deviations for the ggF process, and 1.9 (2.7) for the VBF process.

Figures 8.3 to 8.5 show post-fit distributions of key variables in the analyses. The black points represent the data, the coloured histograms represent the signal and backgrounds contributions. The hatched band denote the sum in quadrature of the statistical and systematic uncertainties on the signal and background, taking
Figure 8.2: The observed (black star) ggF and VBF Higgs boson production cross sections times branching ratio in a two-dimensional plane, along with the SM prediction (red point). The 68% and 95% confidence level contours of the observed values are indicated. Figure from [52].

into account the pulls and constraints on nuisance parameters as obtained from the fit.

In fig. 8.3 the $m_T$, $m_{\ell\ell}$ and subleading lepton $p_T$ distributions are shown for the $N_{jet}=0$ and $N_{jet}=1$ signal regions. A good agreement between the data and the post-fit SM expectation including a Higgs boson is observed. In fig. 8.4 the transverse mass distribution is shown for the combined $N_{jet} \leq 1$ signal region, with a residual plot added in the bottom pad, showing the data minus all the backgrounds.

In fig. 8.5 the distributions of $m_{jj}$, $\Delta y_{jj}$, $m_{\ell\ell}$, $\Delta \phi_{\ell\ell}$ and the BDT score are shown for the $N_{jet} \geq 2$ VBF signal region. The light red histogram represents the VBF signal, the dark red histogram represents the ggF signal. The third BDT bin contains ggF and VBF signal events in approximately equal proportions. A good agreement between the data and the background plus signal prediction is observed in all variables.

The relative impact of the different sources of uncertainty on the measured cross sections are shown in table 8.3. Furthermore, fig. 8.6 shows a ranking of the most impactful nuisance parameters, including their pulls and constraints as computed by the fit. The impact is evaluated by monitoring the change in the measured cross section while varying a nuisance parameter within its constrained uncertainty, with all other NPs kept fixed. For the ggF measurement, the uncertainties due to data statistics and the theoretical uncertainties contribute in about equal proportions to the total. The experimental uncertainties are slightly larger. For the theoretical uncertainties, the lead contributors are the uncertainties on non-resonant $WW$ production and on the ggF signal. The former is dominated by the theoretical uncertainty on the fraction of $WW$ produced through $gg \rightarrow WW$ in the $N_{jet}=0$...
Figures from [52].

obtained from the fit. The contribution from VBF production is too small to be seen.

and background, taking into account the pulls and constraints on nuisance parameters as
denote the sum in quadrature of the statistical and systematic uncertainties on the signal
data, the histograms represent the signal and background contributions. The hatched band

Figure 8.3: Post-fit $m_T$ (a,b), $m_{\ell\ell}$ (c,d) and subleading lepton $p_T$ (e,f) distributions in
the $N_{\text{jet}} = 0$ (a,c,e) and $N_{\text{jet}} = 1$ (b,d,f) ggF signal regions. The black points represent the
data, the histograms represent the signal and background contributions. The hatched band
denote the sum in quadrature of the statistical and systematic uncertainties on the signal
and background, taking into account the pulls and constraints on nuisance parameters as
obtained from the fit. The contribution from VBF production is too small to be seen.

Figures from [52].
Figure 8.4: Post-fit $m_T$ distribution in the ggF analysis for the $N_{\text{jet}} = 0$ and $N_{\text{jet}} = 1$ regions combined, from [52]. The black points represent the data, the histograms represent the signal and background contributions. The bottom pad shows the background subtracted data along with the signal prediction. The hatched band denote the sum in quadrature of the statistical and systematic uncertainties on the signal and background, taking into account the pulls and constraints on nuisance parameters as obtained from the fit.

channel. The latter is dominated by the UEPS modelling uncertainty in the $N_{\text{jet}} = 1$ region. Of the experimental systematic uncertainties, the $b$-jet tagging uncertainty and pileup uncertainty dominate, each at 5%. The NP associated with the $b$-jet tagging uncertainty show a slight pull, caused by the anti-correlation between this NP and the $WW$ normalisation factor. The NP of the pileup modelling uncertainty is pulled by about one standard deviation. The uncertainty on the misidentified lepton estimate is also non-negligible at 5%.

For the VBF measurement, the statistical uncertainty is the limiting factor at 46%. The statistical precision of the MC is also a relatively large source of uncertainty, contributing 23% to the total. Of the theoretical components, the QCD scale uncertainty on the ggF Higgs boson prediction dominates. The $b$-jet tagging uncertainty and the uncertainty on the misidentified lepton estimate contribute 8% and 9%, respectively.

No large over-constraints are observed.
Figure 8.5: Post-fit $m_{jj}$ (a), $\Delta y_{jj}$ (b), $m_{\ell\ell}$ (c) and $\Delta \phi_{\ell\ell}$ (d) and BDT score (e) distributions in the VBF $N_{\text{jet}} \geq 2$ SR. The black points represent the data, the histograms represent the signal and background contributions. In the dashed line the VBF signal is overlaid, scaled by a factor 30. The hatched band denote the sum in quadrature of the statistical and systematic uncertainties on the signal and background, taking into account the pulls and constraints on nuisance parameters as obtained from the fit. Figures from [52].
<table>
<thead>
<tr>
<th>Source</th>
<th>$\frac{\Delta \sigma_{ggF \cdot B_{H \rightarrow WW^{<em>}}}}{\sigma_{ggF \cdot B_{H \rightarrow WW^{</em>}}}}$ [%]</th>
<th>$\frac{\Delta \sigma_{VBF \cdot B_{H \rightarrow WW^{<em>}}}}{\sigma_{VBF \cdot B_{H \rightarrow WW^{</em>}}}}$ [%]</th>
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<tr>
<td>Total</td>
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<td>59</td>
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</table>

Table 8.3: Breakdown of the main contributions to the total uncertainty on $\sigma_{ggF}$ and $\sigma_{VBF}$. Due to correlations between the components, the sum in quadrature of the individual components differs from the total uncertainty. Table from [52].
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Chapter 9

Summary and conclusions

“Work it harder, make it better, do it faster, makes us stronger.”

— Daft Punk

This thesis has summarised the measurements of the Standard Model Higgs boson gluon–gluon fusion and vector boson fusion production cross sections in the $WW^*$ decay channel. The dataset used in the analysis consists of proton–proton collisions at $\sqrt{s} = 13$ TeV, corresponding to 36.1 fb$^{-1}$ of integrated luminosity. By filtering the data for leptonic decays of the $W$ bosons, the background is reduced. Only final states with one electron and one muon are considered, required to be of opposite electric charge and to pass stringent quality criteria. The data is categorised in bins of zero, one and two or more jets to target the different production modes. Each bin uses customised selection criteria to reject background. Production of non-resonant $WW$ pairs constitute the dominating background in the $N_{\text{jet}} = 0$ region, while production of top quark events dominate the other regions. A special class of backgrounds, covered in detail in the thesis, are contributions with misidentified electrons or muons. They originate mainly from processes with the production of a $W$ boson in association with a misidentified lepton. Multijet processes with two misidentified leptons contribute to a smaller extent, accounted for only in the vector boson fusion analysis. Due to the difficulty in simulating the processes accurately, data driven techniques are used for their estimation. By defining a control sample enriched in the $W$+jets background process, the estimate in the signal regions is obtained by scaling the yields in the control sample with dedicated extrapolation factors. The extrapolation factors are primarily estimated in a sample enriched in processes with a misidentified lepton recoiling off a leptonically decaying $Z$ boson. A complementary set of extrapolation factors, used to correct the effects of trigger bias, are estimated in a multijet sample. Two sources of systematic uncertainties in the estimate are evaluated; the uncertainty from subtraction of prompt lepton background contributions, and from differences
in sample composition between $W$+jets and $Z$+jets processes. On average, the envelope of the uncertainties are of the order 40% for both electrons and muons. Due to the component with prompt lepton backgrounds, the uncertainty increases with increasing transverse momentum of the misidentified lepton.

A combined maximum likelihood fit is performed, resulting in an expectation of approximately one thousand Higgs boson events in total. The cross sections times branching ratios are simultaneously measured to be $\sigma_{ggF} \cdot B_{H \to WW^*} = 12.6^{+2.3}_{-2.1}$ pb and $\sigma_{VBF} \cdot B_{H \to WW^*} = 0.50^{+0.30}_{-0.29}$ pb for the gluon–gluon fusion and vector boson fusion modes, respectively. The corresponding Standard Model predictions are $10.4 \pm 0.6$ pb and $0.81 \pm 0.02$ pb. Expressed in terms of signal strengths, defined as the ratio of the observed to the expected, the results are $1.21^{+0.22}_{-0.21}$ for the gluon–gluon-fusion mode and $0.62^{+0.37}_{-0.36}$ for the vector boson fusion mode. The observed (expected) significance of the gluon–gluon fusion mode is 6.3 (5.2) standard deviations above the Standard Model background, and 1.9 (2.7) for the vector boson fusion mode.

The prospects for measuring luminosity during the High-Luminosity phase (HL-LHC) of the collider have also been investigated. At HL-LHC, the inner tracker alone will have difficulties in associating tracks in the forward region to the correct vertex, due to the high expected interaction density along $z$. During the upgrade phase, ATLAS will build and insert the High-Granularity Timing Detector to mitigate the effects of increased pile-up. As a complementary use-case, the detector is found to have promising capabilities to estimate the luminosity. The number of pixel hits is found to scale linearly with collision multiplicity, from $\mu = 1$, where the luminosity measurement must be calibrated, up to values around $\mu = 200$, corresponding to expected running conditions. With the proposed procedure, luminosity estimates can be provided alongside the data taking on a per-bunch basis. In addition, non-linear effects caused by e.g. radiation from activated material may be constrained by exploiting the high timing resolution of the detector.
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