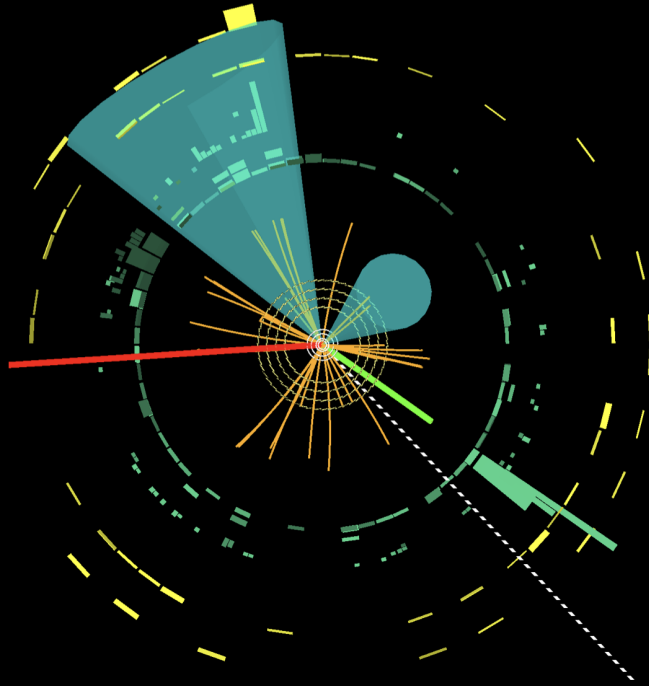


From luminosity to cross-section measurements

Inclusive measurement of the $t\bar{t}$ cross-section using
proton-proton collisions at $\sqrt{s} = 13.6$ TeV with the ATLAS
detector



Dissertation

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Declaration of independent work

I declare that I have completed the thesis independently using only the aids and tools specified. I have not applied for a doctor's degree in the doctoral subject elsewhere and do not hold a corresponding doctor's degree. I have taken due note of the Faculty of Mathematics and Natural Sciences PhD Regulations, published in the Official Gazette of Humboldt-Universität zu Berlin No. 42 on 11 July 2018.

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Abstract

The inclusive $t\bar{t}$ cross-section measurement at a centre-of-mass of 13.6 TeV is presented using 29 fb^{-1} of data recorded by the ATLAS detector at the Large Hadron Collider in 2022. For a cross-section measurement it is necessary to count the events and measure the luminosity of the collider. Additionally, in this measurement, the luminosity uncertainty is the largest uncertainty. The luminosity determination for the 2022 dataset, crucial for numerous ATLAS physics analyses, and in particular for this one, follows the established procedure from Run 2. This methodology is based on three steps: the absolute luminosity calibration using van der Meer scans, the calibration transfer from the special beam conditions during the van der Meer scans to the physics data-taking conditions, and the stability of the luminosity determination. For every step the details of the corrections applied and how the uncertainties are estimated are explained. The preliminary luminosity uncertainty for the 2022 dataset amounts to 2.2%, where the main uncertainties arise from the calibration transfer part and the limited knowledge of non-factorisation effects. The inclusive $t\bar{t}$ cross-section is determined using the b -jet counting method in the dilepton final state. This method obtains the cross-section and the b -jet efficiency simultaneously using $t\bar{t}$ events with exactly one or exactly two b -jets. Through a simultaneous profile likelihood fit of the two yields, the value of the measured $t\bar{t}$ cross-section is found. The measured inclusive $t\bar{t}$ cross-section value is $\sigma_{t\bar{t}} = 850 \pm 3(\text{stat.}) \pm 18(\text{syst.}) \pm 20(\text{lumi.})$ pb, which is 1.5σ lower than the Standard Model prediction. Additionally, the ratio of the Z production in fiducial phase space and the inclusive $t\bar{t}$ cross-section is presented. This ratio is sensitive to the gluon-to-quark PDF ratio and achieves good precision thanks to the cancellation of various systematic uncertainties. The ratio is found to be $R_{t\bar{t}/Z} = 1.145 \pm 0.003(\text{stat.}) \pm 0.021(\text{syst.}) \pm 0.002(\text{lumi.})$, consistent with the Standard Model prediction. Furthermore, the investigation includes an energy ratio of the inclusive $t\bar{t}$ cross-section between 13.6 TeV and 13 TeV, amounting to $R_{13.6/13} = 1.0253 \pm 0.0347$, which is 2.4 standard deviations away from the predicted value. These comprehensive measurements contribute to our understanding of fundamental particle interactions and validate the Standard Model predictions, underlining the significance of precise luminosity determination and cross-section measurements in advancing the knowledge of particle physics.

Zusammenfassung

Die Messung des totalen $t\bar{t}$ -Wirkungsquerschnitts bei einer Schwerpunktsenergie von 13.6 TeV wird anhand von Daten vorgestellt, die vom ATLAS-Detektor am Large Hadron Collider im Jahr 2022 aufgezeichnet wurden und einer Luminosität von 29 fb^{-1} entsprechen. Für eine Wirkungsquerschnittsmessung muss man die Ereignisse zählen und die Luminosität messen. Die größte Unsicherheit bei dieser Messung ist die Luminosität. Die Bestimmung der Luminosität für den Datensatz von 2022, der für zahlreiche Analysen in ATLAS und insbesondere für die vorliegende Analyse von entscheidender Bedeutung ist, erfolgt nach dem bewährten Verfahren von Run 2. Diese Methodik basiert auf drei Schritten: der absoluten Luminositätskalibrierung unter Verwendung von van der Meer Scans, dem Kalibrierungstransfer von den speziellen Strahlbedingungen während der van der Meer Scans zu denen während der Aufnahme der Physikdaten und der Stabilität der Luminositätsbestimmung. Für jeden Schritt werden die Details der angewandten Korrekturen und die Abschätzung der Unsicherheiten erläutert. Die vorläufige Luminositätsunsicherheit für den Datensatz von 2022 beträgt 2.2%, wobei sich die Hauptunsicherheiten aus dem Kalibrierungstransfer und dem begrenzten Wissen darüber ergeben, wie faktorisierbar die Strahlen in den x - und y -Ebenen sind. Der inklusive $t\bar{t}$ -Wirkungsquerschnitt wird mit der b -Jet-Zählmethode im Dilepton-Endzustand bestimmt. Mit dieser Methode erhält man den Wirkungsquerschnitt und die b -jet-Effizienz unabhängig voneinander durch $t\bar{t}$ -Ereignisse mit genau einem oder genau zwei identifizierten b -jets. Durch eine gleichzeitige Profil-Likelihood-Anpassung der beiden Werte wird der Wert des gemessenen $t\bar{t}$ -Wirkungsquerschnitts ermittelt. Er beträgt $\sigma_{t\bar{t}} = 850 \pm 3(\text{stat.}) \pm 18(\text{syst.}) \pm 20(\text{lumi.}) \text{ pb}$, was 1.5σ niedriger ist als die Vorhersage des Standardmodells. Darüber hinaus wird das Verhältnis zwischen der Z -Produktion im gemessenen Phasenraum und dem inklusiven $t\bar{t}$ -Wirkungsquerschnitt ermittelt. Dieses Verhältnis ist empfindlich auf das Gluon-zu-Quark-PDF-Verhältnis und erreicht dank der Aufhebung verschiedener systematischer Unsicherheiten eine gute Präzision. Das Verhältnis beträgt $R_{t\bar{t}/Z} = 1.145 \pm 0.003(\text{stat.}) \pm 0.021(\text{syst.}) \pm 0.002(\text{lumi.})$ und stimmt mit der Vorhersage des Standardmodells überein. Darüber hinaus umfasst die Untersuchung das Verhältnis des inklusiven $t\bar{t}$ -Wirkungsquerschnitts zwischen 13.6 TeV und 13 TeV, das sich auf $R_{13.6/13} = 1.0253 \pm 0.0347$ beläuft, 2.4 Standardabweichungen vom vorhergesagten Wert entfernt. Diese umfassenden

Chapter 0

Messungen tragen zu unserem Verständnis grundlegender Teilchenwechselwirkungen bei und bestätigen die Vorhersagen des Standardmodells. Sie unterstreichen die Bedeutung präziser Luminositätsbestimmungen und Wirkungsquerschnittsmessungen für die Erweiterung des Wissens über die Teilchenphysik.

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1 Introduction

Humanity has always wondered about questions like "where do we come from?" and "what are we made of?". From this curiosity, science was born. The field of particle physics is dedicated to probing the intricate nature of matter and its interactions. Central to this understanding is the Standard Model of elementary particle physics (SM). This comprehensive framework serves as the best physical description of nature, encapsulating the fundamental particles and forces that govern matter and energy.

At the Large Hadron Collider (LHC) physicists collide protons with protons to study the microscopic universe. Protons are composed of quarks and gluons, which are elementary particles. The heaviest quark is called the top quark. This quark is particularly interesting to study since it gives insight into quantum chromodynamics and has the highest coupling with the Higgs boson.

In this thesis, the inclusive $t\bar{t}$ cross-section is measured using 29 fb^{-1} of data from 2022, the first data of Run 3 at the LHC recorded at the centre-of-mass energy of 13.6 TeV at the ATLAS detector. This measurement's accuracy is limited by the luminosity calibration uncertainty. Considerable attention is devoted to the ATLAS luminosity calibration methodology.

Luminosity quantifies the number of collisions happening per unit of area and time, and it is a vital parameter to measure the cross-section of processes and to evaluate the performance of the LHC. It is important, as most physics analyses at the LHC rely on this quantity. In particular, luminosity is needed to determine how frequently a process happens or what the cross-section of a process is.

The connection between luminosity and cross-section is given by

$$R = \sigma \cdot L, \tag{1.1}$$

where R is the rate of events, σ is the cross-section of a process, and L is the luminosity. It can be seen that any uncertainty in the luminosity directly translates into an uncertainty in the cross-section measurement.

The $t\bar{t}$ cross-section is measured using the *b-jet counting method* to extract the $t\bar{t}$ cross-section as well as the *b*-jet efficiency in data; this allows to reduce jet related uncertainties. Measuring the $t\bar{t}$ cross-section is interesting since it is an essential test of Quantum Chromodynamics (QCD) and Parton Distribution Functions (PDFs), whose understanding is essential to the SM. Although this measurement has already been performed with a percent-level precision at the LHC for centre-of-mass energies ranging from 5 to 13 TeV, it is important to measure it again since the $t\bar{t}$ cross-section depends on the centre-of-mass energy at which it is measured, and at 13.6 TeV it is expected that there will be an increase in the value of 12% compared to 13 TeV which should already be visible in early data. Probing $t\bar{t}$ production at higher energies offers insights into the energy dependence of the strong interaction processes governing the top quark production. This exploration not only allows to test the predictions of the Standard Model but also provides a window into potential new physics phenomena that may manifest at higher collision energies. Therefore, through meticulous luminosity measurement and analysis of $t\bar{t}$ cross-sections at new energy regimes, the aim is to deepen the understanding of fundamental particle interactions and pave the way for discoveries beyond the current frontiers of particle physics.

In addition to the inclusive $t\bar{t}$ cross-section, its ratio to the *Z* boson production cross-section is measured, where the *Z* production is measured in a fiducial phase space. Several experimental uncertainties cancel out in the ratio, in particular the large luminosity uncertainty. Thus, a very good precision can be obtained, and the result can be compared to the theory predictions using different PDF sets. Furthermore, given the dominant production modes of the top pair and the *Z* boson, the ratio is sensitive to the gluon-to-quark PDF ratio. Thus, its study gives additional insights into the PDF set predictions and can improve our current knowledge, which benefits many other measurements at the LHC.

This thesis is structured as follows: Chapter 2 introduces the theoretical setup on which this thesis is based: the Standard Model of particle physics. Then the measurement of cross-sections at the Large Hadron Collider is discussed and the expected behaviour of the $t\bar{t}$ cross-section. In Chapter 3 the experimental setup is introduced. First, the Large Hadron Collider is presented with the necessary accelerator physics nomenclature, and then the ATLAS detector used to take the data analysed and its sub-detectors are introduced. Chapter 4 describes the event simulation chain needed for physics analyses in ATLAS. In Chapter 5 it is explained how the events are reconstructed starting from the electrical signals in the detector. In particular, the reconstruction of electrons, photons, muons, and jets will be discussed. Chapter 6 describes details about the luminosity determination in ATLAS. In particular, the van der Meer calibration is discussed in detail, introducing all the corrections and systematic uncertainties and how to estimate them. Finally, Chapter 7 presents the $t\bar{t}$ cross-section analysis. The analysis strategy, event selection, data and MC samples, and results for the inclusive cross-sections are presented, and in the end, the energy ratio to 13 TeV is estimated and discussed.

2 Theoretical setup

Currently, the best description of the microscopic world is given by the Standard Model of elementary particles (SM) [1–4]. The SM describes the particle physics world as composed of elementary particles and fundamental forces. Through its mathematical formulation, it is able to make powerful predictions. For example, it predicted the existence of the Higgs boson discovered in 2012. Unfortunately, the SM is not a complete theory and has its limits. For example, it describes only three out of the four fundamental forces, and it has 19 free parameters. Its predictions are based on data from the experiments and they improve over time.

2.1 Standard Model of elementary particle physics

2.1.1 Elementary particles

Elementary particles are subatomic particles that are not composed of other particles, i.e. they are indivisible and have no internal structure. The atom was believed to be an elementary particle. However, it was later found out that it is composed of a nucleus and electrons. Electrons are elementary particles. The nucleus is made of neutrons and protons, which are themselves composed of quarks. Quarks and electrons are believed to be elementary particles. Elementary particles can be imagined as zero-dimensional point-like objects. An illustration of the atom and its internal structure is shown in figure 2.1.

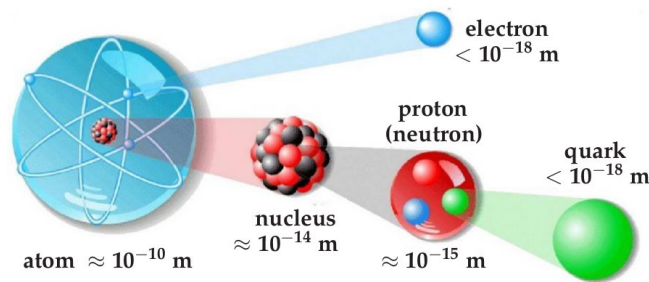


Figure 2.1: *Internal structure of the atom* [5].

The elementary particles of the SM are summarised in figure 2.2, to every particle exists a corresponding antiparticle with same mass but opposite electric charge and magnetic moment. On the left side of the image, the elementary particles composing matter can be seen, which are called fermions. Fermions interact with each other through the exchange of force particles called bosons, as summarised on the right side of the image. Fermions have half-integer spin, while bosons have integer spin. Elementary particles with electric charge participate in the electromagnetic interaction; particles with colour charge participate in the strong interaction; and particles with weak isospin participate in the weak interaction. The interactions between fermions are mediated through the exchange of bosons. The Standard Model has three generations of fermions. They all have the same properties except for the mass. The generations are ordered by mass from the lightest to the heaviest particles. The stable matter on Earth is composed of particles from the first generation. The other generations are unstable and decay quickly into lighter generations.

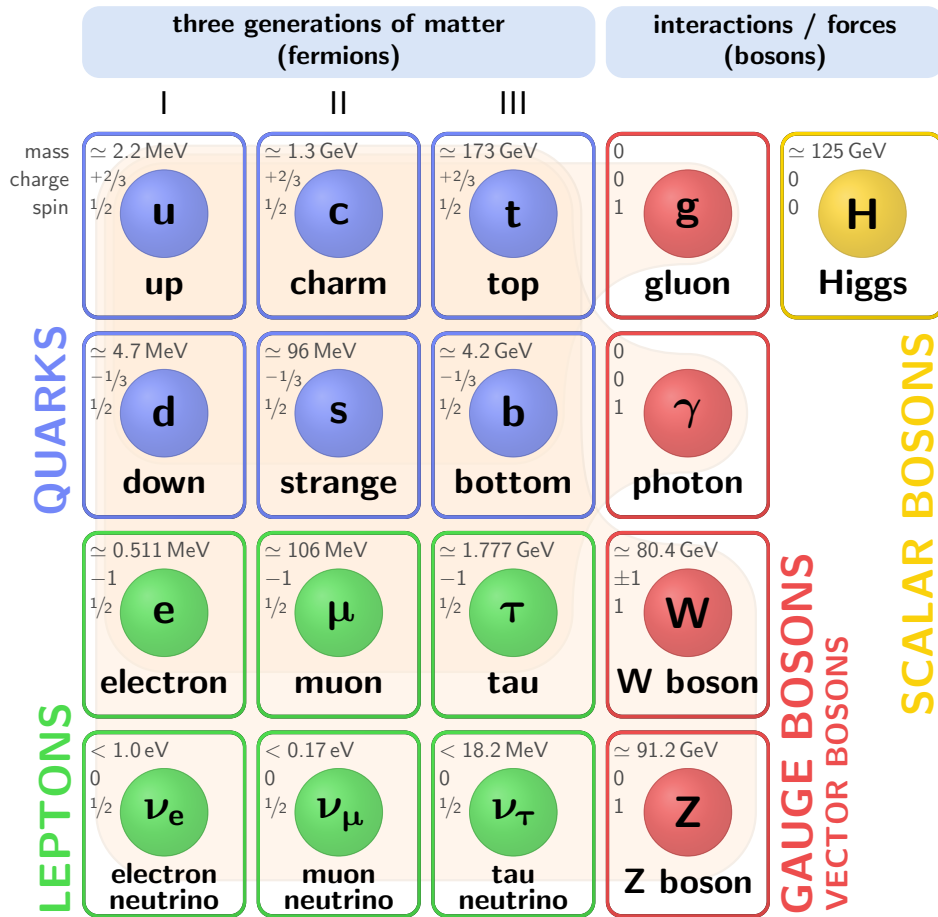


Figure 2.2: Summary of elementary particles and some of their properties in the SM [6].

These heavier generations are interesting to study since they existed at the beginning of the Universe and eventually decayed as it cooled down. The study of these particles can thus give insight into the early Universe shortly after the Big Bang.

As an example, the heavier cousins of the electron are the muon and the tau. Muons are produced in cosmic rays. Taus are highly unstable and decay into a virtual W and a neutrino. As shown in figure 2.2, fermions can be classified into quarks and leptons, each generation has two leptons and two quarks. In contrast to leptons, quarks carry colour and thus interact strongly. Antiquarks carry anticolour. These colours are usually referred to as *red*, *blue*, and *green*. Quarks also have fractional electric charge either $\pm 2/3$ or $\pm 1/3$, while leptons have ± 1 or 0. The different types of quarks are referred to as different flavours: e.g. quarks can have six different flavours: up, down, charm, strange, bottom, and top.

The top quark is, with a mass of 172.5 GeV, the heaviest particle in the SM [7] and has a very short lifetime of around $5 \cdot 10^{-25}$ seconds. As a consequence, the top quark is the only known quark that decays before hadronisation, allowing to study properties of a quark not distorted by hadronisation effects. For these reasons, it is interesting to study and understand this particle better.

2.1.2 Theoretical framework

SM particles' interactions and properties are described by the SM Lagrangian. The SM Lagrangian is built such that it is the simplest Quantum Field Theory (QFT) invariant under local gauge symmetries that describes the experimental observations. The SM Lagrangian is invariant under the following symmetries

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y. \quad (2.1)$$

The first group ($SU(3)_C$) is associated with the strong interaction, while the latter two with the electroweak interaction. A short description of the interactions is given below.

Electroweak interaction The theory describing the unification of electromagnetism and weak interaction is the electroweak (EW) theory developed by Glashow, Salam and Weinberg in the 1960s [1–3]. This theory is invariant under the symmetry groups $SU(2)_L \otimes U(1)_Y$. The connected bosons to $SU(2)_L$ are W_1, W_2, W_3 , and to $U(1)_Y$ the B boson. The W_i bosons interact with each other. The charge associated to $U(1)_Y$ is the hypercharge defined as $Y = 2(Q - T_3)$, where Q is the electric charge, and T_3 is the third component of the weak isospin, which is the charge associated to $SU(2)_L$ and can be $\pm 1/2$ or 0. The observed electroweak bosons W^+, W^-, Z and γ , are a linear combination of the W_1, W_2, W_3 and B bosons. The weak bosons couple only to left-handed particles, at high energy these are equivalent to particles whose spin projection on their momentum vector is in the opposite direction compared to the momentum. When a particle like the W bosons decays, the quarks that appear are *weak eigenstates*. Weak

eigenstates are a mixture of *flavour eigenstates*. The quark weak eigenstates are denoted as d' , s' , b' , while the corresponding flavour eigenstates as d , s , b . The connection between the two eigenstates is given by the Cabibbo-Kobayashi-Maskawa (CKM) matrix [7–9]. This matrix is given by

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}, \quad (2.2)$$

A 3×3 unitary matrix has 9 free parameters (3 real angles and 6 phases). Due to gauge invariance, one of these phases can be rotated away. Of the remaining 8 parameters, 5 can be absorbed into the redefinitions of the quark fields. This leaves 3 real mixing angles and 1 complex phase, resulting in 4 physical parameters that describe the quark mixing in the CKM matrix. The absolute values of the matrix elements are

$$\begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} \approx \begin{pmatrix} 0.974 & 0.226 & 0.004 \\ 0.226 & 0.973 & 0.041 \\ 0.009 & 0.040 & 0.999 \end{pmatrix}. \quad (2.3)$$

A visual illustration of this matrix is shown in figure 2.3.

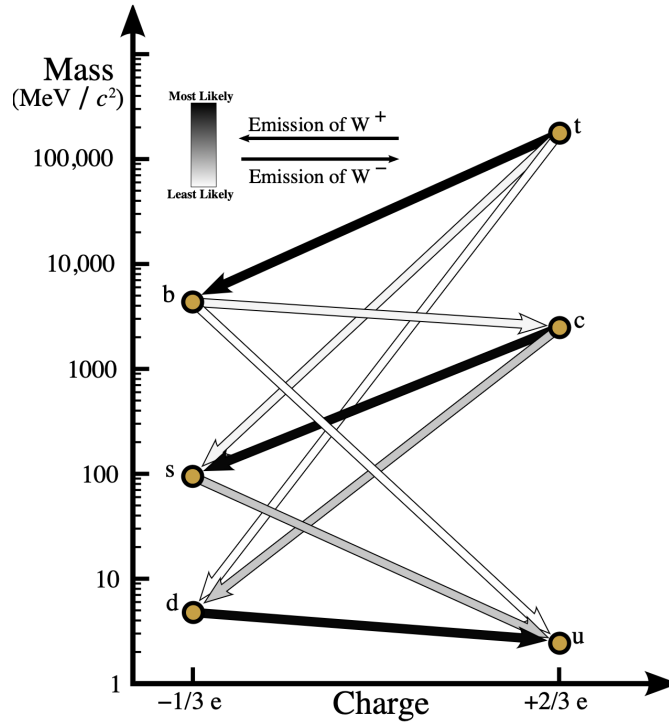


Figure 2.3: Visualisation of the probability of the various possible flavour changes due to the weak interaction weak and flavour eigenstates mixing thanks to the CKM matrix [10].

The CKM matrix describes the likelihood of transforming a certain flavour quark into another flavour quark. It can be seen from equation 2.3 that a transition in the same generation is strongly preferred. Note that the Z boson does not change flavour, while the W bosons are the only particles able to change flavour in the SM.

For neutrinos, a similar mixing mechanism exists, that explains their observed flavour oscillation. The corresponding matrix is called the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [7].

Strong interaction The QFT describing the strong interaction is called Quantum Chromodynamics (QCD) [11, 12]. Since the LHC is a hadron collider, QCD effects are omnipresent, and their understanding is thus very relevant. QCD is described by the symmetry group $SU(3)_C$, where C refers to the colour charge. Quarks carry colour charge and gluons are the force mediators, which can interact with each other and carry a colour and an anticolour [13]. The value of the strong coupling depends on the scale at which it is measured. This is shown in figure 2.4.

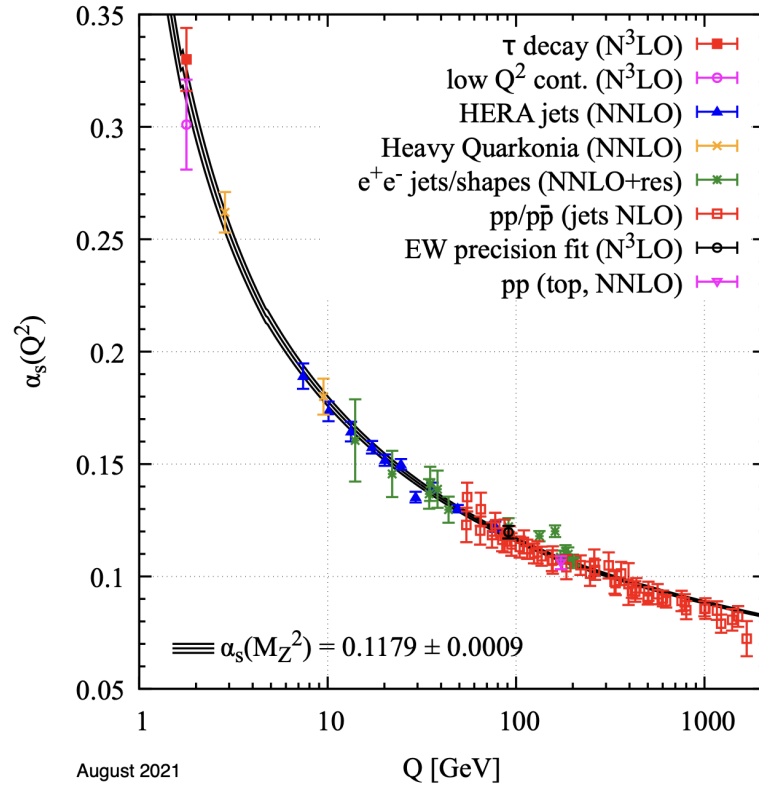


Figure 2.4: Strong coupling (α_s) running as a function of the momentum transfer [7].

The equation describing the evolution of α_s as a function of the momentum transfer scale (Q) is

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + b_0 \ln(Q^2/\mu^2) \alpha_s(\mu^2) + \mathcal{O}(\alpha_s^2)} \text{ with } b_0 = \frac{11N_C - 2N_F}{12\pi}, \quad (2.4)$$

where $N_C = 3$ is the number of colours and $N_f \leq 6$ is the number of fermions with $2m_f < Q$. It can be seen that at short distances, corresponding to high Q values, the value for the strong coupling approaches zero, while at large distances, i.e. low energies, α_s grows to infinity. As a consequence, the larger the distance between two particles, the stronger the force. This results in colour confinement, which is a phenomenon first hypothesised after not observing free quarks. The theory is that strongly interacting particles are always confined into a colourless composite object. The origin of colour confinement is due to be the gluon self-interaction. The resulting colour-neutral composite particles are called hadrons. Out of first principle a hadron can be a colour combined with an anticolour or a combination of three colours. Several types of hadrons exist: mesons are hadrons with one quark and one antiquark, baryons are hadrons with three quarks, tetraquarks are hadrons with two quarks and two antiquarks, and pentaquarks are hadrons with four quarks and one antiquark.

Higgs boson A gauge theory requires massless bosons. Yet, from experimental measurements, it is known that the electroweak bosons have mass. To solve this problem, Brout, Englert and Higgs proposed the Higgs field and the associated Higgs mechanism in the 1960s. According to the theory, there is a scalar field everywhere in the universe that interacts with particles as they travel through it. The stronger a particle interacts with it, the higher the particle's mass. A consequence of the Higgs mechanism, is the existence of a scalar particle known as the Higgs boson. Finding this particle was a long-standing and strongly aimed goal achieved in 2012 by the ATLAS and CMS collaborations [14]. The measurements of the boson's properties gives strong hints that the found particle is indeed the SM Higgs boson. Finding this particle is an indication that the Higgs mechanism giving mass to the bosons works as predicted by the SM. The Higgs boson does also give mass to fermions through the Yukawa coupling. This coupling is linearly proportional to the mass of the fermions. The top quark has the strongest coupling to the Higgs boson, and it thus allows a unique understanding of this scalar particle. Although the Higgs boson is a great answer to the question of how elementary particles get mass, there are still many open questions about it:

- Why do some particles interact with the Higgs field more than others?
- Why does the Higgs boson have a mass of 125 GeV [7]?
- Is the Higgs boson an elementary particle?
- Does the Higgs boson interact with itself?
- What is the exact shape of the Higgs potential?

The particle physics community did spend, and is still spending, years investigating the Higgs bosons' properties. The Higgs particles is special because it is a new particle and the first spin-0 particle that was found, and thus there are a lot of properties to explore.

The simplest Higgs potential possible is

$$V(\phi) = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2, \quad (2.5)$$

where ϕ is the Higgs field, μ and λ are a priori free real positive parameters. In the SM, the Higgs field that enters the Higgs mechanism is described by a field with two complex variables, and it has thus four degrees of freedom. This Higgs potential looks like a Mexican hat, as shown in figure 2.5. It has thus an infinite number of minima with non-zero vacuum expectation value (VEV). For practicality, it is convention to chose the minimum with zero imaginary value and real positive value. Through the symmetry breaking the W and Z bosons acquire mass.

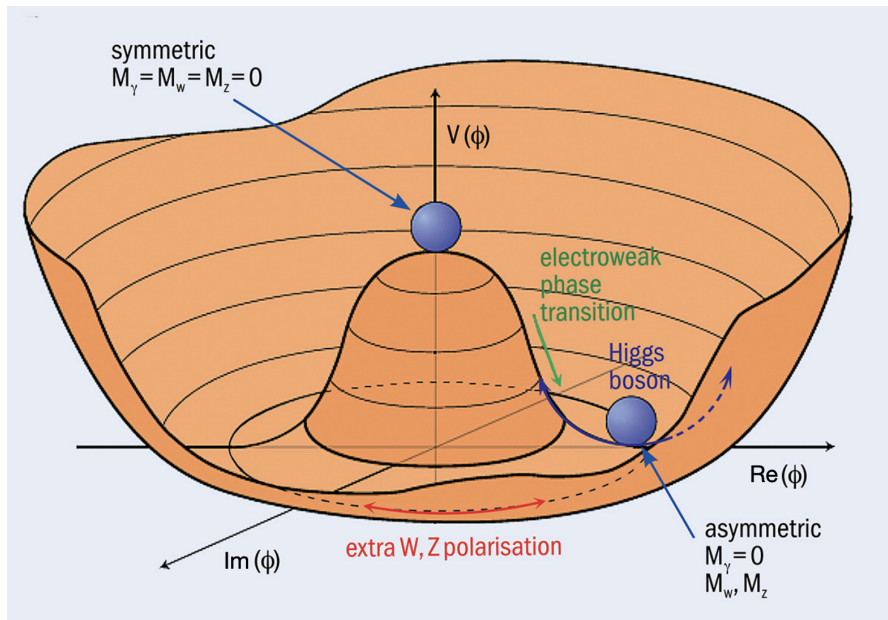


Figure 2.5: A simplified representation of the Higgs potential in three dimensions [15].

In the very early stages of the Universe, the Higgs potential can be imagined as a simple parabola with its minimum at (0,0). The Higgs field was invisible to the elementary particles. As a consequence, all particles were massless at that stage of the Universe. At some point in the history of the Universe, there was a phase transition, and the Higgs potential symmetry got broken and a local minimum was formed.

The exact shape of the Higgs potential is interesting to understand better the Universe. Figure 2.6 the measured top mass compared to the measured Higgs mass. These values are strongly connected to the question of the stability of the vacuum.

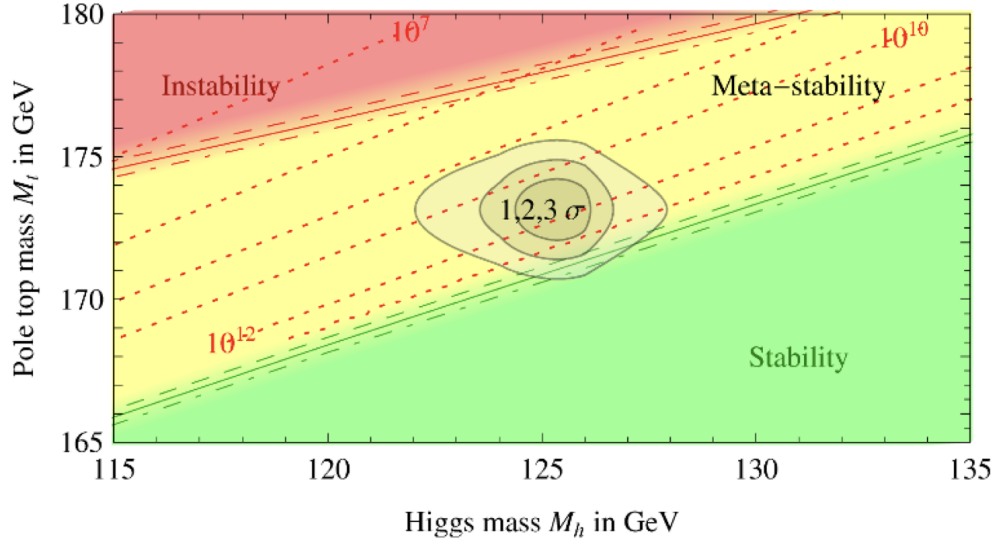


Figure 2.6: Illustration of the Universe stability as a function of the Higgs and the top mass, and the best measured values with their uncertainties [16].

Free parameters in the SM Assuming zero neutrino masses the Standard Model has 19 free parameters, which need to be determined from experimental measurements. There is no unique way to define these parameters since several relations between SM parameters exist. A possible choice of parameters is [7]:

- Higgs couplings (or equivalently masses) of elementary particles (9 fermion masses + 1 Higgs mass),
- CKM matrix elements (4 parameters),
- coupling strengths of fundamental forces (3),
- VEV of the Higgs field (1),
- CP violating angle in QCD (1).

From experimental results it is known that neutrinos have non-zero mass, however, it is not clear how to add this to the SM.

2.1.3 Physics beyond the Standard Model

Although being a very successful theory, the SM has several limitations. A non-exhaustive list of open questions that the SM cannot answer is given here:

- What is the origin of the matter-antimatter asymmetry in the Universe?
- Why is the Universe expansion accelerated?

- What is the nature of Dark Matter (DM) which makes up 27% of the Universe?
- How can the gravitational interaction be added to the SM?
- What is the nature of dark energy which makes up 68% of the Universe?
- Are there more than four dimensions?
- Can all the forces be unified into a single interaction?
- Why does the Higgs couple differently to the different particles?
- Why is there no CP violation in the strong interaction?
- How do neutrinos acquire mass?
- Why are there three generations of particles?
- Is the Higgs boson an elementary particle?
- How does the Higgs boson potential look like?

Many Beyond the Standard Models (BSMs) addressing one or more of the above questions exist. Unfortunately, up to now no evidence for any BSM particle has been found.

2.2 Cross-section calculation at the LHC

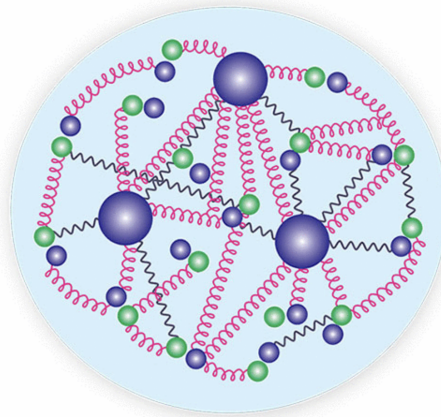


Figure 2.7: Visualisation of the partons inside a proton: the three larger dots represent the valence quarks, the spring lines show the gluon exchanges, the wavy lines are photons, and the other colourful dots are sea quarks [17].

At the LHC, protons are collided. Protons are composite particles; thus, they do not collide as a whole point-like object, but their constituents do. As a consequence, the beam energy does not correspond to the collision energy, as opposed to, for example, electron-positron collisions. Protons are composed of three *valence* quarks, two up-quarks and one down-quark,

gluons from interactions of the quarks, and *sea* quarks from gluon splitting. The particles constituting the proton are called partons. A proton collided at the LHC can thus be imagined as sea quarks, valence quarks, and gluons continuously interacting with each other, as shown in figure 2.7. Since this is happening continuously, the content of the proton changes over time. In pp collisions at the LHC, it is more precise to say that partons are collided. The momentum fraction a parton carries inside the proton is varying. The question that arises is: what kind of parton (gluon, quark flavour) collided, and with what fraction of the proton momentum? The answer is given by the Parton Distribution Functions (PDFs), which provide the distribution of the momentum inside the proton [7, 18].

2.2.1 Parton distribution functions

PDFs describe the number density of a parton with an energy fraction x in the proton with a given momentum at the time of the collision. Unfortunately, PDFs are not yet calculable analytically and have thus to be measured. This is mainly done in deep inelastic lepton-proton scattering (DIS), i.e. protons are collided inelastically with leptons.

PDFs depend on the energy scale of the momentum transfer (Q^2) between the proton and the other colliding particle. The dependency of the PDFs on the momentum transfer can be calculated analytically in QCD perturbative theory. This scale evolution is described by the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution equations [19–23]. As a consequence, the PDFs can be measured at one energy scale and then transferred through the DGLAP equations to the LHC energy scale.

PDFs with two different energy scales (10 GeV^2 and 10^4 GeV^2) are shown in figure 2.8.

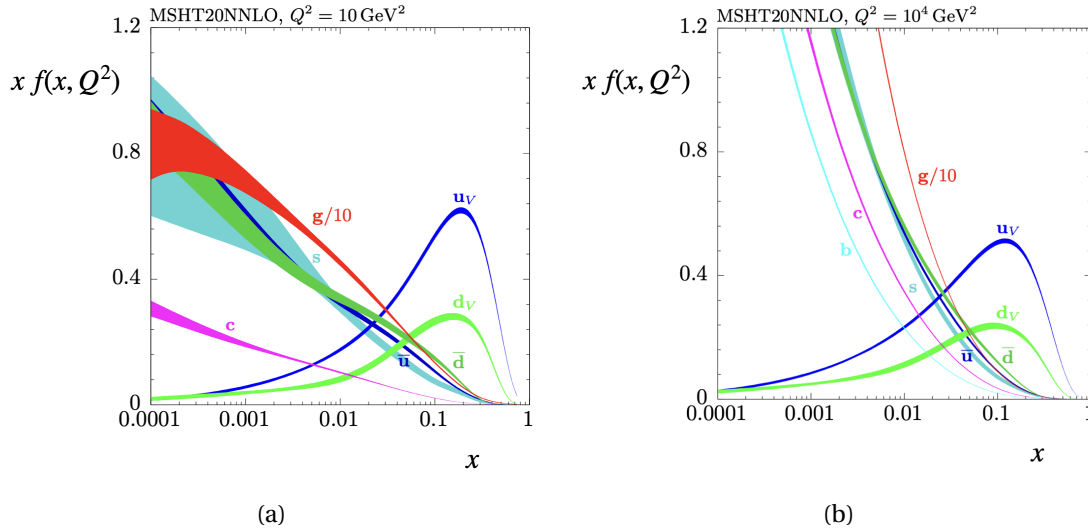


Figure 2.8: PDF distributions as a function of the fraction of proton momentum that the corresponding parton carries. (a) with $Q^2 = 10 \text{ GeV}^2$, and (b) with $Q^2 = 10^4 \text{ GeV}^2$ [24].

At the LHC, the main interest lies in are high-energy processes, and thus the protons colliding have a high fraction of the proton momentum. As a consequence, the interesting processes have parton content, as illustrated on the right side of the plot. It can be seen that the most present partons at large x are the valence quarks. However, uu and dd or ud interactions can have only elastic scattering. Thus, the dominant high energy interaction at the LHC is gg . Antiquark quark interactions are suppressed at high-energies since the antiquark has to come from the sea quark PDFs.

Choice of PDF set Several different PDF predictions exist. This is due to the usage of different input data and fit methodology. In general, the different PDF sets agree, but they have some differences. Each Monte Carlo generator uses a default PDF set[25]. Usually analyses use PDF sets from collaborations, such as MSTW [26], CTEQ [27] and NNPDF [28]. An example of level of agreement of gluon PDF for different PDF sets is shown in figure 2.9.

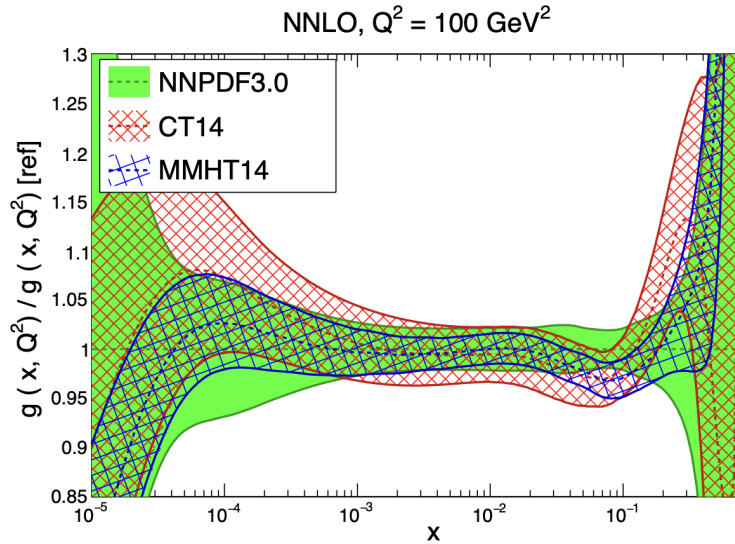


Figure 2.9: Gluon PDF for different PDF sets normalized to the central value of NNPDF3.0 [29].

2.2.2 Cross-section calculations

Assuming the factorisation theorem [30], the cross-section calculation can be split in PDFs and hard interaction. This means that the two parts can be computed independently and then multiplied by each other to get the total cross-section. At low energies, the strong coupling value goes above unity, and thus QCD in this regime cannot be computed perturbatively anymore. Low-energy QCD is less well understood than high-energy QCD.

A parton i carries a momentum fraction $x_i = p_i / p_{\text{proton}}$, thus the centre-of-mass energy of the collision is actually $\sqrt{s_{ij}} = \sqrt{p_i p_j} = \sqrt{x_i x_j} \sqrt{s_{pp}}$ for two colliding partons i and j .

The cross-section of a process $pp \rightarrow X$ can be written as

$$\sigma_{pp \rightarrow X} = \sum_{ij} \int_0^1 dx_i \int_0^1 dx_j \sigma_{ij \rightarrow X}(s_{ij}, \mu_R, \mu_F) f_i(x_i, \mu_F) f_j(x_j, \mu_F), \quad (2.6)$$

where the sum is taken over all possible parton-parton scattering processes. For both partons, an integral is performed over the possible momentum fractions from 0 to 1. $f_i(x_i, \mu_F)$ is the PDF for the parton i , and depends on the parton momentum fraction (x_i) and on the factorisation scale μ_F . μ_F is the scale separating the PDFs from the hard interaction in the calculation, and μ_R is the renormalisation scale, which is the scale at which the matrix element is calculated. $\sigma_{ij \rightarrow X}$ is the partonic cross-section, which corresponds to the hard scattering process and can be computed perturbatively.

The partonic cross-section can be estimated more precisely as

$$\sigma_{ij \rightarrow X} = \int d\Phi_n \frac{1}{2s_{ij}} |\mathcal{M}_{ij \rightarrow X}|^2(\Phi_n, \mu_R, \mu_F), \quad (2.7)$$

where $d\Phi_n$ is the differential phase space and $\mathcal{M}_{ij \rightarrow X}$ is the matrix element of the process. This matrix element can be computed using Feynman diagrams. The idea is to sum the contribution from all possible Feynman diagrams, where there are rules on how to build the matrix element based on the lines and vertices in the diagrams [31]. This matrix element can be calculated at different orders in the coupling constant.

At fixed order, the cross-section value depends on μ_F and μ_R . At infinite order, this dependence should cancel out. However, it is only possible to compute the cross-sections at fixed order; thus there is some dependency on the scales chosen, which is taken into account by a theoretical uncertainty. Although these two scales can be chosen arbitrarily, in general, they are chosen to be reasonable for parton-parton interactions, i.e. $\mu^2 = Q^2$. This choice is not guided by first principles but by physics consideration and experience, it is thus somewhat arbitrary.

2.3 $t\bar{t}$ cross-section

2.3.1 $t\bar{t}$ production and decay

At the LHC, the top quark is dominantly produced in pairs. Table 2.1 shows the cross-sections for several top production processes at the LHC at the centre-of-mass energy of 13.6 TeV. The $t\bar{t}$ cross-section is shown at NNLO+NNLL^I calculated using Top++v2.0 program [32–38], with the assumptions $\mu_R = \mu_F = m_{\text{top}} = 172.5$ GeV, and the PDF set PDF4LHC21 [39].

Process	$\sigma_{t\bar{t}}$ [pb]
$t\bar{t}$	$923.6^{+22.6}_{-33.4}(\text{scale}) \pm 22.8 (\text{PDF} + \alpha_s)$
Single top t -channel	$232.2^{+2.6}_{-1.9}(\text{scale})^{+3.4}_{-2.2} (\text{PDF} + \alpha_s)$
Wt	$87.9^{+2.0}_{-1.9}(\text{scale}) \pm 2.4 (\text{PDF} + \alpha_s)$
s -channel	$10.32^{+0.29}_{-0.24}(\text{scale})^{+0.27}_{-0.27} (\text{PDF} + \alpha_s)$

Table 2.1: Cross-sections for several top production processes at $\sqrt{s} = 13.6$ TeV.

Details on theoretical uncertainty calculations are explained in Chapter 7. Single top production is calculated at NNLO in QCD for t -channel and Wt using the MCFM program [39, 40], and at NLO using Hathor v2.1 [41, 42] for the s -channel. It can be seen that the t -channel production cross-section at the LHC is around four times smaller compared to $t\bar{t}$.

The $t\bar{t}$ production Feynman diagrams at LO are shown in figure 2.10 and figure 2.11.

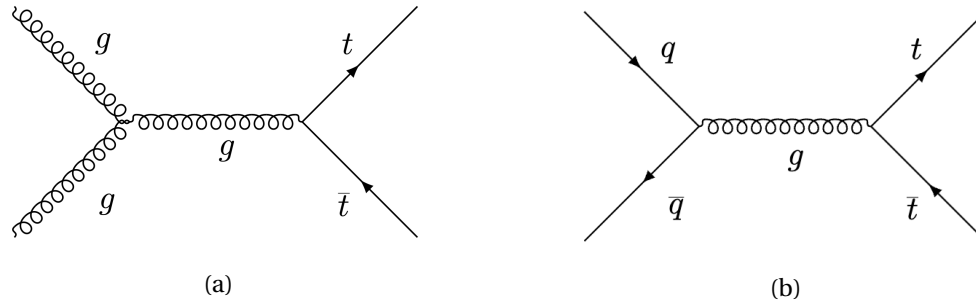


Figure 2.10: $t\bar{t}$ production at LO: (a) gluon-gluon fusion s -channel, and (b) quark annihilation s -channel.

^Inext-to-next leading logarithm

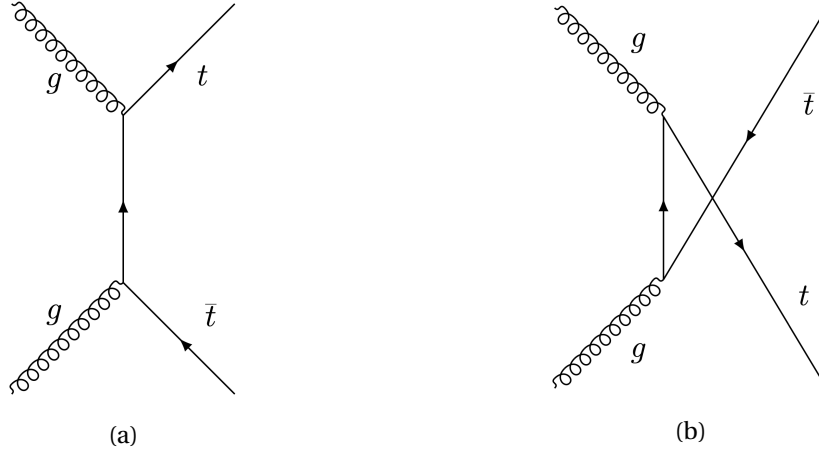


Figure 2.11: $t\bar{t}$ production at LO: (a) gluon-gluon fusion t -channel, and (b) u -channel.

Perturbative theory can be applied to calculate cross-sections in QCD. As a consequence, the calculations in QCD are always done up to a certain power of α_s . This is referred to as Leading Order (LO), Next-to-Leading Order (NLO) and Next-to-Next-to-Leading Order (NNLO) cross-section calculations. For example, all Feynman diagrams shown in figure 2.10 and figure 2.11 are at leading order. Every vertex adds a proportionality of $\sqrt{\alpha_s}$ to the amplitude of the process, and the cross-section has thus a proportionality to α_s^2 . This means that in the $t\bar{t}$ production the LO corresponds to $\mathcal{O}(\alpha_s^2)$, NLO to $\mathcal{O}(\alpha_s^3)$, and NNLO to $\mathcal{O}(\alpha_s^4)$.

An example of higher order Feynman diagrams of $t\bar{t}$ production is shown in figure 2.12.

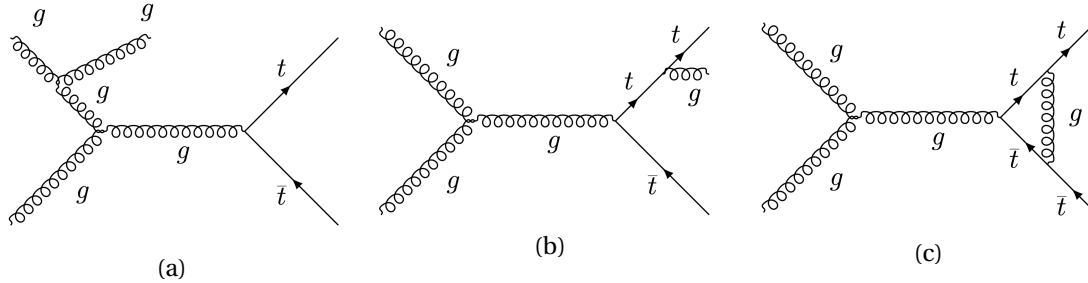


Figure 2.12: Examples of higher order Feynman diagrams for $t\bar{t}$ production. (a) shows an example of ISR and (b) of FSR.

Specifically, the left diagram shows an example of initial-state-radiation (ISR), while the middle one shows an example of final-state-radiation (FSR).

At the LHC, top quark pairs are dominantly produced from gluon initial states. At $\sqrt{s} = 13$ TeV this constitutes $\sim 90\%$ of the events. While the quark-antiquark annihilation is strongly suppressed and constitutes only $\sim 10\%$ of the events.

The top quark decays 99.7% of the time into a W boson and a b -quark [7]. The W boson decays

in 67% of the cases into two quarks and in 33% of the cases into leptons and neutrinos, 11% of the cases into each flavour [7]. Given the decays of the top quark and the W boson, the $t\bar{t}$ process final state's content is distributed as shown in the pie chart in figure 2.13.

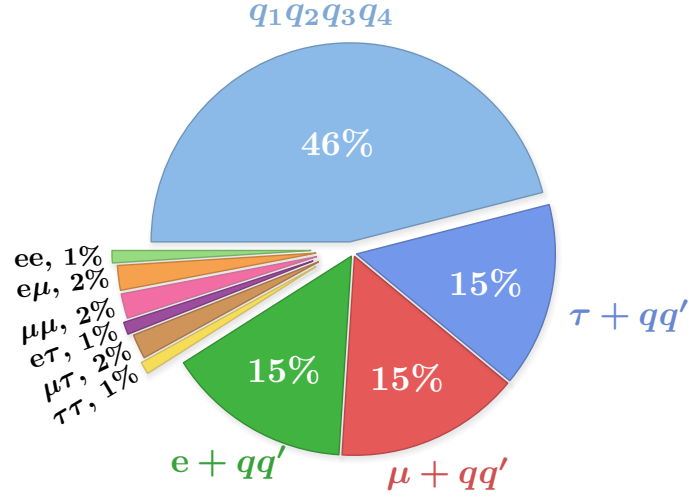


Figure 2.13: Pie chart of the final states of the $t\bar{t}$ production. Modified figure from [43].

2.3.2 Ratio of cross-sections

A technique to cancel some of the uncertainties in a cross-section measurement is to take ratios of cross-sections. In particular, two types of ratio measurements are interesting to check: the ratio of different processes, as for example, $t\bar{t}/Z$ production, and the ratio of the same process at different energies [29, 44].

$t\bar{t}/Z$ ratio This ratio is particularly interesting since several experimental uncertainties cancel out, and thus a very precise result can be obtained. It has been seen that top pairs are dominantly produced via gluon-gluon fusion at the LHC, while the Z is dominantly produced through quark-antiquark annihilation. As a consequence, the ratio of $\sigma_{t\bar{t}}/\sigma_Z$ is sensitive to the gluon-to-quark PDF ratio. Thus, it is interesting to cross-check how well the different PDF predictions agree with the measured value.

$t\bar{t}$ cross-section at different centre-of-mass energies ratio In this type of measurements, several experimental and theoretical uncertainties cancel out at least partially, including missing higher-order theory predictions, and top mass uncertainties. These cancellations make the ratio more sensitive to the choice of the PDF set.

2.3.3 Expected cross-section behaviours

The inclusive $t\bar{t}$ cross-section as a function of the centre-of-mass energy is shown in figure 2.14. The green line represents the theory prediction of QCD at NNLO+NNLL for proton-proton collisions, and the blue line represents the theory prediction for proton-antiproton collisions, both produced using Top++2.0 [32–38]. Note that the two predictions merge at high centre-of-mass energy. The theory uncertainties include PDF uncertainties, scale variations, and α_s uncertainty. Theory predictions and measurements assume $m_{\text{top}} = 172.5$ GeV.

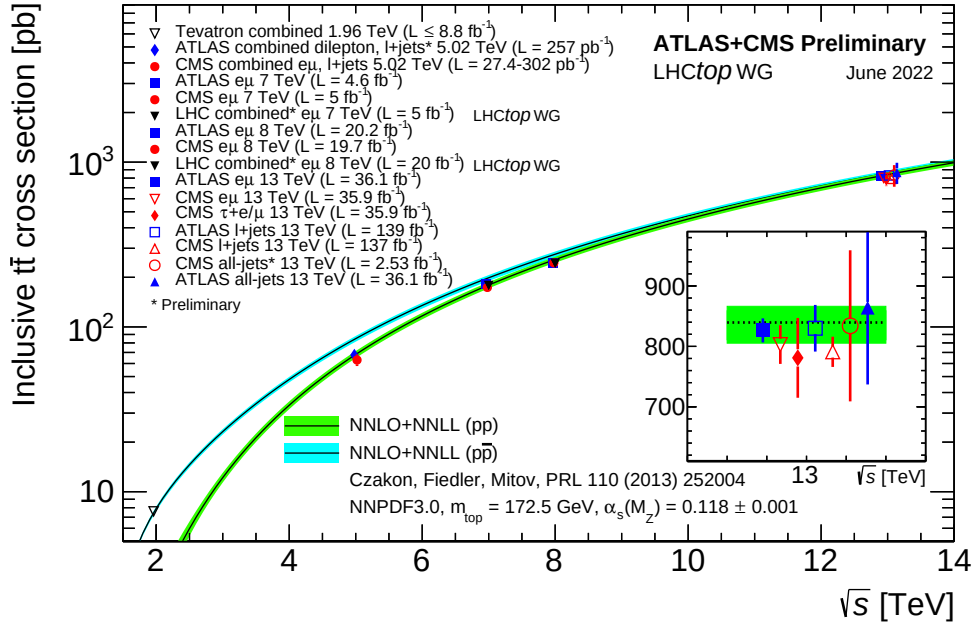


Figure 2.14: Inclusive $t\bar{t}$ cross-section dependency on the centre-of-mass energy for proton-proton and proton-antiproton collisions. Measurements with the same centre-of-mass energy are slightly horizontally separated for better visibility [45].

The inclusive $t\bar{t}$ cross-section depends on the assumed Monte Carlo top mass. Figure 2.15. This plot shows that the cross-section measurement is fairly robust against the assumed top mass use in Monte Carlo.

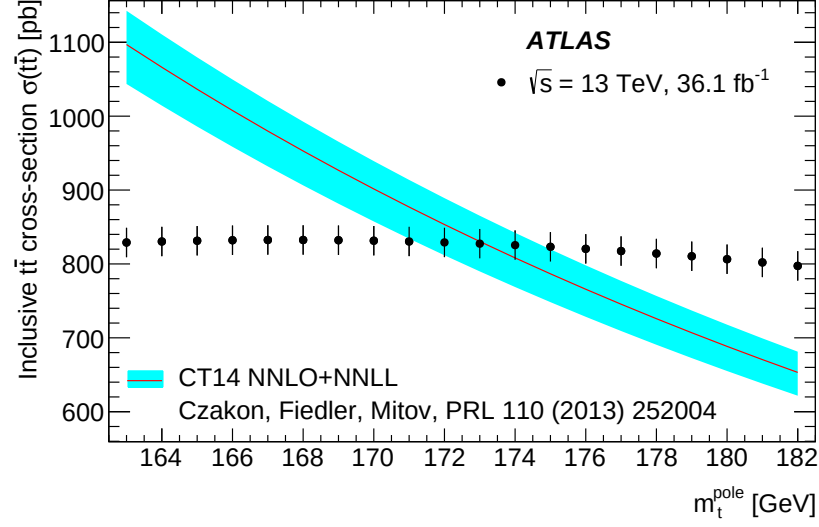


Figure 2.15: The dependency of the predicted inclusive $t\bar{t}$ cross-section on the top mass is shown in cyan, and the measured cross-section values assuming different top masses in Monte Carlo is illustrated with round markers [46].

2.4 Theoretical prediction

The predicted $t\bar{t}$ cross-section is

$$\sigma(t\bar{t})_{\text{NNLO+NNLL}} = 923.6^{+22.6}_{-33.4}(\text{scale}) \pm 16.7(\text{PDF}) \pm 15.6(\alpha_s) \text{ pb} \quad (2.8)$$

using $m_{\text{top}} = 172.5 \text{ GeV}$ and the PDF4LHC21 [39] PDF set. The uncertainties include scale variations, α_s variations, and PDF set variations.

2.4.1 Scale variations

Scale variations refer to the variation of the factorization and renormalization scales. As a default for the theory predictions in this analysis it is assumed $\mu_R = \mu_F = m_{\text{top}}$. The scale variations are calculated following the restricted variation method: μ_R and μ_F are independently varied by a factor of two, while meeting the requirement that they never differ from each other by more than a factor of two. The scale variation uncertainty is defined as the envelope of the restricted variation of the scales and can be interpreted as a quantification of the impact of missing higher order corrections in the theory computation.

2.4.2 Strong coupling variation

α_s is known to a limited precision $\alpha_s(m_Z^2) = 0.1180 \pm 0.0010$. The contribution of this limited knowledge on the cross-section predicted value is obtained by varying α_s by its uncertainty. Concretely, the uncertainty on the $t\bar{t}$ cross-section is computed as

$$\Delta_{\alpha_s} = \frac{\sigma_{t\bar{t}}(\alpha_s = 0.1190) - \sigma_{t\bar{t}}(\alpha_s = 0.1170)}{2}. \quad (2.9)$$

2.4.3 PDF uncertainty

The list of different PDF sets used to compare the prediction of the ratios is shown in table 2.2. A short description of them follows below. All PDF sets predictions are at NNLO.

PDF set name	Number of members	Error prescription	Ref.	m_{top} [GeV]	$R_{t\bar{t}/Z}$	$\sigma_{t\bar{t}}$ [pb]
PDF4LHC21	43	68% CL sym. Hessian	[39]	171.5	$1.2720^{+0.0651}_{-0.0731}$	949^{+33}_{-42}
PDF4LHC21	43	68% CL sym. Hessian	[39]	172.5	$1.2379^{+0.0634}_{-0.0712}$	924^{+32}_{-40}
PDF4LHC21	43	68% CL sym. Hessian	[39]	173.5	$1.2048^{+0.0617}_{-0.0693}$	899^{+31}_{-39}
CT18	59	90% CL asym. Hessian	[47]	172.5	$1.2661^{+0.1078}_{-0.1024}$	928^{+42}_{-48}
CT18A	59	90% CL asym. Hessian	[47]	172.5	$1.2237^{+0.0783}_{-0.0785}$	918^{+40}_{-49}
MSHT20	65	68% CL asym. Hessian	[48–50]	172.5	$1.2340^{+0.0624}_{-0.0571}$	922^{+33}_{-39}
NNPDF4.0	101	Monte Carlo	[51]	172.5	$1.1748^{+0.0361}_{-0.0498}$	902^{+28}_{-37}
ATLASpdf21	43	68% CL sym. Hessian	[52]	172.5	$1.2440^{+0.0779}_{-0.0767}$	979^{+30}_{-44}
ABMP16	30	68% CL sym. Hessian	[53]	172.5	$1.1269^{+0.0473}_{-0.0560}$	906^{+33}_{-41}

Table 2.2: List of the different PDF sets used for the prediction in the $t\bar{t}/Z$ and $t\bar{t}$ at 13.6 TeV energy ratios.

PDF4LHC21 The PDF4LHC21 is the default PDF set for early Run 3 analyses in ATLAS. The PDF prescription gives 40 members, where the first is the central value of the cross-section and the latter are the 68% probability interval eigenvariations. These are by construction orthogonal, thus the PDF uncertainty can be estimated using the symmetric Hessian prescription, as

$$\Delta_{\text{PDF}} = \sqrt{\sum_k (F^k - F^0)^2}, \quad (2.10)$$

where Δ_{PDF} is the PDF uncertainty, F^0 the central value and F^k are the remaining 39 members.

CT18 The first member of the CT18 PDF set is the central value, while the remaining 58 are to estimate the 90% probability interval for the uncertainty on the PDF set using the asymmetric Hessian prescription as

$$\Delta_{\text{PDF}} = \sqrt{\sum_i (F_i^+ - F_i^-)^2} = \sqrt{\sum_i (F_{2i} - F_{2i+1})^2}. \quad (2.11)$$

The members are organised such that up and down variations are alternated [47].

The CT18A PDF set is the same as the CT18 PDF set with in addition the inclusion of the ATLAS precision 7 TeV W/Z data [54].

MSHT20 The MSHT20 PDF set has 65 members organised as for CT18, with the difference that its members cover the probability interval of 68% instead of 90% [48–50]. The PDF uncertainty calculation is obtained using the asymmetric Hessian prescription, as shown in equation 2.11.

NNPDF4.0 The NNPDF4.0 PDF set has 101 members, where the first one represents the central value and the other 100 are MC replicas to estimate the uncertainty of the PDF set. The uncertainty for this PDF set is estimated as follows. First the 100 members are ordered in ascending order and the highest and lowest 16% are removed. The remaining ones are used to estimate the PDF uncertainty for 68% CL interval. This set is denoted as $[F^{(16)}, F^{(84)}]$. The uncertainty on is estimated as

$$\Delta_{\text{PDF}}^{\text{up}} = F^{(84)} - F^{(0)}, \quad \text{and} \quad \Delta_{\text{PDF}}^{\text{down}} = F^{(0)} - F^{(16)}. \quad (2.12)$$

The central value is the median of all MC replicas [51].

ABMP16 The ABMP16 PDF set contains 30 members, where the first member is the central value of the fit and the remaining 29 are eigenvectors used to estimate the 68% CL interval of the PDF uncertainty using the symmetric Hessian prescription, following equation 2.10. In this thesis the PDF set ABMP16als118_5_nnlo is used [53].

ATLASpdf21 This PDF set is obtained using several LHC pp collision measurements at 7, 8 and 13 TeV, and deep inelastic scattering data from ep collisions at the HERA collider. It has a total of 43 members, where the first member is the central value and the other 42 the eigenvectors used to compute the 68% CL interval for the PDF uncertainty using the symmetric Hessian prescription [52], as shown in equation 2.10.

2.4.4 Z fiducial cross-section

The predicted fiducial cross-section at NNLO in QCD and NLO in EW is

$$\sigma_Z^{\text{fid.}} = 746 \pm 0.7(\text{integration}) \pm 3(\text{scale}) \pm 21(\text{PDF}) \text{ pb}, \quad (2.13)$$

for Z bosons decaying into a single-lepton-flavour for leptons before QED radiation. This is obtained using the PDF4LHC21 [39] PDF set and the MATRIX program [55]. The fiducial phase-space is defined by lepton $p_T > 27$ GeV, $|\eta| < 2.5$ and $66 < m_{ll} < 116$.

3 Experimental setup

In this thesis, data collected with the ATLAS detector [56, 57] at the Large Hadron Collider (LHC) [58] at CERN are used. The LHC is a circular proton-proton collider at the border between Switzerland and France. It is the largest and most powerful particle accelerator in the world. The proton-proton collisions obtained at this accelerator are used to study the Standard Model of elementary particles (SM) and to search for physics beyond the Standard Model (BSM). In this chapter, first the LHC and then the ATLAS detector are presented.

3.1 Large Hadron Collider

The LHC was built by the "Conseil Européen pour la Recherche Nucléaire" (CERN), or in English "European Organization for Nuclear Research". CERN is one of the largest physics laboratory in the world, located near Geneva, Switzerland. It gathers over 17'000 people to better understand the world in its smallest constituents.

The LHC accelerator ring has a circumference of 26.7 km, and is situated approximately 100 meters underground. It is hosted in the tunnel of the Large Electron-Positron Collider (LEP), which operated for 11 years, from 1989 to 2000. The upgrade to protons was made since higher collision energies can be reached. Electrons lose a lot of energy due to synchrotron radiation; this effect is negligible for protons since they have a much larger mass than electrons. Furthermore, in proton collisions, given the composite nature of the proton, a range of energies (smaller than 13.6 TeV) are accessible at the same time, see Chapter 2 for more details.

The LHC is designed to accelerate proton beams up to 7 TeV, achieving a centre-of-mass energy of 14 TeV. It started operation in September 2008, however nine days after there was an accident that caused mechanical damage and the release of helium in the tunnel, which forced CERN to shut the LHC down. After some repairs, the LHC restarted in late 2009 with a smaller centre-of-mass energy than intended to avoid another such accident.

The operation of the LHC can be divided into different periods, called Runs, with upgrade

phases in between them, called Long Shutdowns (LSs). Run 1 started in March 2010 and lasted until early 2013. This was the initial operation phase of the LHC with a centre-of-mass energy of 7 TeV in the first two years and 8 TeV in the remaining time. One of the main achievements of this run was the discovery of the Higgs boson in 2012. Run 1 is followed by Long Shutdown 1 (LS1) (2013-2015). During all long shutdowns, extensive maintenance and upgrades are performed while there are no beams. In LS1 in particular, all magnet connections with faulty design like the one causing the 2008 accident were substituted and an additional silicon tracker layer was added close to the beam pipe. From 2015 until 2018, Run 2 was ongoing with a centre-of-mass energy of 13 TeV. During Run 2 ATLAS collected 140 fb^{-1} of data at the highest centre-of-mass energy yet achieved until 2022. The Run 2 data is still being analysed and explored. Long Shutdown 2 followed (2019-2022) with upgrades. In particular, one of the muon detectors was upgraded to prepare for High Luminosity LHC (HL-LHC), the old linear accelerator at the start of the acceleration chain exchanged with a new one, and another accelerator in the accelerator chain leading to LHC (the Proton Synchrotron Booster) was upgraded to reduce the beam emittance. In summer 2022, Run 3 was started with a centre-of-mass energy of 13.6 TeV, and it is planned to last until the end of 2025. This will be followed by Long Shutdown 3 that will prepare the LHC for HL-LHC, where around 140-200 average collisions per bunch-crossing are expected, compared to the current Run 3 design of ~ 60 . This constitutes a major challenge for the hardware and software of all detectors.

The most significant achievement of the LHC is the discovery of the Higgs boson in 2012. This confirms the existence of the Higgs mechanism, which gives origin to the elementary particles masses. Additionally, the LHC contributed to precision tests of the SM and searches for BSM physics. This leads to a better understanding of the behaviour of particles and to constraints on properties of hypothetical particles and eliminate possible theoretical models. The LHC also collides heavy ions to create a state of matter called quark-gluon plasma (QGP), which is believed to exist shortly after the Big Bang, i.e. high temperature and densities. This allows to better understand the early universe.

3.1.1 Particle acceleration at the LHC

At the LHC, particles are accelerated using radiofrequency (RF) cavities. On each LHC ring, eight such cavities are positioned. Inside an RF cavity, there is a periodically oscillating electromagnetic field. At the LHC; this field oscillates with a frequency of 400 MHz. When particles pass at the right moment, they get accelerated through the electric field. RF cavities require the beams to be bunched, a continuous beam could not be accelerated in this way, since half of the particles in the beam would get decelerated. The oscillating electromagnetic field has also the additional practical property of focusing the bunches in the longitudinal direction. This works since particles that are a bit too fast get less acceleration, while particles that are a bit too slow get more acceleration than the ideal particle which passes just at the

right moment.

The LHC circumference and the RF cavities frequency create exactly 35'640 RF buckets in which particles get accelerated. Only 1 in 10 buckets is filled with $O(10^{11})$ protons, which is called a bunch. This means that maximally 3564 bunches can be filled. The distance between RF buckets is 2.5 ns, consequently the bunches are separated by 25 ns. Both proton beams have this structure, and two colliding bunches get an ID called bunch-crossing ID (BCID).

The LHC is a circular accelerator, thus the second important component to accelerate particles at the LHC is how to keep them on a circular orbit and have specific properties. This is a very complex task, which is achieved by using superconducting magnets. They are able to create stronger magnetic fields than conventional magnets, allowing to accelerate particles to higher energies. To function, these magnets are kept at the very low temperatures of 2 K. Several types of magnets are used to control different aspects of the beams. The two most important ones are the dipole and quadrupole magnets. 1232 dipole magnets with a field strength of 8.33 T are used to keep the beams on a circular orbit. 392 quadrupole magnets having a magnetic field of 6.8 T are employed to focus particles in a similar way to how lenses focus light. Without focusing of the beams through quadrupoles, they would collide with the beampipe and get lost. Another good reason to focus beams is that in this way a high collision rate can be achieved. This leads to a high event rate of the processes studied and thus a good understanding of them. The event rate (R) of a process can be described as

$$R = \frac{dN}{dt} = L \cdot \sigma, \quad (3.1)$$

where L is the instantaneous luminosity, and σ is the cross-section of the process. The cross-section is a physics constant for a given centre-of-mass energy, thus to increase the rate only luminosity can be increased. The currently achieved instantaneous luminosity is $L = 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ [57]. Luminosity can be expressed through beam parameters alone as

$$L = \frac{n_1 n_2 f_r n_b}{4\pi\sigma_x\sigma_y}, \quad (3.2)$$

where f_r is the LHC revolution frequency amounting to 11'245.5 Hz, n_1 is the number of protons in the bunch of beam 1, n_2 is the number of protons in the bunch of beam 2, n_b is the number of colliding bunches, σ_x the beam width in x plane, and σ_y the beam width in y plane. More details on luminosity can be found in Chapter 6.

From equation 3.2, it can be seen that luminosity increases by increasing the number of protons in the bunches, filling more bunches in the beam or making the beams smaller when colliding them.

The amount of data collected in a given period of time is often quantified using integrated

luminosity. This is the instantaneous luminosity integrated over a given time, defined as

$$L_{\text{int}} = \int L_{\text{inst}} dt. \quad (3.3)$$

The disadvantages when increasing luminosity are that it is harder to control bunches with more protons and smaller beams and a larger average number of collisions in a bunch-crossing is obtained. This quantity is referred to as pileup and is often denoted by $\langle\mu\rangle$. A large pileup is a challenge for the hardware and software of the detector to handle in the readout but also in the analysis to measure precisely quantities as the $t\bar{t}$ cross-section.

The focus of a beam can be described by the β function, which characterizes the transverse size of the particle beam along the beamline. It has a horizontal (β_x) and a vertical (β_y) component, given in units of length. For data taking, it is particularly interesting to know the β function's value at the collision point; this is called β^* . The smaller the value, the stronger the focusing of the beams, and as a consequence, the larger the collision probability and the more pileup and luminosity.

Another important quantity for accelerator physics is the emittance (ϵ). Emittance quantifies the spread of particles in the phase space, i.e. the spread of the particles in the beam in position and momentum. As a consequence, to achieve a high beam quality and intensity, it is required to have a small emittance. Similarly to the β function, there is a horizontal (ϵ_x) and a vertical (ϵ_y) component, both are given in mm·mrad (millimeter-milliradian).

The size of the beam is give by

$$\sigma_x = \sqrt{\epsilon_x \beta_x} \quad \text{and} \quad \sigma_y = \sqrt{\epsilon_y \beta_y}, \quad (3.4)$$

where σ_x and σ_y are respectively the beam widths given by the root-mean-square (RMS) sizes of the particle distribution in the horizontal and vertical planes.

One last important quantity to characterise the motion of particles in an accelerator is the betatron tune (Q), also simply called tune. It is the number of betatron oscillations a particle makes around the accelerator in a given second, i.e. how many oscillations the particle completes along the beamline in x and y planes (Q_x and Q_y). This quantity is dimensionless and can be an integer or a fractional number. It is important to control the tune to get stable beams in the accelerator since they can create resonances that make the beams less stable and can lead to beam degeneration or even beam loss. The tunes can be controlled by changing the strength and frequencies of the elements (e.g. quadrupoles) in the accelerator [59]. A quadrupole magnet typically consists of four magnetic poles arranged in a specific configuration to achieve focusing of charged particles passing through it in one plane and defocusing in the other plane.

In usual data taking conditions, bunches are arranged in bunch trains, which means that several slots in a row are filled. In some special fills, the bunches are filled with empty slots between them and are called isolated bunches. ATLAS divides the recorded data into time

intervals, usually of 60 seconds, called luminosity blocks (LBs). These are time intervals over which it is assumed that the experimental conditions are stable, i.e. the instantaneous luminosity is a constant.

3.1.1.1 A typical LHC fill

In figure 3.1 the instantaneous luminosity as a function of time for a typical LHC fill is shown. It can be seen that in the start of the fill the luminosity stays approximately constant. This is achieved through β^* levelling. In this method, first beams with larger β^* are collided, and then the β^* is reduced to maintain the luminosity around the same level. This means that the beams are squeezed more and more over time to achieve the same amount of collisions. The goal is to reach high luminosity for a longer period of time. The beams are not squeezed to a maximum from the start because the detectors cannot yet handle that much pileup in the readout.

It can also be seen that when β^* levelling is stopped the luminosity slowly decays over time until the fill is dumped.

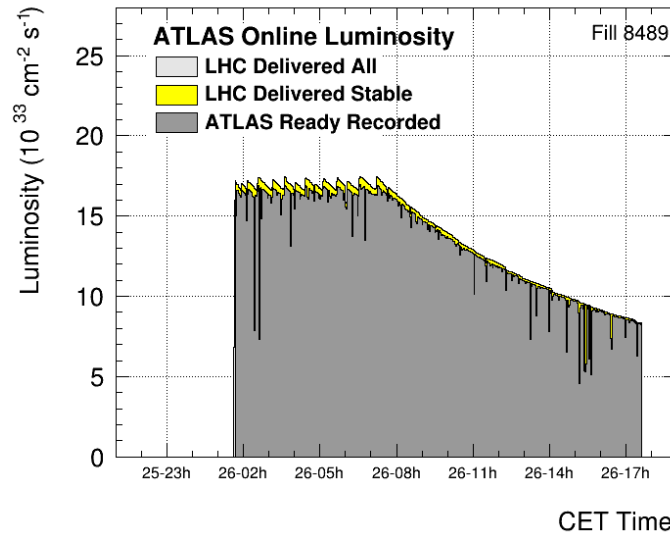


Figure 3.1: Instant luminosity during a typical fill at the LHC in 2022.

3.1.2 CERN accelerator complex

The LHC collides protons with an energy of 6.8 TeV. To accelerate the protons to this energy a sequence of accelerators is used. This accelerator complex is shown in figure 3.2.

Hydrogen atoms are put in a strong electric field to take away the electrons in the atoms, leaving them protons. These protons are then accelerated with a linear accelerator (Linac4) to

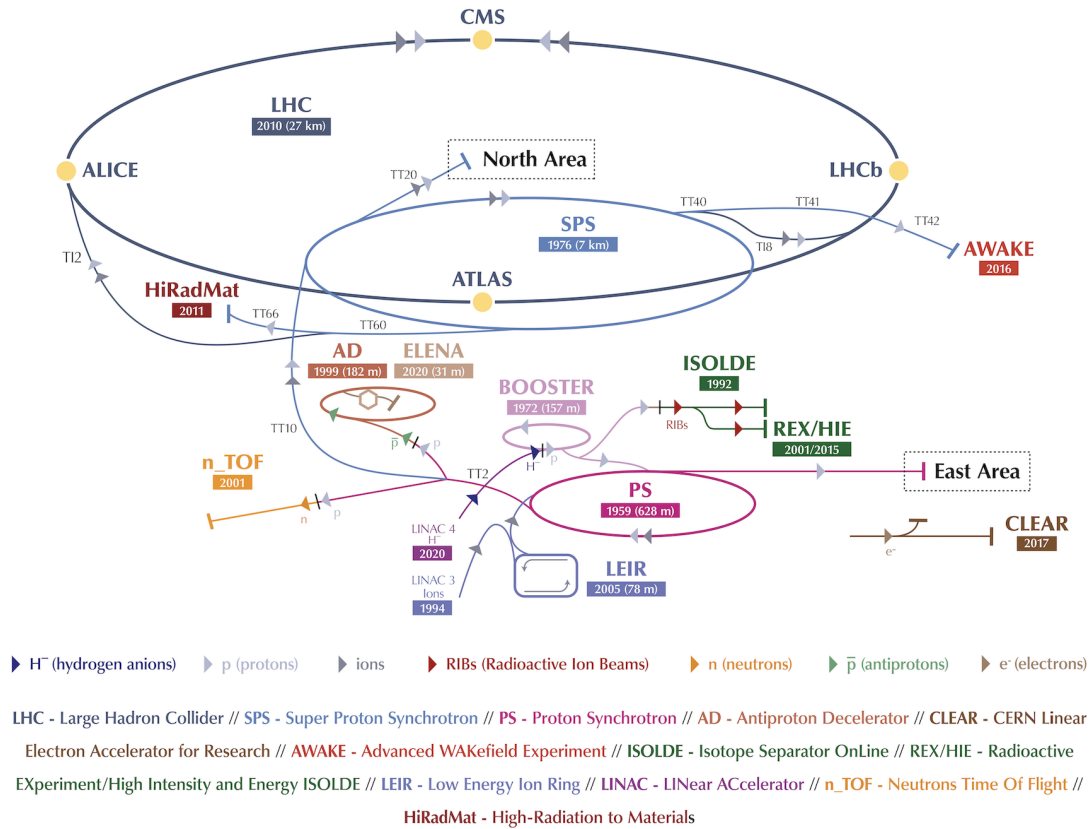


Figure 3.2: Overview of the CERN accelerator complex [60].

50 MeV [61]. Afterwards, the proton beam is injected into the first circular collider, the Proton Synchrotron Booster (PSB) where it is further accelerated to 2 GeV. Then, the beam is sent to the Proton Synchrotron (PS), which is able to boost the protons up to an energy of 26 GeV. From the PS, the proton beam is injected to the Super Proton Synchrotron (SPS) where it is accelerated to 450 GeV. And then finally the beam is injected into two rings of opposite directions in the LHC. There both beams reach an energy of 6.8 TeV.

The accelerator chain with the energies reached at each step is illustrated schematically in figure 3.3.

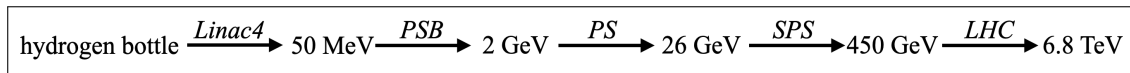


Figure 3.3: Schematic illustration of the proton beam acceleration at the LHC in Run 3.

3.1.3 LHC experiments

The LHC is composed out of eight arcs and eight straight sections. To each section underground installations and technical infrastructures are associated. These locations are referred to as LHC points, see figure 3.4. The main experiments are located at IP1, IP5, IP2 and IP8, being the ATLAS, CMS, ALICE, and LHCb experiments, respectively. Beam 1 is injected clockwise at IP2, while beam 2 counter-clockwise at IP8. The beam dumps are located at IP6, and the remaining two IPs have collimators cleaning the beams.

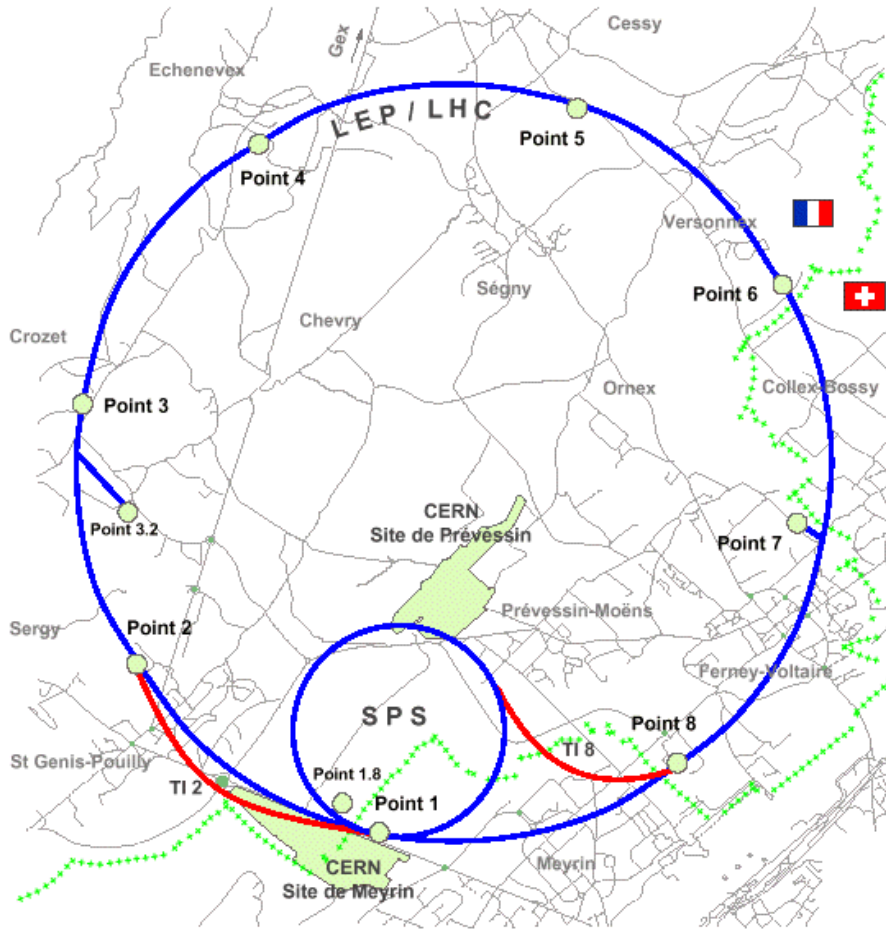


Figure 3.4: Illustration of the LHC points on a map [62].

The LHC rings cross in the straight sections, creating four interacting points. At each of them, an experiment to study the particles produced in the collisions is located. These four main experiments are:

- **ATLAS** (A Toroidal Lhc ApparatuS) [56]: a general purpose experiment, performing precision measurements of the SM, in particular the Higgs boson, and looking for BSM

physics,

- **CMS** (Compact Muon Solenoid) [63]: another general purpose experiment with the similar scientific goals as ATLAS but different technologies,
- **ALICE** (A Large Ion Collider Experiment) [64]: designed for heavy-ion collisions to study the physics of the quark-gluon plasma and QCD,
- **LHCb** (Large Hadron Collider beauty) [65]: designed to study B meson physics and CP violation.

In addition, the LHC has five smaller experiments, using the same collision points as the above:

- **TOTEM** (TOTal, Elastic and diffractive cross-section Measurement) [66]: located on either side of the CMS detector; this detector is used to study forward protons, i.e. protons emitted at a small angle from the collisions, to study elastic scattering and diffractive processes,
- **LHCf** (Large Hadron Collider forward experiment) [67]: positioned along the beamline on either side of the ATLAS detector at 140 m from the centre of the detector, it is used to study particles produced in the very forward region to understand cosmic ray interactions better,
- **MoEDAL** (MONopole and Exotics Detector at the LHC) [68]: located close to LHCb, it looks for exotic particles like the hypothetical particles with only one magnetic pole called magnetic monopoles,
- **FASER** (ForwArd Search ExpeRiment) [69]: positioned close to the ATLAS detector; this experiment looks for neutrinos and long lived particles,
- **SND** (Scattering and Neutrino Detector) [70]: located close to the ATLAS detector; this experiment studies neutrinos by looking at a smaller angle to the beampipe than FASER.

3.2 ATLAS detector

The ATLAS detector at the LHC is the largest detector that has ever been constructed for a particle collider. It is a general purpose detector with the shape of a cylinder of length 44 m and diameter 25 m, with an almost full 4π coverage. The ATLAS detector is illustrated in figure 3.5. The beampipe passes in the middle and the particles collide in the centre of the detector.

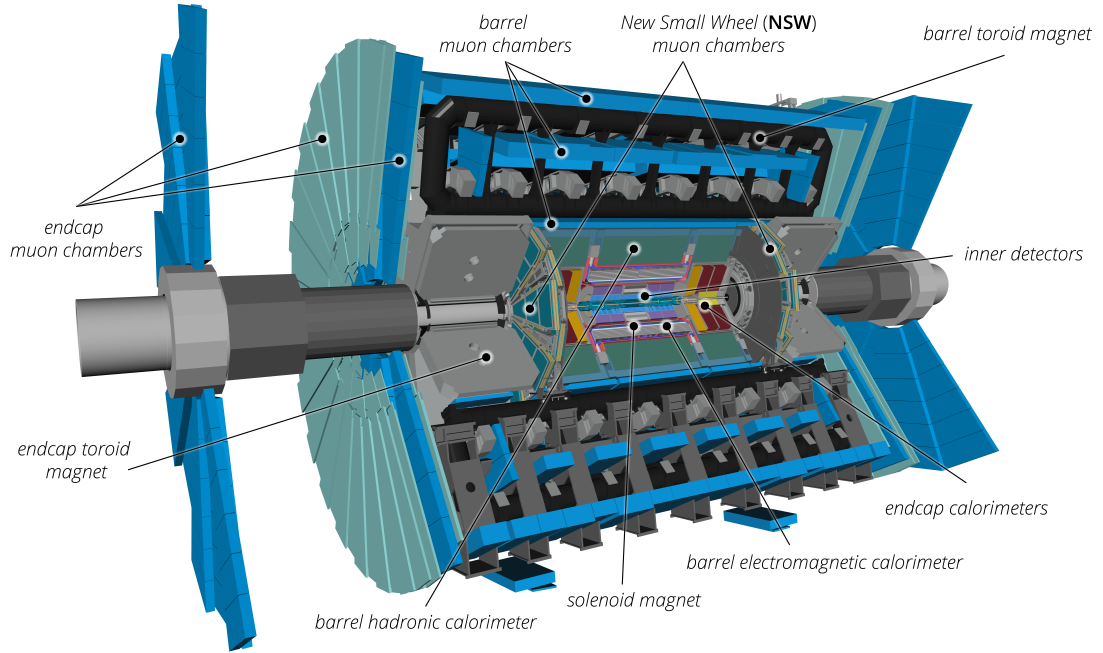


Figure 3.5: *Illustration of the ATLAS detector and its sub-detectors [57].*

ATLAS is composed of different detecting sub-systems layered in concentric cylinders around the beampipe in the central region, and as perpendicular discs to the beampipe in the forward region. The Inner Detector (ID), which is located closest to the beampipe, is used to determine the trajectories of charged particles, which allows to measure the charge and momenta of particles by using the magnetic field produced by the solenoid surrounding it. The Inner Detector is surrounded by the calorimetric system, which is used to measure the energy of particles. The Muon Spectrometer, which is located in the outermost part of the detector, measures the trajectories of muons and their charge and momenta by using the toroid magnetic field. In the following, some of the ATLAS nomenclature will be described shortly, as well as the sub-detectors and how the trigger and data acquisition system work. More detailed descriptions of the ATLAS sub-detectors can be found in reference [56] and the LS2 upgrade in reference [57].

3.2.1 Nomenclature

The ATLAS coordinate system is a right-handed cylindrical coordinate system, as shown in figure 3.6. The z -axis points along the beampipe, the x -axis points to the centre of the LHC ring, the y -axis upwards, and the origin lies at the Interaction Point (IP).

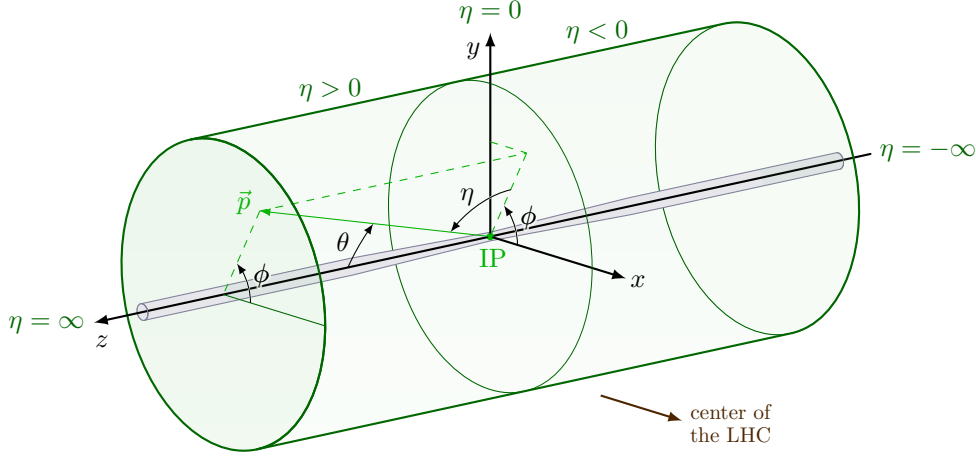


Figure 3.6: *Illustration of the ATLAS coordinate system [71].*

The x - y plane, the plane perpendicular to the z -axis, is called the transverse plane. The azimuth angle (ϕ) is measured from the x -axis in the transverse plane around the z -axis, and the polar angle (θ) is the angle between the particle and the z -axis, as shown in figure 3.6. An important kinematic variable to describe particles is the rapidity, which is defined as

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right). \quad (3.5)$$

The difference in rapidities is a Lorentz invariant for boosts in the z direction. For reconstructed particles, it is however more convenient to use the pseudorapidity since they are equivalent in the limit of massless particles. Pseudorapidity is defined as

$$\eta = -\ln \left(\tan \left(\frac{\theta}{2} \right) \right). \quad (3.6)$$

An illustration of pseudorapidity in y – z plane and its relation to the polar angle is shown in figure 3.7.

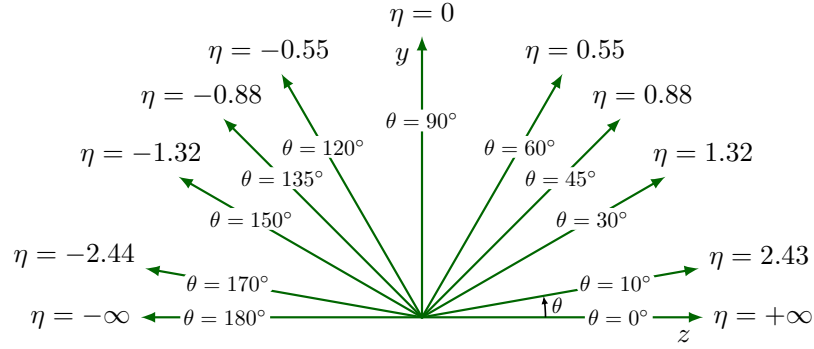


Figure 3.7: Pseudorapidity illustration and its relation to the polar angle [71].

Other quantities that are important to understand the kinematics of particles are the angular distance and the impact parameters.

The angular distance between particles is defined as

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}, \quad (3.7)$$

where $\Delta\eta = \eta_1 - \eta_2$ and $\Delta\phi = \phi_1 - \phi_2$, with $\Delta\phi \in [-\pi, \pi)$.

The impact parameters are used to quantify the distance between the interaction point (IP) and a particle. The impact parameters are illustrated in figure 3.8. The transverse impact parameter (d_0) is the shortest distance between the particle's track and the beamline in $x-y$ plane. This closest approach point's z coordinate is named z_0 . The corresponding longitudinal impact parameter is thus $z_0 \sin(\theta)$.

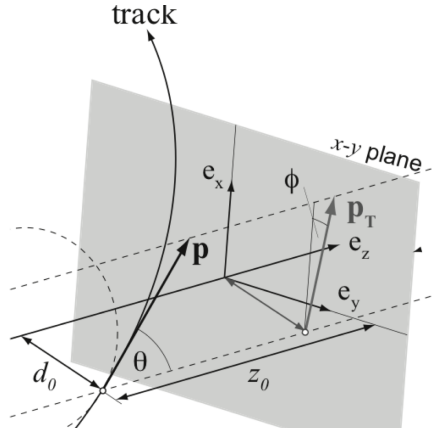


Figure 3.8: Illustration of the impact parameters in longitudinal and transverse planes [72].

The ATLAS detector can be divided into two regions: the central part, called barrel, and the forward parts, called endcaps.

It is practical to use (r, ϕ) coordinates to describe the kinematics of particles in the transverse plane. Quantities projected to this plane are particularly interesting to study, since in proton-proton collisions the initial momentum along the z -axis is not known exactly. This is because the particles colliding are the partons inside the proton and their exact energy is not known, see Chapter 2 for more information. In the transverse plane the initial momentum is known to be zero. Thus, the sum of momenta of all particles in a proton-proton collision in the transverse plane has to be zero at all times. This property is very interesting to look for the detection of invisible particles like neutrinos and BSM particles like DM candidates, since they would not be detected and thus the sum of momenta in the transverse plane would not sum up to zero. For that purpose, the missing transverse momentum (MET) is defined as the negative sum of the transverse momenta of all detected particles as

$$E_T^{\text{miss}} = |\vec{p}_T^{\text{miss}}|, \quad (3.8)$$

where

$$\vec{p}_T^{\text{miss}} = - \sum_{i \in \text{detected}} \vec{p}_T^i. \quad (3.9)$$

The transverse momentum is defined as $p_T = (p_x, p_y)$.

3.2.2 Magnet system

Two types of superconducting magnets are used in the ATLAS detector: the solenoid and three toroids. Their operational temperature is 4.5 K (-268°C). The purpose of the magnetic system in ATLAS is to bend the trajectories of charged particles to measure their momenta.

The solenoid is located around the Inner Detector with a size of 2.56 m in diameter and a length of 5.8 m, and it creates a magnetic field of around 2 T. The magnetic field is oriented parallel to the z -axis to bend particles in the transverse plane.

The toroid magnets are divided in barrel and endcaps covering respectively the pseudorapidities $|\eta| < 1.6$ and $1.4 < |\eta| < 2.7$. The barrel magnets are composed of 8 coils and weight 830 tonnes. The coils have a length of 25.3 m and the outer diameter of the system is 20.1 m, while the endcap toroids have a diameter of 10.7 m.

3.2.3 Inner detector

The ID [57, 73, 74], shown in figure 3.9, is a 6.2 m long cylinder with a diameter of 2.1 m, covering a pseudorapidity range of $|\eta| < 2.5$. The aim of the ID is to reconstruct trajectories of charged particles, called *tracks*, interacting with its material. From these trajectories the direction of the particle can be reconstructed, as well as its charge and impact parameters, the momentum of the particle. The ID is designed to achieve an excellent position resolution of

the passing particle. The ID can be divided into three sub-detectors: the Pixel detector, the SemiConductor Tracker (SCT) and the Transition Radiation Tracker (TRT). The first two are based on silicon technology, while the latter is based on drift tubes.

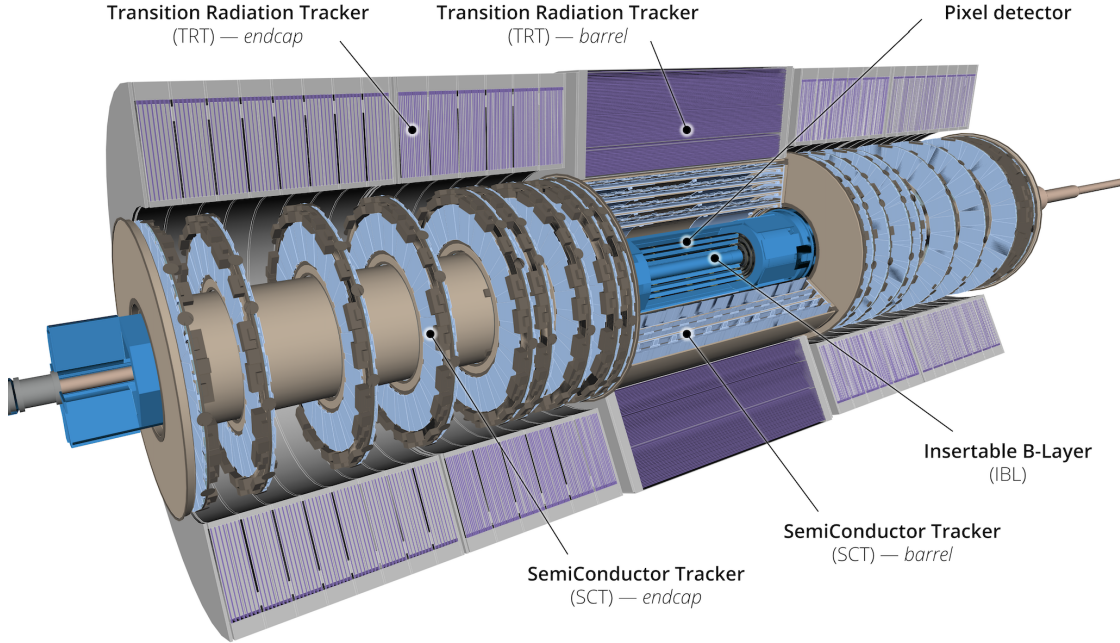


Figure 3.9: An illustration of the ATLAS inner detector and its sub-detectors [57].

Pixel detector The pixel detector is the innermost part of the ID. It is composed of four layers in the barrel and three endcap discs on each side of the IP. The innermost barrel layer is called Insertable B-Layer (IBL) [75]. It was added during LS1 at a distance of 3.3 cm from the beam axis to improve the longitudinal resolution and robustness of tracking in particular in high pileup conditions. The other three barrel pixel layers lie at radii of 5.05 cm, 8.85 cm, and 12.25 cm, respectively. The endcap discs are positioned along the z -axis in the range $|z| = 49.5\text{--}65.0$ cm covering radii from 8.88 cm to 14.96 cm. This corresponds to the coverage of the pseudorapidity range $|\eta| < 2.5$. The IBL has a slightly larger pseudorapidity range coverage of up to $|\eta| < 3$. The pixel detector is composed of pixelated silicon sensors of size $50 \times 400 \mu\text{m}^2$ and $50 \times 600 \mu\text{m}^2$, while the IBL pixels are smaller with a size of $50 \times 250 \mu\text{m}^2$. The intrinsic position resolution obtained by the pixel detector is $10 \mu\text{m}$ in the transverse plane and $115 \mu\text{m}$ in the longitudinal plane.

Semiconductor Tracker The SCT is composed of silicon strip sensors. Four double layers in stereo in the barrel covering $|z| < 74.9$ cm and $r = 29.9\text{--}51.4$ cm, and 9 endcap discs on each side of the IP situated in the z -axis range $|z| = 85.38\text{--}272.02$ cm. The SCT also covers the

pseudorapidity range $|\eta| < 2.5$. The intrinsic position resolution obtained by the SCT is $17 \mu\text{m}$ in the transverse plane and $580 \mu\text{m}$ in the longitudinal plane.

Transition Radiation Tracker The TRT is situated in the outermost part of the ID. This detector is composed of thin straw-like drift tubes filled with gas, with a 0.03 mm gold-plated tungsten wire in the centre. The diameter of the tubes is only 4 mm , while their length amounts to 144 cm in the barrel and 37 cm in the endcaps. In the barrel region the tubes are arranged parallel to the beampipe, and in the endcaps perpendicular to it. The TRT covers a smaller pseudorapidity range than the rest of the ID, covering only up to $|\eta| < 2$. Its position resolution is also worse than the rest of the ID sub-detectors and amounts to $130 \mu\text{m}$ for each straw. However, a particle usually crosses at least 20 straws improving the resolution by one order of magnitude. A charged particle passing in the tubes ionises the gas (xenon or argon) in it, creating an electrical signal in the tube. The interesting part about the TRT is that it can be used for particle identification by using the transition radiation. The material between the drift tubes has a different dielectric constant than the tubes themselves, thus a charged highly relativistic particle passing through the two materials produces transition radiation photons. In the tubes filled with a mixture of xenon, the produced transition radiation photons are detected via photoelectric effect and converted into an electric signal. This gives a larger signal than just a charged particle passing. The transition radiation intensity is proportional to the Lorentz gamma factor of a particle $\gamma = E/(mc^2)$, thus the lightest charged particles produce the most transition radiation. This allows to distinguish electrons from other particles. The transition radiation is the reason why the TRT can be used for electron identification and to distinguish electrons from pions. Due to gas leaks and the xenon being expensive several parts of the TRT are now filled with argon instead. The transition radiation in argon is not detected, thus the TRT works only as a tracker in these regions. Unfortunately, in Run 3 the whole barrel is filled with argon instead of xenon.

3.2.4 Calorimeters

The ID and the solenoid magnets are surrounded by the calorimeters. They are used to measure the energy of particles and give limited directional information. The calorimetric system is illustrated in figure 3.10.

A particle interacts with the calorimeter material creating a shower of particles and depositing all its energy. In this way, the energy of the particle can be detected and quantified.

In ATLAS, there are two types of calorimeters: electromagnetic calorimeters and hadronic calorimeters [76, 77]. This design choice is motivated by the different interaction of particles with matter: while light particles such as electrons and photons predominantly interact electromagnetically, hadrons interact primarily via strong interactions. Thus, for electromagnetic calorimeters passive materials with high atomic number (Z) are chosen to increase the proba-

bility of pair production in the material and contain the electromagnetic shower created in the calorimeter. In the hadronic calorimeter lighter material (lower Z) can be used since the aim is to equalise the length of electromagnetic and hadronic showers. In both cases, a shower of secondary particles is created.

Both calorimeter types are based on sampling strategy, i.e. they are composed of alternating layers between a passive material in which particles interact and create more particles, and an active material in which the particles are detected. The calorimeters cover a pseudorapidity range of $|\eta| < 4.9$.

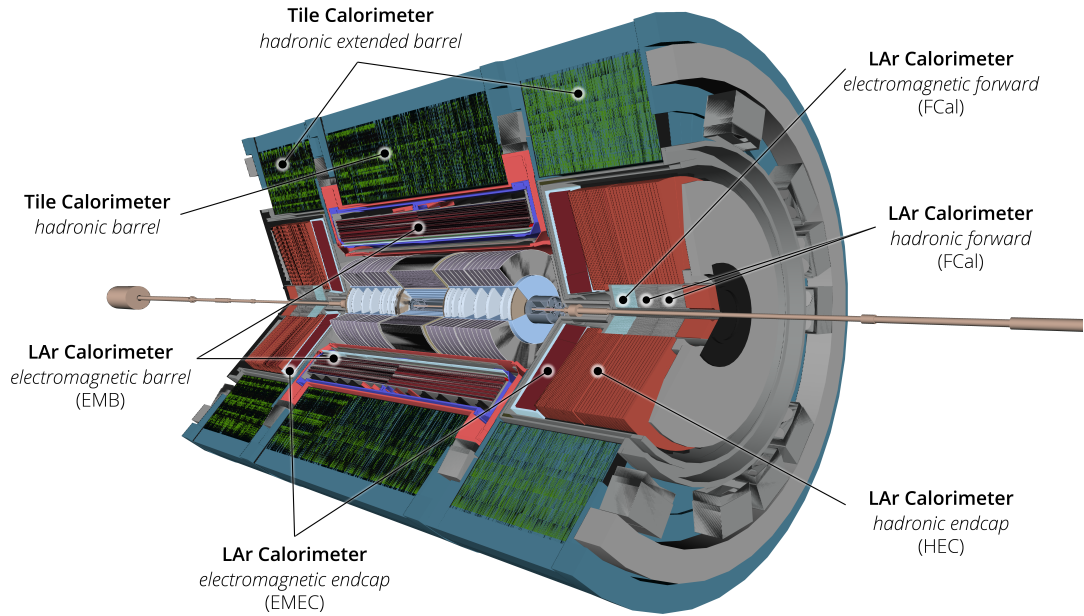


Figure 3.10: An illustration of the ATLAS calorimeters and its sub-detectors [57].

Electromagnetic Calorimeter The electromagnetic calorimeter (ECAL) is composed of the barrel (EMB), the endcap regions (EMEC), and the forward region (FCal), they cover respectively the pseudorapidity ranges $|\eta| < 1.475$, $1.375 < |\eta| < 3.2$, and $3.1 < |\eta| < 4.9$. The ECAL is used to absorb and measure the energy of electrons and photons. The active material is liquid argon (LAr) while the passive material are lead plates in the barrel region and copper in the FCal. The incoming electron emits bremsstrahlung photons, which produce an electron-positron pair. An incoming photon produces an electron-positron pair that emit photons. This gives origin to a cascade effect of production of new particles called *electromagnetic shower*. The LAr layers are ionised by the passing particles. The readout electrodes placed between the passive material collect the ionisation signal and convert it into an electrical signal that is proportional to the energy deposited.

Hadronic Calorimeter The hadronic calorimeter (HCAL) is located right after the ECAL. It can be decomposed into three regions: the barrel, the endcaps (HEC) and the forward region (FCal). They cover respectively the pseudorapidity ranges $|\eta| < 1.7$, $1.5 < |\eta| < 3.2$, and $3.1 < |\eta| < 4.9$. The first one is also called *Tile calorimeter* or simply *Tile* since it is based on alternating layers of iron and scintillating tiles. HEC has copper as the passive material and FCal copper and tungsten. The particles interact with the passive material generating a shower of new particles which interact with the active material. The photons produced in the active material are then read out by photomultipliers (PMTs) and converted into an electrical signal. A schematic illustration of the Tile cells is shown in figure 3.11.

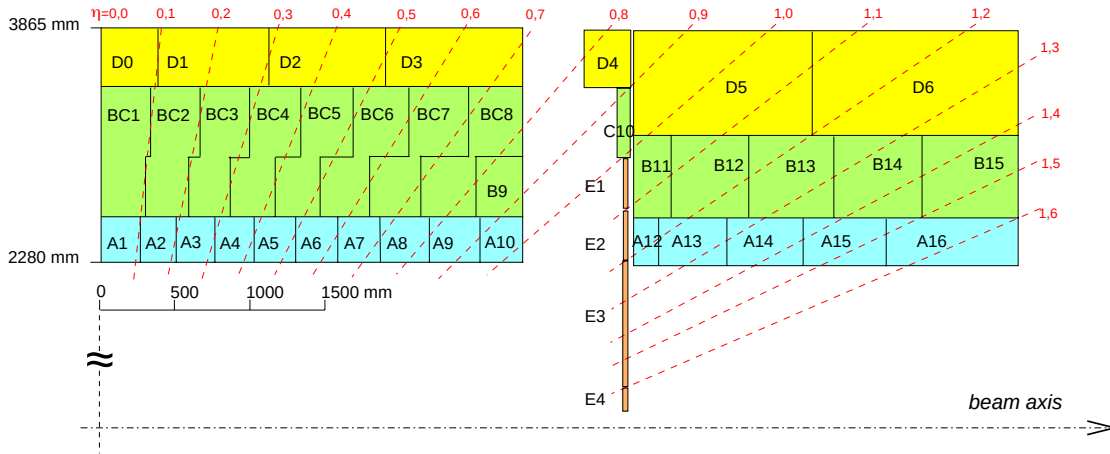


Figure 3.11: An illustration of the tile calorimeter cells [78].

3.2.5 Muon Spectrometer

The ATLAS muon detectors [57, 79], called *Muon Spectrometer* (MS), are shown in figure 3.12. Due to their location, behind the calorimeters, no particles apart from muons are detected by the muon spectrometer. The muons pass the ID and calorimetric system without being stopped due to their small interaction with the material. The MS can measure the position of a muon with a precision of up to $50 \mu\text{m}$. The trajectories of muons are bent by the toroid magnets to determine the muon charge and momentum.

The MS is based on five different detector types: the Monitored Drift Tubes (MDTs), the Thin Gap Chambers (TGCs), the small-strip TGCs (sTGCs), the Micromegas (MM), and the Resistive Plate Chambers (RPCs).

The MDTs are gas-filled drift chambers, with tube geometry having a diameter of 3 cm, and a wire in the centre. A voltage is applied between the tube and the wire. The drift tubes are arranged in six layers to form a chamber such that three layers are on each side of the support structure. A passing muon ionises the gas, producing electrons that drift to the central wire. This produces an electrical signal that can be read out. The MDTs are slow but precise: they

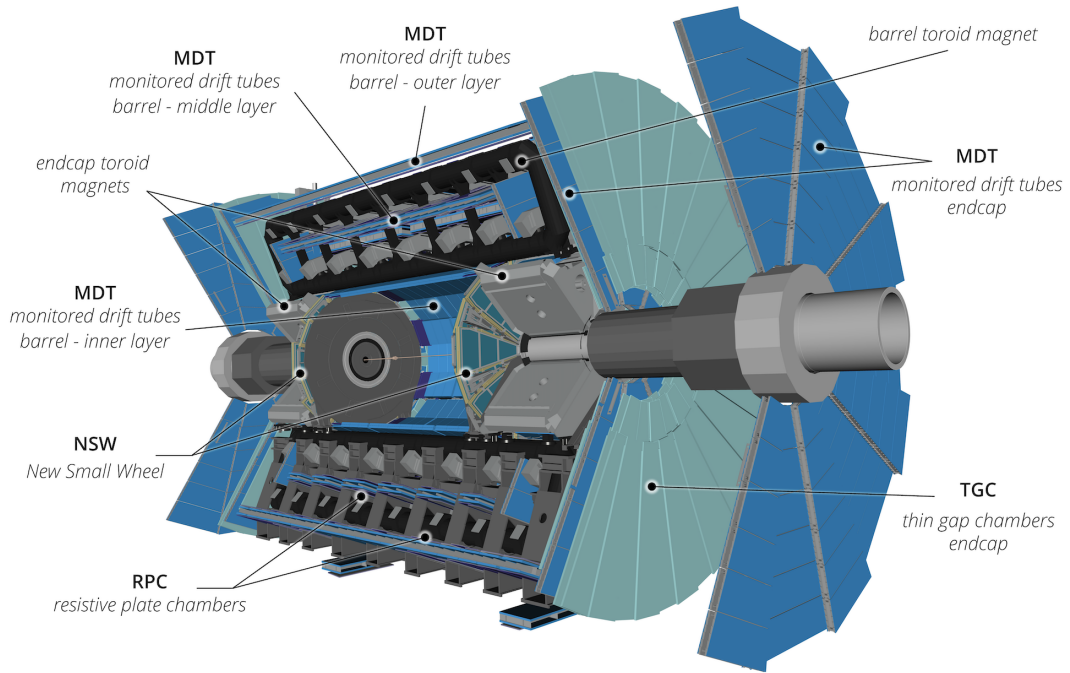


Figure 3.12: An illustration of the ATLAS muon detectors and its sub-detectors [57].

can achieve a spatial resolution per tube of $80\ \mu\text{m}$, and per chamber of $35\ \mu\text{m}$, with a time resolution of $1.2\ \mu\text{s}$ [80].

The TGCs, placed in the endcaps of the ATLAS detector, are multi-wire proportional chambers, i.e. they are composed of wires in a gas mixture situated between two plate at an electrical potential difference. The wires themselves are very thin, with a diameter of only $30\ \mu\text{m}$. A passing muon ionises the gas; this signal is then detected by the wires. This detector technology has a poor spatial resolution of up to $7\ \text{mm}$, but an excellent time resolution of $4\ \text{ns}$.

The New Small Wheel (NSW), installed during LS2, lies between the calorimeters and the endcap toroidal magnets. It is composed of two technologies: the small-strip TGCs (sTGCs) and the micro-mesh gaseous structure called Micromegas (MM). The sTGCs are TGCs with higher tracking precision. Micromegas is a drift electrode with a gas mixture in between. Close to the readout cathode a micro-mesh is positioned to create a strong amplification region thanks to the geometry with holes of the micro-mesh. A traversing muon ionises the gas, freeing electrons that drift to the micro-mesh. There they get amplified thanks to the micro-mesh, which generates electron avalanches that are read out by the electrode. The NSW is fast enough to be used for trigger purpose and has also an excellent position resolution for muon tracking.

A RPC has parallel plastic plates at an electrical potential difference with a gas mixture in between to detect particles. A RPC is illustrated in figure 3.13. A passing muon ionises the

gas producing primary electrons. These are amplified by the electric potential difference to produce a signal. Perpendicular to the plastic plates, strips are installed to read out the signal. The RPCs have a poor spatial resolution of 1 cm, but an excellent time resolution of 1.5 ns. The MDTs are used for precise position measurement of muons, while the RPCs and the TGCs are mainly used for trigger purposes with additional information on tracking.

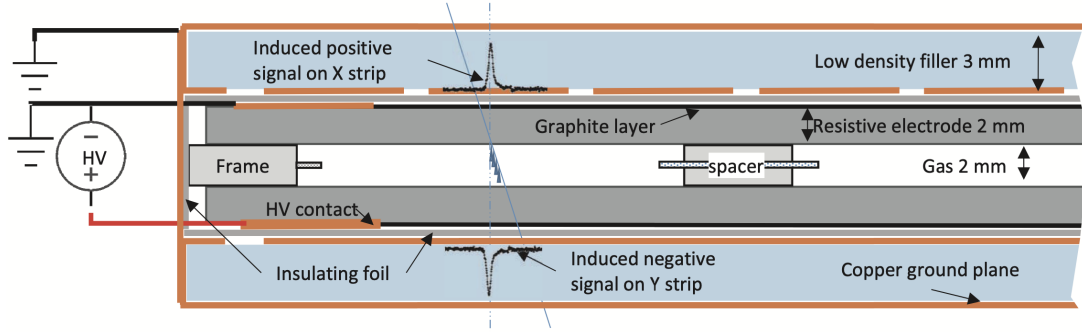


Figure 3.13: *Illustration of a RPC [81].*

Three layers of MDTs can be distinguished in the barrel region. They are situated at $|r| = 5$ m, 7.5 m and 10 m in a concentric cylindrical way. The RPCs are used in the barrel region and placed just before the MDT chambers. A fourth RPC is added just after the second MDT chamber. In the endcap region, there is the NSW at $|z|$ -coordinate of 7.4 m, and at 10.8 m, 14 m and 21.5 m there are MDTs. The middle MDT wheel has a wheel of TGCs in front, and it is followed closely by two other TGCs wheels.

3.2.6 Luminosity detectors

Several detectors can measure luminosity in ATLAS: LUMinosity Cherenkov Integrating Detector (LUCID), beam condition monitor (BCM), ID and calorimeters. The corresponding detectors are indicated in figure 3.14.

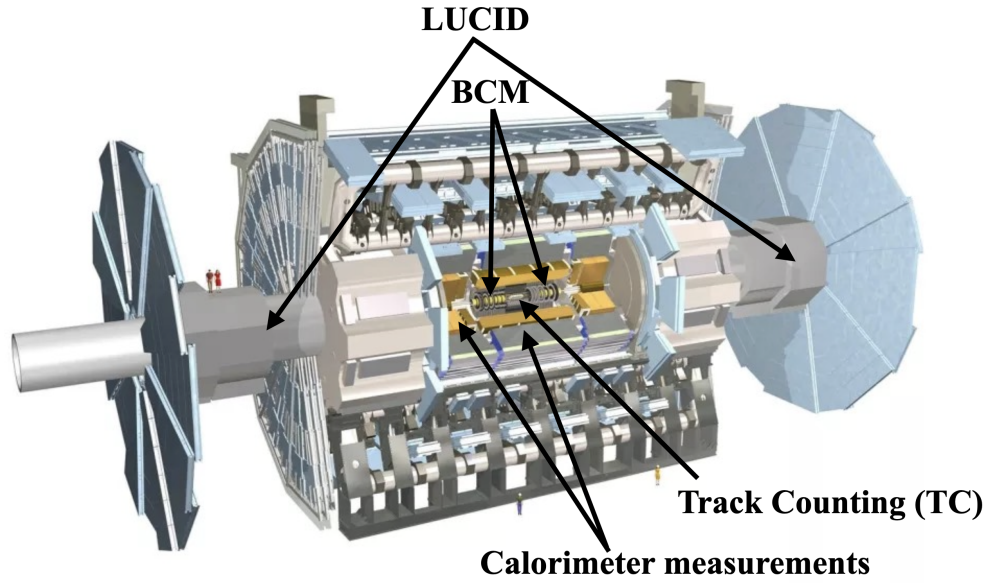


Figure 3.14: The ATLAS detector and the position of its luminometers [82].

LUCID LUCID is situated in the forward region of the ATLAS detector, around 17 m away from the IP on both sides [83, 84]. On each side of the IP, very close to the beampipe, 16 PMTs are situated around the pipe as shown in figure 3.15.

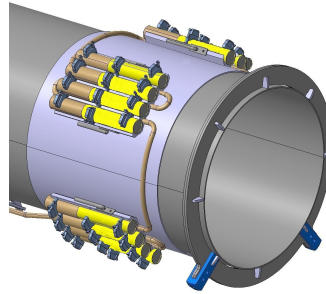


Figure 3.15: PMTs position around the beampipe, 16 PMTs on each side of the ATLAS IP. [82].

The PMTs have a quartz window in which passing charged particles emit Cherenkov radiation. The resulting photons are converted into electrons, amplified and read out as an electrical signal by the PMTs themselves. The quartz windows are coated with a radioactive source (Bi-207) to calibrate the output signal, i.e. the PMT voltage is adjusted to have a constant pulse amplitude or charge over time.

The 16 PMTs on each side allow for several different readout combinations. This creates a large variety of luminosity algorithms to compare. With dedicated electronics, the LUCID signal is read out at every bunch-crossing, i.e. the 3564 bunch slots can be read out separately.

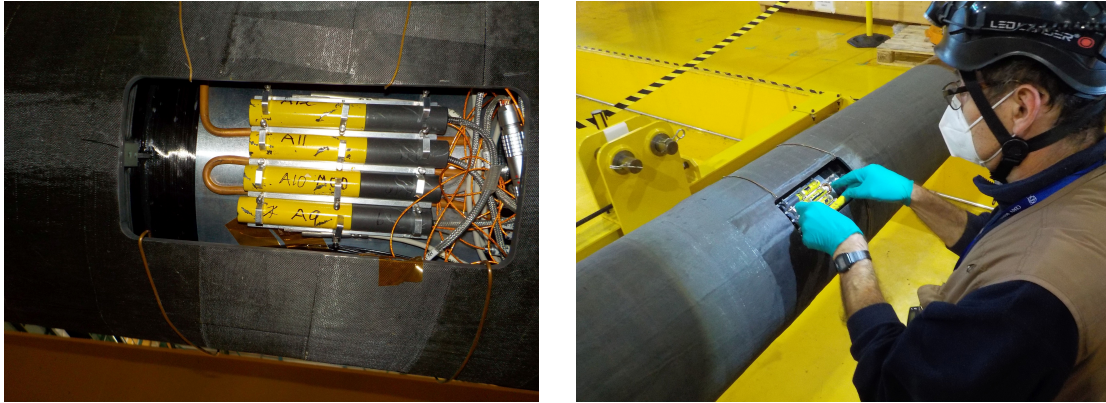


Figure 3.16: *LUCID tubes installed around the beampipe [82].*

BCM The Beam Condition Monitor (BCM) diamond detectors are built to monitor background and beam losses. When these are too high the detectors abort the beams quickly to protect the inner detector. The BCM is located 184 cm away from the IP on both sides of the ATLAS detector at $|\eta| = 4.2$. Each station has four diamond sensors which are arranged around the beampipe at a radius of around 55 mm, two horizontally and two vertically. The detectors are based on charged particles ionizing the diamond, which signal is amplified by the module, digitalised and read out by appropriate fast electronics. Because of their good time resolution the BCM detectors allow to distinguish particles from the collision from the background ones. A collision will create particles that generate a simultaneous signal on both sides, while the background particles do not reach the detectors at the same time. Furthermore, this good time resolution allows the BCM to provide bunch-by-bunch measurements [85][86].

3.2.7 Trigger and Data Acquisition

Bunches at LHC cross every 25 ns; this results in a collision rate of 40 MHz. The produced data exceeds the data acquisition capabilities and CERN storage availabilities. However, the most interesting events for this analysis are not so common. The most common collisions at the LHC are the elastic collisions called soft interactions where protons interact collectively. The collisions that are interesting for high energy particle physics research are inelastic high energy collisions. In particular, events with very energetic leptons, photons and hadronic jets or a large MET are interesting.

To decide quickly which events to record for further analysis, ATLAS uses a sophisticated Trigger and Data Acquisition system (TDAQ). This reduces the event rate in two steps: first a hardware based trigger called Level-1 (L1) trigger [87] reduces the event rate from 40 MHz to maximally 100 kHz, and then a software based High-Level Trigger (HLT) [88] reduces the event rate further to 3 kHz on average over an LHC fill.

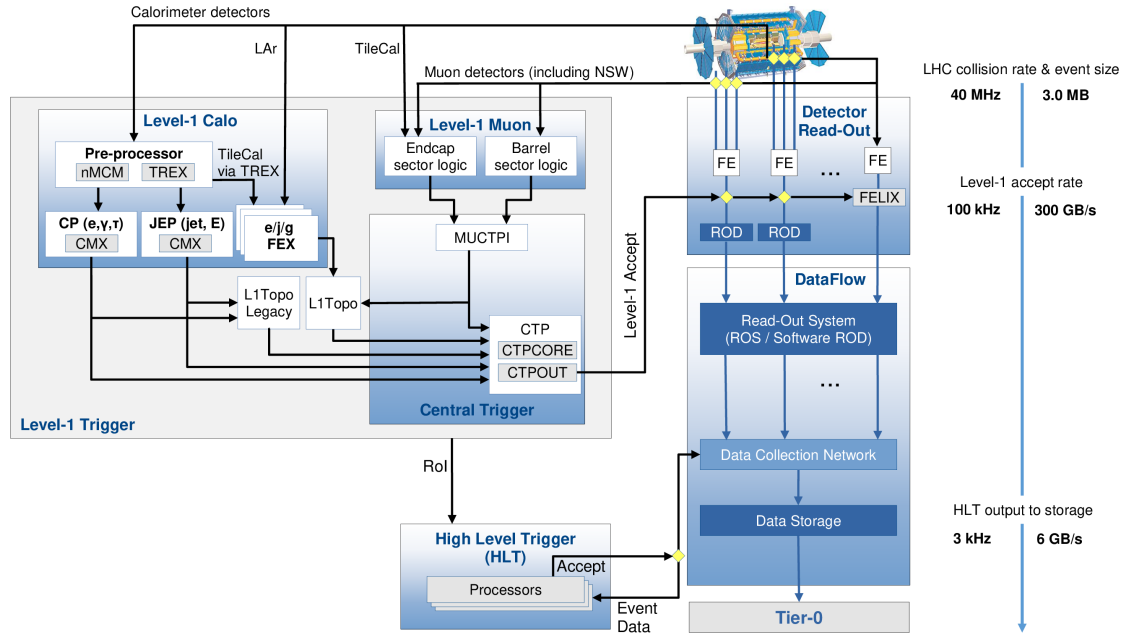


Figure 3.17: An illustration of the ATLAS detector trigger and data acquisition system [57].

A schematic illustration of this can be found in figure 3.17. The L1 trigger is composed of the L1 Calorimeter and L1 Muon triggers, focusing on specific detector objects like jets, electrons, photons, and muons. These triggers utilise algorithms that share information about these objects (FEX). Some of the triggers are put together into the L1Topo trigger, which considers the total energy from calorimeters, kinematic thresholds, and topological variables such as angular separation and invariant mass. All L1 triggers are integrated into the Central Trigger Processor (CTP), which rapidly decides whether to retain an event based on calorimeter and muon spectrometer data within 2.5 microseconds, necessitating fast custom electronics. Accepted events by the CTP are directed to ReadOut Drivers (RODs) for conversion into raw data format, then to the ReadOut System (ROS) for temporary storage until processed by the High-Level Trigger (HLT). The L1 trigger delineates possible trigger object regions in the detector as Regions of Interest (RoIs). These RoIs are forwarded to the HLT to aid in event retention decisions. The HLT trigger, a software-based system, employs fast and subsequently more intricate algorithms to extract comprehensive information from RoIs, approximating offline selection procedures used in analyses. The events passing HLT are then sent to permanent storage to be used in offline analyses.

4 Event simulation

Only the signals produced by final states of processes are contained in data. As a result, data include, in addition to the signal of interest, processes leading to the same final state. The non-signal processes are called backgrounds. To quantify the contribution of backgrounds to data, simulations are needed. Often, processes resulting in the same final state studied are simulated using Monte Carlo (MC) simulations. The production of particles and their kinematic properties is based on quantum processes, and it is thus random. However, the distributions of particles' properties are not and can be studied. MC simulations mimic these distributions. Additionally, for background modelling, MC simulations can be used to study the expectation for any property of both the signal and background processes. For example, they can be used to optimise event selection and the corresponding efficiencies. In this chapter, the general simulation chain in ATLAS and the MC samples used in this thesis are presented. More details can be found in reference [89].

4.1 LHC collision

An LHC collision can be imagined, as shown in figure 4.1. The collision starts with two incoming protons, one from the left and one from the right. The protons are illustrated as three incoming arrows and a light green blob in the central part of the image. The most energetic interaction of the incoming partons is shown as a large red blob, and it is referred to as *hard interaction*. This is the collision of interest for most physics analyses at the LHC, including the analysis presented in this thesis.

Particles created in the hard interaction are illustrated as red lines going out of the largest red blob: a gluon and three particles, corresponding in this illustration to two top quarks and a Higgs particle. These particles decay further into strongly interacting particles, which radiate gluons. Gluons can radiate other gluons or split into a quark-antiquark pair. This sequence of processes forms a cascade of particles called *Parton Shower* (PS).

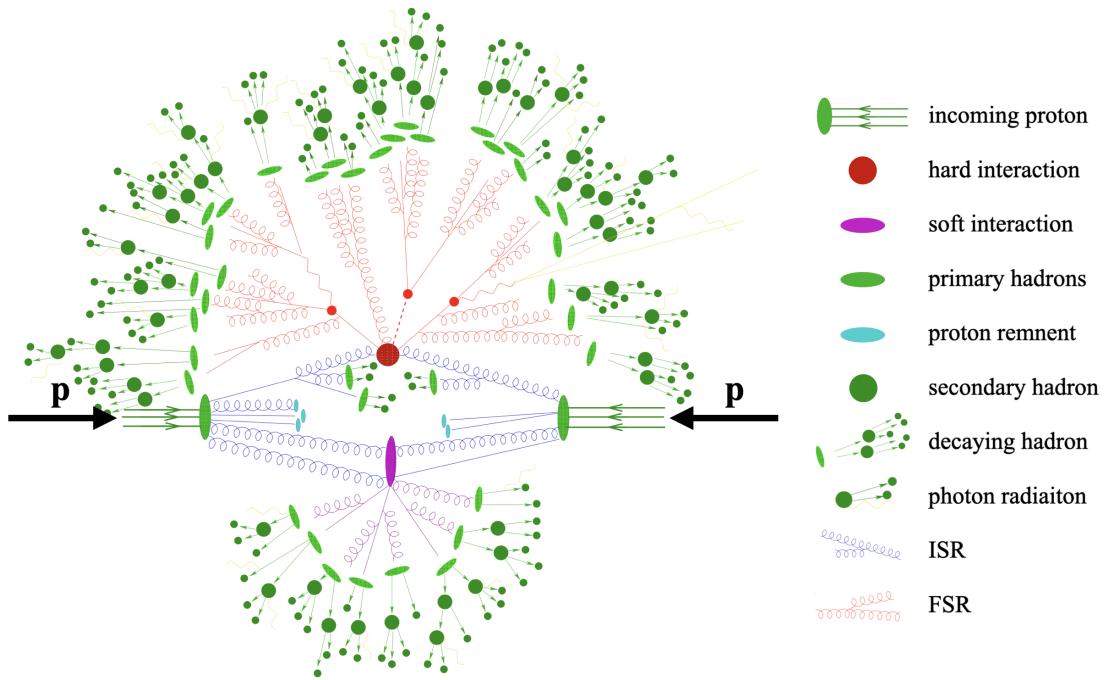


Figure 4.1: Schematic representation of a $t\bar{t} + H$ event [90].

The particles produced in the shower carry colour. However, only colourless particles are observed in the detector due to QCD confinement. This means that coloured partons form colourless bound states of hadrons, hence the name *hadronisation*. The resulting hadrons are called primary hadrons (light green blobs), and their decay products, if hadrons, are known as secondary hadrons (dark green blobs). QCD radiation is called final state radiation (FSR), if the final state particles emit it (here in red) or initial state radiation (ISR), if the initial particles radiate gluons (here in blue). Note that the notions of ISR and FSR are an approximation, since due to the quantum nature of the processes, they cannot be distinguished. The proton remnant can interact, as shown in purple, and form the *underlying event*.

4.2 Factorisation

Factorisation is the idea that calculations at different energy scales can be estimated separately and then multiplied together. MC simulations are based on factorisation calculations into several energy transfer scale parts. The hard interaction is in the high-energy transfer regime: two partons come in and a few energetic particles go out. This process can be computed perturbatively from first principles, and the resulting cross-section can be obtained at fixed order in perturbative QCD. The low-energy transfer regime cannot be computed by perturbation theory since the strong coupling constant grows above one. On this scale, particles are domi-

nated by confinement and soft QCD processes. This regime needs phenomenological models implemented in MC simulations. The transition between the two scales is obtained through parton shower. Both scales and the transition region are modelled using MC techniques.

4.3 Simulation chain

An overview of the simulation chain is shown in figure 4.2. The first simulation step is the computation of the matrix element (ME), followed by the parton shower modelling and the hadronisation. Afterwards, pileup simulations are done. At this stage, the complete event has been generated. Next, the interaction with the detector is simulated. The output of this last step are *hits* in the detector that are then digitised, simulating the analogue-to-digital conversion of the detector readout. The very last step in a MC simulation is the same as in data: the digital signals of the detector are reconstructed into objects related to the particles that created the signals in the detector. More about particle reconstruction can be found in Chapter 5. To produce MC simulations, ATLAS has its own infrastructure [89] based in particular on the toolkit GEANT4 [91] for the detector simulation part. Each step of the MC simulation is described in more detail in the following.

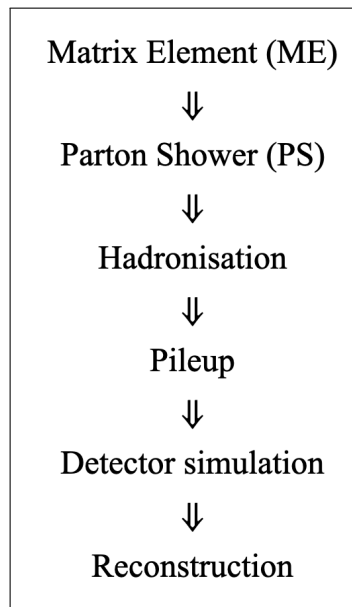


Figure 4.2: *Illustration of the MC simulation chain.*

4.4 Simulation of particles final states

4.4.1 Matrix element

To compute the hard interaction, it is necessary to know what fraction of the protons' momenta the incoming partons carry. This is obtained from parton distribution functions (PDFs), more about PDFs can be found in Chapter 2. The choice of PDF is essential for this calculation, and it can change the cross-section estimation of the process considered. Once the momenta of the incoming partons are known, the matrix element can be computed from Feynman diagrams at a fixed order in perturbative QCD.

4.4.2 Parton shower

Partons radiate gluons like electrons radiate photons, this is called QCD radiation. The radiated gluons can produce quark-antiquark pairs, which can again radiate other gluons. Note that, gluons self-interact and thus radiate gluons themselves. These processes together give origin to a cascade of particles creating a parton shower. The PS can approximate higher-order perturbative corrections to the ME. This is because a LO Feynman diagram radiating a gluon can be considered a NLO ME Feynman diagram. This creates a convolution between the PS and ME estimations. It is thus important to perform a *match and merge* step to avoid double counting of processes between ME and PS. Slowly, as the parton shower evolves, partons have less and less energy until they have a virtuality of the order of 1 GeV. At that point, confinement dominates and the PS stops.

4.4.3 Hadronisation

Hadronisation is at an energy scale where perturbation theory cannot be applied. Thus, an accurate first-principles description is not known, and different models are used. The two most common models are the Lund string and the Cluster models [92–94]. After hadronisation, the formed hadrons, called *primary hadrons*, can decay into more stable particles called *secondary hadrons* if hadrons. The hadronisation is very fast ($O(10^{-24})$ s), it cannot be distinguished from PVs and it is thus invisible to the detector [95]. The particles measured by the detector are either primary or secondary hadrons. The particles at this stage of the simulation are referred to as *particle level* particles. More precisely, in ATLAS, particle level means particles with a lifetime greater than 10^{-11} s, so particles that fly through the detector before they decay.

Lund string model The Lund string model [92, 93] is based on the idea of linear confinement between quarks. Two quarks are imagined to have a string connecting them. When they fly apart, the string stores more energy until it has enough energy to create two new quarks. Then

the string splits. A visual representation of how this model works for a quark-antiquark pair is shown in figure 4.3.

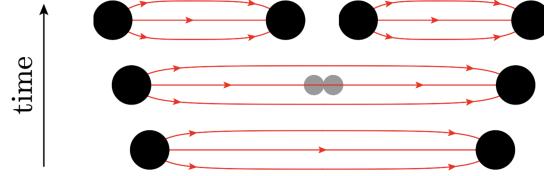


Figure 4.3: *Illustration of the Lund string model for quark-antiquark pair [7].*

An illustration of the Lund string model with an additional gluon is shown in figure 4.4. A quark-antiquark pair with a gluon remains at the end of a PS, together they form a string. The gluon is a "kink" in the string. The string at different times is shown in red: dark red, followed in time by light red. While the string grows, the gluon loses energy. The string grows until the gluon loses all its energy and disappears from the string.

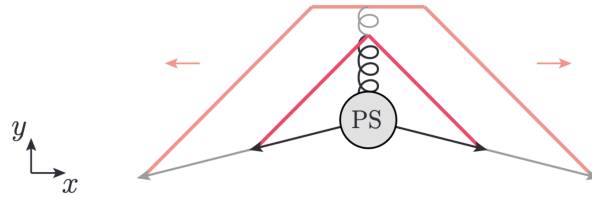


Figure 4.4: *Illustration of the Lund string model for quark-antiquark pair with an associated gluon [7].*

The order of the splitting is irrelevant, i.e. in figure 4.3 whether the left side or the right side splits first does not matter. The string stops splitting when the quark-antiquark pair reaches an invariant mass of the order of the masses of hadrons.

Cluster model The cluster model is based on the idea of pre-confinement. The model starts with the endproducts of the parton shower. If there are any gluons left, they are force-split into a quark-antiquark pair. Then colour singlet clusters are constructed as illustrated in figure 4.5. At the end of this hadronisation process, the clusters can decay into lighter hadrons.

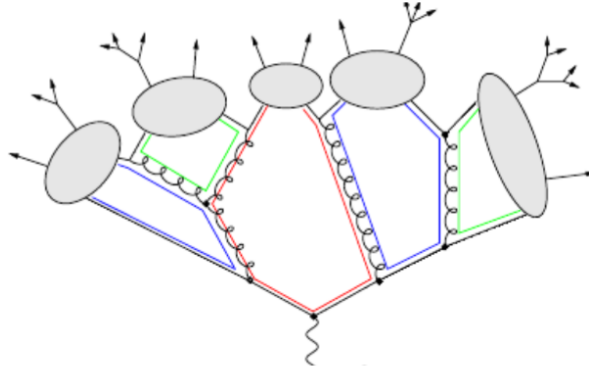


Figure 4.5: *Illustration of the cluster model for hadronisation [96].*

4.4.4 Jets

A parton produces a stream of particles keeping a direction close to the direction of the original parton. After parton shower, it is unclear which particle originates from which parton. A jet algorithm is therefore required. This algorithm must be able to run on inputs of three different processing levels: the parton level, the hadron level and the reconstruction level. It must also be infrared and collinear safe [97]. For this, ATLAS mostly uses the anti- k_t algorithm.

4.4.5 Anti- k_t algorithm

The anti- k_t algorithm, implemented in the FASTJET [98] software, takes as inputs particle objects and calculates the distance between all of them. For pairs of particle objects, the distance is defined as

$$d_{ij} = \min \left(\frac{1}{p_{T,i}^2}, \frac{1}{p_{T,j}^2} \right) \frac{\Delta R_{ij}}{R^2} \quad (4.1)$$

where R is an adjustable parameter chosen to be 0.4 in the jets used in ATLAS. A distance of a single particle object is defined as

$$d_i = \frac{1}{p_{T,i}^2} \quad (4.2)$$

The idea of the anti- k_t algorithm is to check if the distance of a single particle object is smaller than any distance to any other particle object. In the first case, the single particle object is defined as a jet, and in the second case, the pair of particle objects is merged into a single particle object. This process is repeated until only jets exist [99, 100]. The anti- k_t algorithm has the property of first clustering high transverse momentum particle objects with soft ones due to its dependency on the inverse of p_T . In the easiest cases where there is no other high p_T particle object in a radius of $\Delta R = 0.8$ this forms a cone-shaped jet. Other characteristics of

this algorithm are that every hadron is uniquely assigned to a jet, and there is significant noise from the underlying event and pileup. The reconstructed jet from MC simulation without the detector simulation part is referred to as the truth jet.

4.4.6 Pileup

Beside the underlying event and the hard interaction, there can be other protons interacting in the same bunch-crossing, *in-time pileup*, or in a different bunch-crossing, *out-of-time pileup*. These types of interactions are summarised under the name *pileup*. The amount of pileup in an event depends strongly on the instantaneous luminosity of the colliding beams. Thus, different runs can have different amounts of pileup, and the amount of pileup changes during a run. For 2022 the average pileup is ~ 50 .

4.4.7 Different MC simulations

Several common MC generators are used in ATLAS: MADGRAPH5_AMC@NLO [101], POWHEG BOX V2 [102], PYTHIA [103], HERWIG [104, 105] and SHERPA [90]. The first two are specialised in the computation of the matrix element at NLO. The latter three are multipurpose event generators able to simulate everything from the hard interaction through PS to particle decays. PYTHIA and HERWIG estimate the ME only at LO. If a higher order matrix element is desired, often a higher order ME generator is then interfaced with PYTHIA or HERWIG. SHERPA is able to estimate the hard interaction at NLO. For the hadronisation, SHERPA and HERWIG have a cluster model, while PYTHIA is based on a string model. For modelling heavy hadron decays, EVTGEN [106] is often interfaced at the end of the generation chain.

MC tuning MC simulations are approximations of processes happening in nature. Thus, they often need to be adjusted to best model the observed data. Each MC simulation has a set of free model parameters. These are tuned such that the simulation agrees with the data based on previous, independent measurements. The tuned parameters are then published and used in analyses like this one. Not all parameters can be tuned exactly, so the impact of their not-exact knowledge has to be estimated using uncertainties. Only a few parameters change the event properties significantly [7].

4.5 Detector simulation

Once the full collision event has been generated, the interactions of particles with the detector material are simulated using GEANT4. This is the most computationally expensive part of the MC simulation. Most of the CPU time is spent simulating the particle interaction with the

calorimeter material ($\sim 80\%$ of the time). To speed up the slowest parts of the event simulation, which are the showers in the calorimeters, a fast simulation can be used. In this thesis, full simulation samples are used, but fast simulation samples are also available. The newest fast simulation is AtlFast3 (AF3) [107], which is an improved fast simulation compared to AtlFast2 (AF2) [89]. In particular, the calorimeter part alone is now $O(500)$ times faster than the full simulation and is able to reproduce the full simulation calorimeter shower shapes much more accurately [107]. After the event's interaction with the detector is simulated, the energy is stored. In a separate step, these energy deposits are digitalised and the pileup is added. At this stage the MC simulated event has the same format as data. Thus, it is reconstructed in the same way using the same software. MC simulated events contain in addition to the raw signals the truth level information (particle level), thus the reconstructed objects can be studied in comparison to the truth objects which is useful in several areas of the analysis.

4.6 Corrections to simulation objects

The simulated objects might not always take into account all the features seen in data. Thus, scale factors and pileup reweighting is used to correct MC.

Scale factors Differences between MC simulation and data result in different efficiencies for objects, e.g. isolation efficiencies. The MC simulation is corrected by dedicated scale factors (SFs).

Pileup reweighting The in-time pileup in simulation might not correspond to the one found in data, to correct this, *pileup reweighting* is done. To each MC event, a weight is applied to match the pileup distribution in data. For example, if the simulation has a too large average number of interactions in the same bunch-crossing (average μ), the simulated events with high average μ get a lower weight. In this way, the simulation represents the data better. Pileup reweighting can be done either on average μ being the average over a LB and BCIDs or on the *actual* μ taking the variation over the bunches into account. The choice of which one is better for the analysis depends on which pileup reweighted distribution represents the data best. In this analysis the pileup reweighting was done on the actual μ .

5 Object reconstruction

At each proton-proton collision, a large amount of particles is produced and flies through the ATLAS detector. The particles interact with the sub-detectors depositing energy in them. These energy deposits are converted into electrical signals, which are digitalized and stored. The particle's properties are measured from these initial digital signals. A visualisation of different particles interacting with the ATLAS sub-detectors is shown in figure 5.1.

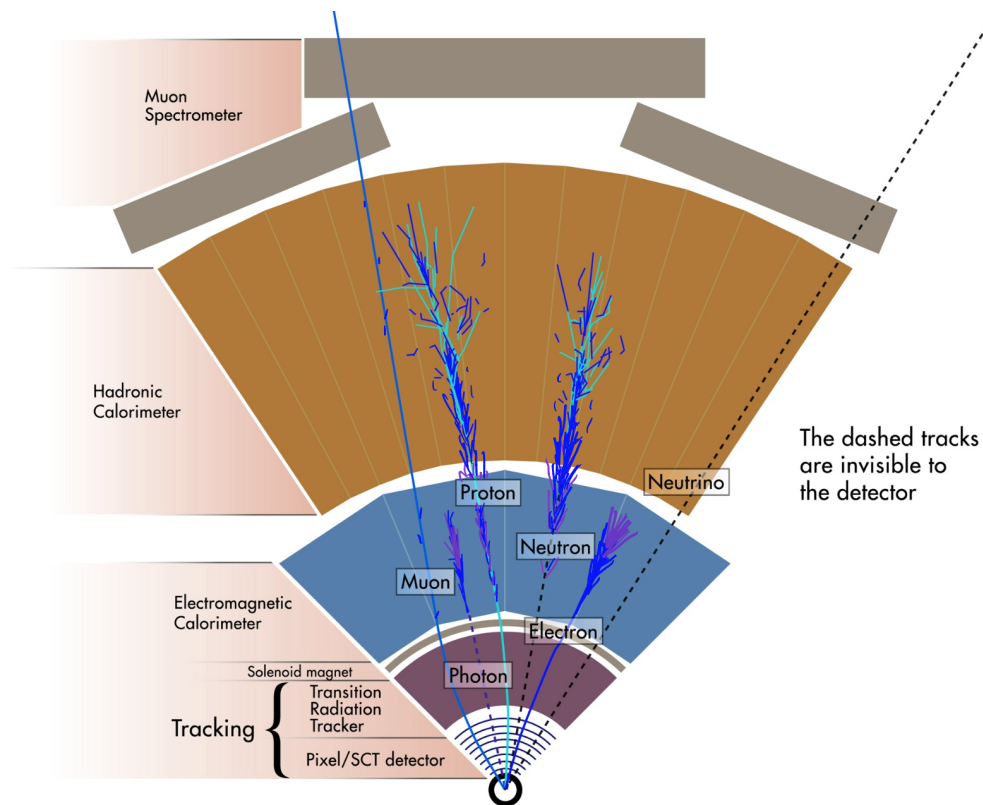


Figure 5.1: Visualisation of different particles' interactions in a section of the ATLAS detector [108].

Electrically charged particles ionise the inner detector's material, leaving *hits*. These hits are used to reconstruct the particles' trajectories. Electrons and photons interact with the ECAL producing electromagnetic showers through Bremsstrahlung and pair production. Due to the Bremsstrahlung component, this effect is dominant for electrons and photons, and negligible for all other particles. Thus, only photons and electrons deposit all their energy in the ECAL. Photons can be distinguished from electrons since they are electrically neutral, and thus not having a track in the ID. However, around half of the photons convert into an electron-positron pair in the ID, which makes it difficult to distinguish them from electrons. Hadrons interact with the HCAL forming a hadronic shower. The only particle detected in the muon spectrometer are muons, since all other particles are stopped by the calorimeters. Knowledge about neutrinos and other particles that are not seen by the ATLAS detector can be gained by looking at the missing transverse momentum of an event. This chapter explains in more detail how the different particles are reconstructed, identified, and defined for this analysis.

5.1 Constituents used in particle reconstruction

Particles either deposit energy in the calorimeter, or leave hits in the trackers, or both. Thus, using the hits in the trackers, trajectories are reconstructed, and the energy deposit in the calorimeter is quantified to extract the events' properties. The essential ingredients for particle reconstruction are trajectories (*tracks*) and energy deposits (*calorimeter clusters*) of particles in the event.

5.1.1 Tracks

Charged particles leave an electrical signal in the ID. A hit is defined as a signal above a predefined threshold to distinguish it from the noise. Given the ID coverage, only tracks within $|\eta| < 2.5$ can be reconstructed. In ATLAS, track reconstruction happens in the seven steps illustrated in figure 5.2 [109, 110]. The hits in the pixel tracker are clustered together into a more accurate position of a particle, then groups of them are used for seeding a track. All possible tracks are reconstructed with additional hits. Then random combinations of hits need to be distinguished from the actual tracks and ambiguities need to be solved. In the end the TRT hits are added to the track.

A charged particle passing through the ID material can interact with several neighbouring pixels or strips. Thus, these hits are grouped together to get an accurate position of the passing particle. Such a group of hits is called an ID-cluster. Neighbouring pixels or strips are defined as the ones having a hit each and sharing a corner or an edge. Once an ID-cluster is formed, the 3D position of the cluster can be measured from the stereo angle in the silicon strips and the point in space where the charged particle passed through the pixel. In this clustering step

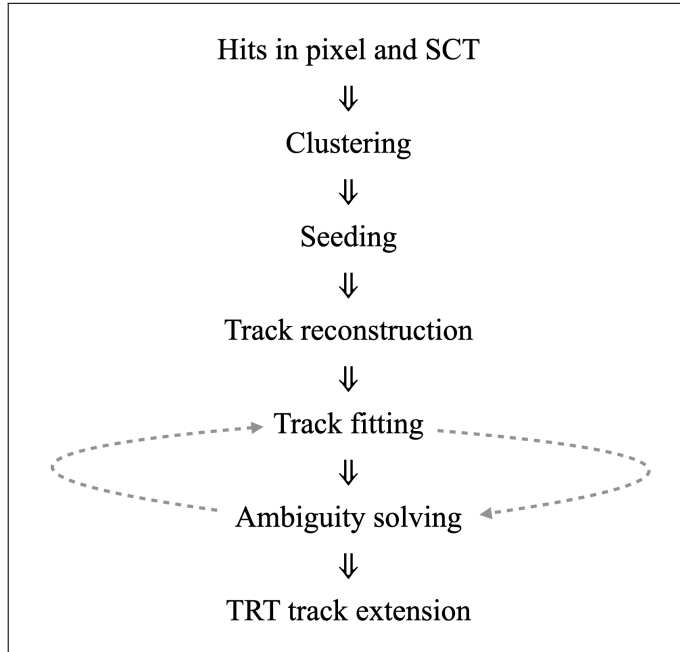


Figure 5.2: *Seven step track reconstruction in ATLAS.*

of tracking, hits from the pixel detectors and the SCT are grouped into *ID-clusters*, while hits from the TRT are ignored for the moment. Seeding is the step in which a set of three ID-clusters are grouped together to form a track seed. A set of three is chosen to maximise the number of possible combinations, i.e. to make sure to get all possible tracks and a first raw estimation of the particles momentum and impact parameters.

The seeds are extended to candidate tracks by using a Kalman filter [111]. The filter builds tracks out of the seeds by using the prediction of the track continuation and the measured hits that remain in the ID. This can create multiple track candidates per seed.

Some of the candidate tracks are random combinations of ID-clusters, and some overlap with other candidate tracks. This ambiguity is resolved in the next step. Candidate tracks are fit and rejected if they do not fulfil all of the following basic quality requirements: $p_T > 400$ MeV, $|\eta| < 2.5$, at least 7 ID-clusters in pixel and SCT, not more than one hole in pixel, maximally two holes in pixel and SCT together, $|d_0| < 2.0$ mm, and $|z_0 \sin \theta| < 3.0$ mm. Where a hole is a place where a hit would have been expected given the track's direction but none was found. For the remaining tracks, a score is assigned based on their properties. The score of a track is based on the number of ID-clusters, number of holes, the fit quality of the track-fit and the logarithm of the momentum of the trajectory. The latter is important to suppress randomly combined tracks, which usually have a low p_T . The track with the best score keeps the ID-clusters, which are removed from any other track candidates. Then the process is repeated until no candidate tracks remain, i.e. all are an accepted track or rejected.

After solving all ambiguities and having a final list of silicon tracks, the TRT hits are added. This is done only in the end, since the TRT has no z coordinate determination. The process is similar to adding additional hits to the seeds: silicon tracks are extended without being modified, and any new ambiguity is solved [109, 112, 113].

5.1.2 Primary vertex

To define particles' properties like impact parameters, the position of the proton-proton collision needs to be known. A primary vertex (PV) is defined as the point in space where a proton-proton collision happened. In a bunch-crossing several protons collide, thus every event has several PVs. Primary vertices are built from the set of reconstructed tracks. The first PV candidate is seeded from the beamspot position in the transverse plane. To this seed, additional tracks are associated. Finally, a fit is performed to obtain the most correct position of the PV and remove any tracks that are incompatible with this fit. The removed tracks are used to build other PVs. This process is repeated until all PVs are built. A PV is defined as having at least two associated tracks. The PV with the largest sum of the squared transverse momenta of the associated tracks is declared to be the hard interaction PV. The motivation for this selection is that PV originating from pileup usually have tracks with lower p_T . Events in physics analyses are required to have at least one PV with at least two tracks with transverse momenta above 500 MeV [114].

5.1.3 Calorimeter clusters

A particle interacting with the ATLAS calorimeter deposits energy in several cells. Thus, these cells need to be grouped to obtain the full energy deposit of the particle. The algorithm used for this purpose in ATLAS is called the *topological clustering algorithm*. It is not designed to separate the energy deposits of different particles. The algorithm for *topo-cluster* reconstruction is based on the following procedure. For every cell a signal-to-noise ratio is defined as $\zeta_{\text{cell}} = E_{\text{cell}} / \sigma_{\text{cell}}^{\text{noise}}$. Cells with $\zeta_{\text{cell}} > 4$ are used as seeds for topo-clusters. Then the topo-cluster is expanded in two steps: first, neighbouring cells with $\zeta_{\text{cell}} > 2$ are added, and then to this group of cells, all neighbouring cells without any energy deposit conditions are added. This is often referred to as a 4-2-0 clustering scheme. The last step in topo-cluster creation is to split the topo-clusters with several local maxima into several topo-clusters. This is particularly important for analysing the jet substructure, which is relevant for heavy particles' identification, as well as, distinguishing jets of different flavours. Topo-clusters can lie in both ECAL and HCAL since both sets of cells are used together in the algorithm [115].

5.2 Electrons and photons

Electrons are reconstructed using ECAL topo-clusters and ID tracks. ECAL topo-clusters are topo-clusters with more than 50% of energy deposit in the ECAL calorimeter. To each ECAL topo-cluster, one or several ID tracks are matched using criteria including the angular separation between the two and the number of ID-clusters each track has. Since electrons radiate photons in the ID, which can then convert to an electron-positron pair that is also detected by the ID, several tracks are permitted to match to the same topo-cluster. When paired with related tracks, a topo-cluster creates a supercluster. The electron is defined by this supercluster. The HCAL topo-clusters are used to suppress hadrons. This is because electrons do not have HCAL topo-clusters. To each matched track, a score is assigned based on the angular separation to the topo-cluster, the number of ID-clusters and the type of ID-clusters. The track with the best score is the one defining the electrons' properties [116, 117].

Photons are reconstructed in a similar way as electrons, with the difference that around half of them do not leave a track in the ID. Several algorithms exist to reconstruct these conversion photons by using tracks in the ID.

For the analysis presented in this thesis, reconstructed electrons need to pass a kinematic selection with $p_T > 27$ GeV and $|\eta| < 2.47$. Furthermore, the transition region between the barrel and the endcap electromagnetic calorimeter is excluded ($1.37 < |\eta| < 1.52$), and electrons are required to pass the following impact parameter selection: $|z_0 \sin(\theta)| < 0.5$ mm and $|d_0/\sigma(d_0)| < 5$.

To distinguish electrons from noise or pions, a likelihood discriminant is used. This discriminant is based on the ID tracks and the ECAL topo-cluster information and properties. In this thesis, a cut on the discriminant is used, referred to as *tight* corresponding to an average identification efficiency of 80% while having a very good background rejection. Different cuts on the discriminant define different working points (WP). Looser identification WP exist with higher identification efficiency but lower background rejection. The choice of which identification to use depends on the analysis' needs [118].

When an electron originates from the hard interaction, it is referred to as *prompt*. While they are called *non-prompt* in all other cases, most of them originate from heavy-flavoured hadron decays and photon conversion. Due to their production mode, non-prompt electrons have more activity surrounding them than prompt ones. This property of being more isolated can be exploited to identify prompt electrons. The isolation criteria applied for electrons in this thesis are $p_T^{varcone30}/p_T < 0.4$ and $E_T^{cone20}/p_T < 0.15$. Where *cone20* refers to a cone with $\Delta R = 0.2$ around the electron without counting the electron's momentum or energy deposit, and *varcone30* refers to a cone with $\Delta R = \min(10 \text{ GeV}/p_T^{\text{electron}}, 0.3)$.

Dedicated SFs are applied for electron trigger, reconstruction, identification, and isolation efficiencies. Scale factors for electrons are mainly estimated using the tag-and-probe method in $Z \rightarrow ee$ events. $Z \rightarrow ee$ events are ideal for this, since they have a very clean signature, i.e. very

little background. As an example, for electron reconstruction efficiency, the tag-and-probe method is used to estimate the reconstruction efficiency both in data and in MC, and SFs can be estimated from their ratio.

The electron energy reconstructed in MC usually does not agree exactly with the one measured in data. A ratio of electron energy distribution between MC and data is estimated in $Z \rightarrow ee$ events, and their ratio is used to estimate the energy scale calibration and the energy resolution calibration for electrons [116–118].

5.3 Muons

Muons have the property of passing through the ATLAS detector without being absorbed. This is mostly due to the fact that they are leptons and have a high mass compared to electrons, resulting in a negligible Bremsstrahlung production. Muon reconstruction mostly uses ID and/or MS tracks, with additional information from the calorimeters. The tracks in the ID and MS are reconstructed individually and then combined in a second stage. Depending on which sub-detectors are used for the muon reconstruction, six muon types can be distinguished [119]:

- **Combined (CB) muons:** using both ID and MS tracks, match a MS to an ID track and perform a combined fit;
- **Segment Tagged (ST) muons:** using ID tracks and at least one MS track segments;
- **Inside-Out combined (IO) muons:** using ID tracks and at least three MS hits;
- **Calorimeter Tagged (CT) muons:** using ID tracks matched with energy deposit in the calorimeter, usually used in the region not covered by the MS ($|\eta| < 0.1$);
- **Muon spectrometer Extrapolated (ME) muons:** using only the MS track and a loose requirement of the track originating from the IP, especially used outside the region covered by the ID ($2.5 < |\eta| < 2.7$);
- **Standalone track (SA) muons:** using only MS tracks.

In the analysis presented in this thesis, CB muons are used.

To identify high-quality muons to use in physics analyses, quality criteria are applied to the muon candidates. These include the number of ID-clusters, the number of hits-clusters in the MS, the track fit quality, and the difference between the extracted properties of the ID and MS tracks individually. Several ID WPs are defined to satisfy the needs of different analyses. The standard ID WPs are: *Loose*, *Medium* and *Tight*, the background rejection is increased from *Loose* to *Tight* but the muon reconstruction efficiency is decreased. In this analysis, muons are required to have $p_T > 27$ GeV, $|\eta| < 2.5$ and fulfil the *Medium* ID WP [119].

To suppress non-prompt muons originating from hadron decays, cosmic rays, and pileup, vertex association criteria are used. Meaning that the compatibility of the reconstructed muon

track originating from the hard interaction PV is checked. This is done by applying selection criteria to the impact parameters of the muon [119]. For this analysis, the following requirements are applied: $|z_0 \sin(\theta)| < 0.5$ mm and $|d_0/\sigma(d_0)| < 3$.

On top of the vertex association criteria, isolation criteria are used to reject non-prompt muons. The isolation selection is in particular used to reject muons originating from heavy-hadron decays. For this, two isolation variables are exploited: one track-based and one calorimeter-based. The track-based variable is defined using the total momentum of all tracks within a cone around the muon. The calorimeter-based variable is defined as the sum of all energy deposits within a cone of size $\Delta R = 0.2$ around the extrapolated muon track. Using these two variables, several isolation working points can be defined [119]. Muons used in the analysis presented in this thesis are required to pass the following isolation criteria: $p_T^{varcone30}/p_T < 0.4$ and $E_T^{cone20}/p_T < 0.15$. Where *cone20* and *varcon30* are defined as for the electron just referred to the muon instead.

5.4 Jets

MC truth jets have been introduced in Chapter 4. When adding the detector information a jet of particles is mainly formed in the beampipe, while some of the hadrons might still decay in the ID. The charged particles in the jet interact with the ID and all hadrons are stopped in the hadronic calorimeter. This results in having several tracks and energy deposits for each jet. A schematic illustration of a jet is shown in figure 5.3. The hard interaction represented here created a gluon and two quarks that form a PS and hadronise into mesons and baryons. Due to the very short time span of these processes, they occur well before the particles enter the ATLAS detector. The tracks of charged particles are detected by the ID and the energy of all particles by the calorimeters.

The goal is to be able to reconstruct the properties of the parton initiating the jet from the signals the jet left in the ID and the calorimeters.

Jet reconstruction in ATLAS happens in three steps:

1. **Building blocks:** ID tracks and topo-clusters are reconstructed separately from each other;
2. **Particle Flow algorithm** [120]: using both the ID and calorimeter information, this algorithm prepares inputs for anti- k_t algorithm;
3. **Anti- k_t algorithm** [99]: reconstructs the jets using the Particle Flow objects.

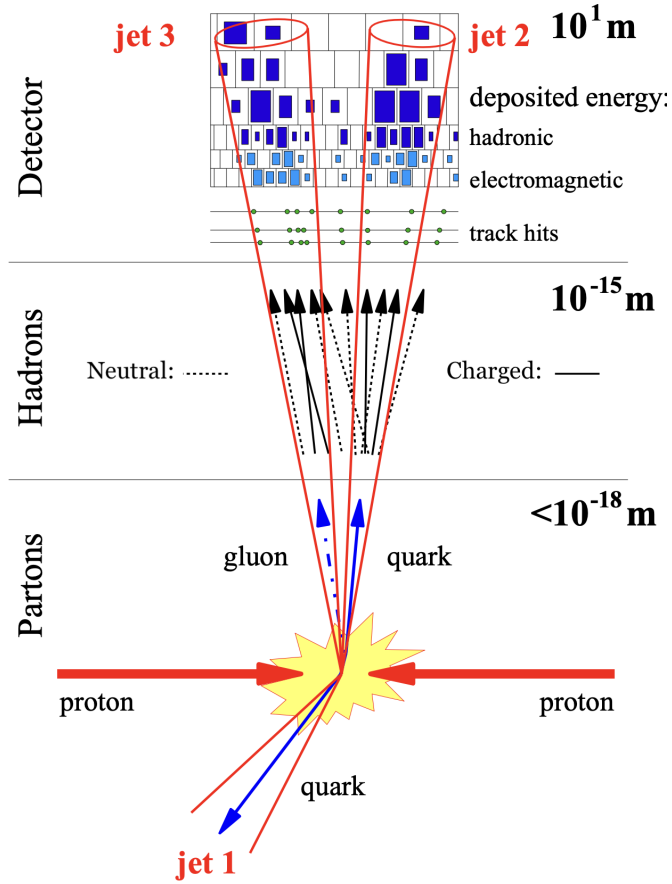


Figure 5.3: Illustration of jet production in ATLAS [13].

5.4.1 Particle Flow algorithm

With the better resolution of p_T of the tracks compared to calorimeter measurements, the particle flow algorithm aims to improve the jet reconstruction resolution, particularly in the low p_T region. The track resolution is able to distinguish tracks originating from other primary vertices, and in this way reduce pileup contamination in the jet reconstruction. The particle flow algorithm favours tracks over calorimeter measurements since the ID tracks have a higher resolution than the calorimeters. In order to prevent double counting, energy deposits in the calorimeter that match a good resolution track are removed. The algorithm procedure is explained in more detail in the following [120–122]:

- **Selection of good tracks:** good resolution tracks are defined as having at least nine hits in silicon detectors, no holes in the pixel detector and $p_T > 0.5$ GeV. Highly energetic particles can have a lot of activity around them in the calorimeters. Therefore, a precise

energy subtraction in these cases might not be possible. The subtraction is only done for tracks with p_T below 100 GeV or that have a low activity associated with them in the calorimeter [122];

- **Match ID tracks to topo-clusters:** matching of each track to a single topo-cluster;
- **Estimate energy deposit of track particle:** estimation of expected energy deposit of the particle based on its track and matched topo-cluster position;
- **Probability of more than one topo-cluster:** calculate the probability that the particle deposited its energy in more than one topo-cluster;
- **Decide if to add more topo-clusters to the track:** decide based on the previous step if the particle deposited energy in more than one topo-cluster and match more topo-clusters if that is the case;
- **Energy subtraction from topo-clusters:** subtract the energy deposit of the track particle from the topo-cluster(s) cell-by-cell;

The last step is important to avoid double counting of the same particle in the anti- k_t algorithm. The output of the particle flow algorithm is a list of tracks, modified topo-clusters from the energy subtraction method, and unmodified topo-clusters if they do not have an associated track particle.

5.4.2 Jet Energy Scale and Resolution

In contrast to the interactions of electrons and photons in the electromagnetic calorimeter, in the hadronic calorimeter not all particles are detected. For example low-energy neutrons originating from nuclear interactions of hadrons might be too soft to be seen by the calorimeter, or some nuclear deexcitation might take too long to be detected. As a consequence, the reconstructed jet energy in the detector does not represent the real scale of the jet energy. The absolute scale of the energy of a jet cannot be obtained from the detector measurement alone. The energy scale calibration of a jet relies on MC simulation. The data needs to be corrected using MC simulation, and thus there is a dependency of the jet energy scale (JES) and resolution (JER) calibration on the MC generator used.

The energy calibration of jets is done as follows:

- **Pileup:** the contributions from pileup are removed using *area subtraction*. This is the method where pileup is assumed to be homogenous in the detector, and an empty region is used quantify pileup. This is then subtracted everywhere;
- **MC truth matching:** reconstruction level MC jets are matched to truth level MC jets to take into account detector effects;
- **Jet energy ratio:** the transverse momentum ratio between reconstruction and truth level is computed as $p_{T,MC}^{reco}/p_{T,MC}^{truth}$. This typically produces a Gaussian distribution;

- **JES:** from the shift of the mean of the Gaussian distribution the correction to the jet energy scale [122] is found;
- **JES correction:** the JES correction found is applied to data and MC;
- **In-situ calibration:** the JES calibration is corrected using data to take into account detector effects that are not simulated. This is done by using well-balanced events like $Z \rightarrow ll + \text{jet}$ or $Z \rightarrow \gamma + \text{jet}$. In these events, the momentum balance is exploited to correct the energy of jets in the reconstructed data, different events are used in different kinematic regions. Concretely an in-situ JES correction is estimated from requiring $\left(\frac{p_T^{\text{tag}}}{p_T^{\text{probe}}}\right)^{\text{MC}} / \left(\frac{p_T^{\text{tag}}}{p_T^{\text{probe}}}\right)^{\text{data}} = 1$, where *tag* is either the photon or the two leptons and the *probe* is the jet;
- **In-situ JES correction:** this in-situ JES correction is then applied to the data analysed;
- **JER:** from the width of the ratio distribution, the jet energy resolution [122] is found.

The JES and JER uncertainties include contributions from the uncertainty to remove pileup contributions from the jet, dependency of jet flavour since different flavour jets have different hadronic content, dependency on the MC generator used for the calibration and the reference objects used for the calibration. The difference in JER between MC and data in balanced events is included in the JER uncertainty. The uncertainties vary as a function of jet transverse momentum and pseudorapidity. At low momentum, the uncertainties are dominated by pileup and flavour uncertainties, while at high momenta, the uncertainties originate mainly from conservative extrapolation of the uncertainties at lower momenta since there is a lack of calibration data at high momentum. In this thesis, JES and JER uncertainties estimated in Run 2 are used with additional uncertainties estimated in MC simulation to take into account the differences between Run 2 and Run 3 data-taking conditions.

After the jets are reconstructed and calibrated, they are required to have $p_T > 30$ GeV and $|\eta| < 2.5$.

5.4.3 Jet Vertex Tagger

To reduce the amount of jets originating from pileup, the Jet Vertex Tagger (JVT) is used. This is necessary since some of the pileup jets can have a high enough energy to be confused with jets from the hard interaction. For this, the neural network based JVT (NNJVT) discriminant is used for jets with p_T below 60 GeV. This is a successor to the JVT [123]. It uses the jet four-momenta, associated tracks, and PVs to distinguish jets originating from pileup from those coming from the hard interaction studied.

5.4.4 Flavour tagging

After determining the kinematics of a jet it is interesting to find out the jet's flavour. This is done through flavour tagging; the following flavours are distinguished: b -quark, c -quark and light, including the other quarks and gluons. A b -jet is a jet originating from a b quark and containing a B hadron. Similarly, a c -jet originates from a c quark, and light-jet from a light quark or gluon [124]. In this analysis final state there are two b -quarks, thus it is interesting to identify the corresponding two b -jets in order to distinguish the signal from backgrounds.

b -tagging is the process of identifying jets originating from a b -quark. This is done by relying on the properties of the B hadron, especially its long lifetime, which creates a secondary vertex inside the jet. An illustration comparing the b -jet to the light-jet structure is shown schematically in figure 5.4. The orange dashed line represents the beamline. The impact parameter in the transverse plane d_0 and its z coordinate z_0 are displayed as well.

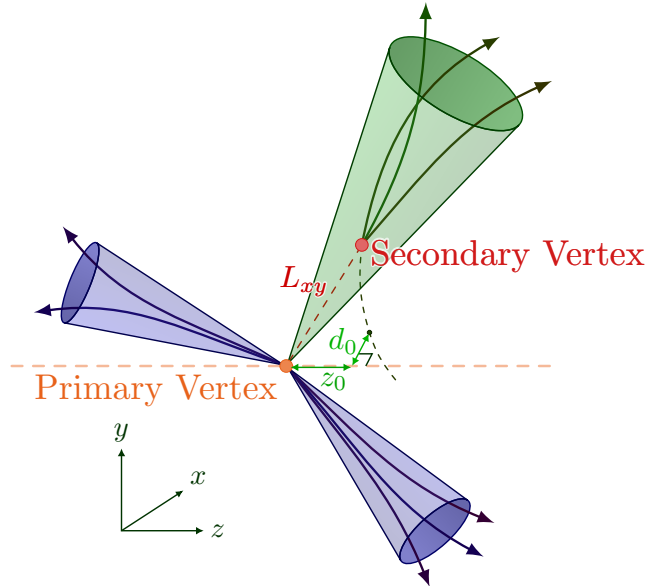


Figure 5.4: Illustration of production of two light-jets and one b -jet [125].

The b -tagging procedure used in early Run 3 data in ATLAS follows the following steps [126, 127]: first a jet is selected, then tracks are matched to it using their angular distance to the jet, afterward vertices inside the jet can be built, and finally these inputs are given to algorithms that build a discriminant to classify the jets. The algorithms can be divided into two categories: *low-* and *high-level algorithms*.

The low-level algorithms are designed to exploit the properties of the B hadron. Due to the CKM matrix it has a long lifetime (~ 1.5 ps), which gives origin to a secondary vertex inside the jet. The decay length is $O(\text{mm})$ [7]. This causes the jet to have large impact parameters

associated to some of its tracks as shown in figure 5.4. Also the decay chain of the B hadron can be used in its identification. b -jets have typically a higher multiplicity than c - or light-jets, i.e. more hadrons are created and thus more tracks are associated to the jet.

Three low-level algorithms are used:

- **JetFitter [128]:** exploits the structure of the $b \rightarrow c$ decay chain, it aims to reconstruct the full decay chain by reconstructing multiple decay vertices inside the jet. Its outputs include the number of tracks associated to the jet (*track multiplicity*), the sum of the invariant mass of these tracks, the energy fraction of the vertices in the jet, and the average significance of the decay length in 3D.
- **Secondary vertex (SV1) [129]:** this low-level algorithm extracts information about the presence and location of a secondary vertex in the jet. Its outputs include the invariant mass of the four-momentum sum of all vertex matched tracks, and the distance between PV and SV.
- **Deep Impact Parameter Sets (DIPS) [130]:** low-level algorithm based on Deep Sets neural network aiming to exploit tracks with large impact parameters. It associates to each track the probability of being part of a b -, c - or light-jet. It is also able to take into account the correlations between different tracks.

The DL1d is a high-level tagger, which combines the outputs from the low-level algorithms into probabilities of each jet being a b -, c - or light-jet, these probabilities are then combined into a single number discriminant to identify b -jets [131]. The DL1d is a deep feed-forward neural network that exploits all the information and correlations to improve background rejection. DL1d is the standard b -tagging algorithm in ATLAS for early Run 3 analyses. From the output probabilities, the DL1d discriminant is built as

$$D_{\text{DL1d}} = \ln \left(\frac{P_b}{f_c \cdot P_c + (1 - f_c) \cdot P_l} \right) \quad (5.1)$$

where f_c is the fraction of events containing c -jets in background samples used for training the neural network.

A summary of b -tagging in ATLAS is shown in figure 5.5. The low-level algorithms outputs are fed as inputs to the high-level DL1d tagger, that produces probabilities for a jet to be a b -, c - or light-jet. These three probabilities are combined to define the DL1d discriminant.

An illustration of the discriminant and the flavour probabilities is shown in figure 5.6. For high values of the discriminant, only b -jets are present, i.e. there are no misidentified c - or light-jets. However, beside high purity, it is also important to identify as many b -jets as possible, i.e. to have a high identification efficiency, especially for analysis with a small amount of data. Thus, the cut on the discriminant needs to be chosen such that there is a good b -jet efficiency and, at the same time, a good background rejection. This component is analysis dependent. Thus, different working points are defined. An example of such a cut is illustrated in figure 5.6.

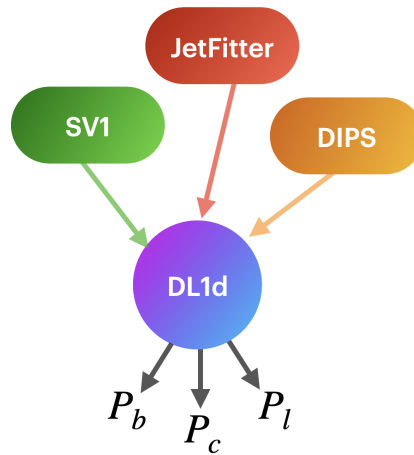


Figure 5.5: Illustration of b -tagging in ATLAS early Run 3 analyses.

The normalised probability distributions for b -, c - and light-jets are shown. The distributions do not represent the results of an existing b -tagging algorithm but are instead created from random numbers for illustration purposes. To each WP, a b -jet tagging efficiency, c -jet mistagging efficiency, and a light-jet mistagging efficiency is associated. For this analysis, the working point 77% is chosen: the associated average b -jet tagging efficiency is 77%, the c -jet mistagging efficiency is 16%, and the light-jet mistagging efficiency is 0.38%.

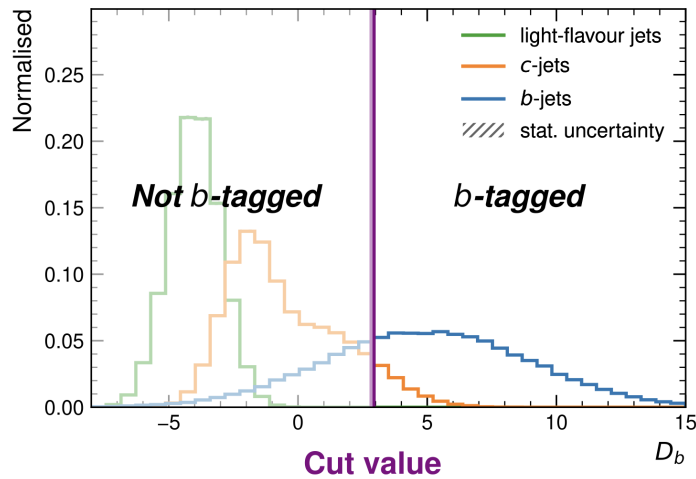


Figure 5.6: Illustration of the cut applied for the 70% WP [126].

5.5 Overlap removal

Electrons, photons, muons and jets are reconstructed independently of one another. As a result, it can happen that some of the objects share the same constituents. This may occur, for example, when the signal produced by a jet resembles an electron signal. The last step in particle reconstruction performs a process known as *overlap removal* in order to prevent this double counting. The following step-by-step procedure is used to solve the ambiguities for this analysis [132]:

1. **Electron $\subset$ muon reject:** reject all electrons that share tracks with muons;
2. **Electron $>$ jet:** the closest jet to an electron (within $\Delta R < 0.2$) is removed. This reduces the double counting of electron energy deposits as jets;
3. **Jet $>$ electron:** if an electron lies within $\Delta R < 0.4$ from a jet, the electron is removed. This reduces the impact of non-prompt leptons;
4. **Muon $>$ jet:** if a jet has less than three tracks associated to it and has a muon within $\Delta R < 0.4$, the jet is removed;
5. **Jet $>$ muon:** if a muon lies in $\Delta R < 0.4$ from a jet, the muon is removed.

These steps are applied in order as presented. The final reconstructed particles are used for the analysis done in this thesis.

6 Luminosity determination

In ATLAS, the luminosity determination in Run 3 follows the same procedure as in Run 2. A detailed description can be found in reference [133].

The method can be divided into three major parts:

- 1) **Absolute luminosity scale calibration**
- 2) **Calibration transfer**
- 3) **Stability of the luminosity determination**

The first part involves determining the absolute scale of luminosity in special beam conditions, the second part is to apply this calibration to the data-taking beam conditions, and the third part assesses the stability of the luminosity determination over time.

6.1 Luminosity measurement at ATLAS

At ATLAS there are several overlapping and complementary methods to measure luminosity. All the methods are based on measuring a quantity that is proportional to luminosity. Three methods can be distinguished: hit or event counting method, track counting method and calorimeter method. The different methods allow to cross-check the measured luminosity and measure it in all regimes. The methods used for the van der Meer scan calibration are the hit or event counting one. They will be explained in more detail in the following presenting the different luminometers used.

Hit or event counting method This method is based on the luminometers LUCID, and BCM and counts the amount of hits or events these register. It has a bunch-by-bunch resolution and works best in low μ regime. Thus, this method can be absolutely calibrated through vdM scans.

Track-counting Track-counting is based on silicon trackers, SCT and pixel detectors including IBL [56]. The measured quantity is the average number of tracks per bunch-crossing, averaged over a luminosity block (LB). Tracks are required to have a transverse momentum above 0.9 GeV, an impact parameter significance of $|d_0|/\sigma_{d_0} < 7$, be reconstructed in the barrel region ($|\eta| < 1.0$), have at least nine hits, and at most one missing pixel hit where there is expected to be one based on the track. The per bunch resolution of track-counting is statistically limited in van der Meer scans, meaning that track-counting has measurements only for some of the nominally filled bunch slots but not for all of them.

Calorimeters The calorimeter measurement is obtained from the endcap electromagnetic calorimeter, forward calorimeters and the scintillating-tile hadronic calorimeter [56]. The endcap and forward calorimeters measure luminosity through the gap currents in the liquid argon, while the scintillating-tile hadronic calorimeter uses the signal produced by the plastic scintillator. The produced photons are converted through photoelectric effect and read out with PMTs. The measured currents are proportional to the number of particles traversing the corresponding calorimeter and thus to the luminosity. Unfortunately, calorimeters can only provide bunch-integrated luminosity measurements, i.e. the sum over all the bunch slots.

6.2 Absolute luminosity scale calibration

6.2.1 What is luminosity?

As seen in Chapter 1, the instantaneous luminosity (L) is defined as the proportionality constant between the event rate (R) and the cross-section (σ) [133]. The total interaction rate (R) can be written as the average multiplicity of a process (μ), times the number of bunches (n_b) and the LHC revolution frequency (f_r)

$$L = \frac{\mu}{\sigma} n_b f_r. \quad (6.1)$$

The above equation is valid for any process. In the case of the LHC, protons are being collided, and the process considered is the inelastic proton-proton scattering

$$L = \frac{\mu_{\text{inel}}}{\sigma_{\text{inel}}} n_b f_r. \quad (6.2)$$

Luminosity detectors have a limited detection efficiency (ϵ). Thus, what they measure is the visible part of μ_{inel} and σ_{inel} , i.e. $\mu_{\text{vis}} = \epsilon \mu_{\text{inel}}$ and $\sigma_{\text{vis}} = \epsilon \sigma_{\text{inel}}$.

Luminosity can be expressed through these variables as

$$L = \frac{\mu_{\text{vis}}}{\sigma_{\text{vis}}} n_b f_r. \quad (6.3)$$

μ_{vis} can be calculated directly from the luminometer's measurement. The extraction of the absolute calibration constant of luminosity (σ_{vis}) requires a van der Meer analysis. Once it is found the luminosity at any point in time can be obtained simply by measuring μ_{vis} .

The van der Meer analysis was invented by Simon van der Meer in 1968 for the Intersecting Storage Rings (ISR) at CERN [134]. The ISR had continuous beams compared to the LHC bunched beams. The application of the van der Meer scan method remains valid also in case of bunched beams as proven by Carlo Rubbia in 1977 [135].

More precisely, with a van der Meer (vdM) analysis the visible cross-section is measured, through vdM scans. A vdM scan is a scan of the beams through each other, first in one plane (e.g. x plane), and then in the other (e.g. y plane), while staying head-on in the non-scanning plane. The goal is to measure μ_{vis} at different beam-beam separations. This can be viewed schematically in figure 6.1: the filled blobs represent an x scan and the empty ones a y scan. Van der Meer scans are done in special beam conditions: low number of average interactions per bunch-crossing (low- μ), isolated bunches, low-intensity bunches (i.e. low number of protons per bunch), and no crossing angle between the beams. These conditions are chosen such to have a low- μ to have a regime where the luminosity detectors do not saturate, the non-linearity effect and the beam-beam effects are small. Isolated bunches are chosen to avoid interactions with the other bunches in the train.

Between the luminosity measurement methods in ATLAS only LUCID and BCM can be calibrated in the low- μ regime. Track-counting has a small statistic at low- μ and it can thus not be used to be absolutely calibrated in the vdM scans. The calorimeter measurement has a low time resolution, only bunch-integrated measurement, and can thus not be absolutely calibrated through vdM scans. To account for the detector response change over time due to effects as for example detector aging, at least one vdM scan per year is performed. This is the reason why having done the absolute luminosity scale calibration once is not enough.

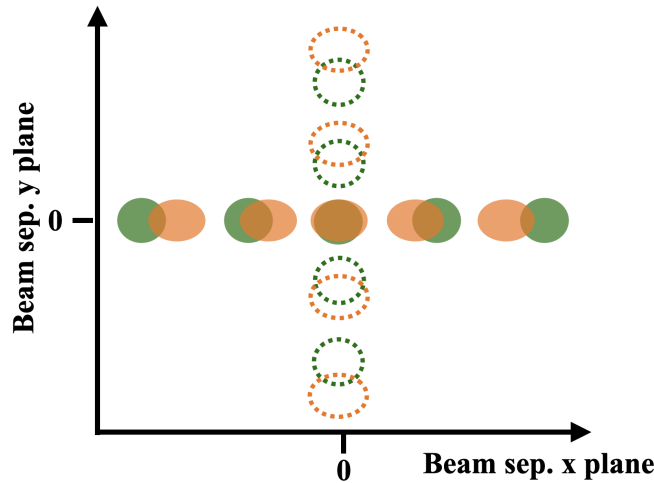


Figure 6.1: A schematic view of a van der Meer scan pair: the filled ellipses represent a x scan, and the empty dashed ellipses represent a y scan.

6.2.2 Luminosity from basics

Assume two colliding bunches (1 and 2) with a separation Δy in y plane as shown in figure 6.2.

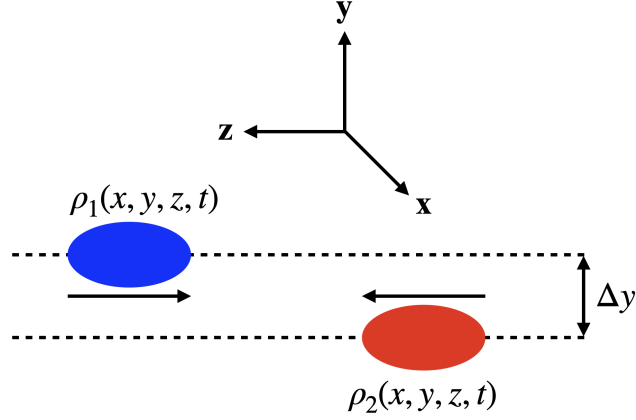


Figure 6.2: Schematic visualisation of two bunches colliding.

The luminosity can be obtained for two colliding bunches (1 and 2) and their normalised proton density ($\rho_1(x, y, z, t)$ and $\rho_2(x, y, z, t)$) as

$$L = K n_1 n_2 f_r \int \int \int \int_{-\infty}^{\infty} \rho_1(x, y, z, t) \rho_2(x, y, z, t) dx dy dz dt \quad (6.4)$$

where K is the kinematic factor, n_1 and n_2 the number of protons in beam 1 and beam 2, respectively, f_r the revolution frequency, and $\rho_i(x, y, z, t)$ the normalised particle densities of the colliding bunch i .

The kinematic factor is given by

$$K = \sqrt{(\vec{v}_1 - \vec{v}_2)^2 - \frac{(\vec{v}_1 \times \vec{v}_2)^2}{c^2}}, \quad (6.5)$$

where $\vec{v}_i$ is the velocity of the colliding bunch i . By assuming head-on collisions at the speed of light, this can be simplified to $K = 2c$. By assuming furthermore, that the bunch densities can be factorised in x , y , and z plane

$$\rho(x, y, z, t) = \rho_x(x) \rho_y(y) \rho_z(z \pm ct), \quad (6.6)$$

one finds

$$L = n_1 n_2 f_r \int_{-\infty}^{\infty} \rho_{1x}(x) \rho_{2x}(x) dx \int_{-\infty}^{\infty} \rho_{1y}(y) \rho_{2y}(y) dy, \quad (6.7)$$

where the integral over z and t cancels with K .

6.2.3 Luminosity from beam parameters

Luminosity can be better understood when expressed in terms of beam parameters. To do so, the bunch densities are assumed to have a Gaussian distribution

$$\rho(k) = \frac{1}{\sqrt{2\pi}\sigma_k} \exp\left(-\frac{k^2}{2\sigma_k^2}\right) \text{ with } k = x, y, \quad (6.8)$$

where σ_k is the beam width in plane k . These Gaussian distributions can be inserted in equation 6.7 and by using the identity

$$\int_{-\infty}^{\infty} \exp(-(at^2 + bt + c)) dt = \sqrt{\frac{\pi}{a}} \exp\left(\frac{b^2 - ac}{a}\right), \quad (6.9)$$

equation

$$L = \frac{n_1 n_2 f_r}{2\pi \sqrt{\sigma_{1x}^2 + \sigma_{2x}^2} \sqrt{\sigma_{1y}^2 + \sigma_{2y}^2}} \quad (6.10)$$

can be found. If furthermore, equal beam widths are assumed for both bunches in both planes, i.e. $\sigma_{1x} = \sigma_{2x}$ and $\sigma_{1y} = \sigma_{2y}$, equation 6.10 can be simplified to

$$L = \frac{n_1 n_2 f_r}{4\pi \sigma_x \sigma_y}. \quad (6.11)$$

Most parameters of the last equation are known: f_r is known by construction, and $n_1 n_2$ can be found by specific detectors. But the beam widths σ_x and σ_y are not known and need to be measured.

6.2.3.1 Van der Meer scans formalism derivation

The visible cross-section as a function of the convolved beam widths can be derived from first principles. From equation 6.7, the luminosity for a single bunch-crossing (L_b) for a general beam-beam separation of Δx in x plane and of Δy in y plane can be written as

$$L_b(\Delta x, \Delta y) = n_1 n_2 \int_{-\infty}^{\infty} \rho_{1x}(x) \rho_{2x}(x + \Delta x) dx \int_{-\infty}^{\infty} \rho_{1y}(y) \rho_{2y}(y + \Delta y) dy. \quad (6.12)$$

The idea of a van der Meer scan is to find luminosity through the measurement of the multiplicity for different beam-beam separations. To achieve that, scans in a plane (x or y) are performed while having zero nominal separation in the other plane.

The luminosity for zero nominal separation in y plane and a beam-beam separation of Δx in x plane is

$$L_b(\Delta x, 0) = n_1 n_2 \int_{-\infty}^{\infty} \rho_{1x}(x) \rho_{2x}(x + \Delta x) dx \int_{-\infty}^{\infty} \rho_{1y}(y) \rho_{2y}(y) dy. \quad (6.13)$$

The corresponding multiplicity can be expressed using the visible cross-section as

$$\mu(\Delta x, 0) = \sigma_{\text{vis}} L_b(\Delta x, 0) = \sigma_{\text{vis}} C_y \int_{-\infty}^{\infty} \rho_{1x}(x) \rho_{2x}(x + \Delta x) dx, \quad (6.14)$$

where C_y is a constant with respect to Δx variations.

When integrating equation 6.14 on both sides over Δx and taking into account that the beam densities are normalised ($\int_{-\infty}^{\infty} \rho(x) dx = 1$), the following equation can be obtained

$$\int_{-\infty}^{\infty} \mu(\Delta x, 0) d(\Delta x) = \sigma_{\text{vis}} C_y. \quad (6.15)$$

When inserting this result into equation 6.14, and dividing both sides by the left-hand side of equation 6.15

$$\frac{\mu(\Delta x, 0)}{\int_{-\infty}^{\infty} \mu(\Delta x', 0) d(\Delta x')} = \int_{-\infty}^{\infty} \rho_{1x}(x) \rho_{2x}(x + \Delta x) dx \quad (6.16)$$

is obtained. An equivalent derivation can be done for the case of having zero nominal separation in x plane and Δy in y plane.

By substituting equation 6.16 and its corresponding equation for the y plane into equation 6.12, luminosity at a general beam-beam separation of Δx in x plane and of Δy in y plane can be written as

$$L_b(\Delta x, \Delta y) = n_1 n_2 \frac{\mu(\Delta x, 0)}{\int_{-\infty}^{\infty} \mu(\Delta x', 0) d(\Delta x')} \frac{\mu(0, \Delta y)}{\int_{-\infty}^{\infty} \mu(0, \Delta y') d(\Delta y')}. \quad (6.17)$$

Consequently

$$L_b(0, 0) = n_1 n_2 \frac{\mu(0, 0)}{\int_{-\infty}^{\infty} \mu(\Delta x', 0) d(\Delta x')} \frac{\mu(0, 0)}{\int_{-\infty}^{\infty} \mu(0, \Delta y') d(\Delta y')}. \quad (6.18)$$

The measured head-on beam-beam separation might be different from the nominal zero separation. To take this into account, it will be assumed here that the head-on case for the x plane lies at Δx_0 and for the y plane at Δy_0 . This idea is shown schematically in figure 6.3.

The convolved beam sizes are defined as

$$\Sigma_x = \frac{1}{\sqrt{2\pi}} \frac{\int_{-\infty}^{\infty} \mu(\Delta x, 0) d(\Delta x)}{\mu(\Delta x_0, 0)} \quad \text{and} \quad \Sigma_y = \frac{1}{\sqrt{2\pi}} \frac{\int_{-\infty}^{\infty} \mu(0, \Delta y) d(\Delta y)}{\mu(0, \Delta y_0)}, \quad (6.19)$$

where $\mu(\Delta x_0, 0)$ and $\mu(0, \Delta y_0)$ are respectively the peak of the x and the y scans. Using the above defined convolved beam widths the luminosity at zero separation is given by

$$L_b(0, 0) = \frac{n_1 n_2}{2\pi \Sigma_x \Sigma_y} \frac{[\mu(0, 0)]^2}{\mu(\Delta x_0, 0) \mu(0, \Delta y_0)}. \quad (6.20)$$

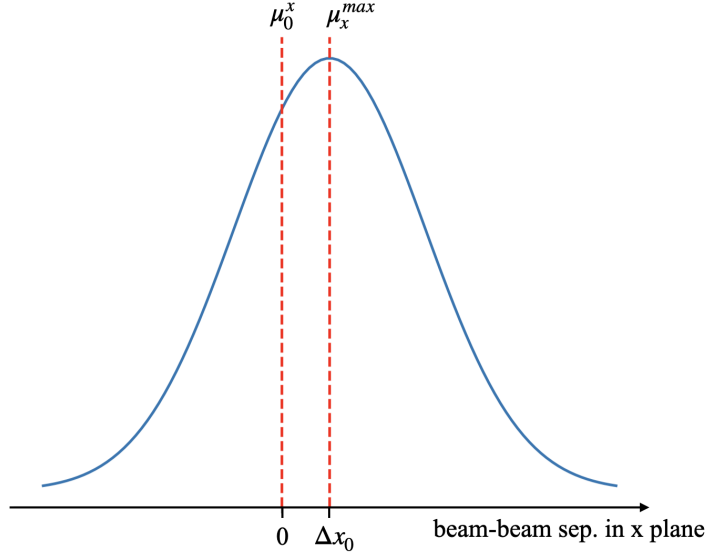


Figure 6.3: A schematic example of a scan curve with nomenclature used in the derivation for the x plane.

Thus, the luminosity calibration constant can be expressed as

$$\sigma_{\text{vis}} = \frac{\mu(0,0)}{L_b(0,0)} = \frac{2\pi\Sigma_x\Sigma_y}{n_1n_2} \frac{\mu(\Delta x_0,0)\mu(0,\Delta y_0)}{\mu(0,0)}. \quad (6.21)$$

This method remains valid in case of a crossing angle [136].

For the rest of the chapter the following nomenclature will be used

$$\begin{aligned} \mu_x^{\text{max}} &= \mu(\Delta x_0, 0), & \mu_x^0 &= \mu(0, 0) \text{ (obtained from x scan),} \\ \mu_y^{\text{max}} &= \mu(0, \Delta y_0), & \mu_y^0 &= \mu(0, 0) \text{ (obtained from y scan).} \end{aligned}$$

Following this the convolved beam widths and the visible cross-section can be written as

$$\Sigma_x = \frac{1}{\sqrt{2\pi}} \frac{\int_{-\infty}^{\infty} \mu(\Delta x, \Delta y_0) d(\Delta x)}{\mu(\Delta x_0, 0)} = \frac{1}{\sqrt{2\pi}} \frac{\int_{-\infty}^{\infty} \mu_x(\Delta x) d(\Delta x)}{\mu_x^{\text{max}}}, \quad (6.22)$$

$$\Sigma_y = \frac{1}{\sqrt{2\pi}} \frac{\int_{-\infty}^{\infty} \mu(\Delta x_0, \Delta y) d(\Delta y)}{\mu(0, \Delta y_0)} = \frac{1}{\sqrt{2\pi}} \frac{\int_{-\infty}^{\infty} \mu_y(\Delta y) d(\Delta y)}{\mu_y^{\text{max}}}, \quad (6.23)$$

$$\sigma_{\text{vis}} = \frac{2\pi\Sigma_x\Sigma_y}{n_1n_2} \frac{\mu(\Delta x_0, 0)\mu(0, \Delta y_0)}{\mu(0, 0)} = \frac{2\pi\Sigma_x\Sigma_y}{n_1n_2} \frac{\mu_x^{\text{max}}\mu_y^{\text{max}}}{(\mu_x^0 + \mu_y^0)/2}, \quad (6.24)$$

where μ_y^{max} and μ_x^{max} are the multiplicities at real zero separation (i.e. the peaks of the scan curves), and μ_y^0 and μ_x^0 are the multiplicities at nominal zero separation. $\mu(0,0)$ is the average between the x and y plane. Notice that the integral $\int_{-\infty}^{\infty} \mu_x(\Delta x) d(\Delta x)$ corresponds to integrating the scan curve of figure 6.3 over the x -axis.

6.2.4 Bunch population measurement

To find the visible cross-section, the precise determination of the number of protons in each bunch is important. Given that protons are charged particles, this is quantified through a current measurement called "bunch current".

To measure the bunch currents, three LHC detectors are used: the Fast Beam Current Transformer (FBCT), the Beam Pickup and Timing System (BPTX), and the Direct Current Current Transformer (DCCT) [58]. The first two measure the bunch-by-bunch fraction of the beam currents, i.e. what fraction of the total charge each bunch carries, as well as the total beam currents. The FBCT is used as the default detector and the BPTX for cross-checking it. Their total bunch current measurement is limited in precision, thus a third detector is needed to measure this quantity precisely. This is exactly the purpose of the DCCT. The bunch currents are obtained by normalizing the integrated current measured by FBCT to that measured by the DCCT. From the bunch currents can be obtained the bunch populations.

Ghost and satellite charges The RF buckets, 2.5 ns long, are shown in figure 6.4. Ten RF buckets form a slot. An RF bucket is called "filled" when there is a bunch in it, the corresponding slot is then also called "filled". Only every ten RF bucket is filled, i.e. one RF bucket per slot. Some protons can fall out of time for example due to electromagnetic repulsion from other protons. These protons might be in time for one of the next RF buckets. Satellite charges are protons that are captured in a nominally empty RF bucket in the same slot. Ghost charges are protons which are captured in an RF bucket in a nominally empty slot. They are called "nominally" empty because they are supposed to be empty in theory but might not be empty in practice.

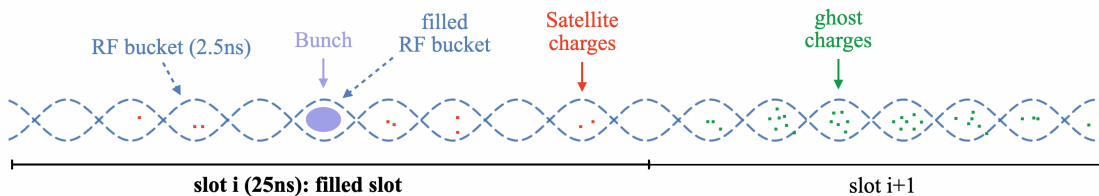


Figure 6.4: Visualisation of satellite and ghost charges in the LHC slots and RF buckets.

DCCT The DCCT measures the total beam currents and cannot resolve slots or bunches. Two DCCT detectors are located at each ring for redundancy. The precision that can be obtained by a DCCT measurement is at the level of $1\mu\text{A}$. Given its bunch-integrated measurement, it cannot distinguish nominally filled bunches, satellite and ghost charges. Therefore, the satellite and ghost charges need to be subtracted from the DCCT measurement [137].

FBCT and BPTX To ensure redundancy, two FBCT detectors are positioned along each of the LHC rings at Point 4, with an additional pair located at each beam dump line. The FBCT performs particularly well in the low beam intensities regime and has a time resolution of 25 ns, which allows it to differentiate between ghost charges and the nominally filled slot. In contrast, the BPTX, with its impressive time resolution of 90 ps, can distinguish satellite charges from the nominally filled bunch. Both the FBCT and BPTX cannot measure currents below a certain threshold, as a consequence although the time resolution is good enough BPTX might not measure the satellite charges if they are too small.

Since the BPTX has higher noise than the FBCT, the latter is chosen as the default tool to measure bunch-by-bunch fractions of the beam currents. The difference between FBCT and BPTX is taken into account by a corresponding systematic uncertainty.

6.2.5 Van der Meer scan program overview

An overview of the van der Meer scan program of November 2022 is shown in figure 6.5.

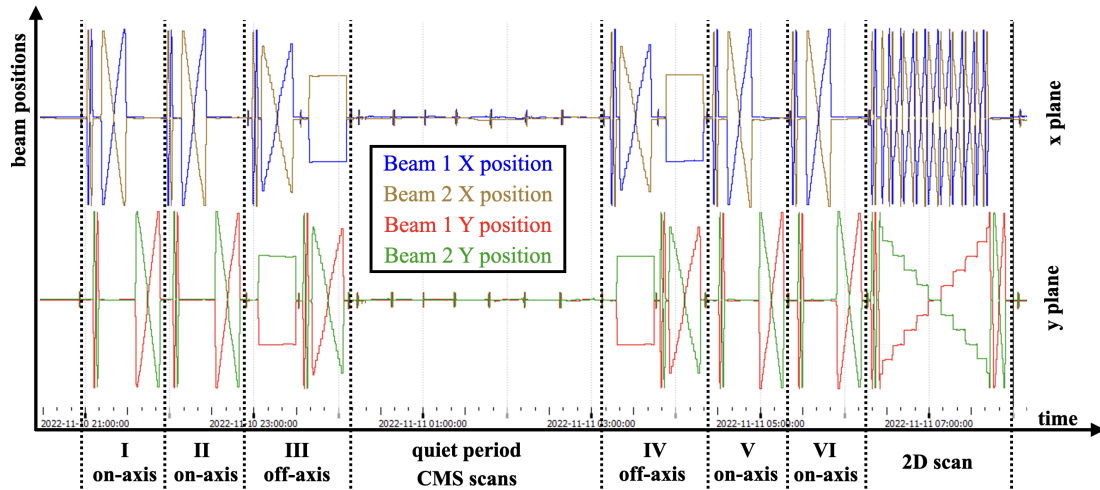


Figure 6.5: Overview of the van der Meer scan program of November 2022.

Starting on the left of the plot, first a mini-standardization scan is performed to centre the beams and make the scans more reproducible, followed by an x scan and then a y scan. This gives one on-axis scan pair. The vdM program in 2022 consisted of two on-axis scans followed by an off-axis scan, a quiet period, and then a second scan part composed of off-axis, two on-axis and a 2D scan. During the quiet period ATLAS takes head-on data and CMS performs vdM scans. The 2D scan is the first 2D van der Meer scan ever taken in ATLAS.

An on-axis scan is a scan where the beams in the non-scanning plane have zero separation, while they have some separation in the off-axis scans. An illustration of the difference between an on-axis and an off-axis scan is shown in figure 6.6.

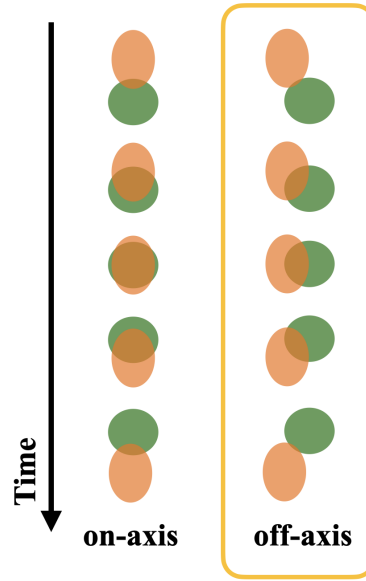


Figure 6.6: A schematic illustration of an on-axis scan on the left and an off-axis scan on the right.

In the fill used for the scans there are 146 isolated bunches, with 144 of them colliding in ATLAS and CMS, 35 in ALICE and 22 in LHCb [138]. There is no crossing angle, the average number of interactions per bunch-crossing is around one when the beams are head-on, the β^* is 19.2 m, and the beam energy is 6.8 TeV.

6.2.5.1 Luminosity algorithms for hit or event counting

The luminosity algorithms can be separated in two categories: the hit and the event counting algorithms. A hit is defined as a signal above a predefined threshold in a tube. A hit counting algorithm counts the number of hits in a tube or a group of tubes. The number of hits are summed over each LB [85]. An event counting algorithm counts the number of times there is at least 1 hit in a tube or a group of tubes during the corresponding bunch-crossing. The number of events is summed over each LB. The HitOR algorithms combine 8 LUCID tubes readouts (see appendix 8).

6.2.6 Default choices

The rate divided by the bunch population is fitted as a function of the separation using a Gaussian-like function to extract the convoluted beam widths and the peak values. Several different fit models can be used, in this analysis the default fit model is a Gaussian multiplied by a 6th-order polynomial (GP6). A typical scan curve is shown in figure 6.7, it can be seen that

at large beam-beam separation (tails) the interaction rate is low. This means that the dominant contribution to the visible cross-section comes from the central region of the curve. The default algorithm for this analysis is lucBi2HitOR (see appendix 8), and the bunch populations are measured by default by FBCT and the overall bunch-integrated scale is normalised to the DCCT measurement.

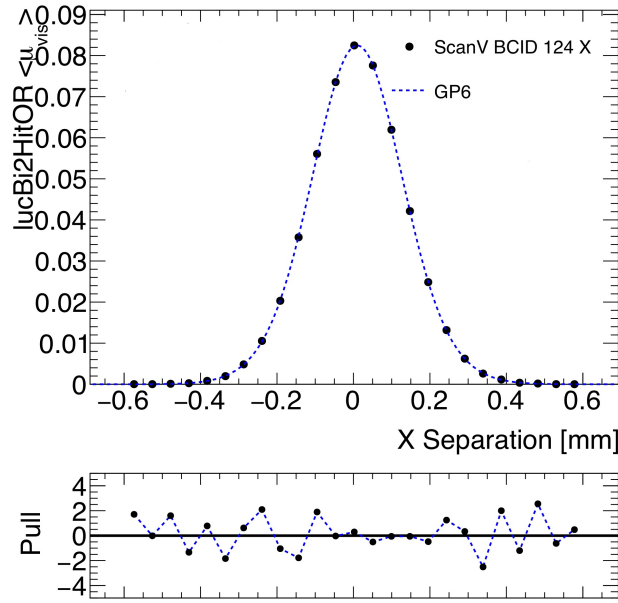


Figure 6.7: An example of a scan curve with a GP6 fit.

6.2.7 Corrections

To obtain a precise central value for the absolute luminosity calibration, several effects need to be taken into account. These effects are corrected for during the van der Meer scan analysis. Below is a list of the corrections considered:

- satellite and ghost charge corrections to DCCT,
- BPTX and FBCT bunch current offset correction,
- detector background correction (background subtraction),
- orbit drift correction (ODC),
- beam-beam corrections,
- emittance change correction,
- length scale calibration (LSC),

- non-factorisation correction.

Each correction will be explained in detail and its effect on the visible cross-section quantified. The order in which the corrections are applied will also be discussed.

6.2.7.1 Satellite and ghost charge corrections

The satellite and ghost charges are measured through synchrotron radiation by the longitudinal density monitor (LDM) [139]. The ratio of the number of ghost and satellite charges with respect to the total beam current is shown in figure 6.8.

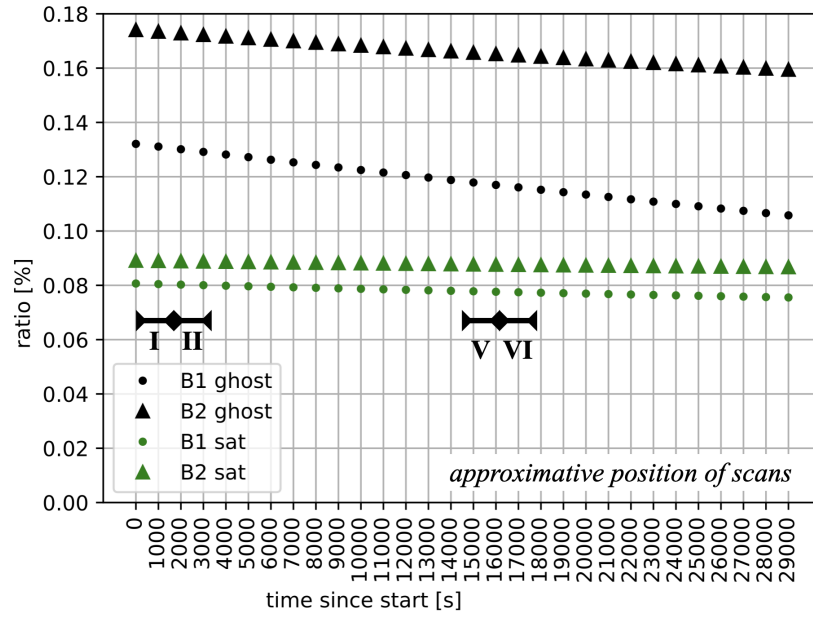


Figure 6.8: Ghost and satellite charge ratios to the total beam currents over time.

A 2nd-order polynomial fit to the LDM-measured ratios is performed to obtain a ghost and satellite charge value at any given point in time. The correction is applied by subtracting both charges from the DCCT measurement at every LB.

The ghost charges are usually measured with the LHCb SMOG system. This system was unfortunately not fully working during the scan period in 2022. However, the LDM are compared to the SMOG measurement in the time after the scans are taken, and they agree well.

6.2.7.2 Bunch currents offsets

The visible cross-section is a physical constant. It is thus not expected to depend on the bunch currents. In reality, however, a dependency between the measured cross-section and the measured bunch population is observed, as shown in figure 6.9. The origin of this phenomenon is not well understood [137]. The dependency is non-physical and needs to be corrected. The correction is obtained by assuming that the dependency of σ_{vis} on $n_1 n_2$ is a straight line with an offset.

The corrected values are obtained by minimizing

$$\chi^2(\overline{\sigma}_{\text{vis}}, b_1, b_2) = \sum_{i \in \text{BCIDs}} \left(\frac{\overline{\sigma}_{\text{vis}} S(b_1, n_1^i) S(b_2, n_2^i) - \sigma_{\text{vis}}^{\text{no offs}, i}}{\Delta \sigma_{\text{vis}}^{\text{no offs}, i}} \right)^2, \quad (6.25)$$

$$\text{with } S(b_k, n_k^i) = \frac{n_k^i + b_k \cdot (n_k^i - \overline{n}_k)}{n_k^i},$$

where $\sigma_{\text{vis}}^{\text{no offs}, i}$ is the visible cross-section without bunch current offset correction, $\Delta \sigma_{\text{vis}}^{\text{no offs}, i}$ is the statistical uncertainty on it, and S is the variation due to the bunch population n_k with $k \in \{1, 2\}$. S does correct the fitted average $\overline{\sigma}_{\text{vis}}$ by the bunch populations n_1^i and n_2^i modified by the offsets, where $\overline{n}_1$ and $\overline{n}_2$ stand for the average bunch population [133].

The visible cross-sections for all BCIDs in each scan with and without bunch current offset correction for bunch current measurements using FBCT, are shown in figure 6.9. The dependency of σ_{vis} on $n_1 n_2$ is reduced after the correction, this can be seen through the reduction of the fitted slope.

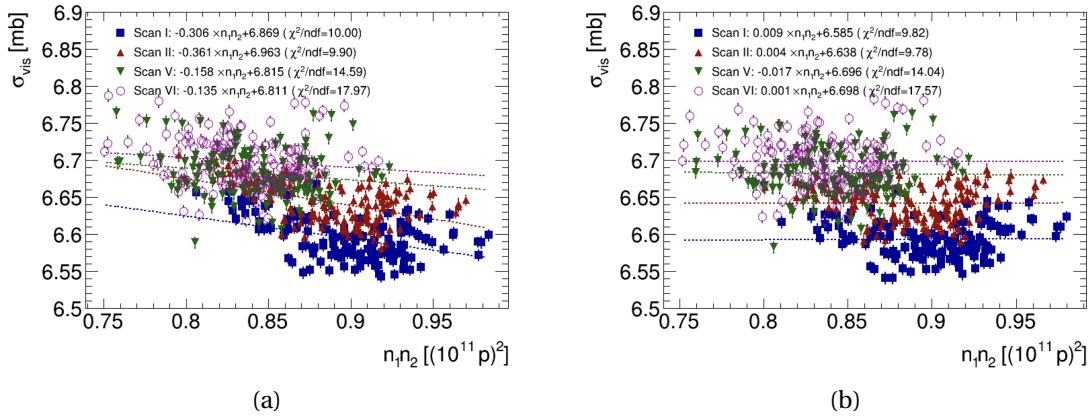


Figure 6.9: σ_{vis} for each BCID and scan as a function of the bunch populations obtained from FBCT: before (a) and after (b) bunch current offset correction.

6.2.7.3 Background correction

In the LUCID detector measurement the following backgrounds are present: instrumental noise, beam gas interactions, and afterglow.

The instrumental noise is dominated by signals from the radioactive decays of the Bismuth calibration source. The beam gas interactions are mainly protons interacting with the residual gas molecules in the beampipe, and afterglow are random hits from induced activity in the detectors.

The afterglow and instrumental noise are estimated from the empty bunches just before the colliding bunch. The beam gas interaction background is estimated from the non-colliding bunches, i.e. the filled unpaired bunches. The beam gas background is corrected for the instrumental noise and afterglow. All these backgrounds (BGs) are several orders of magnitude smaller than the signal in the peak region as can be seen in figure 6.10.

To take these backgrounds into account in the analysis, the background subtraction method is used. It consists of estimating and subtracting the backgrounds using the non-colliding or empty bunches from the signal for each bunch and LB.

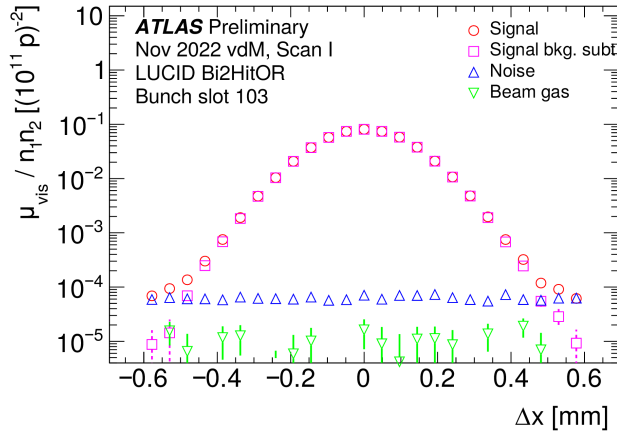


Figure 6.10: The visible rate is divided by the bunch population and shown as a function of the beam-beam separation in the x plane [140].

6.2.7.4 Orbit drift correction (ODC)

The effects of beams moving when they should be still is called "orbit drift" (OD). This has multiple origins, including Earth tides, quadrupole magnet movements due to temperature variations, and slight movements of the ground.

The orbit drift can be measured with beam position monitors (BPMs). At LHC, there are two different types of BPMs: DOROS BPMs and arcBPMs. DOROS BPMs are detectors in the closed orbit bump, i.e. close to the IP, and they are sensitive to the beam-beam separation during a scan, while the arcBPMs are further away from the IP in the arcs and are interpolated to the IP,

i.e. they are not sensitive to the movement of the beams during the scan.

The standard procedure within the ATLAS vdM calibration is to estimate the orbit drift and its corresponding correction by fitting the measurement of the BPMs in the LBs just outside the scans with a linear function and extracting the slope from it [133]. The points inside the scan are not used since they are strongly impacted by other effects, e.g. beam-beam deflection and magnetic non-linearities. The maximum amount of points possible is used for the fit in every scan, this number varies from scan to scan. Unfortunately, often only a few points can be considered for DOROS BPMs because of mini-standardisation scans that would bias the result. Furthermore, only a small amount of points is available in the region between the x and y scans.

The arcBPMs have more noise than the DOROS BPMs, thus their orbit drift is estimated with an additional step. First a second-order polynomial to four points before, one in the middle and four points after the scan is fit. From this fit the points at the border of the scan are extracted. To these a linear fit is performed. DOROS BPMs measurements are anchored to arcBPMs measurements in the first point to better compare them, this can be done without problems since only relative values are important for this correction.

The method described above with the linear fits for arcBPMs and DOROS BPMs is shown in figure 6.11.

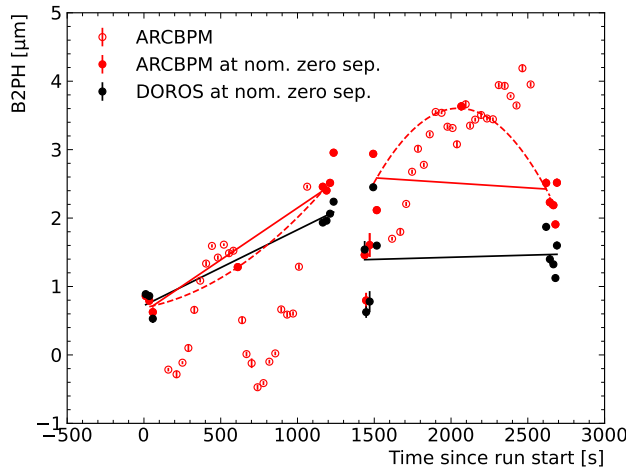


Figure 6.11: The beam position of beam 2 in the horizontal plane is shown as a function of time in seconds.

The orbit drift correction depends on the difference of the slopes between the two beams in x and y plane. The BPMs are in good agreement when they have the same slope.

The ODC can be separated into in-plane and off-plane ODC. The in-plane ODC calculates the real separation with orbit drift correction as: $(real\ separation) = (nominal\ separation) + (drift\ of\ beam\ orbit)$, where the nominal separation is the set or expected separation, and the drift of

the beam orbit is the orbit drift (OD). This can be expressed mathematically as

$$\begin{aligned}\delta x_{\text{corr}}(t) &= \delta x(t) + d_{1x}(t) - d_{2x}(t), \\ \delta y_{\text{corr}}(t) &= \delta y(t) + d_{1y}(t) - d_{2y}(t),\end{aligned}\tag{6.26}$$

where δx_{corr} is the real (corrected) separation in x plane, δx is the nominal (uncorrected) separation in x plane, $d_{1x}(t)$ is the drift of beam 1 and $d_{2x}(t)$ the drift of beam 2 in x plane, analogous for the y plane [133].

The off-plane orbit drifts are evaluated by comparing the orbit drifts at the peak of the x and y scans of the same vdM scan pair. The visible cross-section can be written as

$$\sigma_{\text{vis}} = 2\pi \Sigma_x \Sigma_y \frac{G_x(\Delta x_0) G_y(\Delta y_0)}{(G_x(\Delta H) + G_y(\Delta V))/2},\tag{6.27}$$

where G_i is the function fitting the curve in i -plane, Δi_0 is the offset in plane i , ΔV , ΔH the vertical and horizontal drifts between x and y scans [133].

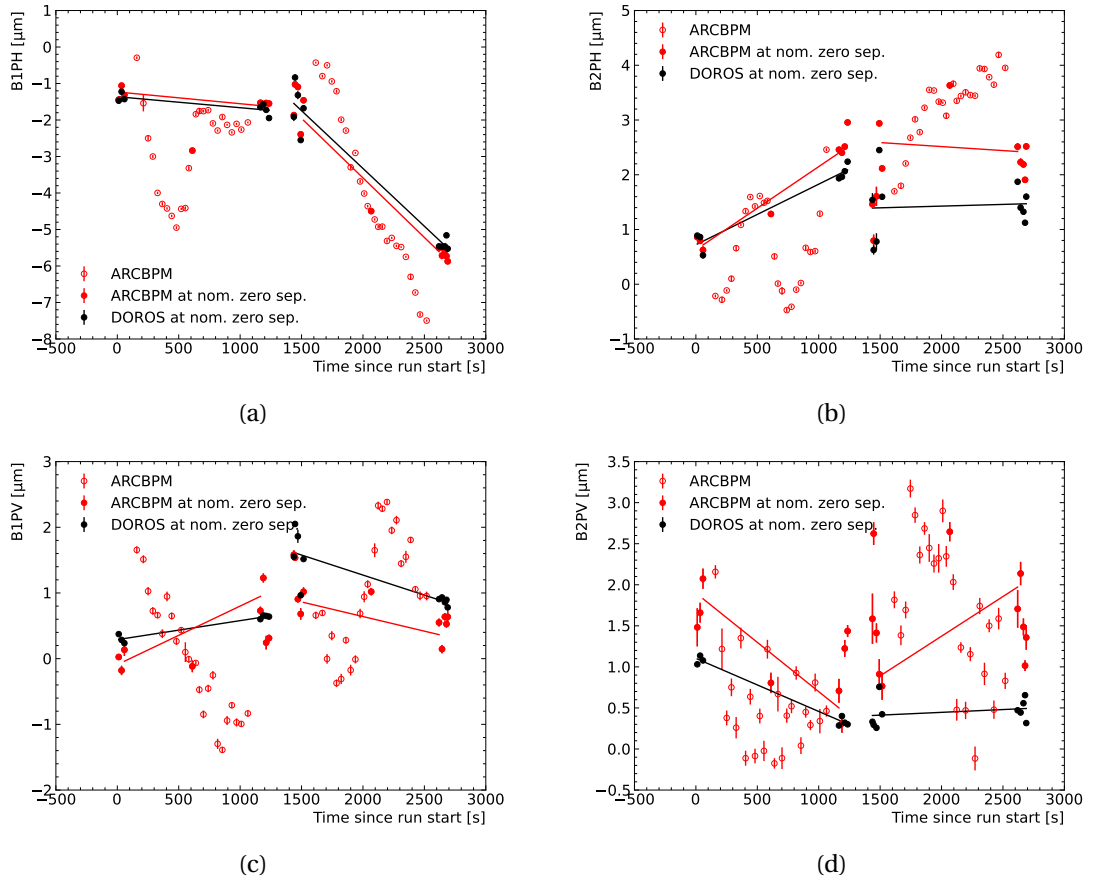


Figure 6.12: BPM positions for Scan I: (a) beam 1 in the horizontal plane, (b) beam 2 in the horizontal plane, (c) beam 1 in the vertical plane, and (d) beam 2 in the vertical plane.

The ODC is calculated for each scan separately. As an example, plots for Scan I are shown in figure 6.12. These plots are representative of all four scans. The orbit drift correction appears random because several different effects contribute to it in a complicated way.

The DOROS measurements seem to be more consistent between the single points than the arcBPMs measurements. Thus, in the 2022 van der Meer scan analysis, DOROS BPMs are used as the default BPMs, while arcBPMs are used for cross-checking DOROS BPMs. The difference between the two types of BPMs is used to estimate the systematic uncertainty of the correction.

6.2.7.5 Beam-beam corrections

The beams interact electromagnetically with each other, since both are charged, this causes beam-beam effects. These can be classified into two categories: beam-beam deflection and optical distortion. A schematic view of these effects is shown in figure 6.13. The first one is the mutual deflection of the two beams, since both beams are positively charged, and the second one is the mutual (de-)focusing of the beams when they pass through each other, similar to a quadrupole magnet effect. As the vdM methodology assumes beams whose widths do not change with varied separations, the corrections adjust the beams to beams without beam-beam effects.

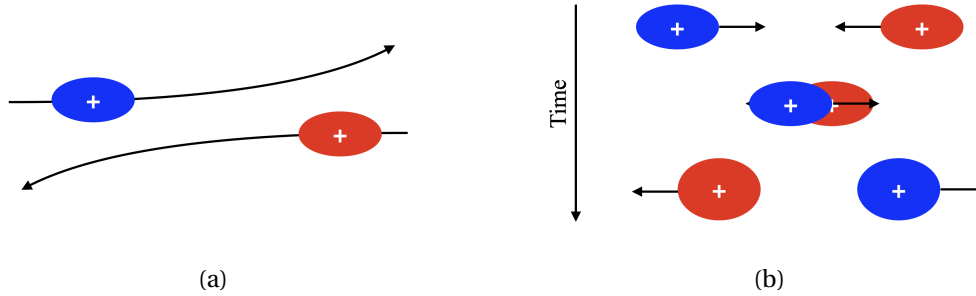


Figure 6.13: A schematic representation of beam-beam effects. (a) the beam-beam deflection can be seen, and (b) the optical distortion is shown.

The beam-beam deflection correction is based on analytical calculation of the effect (Bassetti-Erskine formula [141]), which is cross-checked with simulation. It corrects the separation of the beams at every scan step. The optical distortion correction is based on a simulation (B*B [142]+COMBI [143]) and it is a factor correcting the interaction rate at every scan step [144]. Both corrections are applied bunch-by-bunch.

Both effects rely strongly on the beam parameters, which can be absorbed in the round-beam parameter ξ :

$$\xi = \frac{r_p N \beta^*}{4\pi\gamma\sigma^2}, \quad (6.28)$$

where N is the bunch population average $N = (n_1 + n_2)/2$, $\gamma = E/m_p$, $\sigma^2 = \frac{1}{2}\Sigma_x\Sigma_y$, and $r_p = 1.534695 \cdot 10^{-18}$ m is the classical proton radius. In ξ only one β^* is present because round beams are assumed, i.e. $\beta_x^* = \beta_y^*$.

The beam-beam deflection and the optical distortion corrections are both affected by the tune shift. A tune shift can be due to collisions in other IPs. It can be quantified by the formula

$$\Delta Q = (-0.50 \pm 0.02)n_{\text{IPs}}\xi, \quad (6.29)$$

found though simulation (COMBI [143]), where n_{IPs} is the fractional number of non-scanning IPs having collisions. Non-scanning IPs are IPs where the bunches are colliding but they are not performing a vdM scan. For example, while ATLAS does vdM scans, by symmetry CMS has non-scanning collisions, thus 0.5 for beam 1 is added to 0.5 for beam 2, giving $n_{\text{IPs}} = 1$. In addition, it is also possible that one or both beams collide in LHCb or ALICE.

The input values used for the beam-beam corrections are reported in table 6.1, where Q_x and Q_y are the tunes in x and y planes respectively.

Energy	Q_x	Q_y	β^*	n_{IPs}	Σs	$n_1 n_2$
6.8 TeV	0.31	0.32	19.2 m		bunch-by-bunch values	

Table 6.1: *Input values used in the beam-beam correction calculations.*

An example of the beam-beam deflection correction is shown in figure 6.14 as a function of the beam-beam separation. The beam-beam deflection correction is symmetrical and has no effect at zero separation.

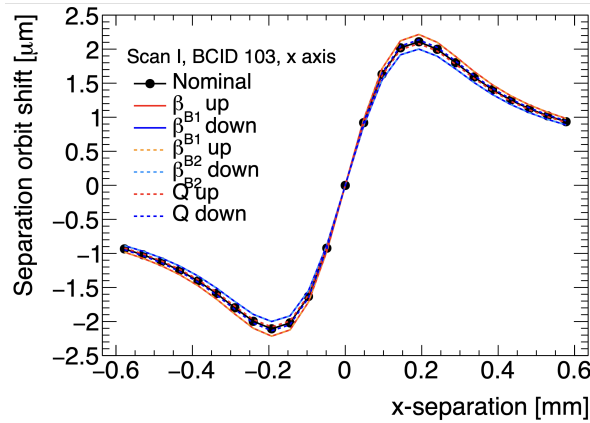


Figure 6.14: *Beam-beam deflection correction as a function of beam-beam separation in x plane for scan I, BCID 103.*

The optical distortion correction is shown in figure 6.15. It is applied as a multiplicative scaling factor to the interaction rate, the correction is the smallest for zero separation, but it is not exactly one.

The beam-beam deflection correction is applied first, and then the optical distortion correction on top of it. The beam-beam deflection correction does change the beam-beam separation which changes the effect of the optical distortion on the visible cross-section. The order of these corrections has a negligible impact on the visible cross-section.

It has been checked for both corrections that their effect on the convolved beam widths and visible cross-section is as expected: the beam-beam deflection correction increases the beam widths and the visible cross-section, and the optical distortion correction does decrease both.

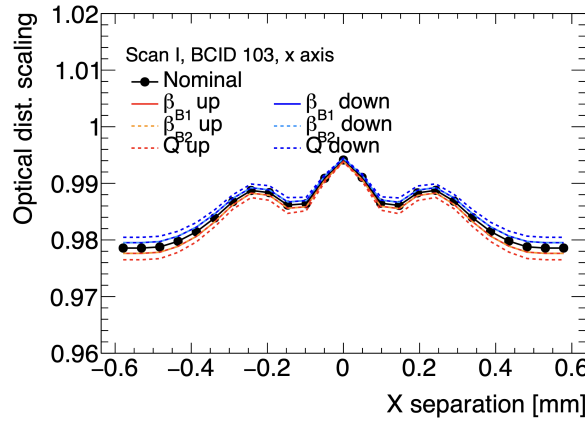


Figure 6.15: Optical distortion correction factor as a function of beam-beam separation in x plane for scan I, BCID 103.

6.2.7.6 Emittance change correction

The experimental visible cross-section is computed from the x and y scan as

$$\sigma_{\text{vis}}(\hat{t}_x, \hat{t}_y) = 2\pi \frac{\frac{\mu_x^{\text{max}}}{n_1 n_2}(\hat{t}_x) \frac{\mu_y^{\text{max}}}{n_1 n_2}(\hat{t}_y)}{\left(\frac{\mu_x^0}{n_1 n_2}(\hat{t}_x) + \frac{\mu_y^0}{n_1 n_2}(\hat{t}_y) \right) / 2} \Sigma_x(\hat{t}_x) \Sigma_y(\hat{t}_y), \quad (6.30)$$

where $\hat{t}_x$ and $\hat{t}_y$ are the times of the centre of the x and y scans respectively. The x and y scans are taken one after the other and thus at different times. The issue is that over that period the beam emittances did change. The beam sizes are proportional to the square root of the emittance in the given plane. Thus, the beam sizes grow with the emittance. The dependency of the convolved beam widths in both planes as a function of time is shown in figure 6.16. To find the correct visible cross-section, the scans must be extrapolated to the same time.

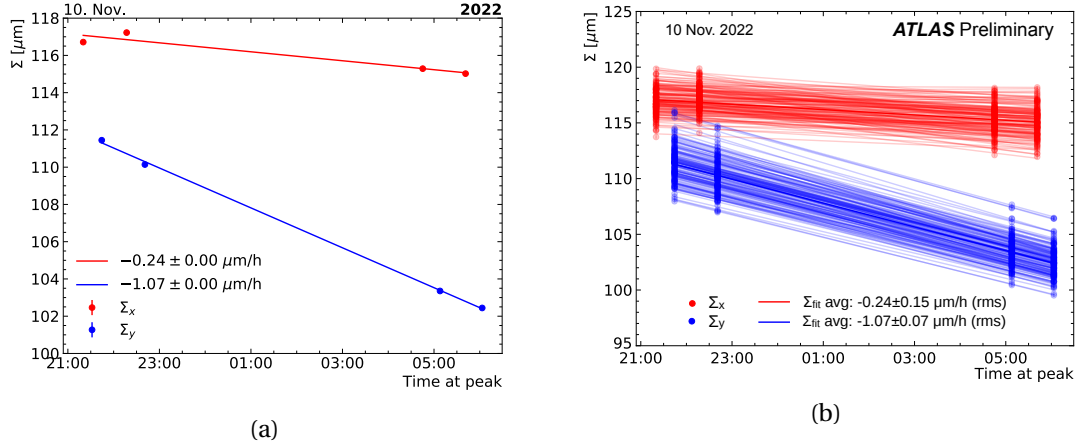


Figure 6.16: Time evolution of the convolved beam widths in both planes: (a) BCID averaged and (b) per BCID.

The time in the middle between the two scans is chosen for this purpose

$$t_{\text{mid}} = \hat{t}_x + \frac{\hat{t}_y - \hat{t}_x}{2}. \quad (6.31)$$

In practice, the peak in both planes varies in the same way over time. This means that the peak values at t_{mid} should be the same in both planes and can be obtained by calculating the average of the peak values of the two planes.

For the convolved beam sizes, a linear fit over the four on-axis scans is performed in each plane. The Σ values of the different scans are consistent with a linear behavior. The Σ at t_{mid} is extracted from the fit and used to calculate an emittance-change-corrected visible cross-section. The emittance change for different BCIDs can be significantly different, as can be seen in figure 6.16b, thus this correction is estimated and applied bunch-by-bunch.

To a good approximation, the peak of the scan curve is at zero separation, i.e. $\mu_i^0 = \mu_i^{\text{max}}$ for $i = x, y$, the emittance-change-corrected visible cross-section can be expressed as

$$\sigma_{\text{vis}}(t_{\text{mid}}, t_{\text{mid}}) = 2\pi \frac{\frac{\mu_x^{\text{max}}}{n_1 n_2}(\hat{t}_x) + \frac{\mu_y^{\text{max}}}{n_1 n_2}(\hat{t}_y)}{2} \Sigma_x^{\text{fit}}(t_{\text{mid}}) \Sigma_y^{\text{fit}}(t_{\text{mid}}). \quad (6.32)$$

The emittance change correction can then be quantified by

$$c = \frac{\sigma_{\text{vis}}(t_{\text{mid}}, t_{\text{mid}})}{\sigma_{\text{vis}}(\hat{t}_x, \hat{t}_y)} - 1 = \frac{\Sigma_x^{\text{fit}}(t_{\text{mid}}) \Sigma_y^{\text{fit}}(t_{\text{mid}})}{\Sigma_x(t_x) \Sigma_y(t_y)} - 1. \quad (6.33)$$

The emittance change correction is shown in figure 6.17, showing a significant variation between bunches.

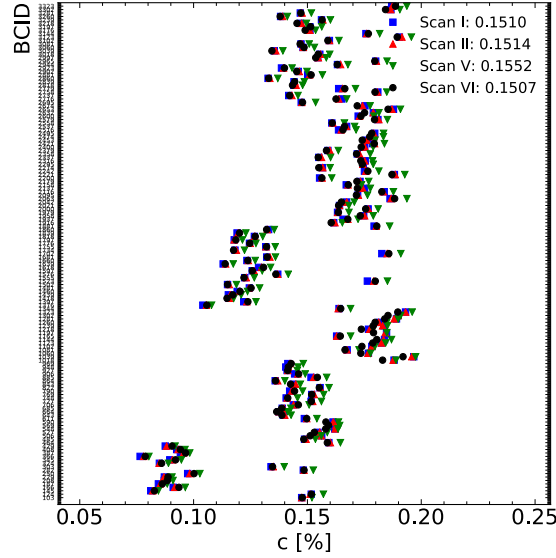


Figure 6.17: *Emittance change correction for all bunches and scans.*

6.2.7.7 Non-factorisation correction

The van der Meer scan formalism described in section 6.2.2 assumes factorisable beam profiles in x and y planes, i.e. the particle density functions can be written separately for the two planes. This is assumed when doing

$$\rho(x, y) = \rho_x(x)\rho_y(y). \quad (6.34)$$

Unfortunately, in reality, beams are sometimes not fully factorisable. To take this into account, a non-factorisation correction is introduced.

Hints of the factorisability of beams are obtained by comparing the convolved beam widths between the on- and off-axis scans [145]. If the beams are factorisable these should be equal, the more they differ, the more the beams are assumed to be non-factorisable.

The convolved beam widths' evolution over time with the off-axis scans included is shown in figure 6.18, clearly illustrating that the scans done with a separation in the non-scanning plane have larger convolved beam widths than the ones done with zero separation in the non-scanning plane. This difference in convolved beam widths between off- and on-axis scans proves that the luminosity distribution depends on the non-scanning plane beam-beam separation, and it is a strong hint that the beams are not factorisable.

An estimation of the non-factorisation effects is obtained by fitting the on-axis vdM scan pairs (x and y scans) simultaneously. In this way, the convolved beam width product can be directly extracted without factorisable assumption as

$$\Sigma_x \Sigma_y = \frac{1}{2\pi} \frac{\int \int \mu_{\text{vis}}(\Delta x, \Delta y) d(\Delta x) d(\Delta y)}{\mu_{\text{vis}}^{\text{max}}}. \quad (6.35)$$

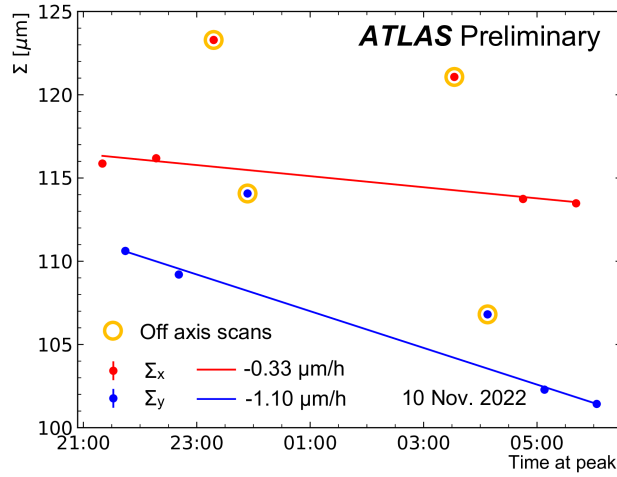


Figure 6.18: *Convolved beam widths' evolution over time for both planes, with off-axis scans shown in yellow circles [140].*

To estimate the non-factorization effects, two fits are compared: one with the assumption that the beams are factorisable, and the other with the ansatz of non-factorisable beams.

For this "2D analysis", the beamspot data [146] are used. From the ID tracks, primary vertices can be reconstructed, and the 3D spatial distribution of the primary collision vertices defines the luminous region. The vdM scan analysis assumes that the beams are factorisable, from how the beamspot width changes for different beam-beam separation in a vdM scan can be learned how non-factorisable the beams are. The rate read out by LUCID is fitted as a function of the 3D beamspot position using a 3D fit model. The LUCID rate is corrected for background subtraction and beam-beam effects. The usage of beamspot data has the advantage of being a precise since the beamspot is measured in data and allowing to fit the two beams separately. A non-factorisable double 3D Gaussian is fitted to each single-beam profile. It is a weighted sum of two 3D Gaussian distributions with arbitrary width and orientation. The fit model can be written as

$$f_i = w_i G_{ai} + (1 - w_i) G_{bi}, \quad (6.36)$$

where $i = 1, 2$ for the two beams, G_{ai} and G_{bi} are two 3D Gaussians, and w_i the weight.

From the fitted functions, corresponding 1D vdM scans can be calculated and the associated luminosity obtained. Using the simulated 1D results, a luminosity ratio to the 2D beamspot analysis can be extracted. This ratio (R) is the factor used as the non-factorisation correction. The obtained scale factor R , is applied to the visible cross-section [133], as

$$\sigma_{\text{vis}}^{\text{corr}} = \sigma_{\text{vis}} / R. \quad (6.37)$$

To reconstruct the vertices for each scan step, many tracks are needed, thus this procedure is only possible for a few BCIDs because of the limited readout rate of the inner detector. In 2022 during the vdM scan session, only nine BCIDs were read out for beamspot data, these nine

BCIDs are representative of all 144 BCIDs used in the 1D vdM analysis.

Since not all BCIDs can be accessed for the non-factorisation effect correction, this correction cannot be calculated for each BCID separately. Thus, the error-weighted average correction of the nine available BCIDs is taken as a correction factor for all BCIDs in a scan. This correction is estimated separately for each scan.

The R values obtained are shown in table 6.2^I.

	R
Scan I	0.9794
Scan II	0.9810
Scan V	0.9920
Scan VI	0.9917

Table 6.2: *The non-factorisation correction factor for all scans.*

From the value of the correction, it can be seen that the non-factorisation effect, if left uncorrected, overestimates the visible cross-section, and thus underestimate the luminosity value. The non-factorisation correction improves the scan-to-scan and the bunch-by-bunch consistency as shown in figure 6.19. Unfortunately, since only a few BCIDs are available in beamspot data, in practice a bunch-by-bunch correction is not applied. This means that some of the residual bunch-by-bunch inconsistencies are due to non-factorisation effect differences between BCIDs.

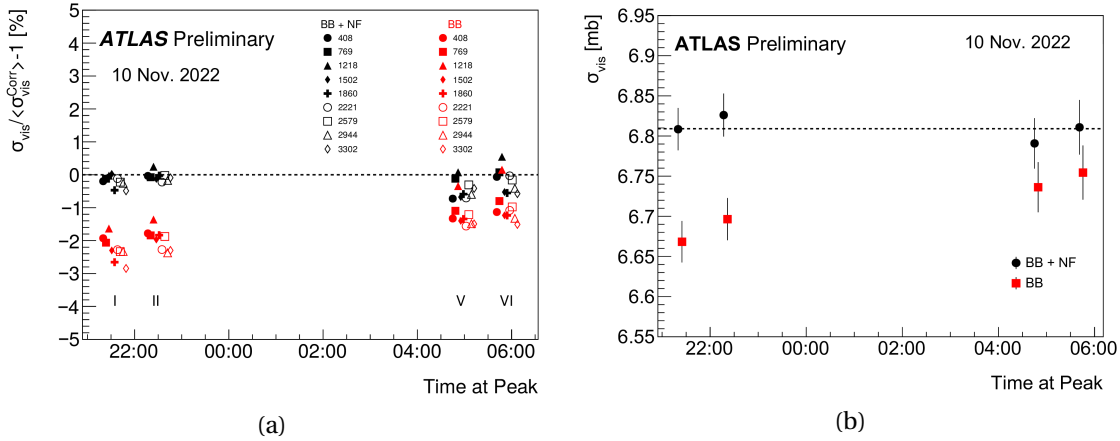


Figure 6.19: *Impact of non-factorisation correction on the visible cross-section values [140]: (a) improvement in bunch-by-bunch consistency in the 9 BCIDs available in beamspot; (b) improvement in scan-to-scan consistency on the average value over all BCIDs.*

^IResults produced by Tim Barklow.

The strength of the non-factorisation effect can vary largely across vdM scan sessions, differs somewhat between BCIDs and evolves during a fill. These observations made in the 2022 dataset agree well with the ones made in Run 1, in particular in the 2012 vdM scan program, where strong non-factorisation effects were observed as well [147]. In 2022, the evolution hints that the beams become more factorisable over time.

6.2.7.8 Length scale calibration

The nominal separation does not correspond exactly to the real separation. This means that the scale that is set is not exactly the real scale. To correct for this, a length scale calibration (LSC) is performed. This is obtained using special scans called "LSC scans" performed, if possible, in the same fill as the van der Meer scans. Van der Meer scans are not suitable for a LSC since the beamspot position remains approximately the same given that the beams are moved in opposite direction. LSC scans consist of four scans: one for each beam and plane (x , y), as shown in figure 6.20.

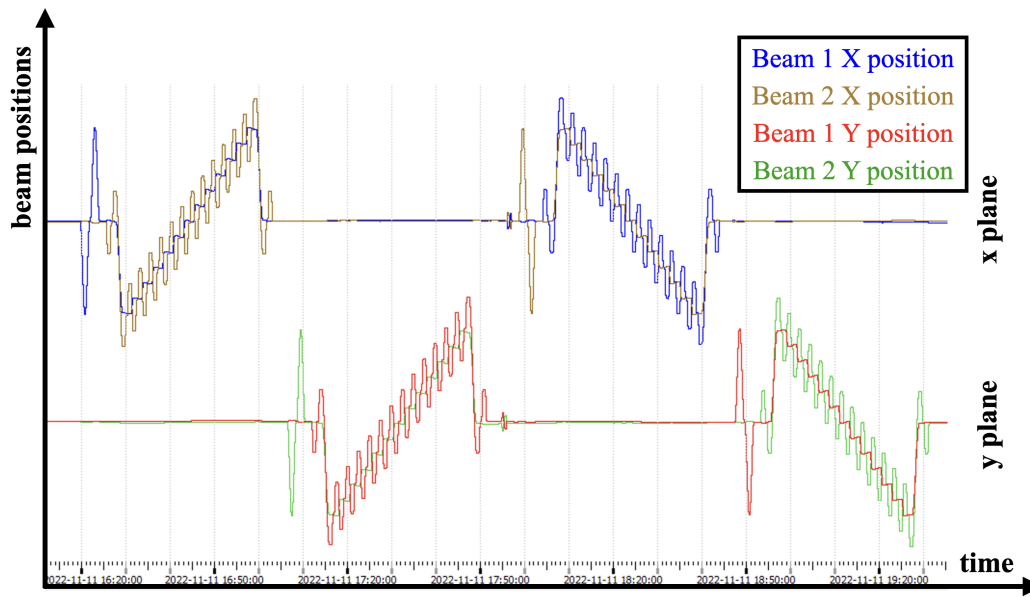


Figure 6.20: Beam positions during the LSC scans in 2022 in horizontal and vertical planes.

Each scan measures the rate at 13 beam positions covering 3σ beam displacement. At each position a mini-scan composed of three points is performed covering -1σ , 0 and $+1\sigma$ displacement. To each mini-scan a gaussian is fit to find the head-on position of the beams. At each measured point, the beamspot position is extracted to a 0.1% level precision thanks to the impressive alignment of the inner detector. Then for each beam and plane, the beamspot position is plotted as a function of the nominal beam position, as shown for beam 1 in hori-

zontal position in figure 6.21.

There are four plots of this type. For each plot a linear fit is performed, and the found slope defines the linear scale M_1^{BiK} , with $i = 1, 2$ and $K = X, Y$.

In this calibration, the orbit drift correction is non-negligible and has been taken into account using arcBPMs. For the LSC, DOROS BPMs cannot be used since they might be sensitive to some residual effects from the steering magnets due to hysteresis.

The extracted linear scales for each beam and plane are shown table 6.3^{II}.

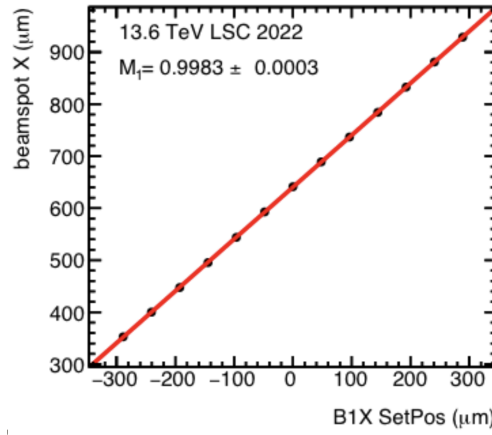


Figure 6.21: Beamspot position in x plane as a function of the nominal position for beam 1 in the horizontal plane without ODC. Figure produced by Richard Hawking.

	M_1
Beam 1 horizontal (B1X)	0.9964
Beam 2 horizontal (B2X)	0.9949
Beam 1 vertical (B1Y)	0.9952
Beam 2 vertical (B2Y)	0.9957

Table 6.3: Linear scales found in the LSC for all beams and planes.

The correction is obtained by the product of the average in x -plane and the average in y -plane

$$L_{xy} = (M_1^{B1X} + M_1^{B2X})(M_1^{B1Y} + M_1^{B2Y})/4. \quad (6.38)$$

For this 2022 LSC analysis, the extracted LSC is $L_{xy} = 0.9911$ [133]. The corrected visible cross-section is obtained as

$$\sigma_{\text{vis}}^{\text{corr}} = L_{xy} \sigma_{\text{vis}}. \quad (6.39)$$

^{II}Results produced by Richard Hawkings.

6.2.7.9 Analysis flow

Figure 6.22 shows the van der Meer scan analysis flow. First, the ghost and satellite charge corrections are applied, followed by the background subtraction and ODC. On top of these corrections, the beam-beam corrections are calculated. After applying the beam-beam corrections, the bunch current offsets are calculated. Next, the emittance change correction is applied bunch-by-bunch, followed by LSC and in the very end the non-factorisation correction is applied.

The order of application of these corrections is sometimes important. The bunch current offset has to be applied after background subtraction, ODC and beam-beam, because it is estimated based on the visible cross-section. The order of application of background subtraction and ODC is irrelevant as well as the order of beam-beam correction and bunch current offset application. Satellite, ghost charge corrections and background subtraction can be exchanged without problems. However, satellite and ghosts charge corrections need to be applied before beam-beam corrections because they affect them. The emittance change correction is estimated after all other corrections (except LSC) because it is based on obtained convolved beam widths and peak values. The LSC correction is applied as a factor acting on the visible cross-section at the end of the analysis.

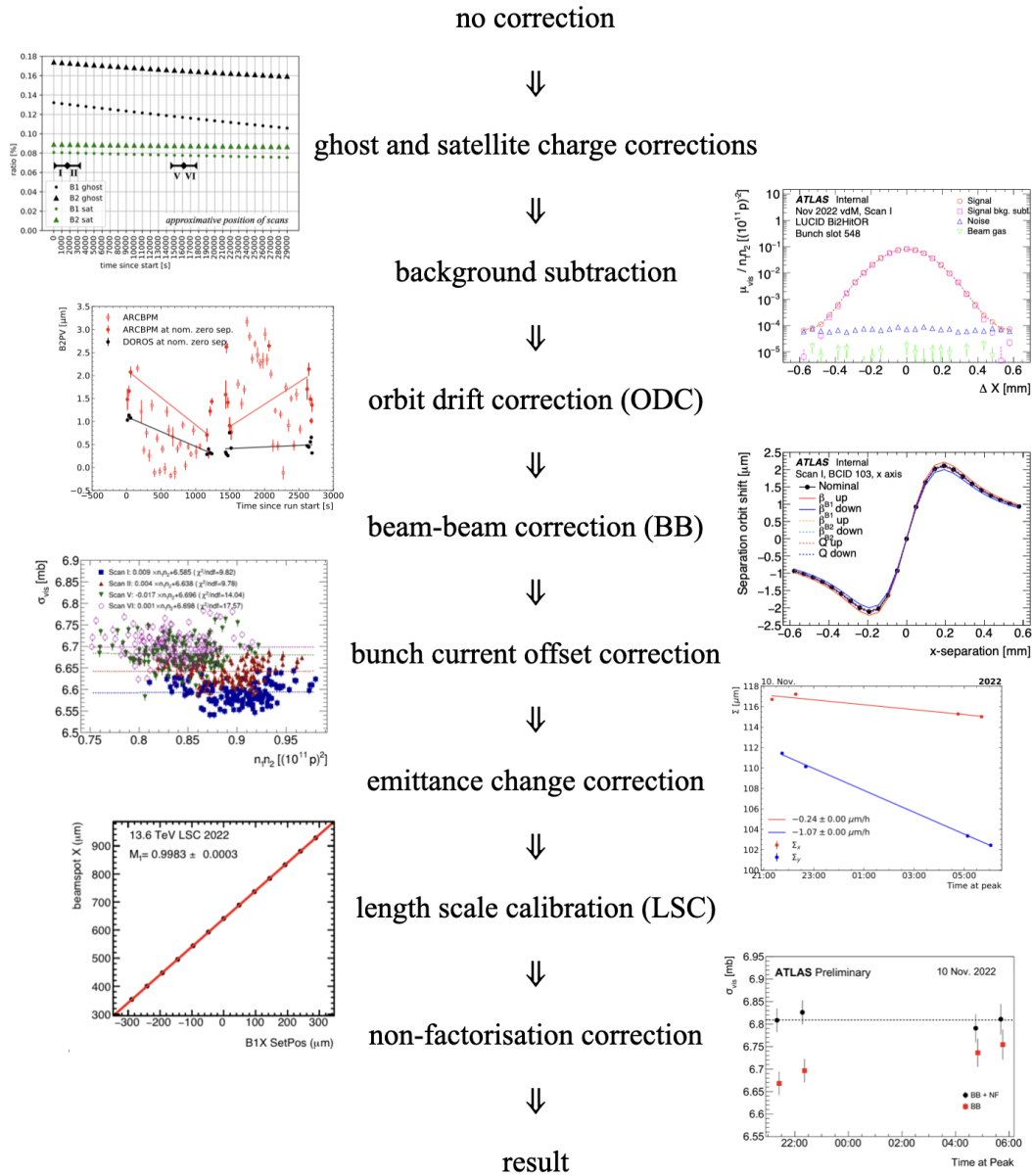


Figure 6.22: Visualisation of the van der Meer analysis flow.

6.2.7.10 Summary of corrections

In this part, the effects of the corrections on the visible cross-section are summarised. The effect of individual corrections and the cumulative effect of the corrections can be found respectively in table 6.4 and in table 6.5.

For some corrections, both the single components and the total correction are shown. For example, it can be seen that both the beam-beam deflection and the optical distortion corrections are $> 1\%$, but they partially compensate each other's shift of the central value of the visible cross-section. The goal is to achieve a sub-percentage precision of the luminosity determination, thus even small contributions are important.

The largest corrections are the non-factorisation correction, the beam-beam corrections, and the LSC. The bunch current offset correction has a negligible contribution to the visible cross-section. In general, the correction effects can vary largely from scan to scan.

	Scan I	Scan II	Scan V	Scan VI
Satellite charge correction	+0.09%	+0.08%	+0.08%	+0.08%
Ghost charge correction	+0.31%	+0.30%	+0.27%	+0.26%
Satellite and ghost corrections	+0.39%	+0.38%	+0.35%	+0.34%
Background subtraction correction	-0.32%	-0.31%	-0.27%	-0.30%
Orbit drift correction	-0.13%	+0.16%	+0.14%	+0.11%
Beam-beam deflection	+2.30%	+2.31%	+2.49%	+2.49%
Optical distortion	-1.35%	-1.35%	-1.47%	-1.44%
Beam-beam correction	+0.92%	+0.93%	+1.02%	+1.03%
Emittance change correction	+0.15%	+0.15%	+0.16%	+0.15%
Bunch current offsets	+0.01%	+0.01%	$< 0.01\%$	$< 0.01\%$
Length scale calibration	-0.89%	-0.89%	-0.89%	-0.89%
Non-factorisation correction	+2.06%	+1.90%	+0.80%	+0.83%

Table 6.4: *The effect of individual corrections on the visible cross-section for the different scans in percentage.*

	Scan I	Scan II	Scan V	Scan VI
Satellite and ghost corrections	+0.39%	+0.38%	+0.35%	+0.34%
+Background subtraction correction	+0.07%	+0.08%	+0.08%	+0.04%
+Orbit drift correction	-0.06%	+0.23%	+0.22%	+0.16%
+Beam-beam correction	+0.85%	+1.16%	+1.22%	+1.18%
+Bunch current offsets	+0.86%	+1.16%	+1.22%	+1.18%
+Emittance change correction	+1.01%	+1.31%	+1.37%	+1.33%
+Length scale calibration	+0.11%	+0.41%	+0.47%	+0.43%
+Non-factorisation correction	+2.22%	+2.36%	+1.28%	+1.27%

Table 6.5: *Cumulative effect of corrections on the visible cross-section for the different scans in percentage.*

6.2.7.11 Fully corrected visible cross-section values

The visible cross-section values with all the corrections applied are estimated for all luminosity algorithms, the different luminosity algorithms are described in appendix 8. The main algorithms' values and their statistical uncertainty are shown in table 6.6. The values are the average over the four on-axis scans.

Algorithm	$\sigma_{\text{vis}} [\text{mb}]$
bcmHEvtOR	19.264 ± 0.005
bcmHORA	9.835 ± 0.003
bcmHORC	11.877 ± 0.004
lucBi2EvtA	20.568 ± 0.005
lucBi2EvtC	20.459 ± 0.005
lucBi2EvtOR	33.917 ± 0.007
lucBi2HitOR	6.7863 ± 0.0009
lucBi2HitORA	6.8098 ± 0.0013
lucBi2HitORC	6.7696 ± 0.0013
lucBiEvtA	20.250 ± 0.005
lucBiEvtC	20.125 ± 0.005
lucBiEvtOR	33.487 ± 0.007
lucBiHitOR	6.6464 ± 0.0009
lucBiHitORA	6.6668 ± 0.0013
lucBiHitORC	6.6266 ± 0.0013

Table 6.6: *Visible cross-section with all corrections applied for all algorithms in mb. The error represents the statistical uncertainty only.*

6.2.8 Systematic uncertainties estimation

After computing the central value of the absolute luminosity calibration, it is important to estimate the uncertainty on the calibration. In this analysis, the statistical uncertainties are negligible compared to the systematic uncertainties. The systematic uncertainties arise from using different methods, different detectors, and knowing the parameters used in the analysis to a limited precision. The different contributions are discussed in detail in the following, and a summary of the systematic uncertainties is given at the end of the section.

6.2.8.1 Non-factorisation correction

The LUCID rates from the on-axis scan pairs as a function of the nominal beam-beam separation are fit simultaneously with a 2D double Gaussian fit function in order to assess the uncertainty on the non-factorization correction. Based on the assumption that this function is

non-factorisable, an approximation of the non-factorization correction can be obtained by predicting simulated 1D scans using the fitted model. The approximation can estimate a non-factorisation correction for any BCIDs, since it does not rely on beamspot data. The systematic uncertainty on the non-factorization correction is defined as the difference between the corrected visible cross-section estimated by this approximation and the one estimated by the default method. The uncertainty is found to be 1.07%.

6.2.8.2 Length scale calibration and magnetic non-linearity effects

This part of the luminosity calibration is work performed by Richard Hawkins. The statistical uncertainty on the LSC is taken as the corresponding systematic uncertainty. An additional uncertainty, related to the LSC, originates from the magnetic non-linearity effects. In the LSC, it is assumed that the relation between the beamspot position and the nominal beam position is linear. Unfortunately, this is not exactly the case, as shown in the residual plots in figure 6.23. In the plot, two sets of points are visible, the "direct" points and the "standard" points. These refer to two comparable methods: the "direct" points are extracted as previously explained (section 6.2.7.8), while the "standard" method refers to finding the peak as in the vdM scan case (rate versus nominal beam-beam separation) and then transfer it to the beamspot peak with the linear relation obtained from the LSC fit [133].

In previous years, the linear fit residuals were observed to have a "∩" shaped distribution in the case of beam 2, while beam 1 had an "∪" shaped distribution of points [133]. This is assumed to be due to hysteresis effects in the steering corrector magnets, since the two beams were moved in opposite directions during the LSC scans. In the 2022 LSC, the beams were again moved in opposite directions during the scans (figure 6.20), however although beam 2 shows a "∩" shaped distribution, beam 1 looks qualitatively different from an "∪" shape (figure 6.23). An estimation of the magnetic non-linearity is obtained by fitting a 3rd- or 5th-order polynomial instead of a linear fit to the beamspot versus the nominal beam-beam separation points. This can be expressed as

$$x_{bs} = M_{1,i} \cdot x_{nom,i} + M_{2,i} \cdot r_i^2 + M_{3,i} \cdot r_i^3, \quad (6.40)$$

for a 3rd-order polynomial and for each beam i . Where x_{bs} is the beamspot position, $x_{nom,i}$ is the nominal position, $r_i = x_{nom,i} / x_{max}$ is the reduced beam position with $x_{max} = 295 \mu\text{m}$, and $M_{1,i}$ is the LSC. The LSC scans have only 13 points each, giving a limited granularity for the magnetic non-linearity estimation. It is thus interesting to use the vdM scans with 25 points each to cross-check the default LSC.

The issue with the vdM scans is that the beamspot position remains approximately the same during the scan, thus, the DOROS BPMs are used instead. The DOROS BPMs measurements need to be offset to the nominal position, this is done by requiring an offset such that the head-on points and the points just before and after the scan have minimal difference to the nominal position.

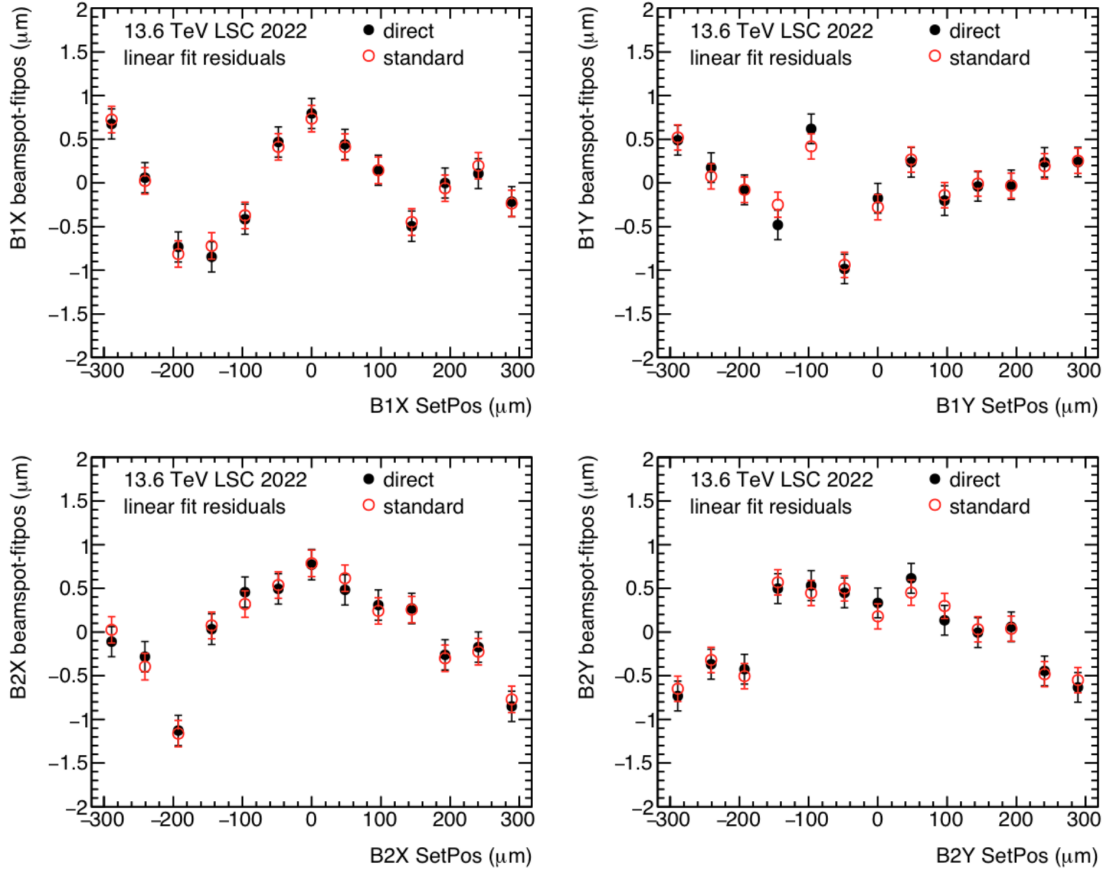


Figure 6.23: LSC residuals from the linear fits for all beams and planes. On the top left for beam 1 horizontal plane, on the top right for beam 1 vertical plane, on the bottom left for beam 2 horizontal plane, and on the bottom right for beam 2 in vertical plane.

Furthermore, the DOROS BPMs suffer from a significant miscalibration of the length scale. After adjusting the offset and the scale of the BPMs to the nominal position, the difference to the nominal position can be plotted for each scan and plane as shown for beam 1 horizontal position in figure 6.24a. It can be seen that all scans, but in particular the on-axis scans, show a strong "S"-shaped curve, this is because the DOROS BPMs are sensitive to the beam-beam deflection effect, which needs to be corrected to see the magnetic non-linearity. Thus, a beam-beam deflection correction is estimated, as shown in figure 6.24b, and applied to DOROS BPMs measurement.

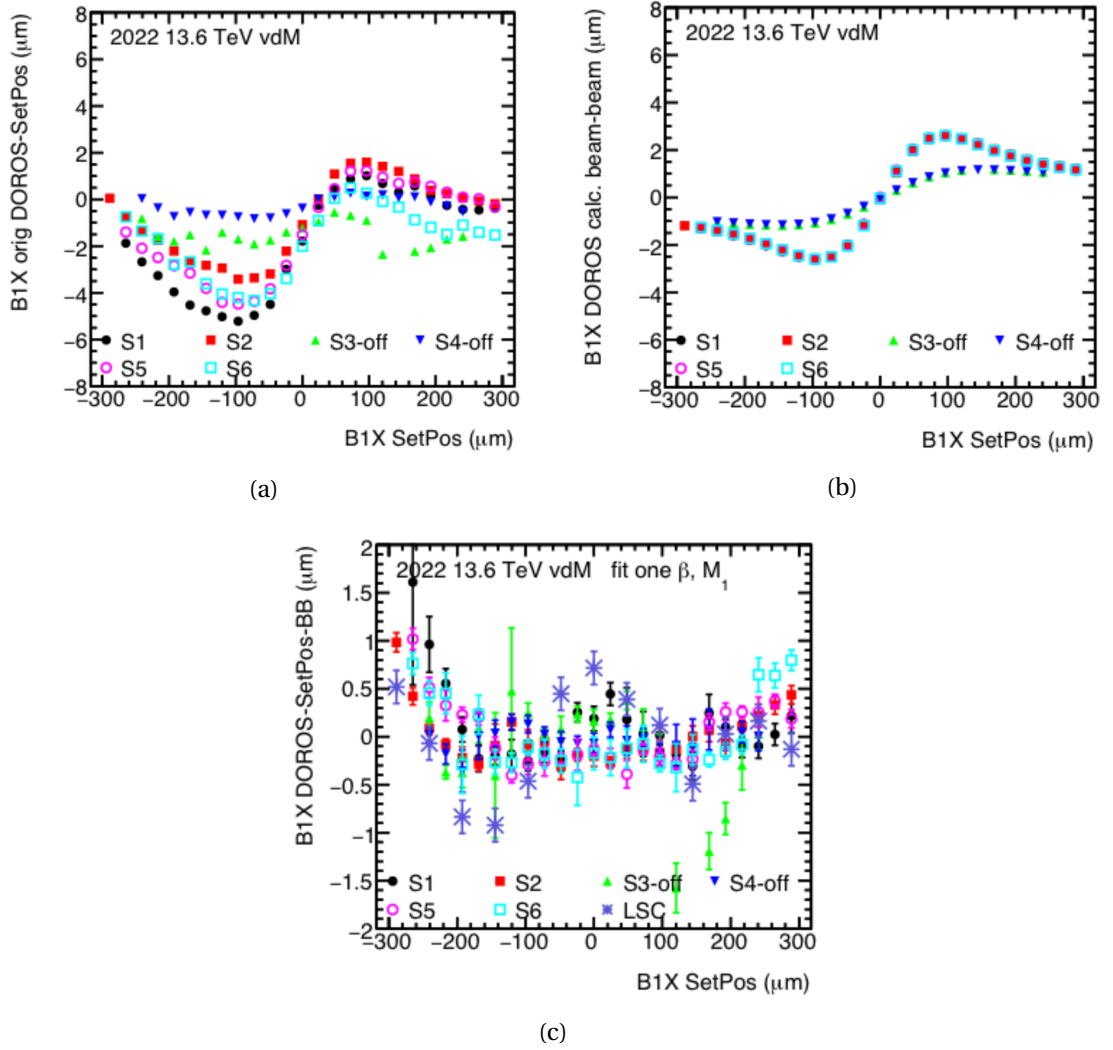


Figure 6.24: Magnetic non-linearity for beam 1 in horizontal position compared to the nominal position. The three plots show: (a) calibrated DOROS BPMs position difference to the nominal position; (b) beam-beam deflection estimation for DOROS BPMs, (c) beam-beam deflection-corrected DOROS BPMs position difference to the nominal position, compared to the LSC scans.

The offset and beam-beam deflection-corrected DOROS BPMs beam positions are then compared to the nominal position in figure 6.24c.

Most of the scans follow approximately an "U"-shaped curve, but not all of them. Furthermore, the LSC residuals for the same beam and plane do not agree well with the DOROS BPMs residuals.

To obtain a LSC from DOROS BPMs a fit to the DOROS BPMs beam position subtracted by the nominal beam position as a function of the scan step is performed. This fit is parametrised as

follows

$$\Delta x_i = D_{x,i}^{\text{cal}} \cdot x_{\text{doros},i} - D_{x,i}^{\text{ofs}} - M_{1,i} \cdot x_{\text{nom},i} - \alpha \cdot \delta x_{bb,i}^{\text{doros}}, \quad (6.41)$$

where Δx_i is the residual difference between DOROS BPMs and the nominal position, $x_{\text{doros},i}$ is the beam position at the IP measured by DOROS BPMs, $x_{\text{nom},i}$ is the nominal position, $D_{x,i}^{\text{cal}}$ is the DOROS BPMs length scale, $D_{x,i}^{\text{ofs}}$ is the DOROS BPMs offset, $\delta x_{bb,i}^{\text{doros}}$ is the beam-beam deflection correction, α is a scale to account for DOROS BPMs' response to a mixture of colliding and non-colliding bunches, and $i = 1, 2$ for the two beams.

$D_{x,i}^{\text{cal}}$, $D_{x,i}^{\text{ofs}}$ and α can be extracted from the fit. However, it is not possible to extract the value of $M_{1,i}$ through this fit since it is degenerate with $D_{x,i}^{\text{cal}}$. To find the value of the $M_{1,i}$, the LSC scans are used. The DOROS BPMs residual position is fitted simultaneously with the LSC scan, to extract all values from the fit. This is done for each beam and plane separately. Notice that this works particularly well in 2022, since the LSC scans are done in the same fill as the vdM scans and have the same beam conditions.

By default, it is assumed that the α value is the same for all scans. However, it was observed in Run 2 that leaving it free for each scan can improve the fit, since this parameter corrects for under- or overestimation of the beam-beam deflection [133].

This DOROS LSC can be performed as well for 3rd- and 5th-order polynomials in the same way as in the default LSC method, by adding additional terms as

$$\Delta x_i^{\text{doros}} = D_{x,i}^{\text{cal}} \cdot x_{\text{doros},i} - D_{x,i}^{\text{ofs}} - M_{1,i} \cdot x_{\text{nom},i} - M_{2,i} \cdot r_i^2 - M_{3,i} \cdot r_i^3 - \alpha \cdot \delta x_{bb,i}^{\text{doros}}. \quad (6.42)$$

The LSCs obtained from all the aforementioned methods are shown in table 6.7^{III}.

Method	L_{xy}	ΔL_{xy}
Linear LSC (default)	0.9911	-
3 rd -order LSC	0.9928	0.17%
5 th -order LSC	0.9920	0.09%
Linear LSC+vdM	0.9939	0.28%
3 rd -order LSC+vdM	0.9937	0.26%
3 rd -order LSC+vdM (free α)	0.9943	0.32%

Table 6.7: LSC values for the different methods and their differences to the default LSC method.

The variation in LSC due to magnetic non-linearities is quantified by taking the maximal difference between these methods. This amounts to 0.32% in 2022.

An additional scale uncertainty comes from the absolute length scale of the inner detector of 0.12%. This has been determined by simulation studies of various realistic misalignment

^{III}Results produced by Richard Hawkings.

scenarios [85]. Unfortunately, these studies have not been yet re-performed for Run 3, thus, the uncertainty taken in this preliminary luminosity calibration is double the Run 2 on: 0.24%.

6.2.8.3 DCCT calibration

The DCCT calibration systematic uncertainty has been estimated by accelerator experts in Run 2 [148], and it is found to be 0.20%. This same value is taken for the preliminary Run 3 calibration as a conservative uncertainty, since due to improvements to DCCT during Long Shutdown 2, this uncertainty is expected to be smaller in Run 2.

6.2.8.4 Uncertainty on the bunch current measurement

The uncertainty on the bunch current measurement is estimated by comparing the measured visible cross-section obtained using FBCT to the one obtained using BPTX. The visible cross-sections are estimated by performing the full analysis with all the corrections and the corresponding bunch current offsets. The scan average differences can be seen in table 6.8. They are expected to be smaller than the per-BCID difference, since the total charge is in both cases normalised to the DCCT measurement. The largest average difference is taken as the overall systematic uncertainty, i.e. 0.01%.

	FBCT/BPTX
Scan I	+0.01%
Scan II	+0.01%
Scan V	+0.01%
Scan VI	+0.01%

Table 6.8: *FBCT versus BPTX systematic uncertainties per scan in percentage.*

6.2.8.5 Uncertainty on the ghost and satellite charge measurements

The uncertainty on the ghost charge measurement is taken to be half of the correction effect on the visible cross-section, and for the satellite charge measurement the full impact on σ_{vis} is taken as an uncertainty. The corresponding systematic uncertainties for each scan are shown in table 6.9. The average is taken as the overall systematic uncertainty, i.e. 0.17%.

	Satellite charge	Ghost charge	Total
Scan I	+0.09%	+0.16%	+0.18%
Scan II	+0.08%	+0.15%	+0.18%
Scan V	+0.08%	+0.14%	+0.16%
Scan VI	+0.08%	+0.13%	+0.15%

Table 6.9: *Satellite, ghost and both together systematic uncertainties per scan in percentage.*

6.2.8.6 Background subtraction method

The uncertainty on the background subtraction method is estimated by comparing the visible cross-section obtained with this method to the one obtained with an alternative method. The alternative method assumes that the backgrounds can be taken into account by a constant term in the fit model since the backgrounds are approximately beam-beam separation independent. This constant term is then not taken into account in the peak and convolved beam width calculations. The largest difference between the two methods determines the uncertainty of the background subtraction method and amounts to 0.06%.

	alternative/default
Scan I	+0.06%
Scan II	+0.03%
Scan V	+0.02%
Scan VI	-0.01%

Table 6.10: *Systematic uncertainty from background estimation for each scan in percentage.*

6.2.8.7 Orbit drift correction

The orbit drift correction systematic uncertainty is estimated by comparing σ_{vis} obtained with the ODC using DOROS BPMs compared to the one obtained with the ODC using arcBPMs. The systematic uncertainty for each scan is shown in table 6.11. The average systematic uncertainty between the four scans, 0.06%, is taken as the overall systematic uncertainty for ODC.

arcBPMs/DOROS BPMs	
Scan I	+0.08%
Scan II	+0.04%
Scan V	-0.05%
Scan VI	-0.08%

Table 6.11: *Orbit drift correction systematic uncertainties per scan in percentage.*

6.2.8.8 Beam-beam corrections

The systematic uncertainty on the beam-beam corrections can be divided in several components as shown in table 6.12. The table is ordered by contribution size of the components to the visible cross-section. It can be seen that the largest contribution comes from the phase advance uncertainty [133]. The value of phase advance in Run 2 is assumed as an upper limit value in Run 3.

To estimate the systematic uncertainty associated to the beam-beam correction, the tune (Q) and the β values are varied one by one, by their upper and lower uncertainty. The difference in visible cross-section is then taken as the systematic uncertainty of the varied parameter.

The contribution of ellipticity, non-Gaussian tails, lattice non-linearities, parametrization, residual effects of the crossing angle, phase advance and beam-beam asymmetry are taken into account. The total beam-beam correction systematic uncertainty is obtained by summing all components in quadrature, and then averaging over the four scans. It amounts to 0.35%.

Uncertainty source [133, 144]	Scan I	Scan II	Scan V	Scan VI
Phase advance	0.20%	0.20%	0.20%	0.20%
Q	0.17%	0.17%	0.18%	0.18%
Non-Gaussian tails	0.15%	0.15%	0.15%	0.16%
Parametrization	0.10%	0.10%	0.10%	0.10%
Tune shift	0.09%	0.09%	0.09%	0.09%
β_{B1}	0.06%	0.06%	0.07%	0.07%
β_{B2}	0.06%	0.06%	0.07%	0.07%
Ellipticity	0.03%	0.03%	0.03%	0.03%
Beam-beam asym.	0.02%	0.02%	0.02%	0.02%
Lattice non-linearities	0.01%	0.01%	0.01%	0.01%
Total error	0.34%	0.34%	0.35%	0.36%

Table 6.12: *Detail of the beam-beam corrections and their systematic uncertainty estimation for each scan in percentage for lucBi2HitOR.*

6.2.8.9 Emittance change correction

The emittance change correction uncertainty is composed of two parts. The first part evaluates the bias of the method and the second part the residual time bias in the correction.

The bias of the method is estimated by comparing the default method (section 6.2.7.6), with an alternative method. The alternative method consists of estimating the correction separately for the first two and the last two scans. A visual representation of the two methods is shown in figure 6.25.

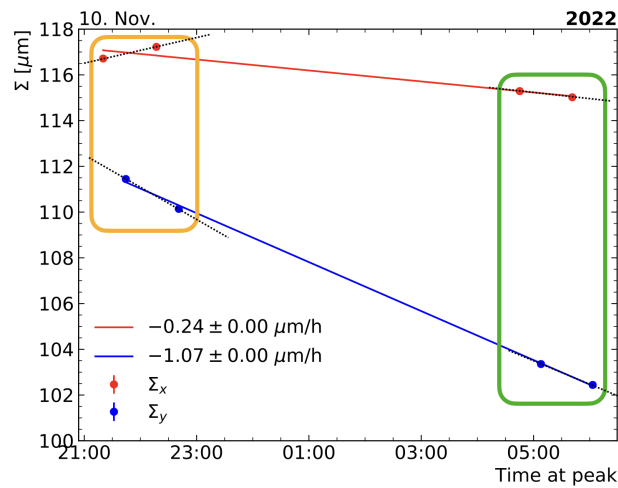


Figure 6.25: Visualisation of the alternative method emittance correction estimation method.

The emittance change correction impact on the visible cross-section for the default and alternative method is shown in table 6.13.

	Emittance correction to σ_{vis}		Difference
	default	alternative	default-alternative
Scan I	0.34%	0.15%	0.19%
Scan II	0.34%	0.15%	0.19%
Scan V	0.14%	0.16%	0.02%
Scan VI	0.14%	0.15%	0.01%

Table 6.13: Emittance change-correction for the default and alternative methods and their percentage difference for each scan.

It can be seen, that the first two scans have a stronger bias in the method than the last two, this is mainly due to the first two x scans, as can be seen in figure 6.25.

The residual time bias of the correction is estimated through residual time differences in the visible cross-section between the values obtained at the time of the peak of the x scan and the

ones at the time of the peak of the y scan.

The emittance change-corrected visible cross-section is obtained as equation 6.30. In theory, the choice of common time for the x and y scan should not matter

$$\sigma_{\text{vis}}(t_{\text{mid}}, t_{\text{mid}}) = \sigma_{\text{vis}}(t_x, t_x) = \sigma_{\text{vis}}(t_y, t_y) = \sigma_{\text{vis}}(t, t). \quad (6.43)$$

However, in practice, there is some residual time dependency. The variation of the visible cross-section for different times is estimated by

$$\Delta c_{\text{time}} = \frac{\max(|\overline{\sigma_{\text{vis}}}(t_{\text{mid}}, t_{\text{mid}}) - \overline{\sigma_{\text{vis}}}(\hat{t}_x, \hat{t}_x)|, |\overline{\sigma_{\text{vis}}}(t_{\text{mid}}, t_{\text{mid}}) - \overline{\sigma_{\text{vis}}}(\hat{t}_y, \hat{t}_y)|)}{\overline{\sigma_{\text{vis}}}(\hat{t}_x, \hat{t}_y)}, \quad (6.44)$$

where

$$\sigma_{\text{vis}}(\hat{t}_x, \hat{t}_x) = 2\pi\mu(\hat{t}_x)\Sigma_x^{\text{meas.}}(\hat{t}_x)\Sigma_y^{\text{fit}}(\hat{t}_x), \quad (6.45)$$

and

$$\sigma_{\text{vis}}(\hat{t}_y, \hat{t}_y) = 2\pi\mu(\hat{t}_y)\Sigma_x^{\text{fit}}(\hat{t}_y)\Sigma_y^{\text{meas.}}(\hat{t}_y). \quad (6.46)$$

The contributions of the two components to the total emittance change uncertainty estimation are given in table 6.14, the total emittance change uncertainty is the sum in quadrature of the two parts.

	method bias	residual time bias	total uncertainty
Scan I	0.19%	0.18%	0.26%
Scan II	0.19%	0.15%	0.24%
Scan V	0.02%	0.17%	0.17%
Scan VI	0.01%	0.17%	0.17%

Table 6.14: *Total systematic uncertainty of the emittance change-correction and its two components in percentage for all four scans.*

The average of the total uncertainty over the four scans is taken as the systematic uncertainty of the emittance change correction, and it amounts to 0.21%.

6.2.8.10 Fit model

To estimate the systematic uncertainty of the applied fit model, GP4 and GP6 fit models are compared. GP4 is a Gaussian multiplied by a 4th-order polynomial. All corrections are applied in each of the models and the obtained visible cross-sections are compared. The individual results for each scan are reported in table 6.15. The largest difference in σ_{vis} between the fit models is used as the systematic uncertainty, amounting to 0.24%.

fit model	
Scan I	+0.04%
Scan II	+0.03%
Scan V	+0.24%
Scan VI	+0.19%

Table 6.15: *Fit model systematic uncertainty, estimated by comparing GP4 and GP6 for all scans in percentage.*

6.2.8.11 Scan-to-scan consistency

The scan-to-scan consistency is calculated as the relative RMS of the obtained visible cross-section of the four scans. This consistency can be expressed as

$$\text{RMS}_{\text{relative}} = \frac{\text{RMS}}{\overline{\sigma}_{\text{vis}}}, \quad (6.47)$$

with

$$\text{RMS} = \sqrt{\frac{\sum_i (\sigma_{\text{vis}}^i - \overline{\sigma}_{\text{vis}})^2}{N - 1}}, \quad (6.48)$$

where $\overline{\sigma}_{\text{vis}}$ is the average σ_{vis} over the N scans, σ_{vis}^i is σ_{vis} for scan i , and $N = 4$.

The visible cross-section obtained for each scan after all corrections, including non-factorisation, are applied and the scan-to-scan consistency systematic uncertainty can be seen in table **6.16** and it is found to be 0.27%.

	Scan I	Scan II	Scan V	Scan VI	Scan-to-scan
σ_{vis}	6.773	6.810	6.772	6.790	0.27%

Table 6.16: *The visible cross-section value for every scan is shown and their scan-to-scan visible cross-section consistency is given on the very right side of the table.*

6.2.8.12 Bunch-by-bunch consistency

The visible cross-section estimation varies between the different BCIDs. This is taken into account by the bunch-by-bunch consistency, which is calculated using an error weighed relative RMS:

$$\text{bunch-by-bunch consistency} = \frac{\sqrt{(\text{RMS})^2 - (\overline{\sigma}_{\text{vis}}^{\text{err}})^2}}{\overline{\sigma}_{\text{vis}}}, \quad (6.49)$$

where the $\overline{\sigma}_{\text{vis}}$ is the mean of the visible cross-sections within a scan, i.e. mean over different bunches, the RMS is of σ_{vis} within a scan, and the $\overline{\sigma}_{\text{vis}}^{\text{err}}$ is the statistical error on the visible

cross-section. The results for each scan can be found in table 6.17. The largest systematic uncertainty, 0.50%, is used as bunch-by-bunch consistency uncertainty.

bunch-by-bunch consistency	
Scan I	+0.35%
Scan II	+0.34%
Scan V	+0.46%
Scan VI	+0.50%

Table 6.17: *Bunch-by-bunch consistency for all scans in percentage.*

6.2.8.13 Luminosity consistency between algorithms and luminometers

To quantify the bias of the preferred LUCID algorithm's choice, a comparison to other LUCID algorithms is performed. Additionally, the bias of the LUCID technology is taken into account by comparing the LUCID algorithms with BCM algorithms.

To quantify the bias, the specific luminosity is used

$$L_{\text{spec}} = \frac{f_r}{2\pi\Sigma_x\Sigma_y}. \quad (6.50)$$

If the calibration of the luminometers and luminosity algorithms would be perfect, this quantity would agree exactly for all of them. The residual difference between luminosity algorithms defines uncertainty coming from the different algorithms and luminometers.

The residual difference is quantified by the deviation of the specific luminosity from the mean

$$y^a = \left\langle \frac{L_{\text{spec}}^{b,s,a} - \langle L_{\text{spec}}^{b,s} \rangle_a}{\langle L_{\text{spec}}^{b,s} \rangle_a} \right\rangle_{b,s}, \quad (6.51)$$

where $L_{\text{spec}}^{b,s,a}$ is the specific luminosity for algorithm a for bunch b in scan s , and $\langle L_{\text{spec}}^{b,s} \rangle_a$ is the mean over all algorithms for bunch b in scan s . This can be seen in figure 6.26, where the y -axis is y^a , i.e. the difference of L_{spec} for one algorithm compared to the mean of all algorithms.

The largest scan-averaged deviation from the mean is taken as the systematic uncertainty and it is found to be 0.43%. The reference luminosity algorithm for this analysis is lucBi2HitOR, and it lies very close to the mean, which shows that it represents well all algorithms and it is thus a good preferred choice.

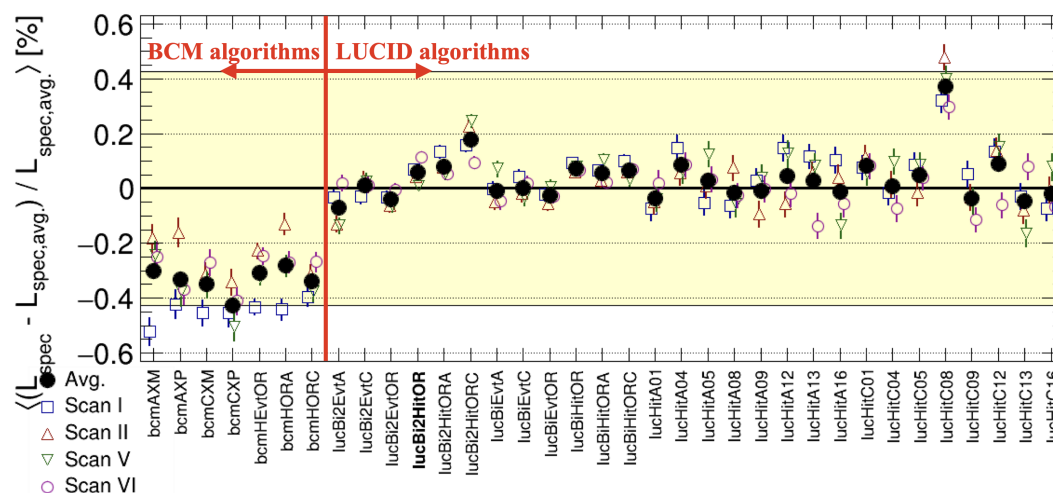


Figure 6.26: Deviation of the specific luminosity from the mean (y^a) for the different algorithms and luminometers with all corrections applied and statistical errors.

6.2.9 Results

All the uncertainties of the absolute luminosity calibration scale are summarised in table **6.18**, ordered from the largest to the smallest. The dominant contribution to the total vdM uncertainty comes from the non-factorisation uncertainty, while the second-leading contribution is less than half of it. This is thus the uncertainty to tackle to improve the absolute luminosity calibration precision. The total uncertainty coming from the absolute luminosity calibration scale is obtained by summing in quadrature all the contributions and amounts to 1.45%.

The visible cross-section for the preferred LUCID algorithm is shown before and after non-factorisation correction application in figure 6.27. All other corrections are applied. It can be seen that the non-factorisation correction increases the visible cross-section and that the scan-to-scan consistency is strongly improved. It should be noted that there are two groups of outliers in scan V and VI which are particularly visible before the non-factorisation application due to graphical representation.

Data sample	2022
Non-factorisation effects	1.07%
Bunch-by-bunch σ_{vis} consistency	0.50%
Luminosity consistency between algorithms and luminometers	0.43%
Beam-beam corrections	0.35%
Magnetic non-linearity	0.32%
Scan-to-scan consistency	0.27%
Inner detector length scale	0.24%
Fit model	0.24%
Emittance change correction	0.21%
DCCT calibration	0.20%
Ghost and satellite charge correction	0.17%
Background subtraction method	0.06%
Orbit drift correction (arcBPMs vs DOROS BPMs)	0.06%
Length scale calibration	0.03%
FBCT versus BPTX	0.01%
Statistical uncertainty	0.01%
Subtotal vdM calibration	1.45%

Table 6.18: Summary of systematic uncertainties for the absolute luminosity calibration in 2022 in percentage. The total uncertainty for this part is given at the bottom of the plot.

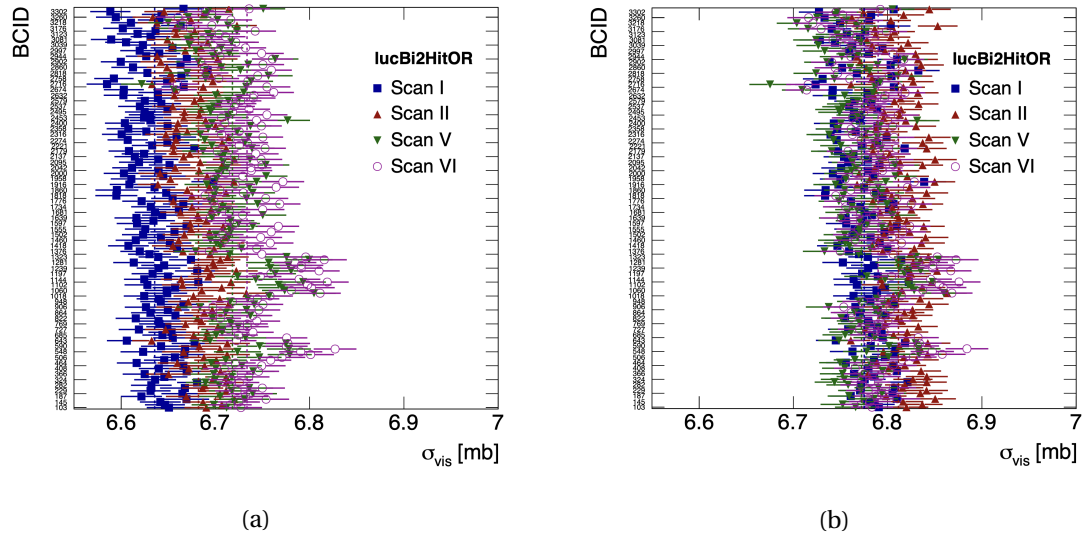


Figure 6.27: The visible cross-section as a function of BCIDs for the four on-axis scans after all corrections except the non-factorisation correction: (a) before non-factorisation correction, and (b) after non-factorisation correction.

6.3 Calibration transfer

As discussed in section 6.2.5, van der Meer scans are taken in special beam conditions: isolated low-intensity bunches, with low pileup, and no crossing angle between the beams. However, physics data are taken in different beam conditions called "physics conditions". These distinguish themselves from the vdM conditions by having high-intensity bunch trains, with a high number of bunches and high pileup, and a crossing angle between the beams.

6.3.1 Calibration transfer correction

To use the absolute luminosity calibration obtained in vdM conditions, a calibration transfer needs to be performed [133]. The reasons for the calibration transfer are summarised visually in figure 6.28.

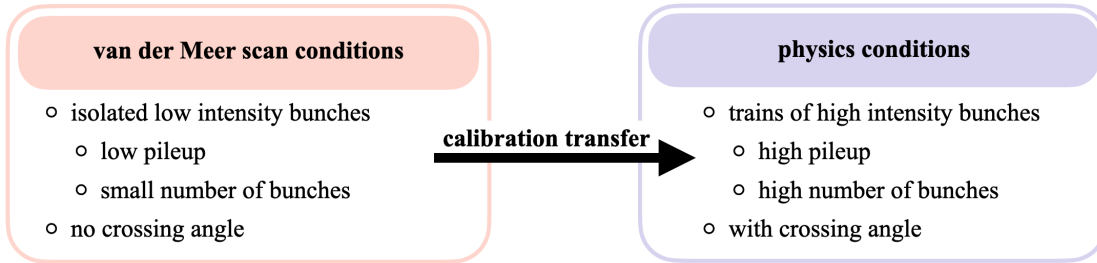


Figure 6.28: Schematic summary of the reasons for the calibration transfer.

The pileup difference between vdM scan conditions and physics conditions is illustrated in figure 6.29. The pileup distribution of physics runs over different years is shown in comparison to the vdM conditions, which have an average number of interactions per bunch-crossing of the order of unity.

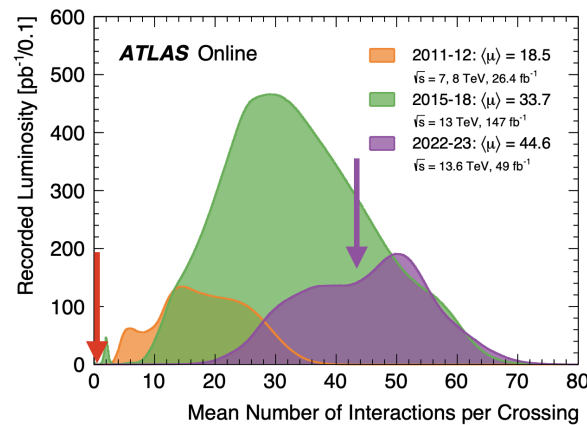


Figure 6.29: Pileup distribution for physics data taking in the different years. The vdM scan conditions are illustrated with a red arrow [149].

It can be seen that over a year, fills with a large variety of pileups are performed, e.g. in 2022-2023 the pileup ranges from ~ 20 to ~ 70 with an average value of ~ 45 . Consequently, the calibration transfer needs to be applied continuously as a function of pileup, due to the luminosity decaying over time. The LUCID dependency on pileup is significantly non-linear and the LUCID measurement needs to be corrected downward for higher pileup: LUCID overestimates the luminosity by an order of 10% in physics conditions.

Track-counting is used to calibrate LUCID at different pileup values, since it is known to behave linearly as a function of pileup. The track-counting luminosity measurement is normalised to the LUCID one in the quite vdM periods. To calibrate LUCID, a run with a long luminosity decay is used, since it gives access to measurement conditions with a large range of average number of interactions per bunch-crossing ($\mu \sim 30 - 50$).

The ratio of track-counting to LUCID luminosity is plotted as a function of pileup in figure 6.30^{IV}. Due to its normalisation to LUCID, the ratio is assumed to be unity around $\mu \sim 1$ with isolated bunches and no crossing angle. The calibration transfer does absorb the order of 1% difference between conditions with isolated bunches and no crossing angle, and conditions with bunch trains and crossing angle.

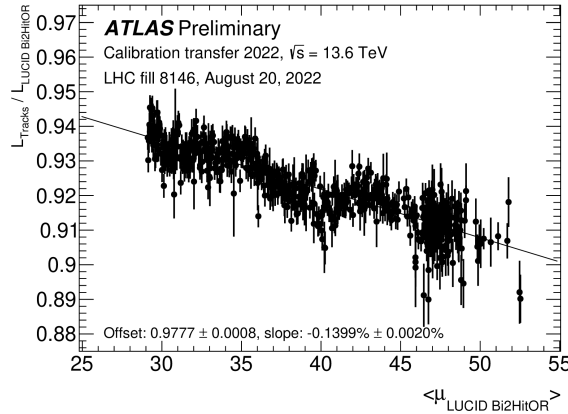


Figure 6.30: Ratio of LUCID to track-counting luminosity as a function of the average inelastic interaction rate extracted from LUCID [140].

A linear fit to this ratio is used to extract the calibration transfer for LUCID for all pileup conditions in physics running. This linear relation of the ratio can be expressed as a LUCID correction

$$\frac{\langle \mu_{\text{corr}} \rangle}{\langle \mu_{\text{uncorr}} \rangle} = p_0 + p_1 \langle \mu_{\text{uncorr}} \rangle, \quad (6.52)$$

where $\langle \mu_{\text{corr}} \rangle$ is the corrected, and $\langle \mu_{\text{uncorr}} \rangle = \mu_{\text{inel}}$ is the uncorrected LUCID pileup value, which is obtained by using the relations $\mu_{\text{vis}} = \epsilon \mu_{\text{inel}}$ and $\sigma_{\text{vis}} = \epsilon \sigma_{\text{inel}}$, with $\sigma_{\text{inel}} = 80$ mb. This correction could in theory be obtained for each bunch individually, however, since physics

^{IV}This is work performed by Vincent Hedberg, Antonio Sbrizzi and Giulia Ripellino.

analyses use the data from all LHC bunches, the average correction is sufficient and therefore there is no need for a per bunch calibration transfer.

6.3.2 Calibration transfer uncertainty

The calibration transfer method assumes that the track-counting luminosity measurement does not suffer from any significant non-linearity with increasing μ , when crossing angle and bunch trains are used instead of isolated bunches and no crossing angle. From Run 2, it is known that any such non-linear dependency is smaller than 1%. However, this is a significant contribution to the sub-percentage aim in precision for the luminosity determination, and thus needs to be taken into account properly by a corresponding calibration transfer uncertainty.

This uncertainty is obtained by comparing track-counting luminosity to calorimeter luminosity, since the latter is known to be very linear as a function of pileup, and thus ideal to cross-check the linearity assumption of track-counting [133].

The plots and results presented in this section are taken from [140]^V. From the calorimeter luminosity measurements at disposal, only tile calorimeter is sensitive at low- μ and can be used for this cross-check. In particular, the following tile calorimeter cells are used: E3, E4, A13 and A14.

Tile is calibrated to LUCID in the quite vdM periods while ATLAS is having head-on collisions. The calibration transfer uncertainty is obtained by comparing the tile calorimeter luminosity measurement with the track-counting one. This can be expressed as a double ratio

$$R_{\text{tile/trk}}^{\text{phy/vdM}} = \frac{R_{\text{tile/trk}}(\text{phy})}{R_{\text{tile/trk}}(\text{vdM})}, \quad (6.53)$$

where $R_{\text{tile/trk}}(\text{phy})$ is the ratio of tile calorimeter luminosity over track-counting luminosity in physics conditions, and $R_{\text{tile/trk}}(\text{vdM})$ is the ratio of tile calorimeter luminosity over track-counting luminosity in vdM scan conditions.

Unfortunately, tile calorimeter suffers from significant activation of the material. The activation of the material decays to a negligible level with various time constants ranging from minutes to several days. For this reason, the vdM fills are carefully scheduled after pauses in the LHC running schedule, such as a technical stop, to minimize this activation problem.

The tile calorimeter activation can be modelled empirically based on the radioactive decay of isotopes produced in interactions of particles with the detector material. The decay of these isotopes over time gives origin to a luminosity signal in the detector. Due to this fact, the tile calorimeter still sees some luminosity after a beam dump. The activation signal from a single

^VThis is work performed by Richard Hawkings and Giulia Ripellino.

source can be expressed as

$$L_{\text{inst}}^{\text{act}} = \Delta t L_{\text{inst}}^{\text{ref}} \frac{f}{\tau} e^{-t\tau}, \quad (6.54)$$

where $L_{\text{inst}}^{\text{act}}$ is the activation signal in tile calorimeter cells after some time t , $L_{\text{inst}}^{\text{ref}}$ the instantaneous LUCID luminosity (with calibration transfer applied), τ the lifetime of the isotope, Δt the duration of a LB, and f the strength of the activation induced signal with respect to $L_{\text{inst}}^{\text{ref}}$. The full activation model is composed of several such decay models for different isotopes (i.e. several τ_i and f_i). For the preliminary calibration transfer uncertainty estimation of 2022, only two such components are taken into account. It has been shown in Run 2, that two components provide a good enough estimation of tile calorimeter activation.

The activation corrected tile calorimeter luminosity can be expressed as

$$L_{\text{int}}^{\text{corr}} = L_{\text{int}}^{\text{calo}} - L_{\text{int}}^{\text{act}} - P\Delta t, \quad (6.55)$$

where $L_{\text{int}}^{\text{calo}}$ is the uncorrected integrated tile calorimeter measurement and P is a pedestal correction.

The relation between the corrected tile calorimeter and track-counting luminosities is given by

$$\frac{L_{\text{int}}^{\text{corr}}}{L_{\text{int}}^{\text{trk}}} = p_0 + \langle\mu\rangle p_1, \quad (6.56)$$

where $L_{\text{int}}^{\text{trk}}$ is the track-counting integrated luminosity, integrated over a LB, and $\langle\mu\rangle$ is the average pileup measured using track-counting.

This above linear relation is fit to the ratio distribution over a fill by minimizing the following quantity

$$\chi^2 = \sum \left(\frac{(L_{\text{int}}^{\text{calo}} - L_{\text{int}}^{\text{act}} - P\Delta t - L_{\text{int}}^{\text{trk}}(p_0 + \langle\mu\rangle p_1))^2}{\sigma_{L_{\text{int}}^{\text{calo}}}^2 + \sigma_{L_{\text{int}}^{\text{trk}}}^2} \right), \quad (6.57)$$

where $\sigma_{L_{\text{int}}^{\text{calo}}}$ is the per-LB uncertainty in the luminosity measurement of tile calorimeter, $\sigma_{L_{\text{int}}^{\text{trk}}}$ is the per-LB uncertainty in the luminosity measurement of track-counting and the sum is taken over all LBs for which both track-counting and tile calorimeter measurements are available.

In 2022, a dedicated "calibration transfer" fill (CT fill) was performed. This CT fill has vdM-like conditions with only 140 isolated colliding bunches, after a period without high luminosity. However, it has low β^* and the usual physics beam crossing angle. During a CT fill, the beams are separated to produce low- μ conditions similar to the vdM conditions for a few hours. Afterwards, the beams are brought head-on and then separated again. This is called a μ -scan because it gives access to a large range of μ values. In the end of the CT fill, a few hours of head-on collisions (high- μ) are taken.

The CT fill is used to estimate the ratio of equation 6.53 using tile calorimeter activation-corrected luminosity measurement. These ratios can be found in table 6.19 and vary up to

1.1% between different tile calorimeter cells.

The residual difference observed in table 6.19 between tile calorimeter and track-counting needs further studies and it is assumed as an upper limit on the uncertainty for the preliminary luminosity determination.

Side	Cell	p_0 ratio
A	E3	1.015
C	E3	1.016
A	E4	1.025
C	E4	1.029
A	A13	1.015
C	A13	1.011
A	A14	1.016
C	A14	1.018

Table 6.19: *Ratio of the tile calorimeter activation-corrected luminosity measurement to the track-counting luminosity in the CT fill for different tile calorimeter cells.*

Further cross-checks of track-counting linearity assumption are performed by looking at high- μ fills with bunch trains. For this, a 144 BCID fill and two 1154 BCID fills are considered. All three have the usual physics conditions involving crossing angle, high luminosity, and bunch trains.

For the three high- μ fills, the activation parameters from the CT fill and a p_1 value of zero are assumed (equation 6.56). Only p_0 is a free parameter in these fits. For the two runs with 1154 BCIDs, only tile calorimeter A-cells can be used, since the response of E-cells is not reliable at high luminosity due to scintillator ageing. The double ratio of p_0 between the three fills and the CT fill is shown in table 6.20.

		144-fill	1154-fill 1	1154-fill 2
Side	Cell	p_0		
A	E3	1.004	-	-
C	E3	1.007	-	-
A	E4	1.007	-	-
C	E4	1.005	-	-
A	A13	1.003	1.005	1.002
C	A13	1.005	1.008	1.006
A	A14	1.001	1.004	1.000
C	A14	1.005	1.002	0.999

Table 6.20: *Tile double ratio for the three high- μ fills.*

The first fill shows a variation of up to 0.7%, the second up to 0.08%, and the third up to 0.6%.

The same procedure is repeated without using activation correction in the high- μ fills. In that case, the double ratio varies up to 1.1%.

In addition, A-cells suffer from PMT gain increase due to high luminosity, leading to overestimation of the luminosity. This effect can be monitored by periodically injecting laser pulses directly into the PMTs and monitoring the response of the scintillators. The laser is fired at a time when no bunches pass through the ATLAS interaction point. The signal obtained through this process for A-cells is compared to D-cells, which are known to have very stable PMT gain. A correction called "laser correction" can be obtained through this comparison to correct the A-cells. This is not estimated yet for 2022, thus an upper limit of the correction is taken as an additional uncertainty and amounts to $\sim 0.5\%$ for A-cells [133].

This uncertainty of $\sim 0.5\%$ is summed linearly with the largest variation in double ratio of p_0 between the three fills and the CT fill, 1.1%. The resulting total calibration transfer uncertainty is found to be 1.5%.

6.4 Stability of the luminosity determination

Once the absolute luminosity calibration and the corresponding calibration transfer is finished, it is important to cross-check the stability of the luminosity determination over time. For this, the calorimeter luminosity and track-counting luminosity are compared to the preferred LUCID algorithm in the different fills in a year.

The plots and results presented in this section are taken from [140] ^{VI}.

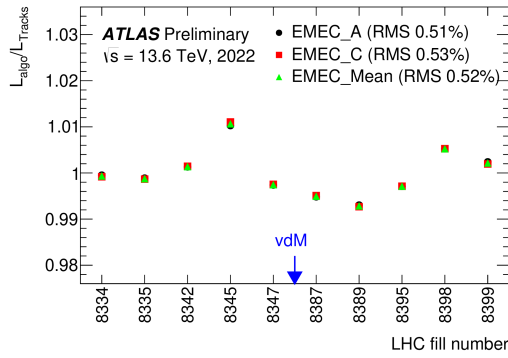
First, the calorimeter luminosity is anchored to track-counting. This is done in the ten fills closest in time to the vdM fill. The ratios of the electromagnetic endcap calorimeter (EMEC) and the electromagnetic forward calorimeter (FCal) to track-counting are shown in figure 6.31.

Each point in the plot is the ratio of the integrated luminosity of the corresponding fill between the calorimeter luminosity measurement and track-counting luminosity. The ratios are normalised such that the average over all ten fills is one. In the legend, the RMS for each case is shown. The largest RMS between the different calorimeters is taken as the "anchoring uncertainty" and amounts to 0.53%.

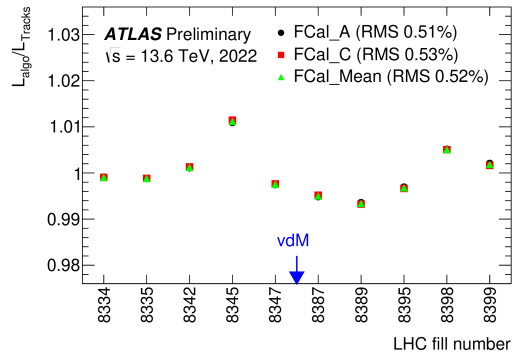
Once the calorimeter luminosity is anchored to track-counting, the evolution of their luminosity ratio to the preferred LUCID algorithm can be plotted for all runs of the year passing data-quality requirements. This ratio is shown in figure 6.32.

Figure 6.33 shows the distributions of the relative differences between calorimeter or track-counting and LUCID luminosity, weighted by the integrated luminosity in each fill. The mean and RMS values are indicated in the plots. The largest mean deviation from zero is taken as the long-term stability uncertainty, and amounts to 0.41%.

^{VI}This is work performed by Antonio Sbrizzi and Vincent Hedberg.



(a)



(b)

Figure 6.31: Anchoring of calorimeter luminosity to track-counting [140]: (a) electromagnetic endcap calorimeter, and (b) electromagnetic forward calorimeter.

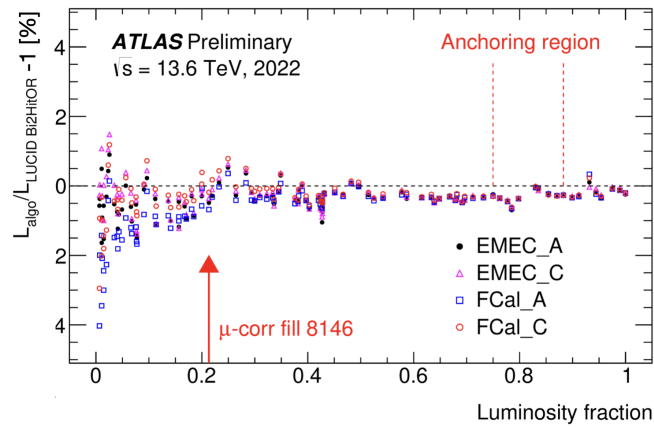


Figure 6.32: Stability of the luminosity calibration [140].

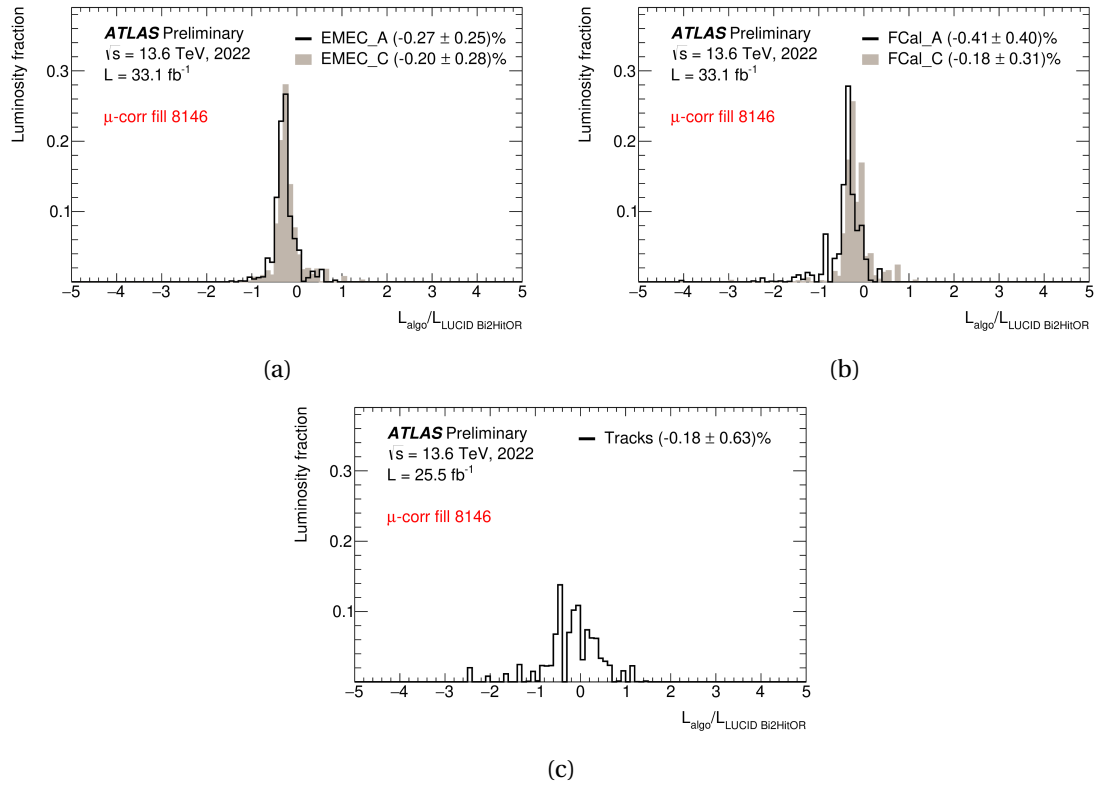


Figure 6.33: Distributions of the relative differences to the preferred LUCID algorithm [140]: (a) electromagnetic encap calorimeter, (b) electromagnetic forward calorimeter, and (c) track-counting.

6.5 Results

All the uncertainties contributing to the total preliminary luminosity determination of Run 3 in 2022 are summarised in table 6.21. The contributions of the calibration transfer, the calibration anchoring and the long-term stability are shown in the lower part of the table. In this preliminary luminosity determination, the calibration transfer, is the largest contribution to the total uncertainty. Usually, the main contribution comes from the vdM part.

Data sample	2022
Non-factorisation effects	1.07%
Bunch-by-bunch σ_{vis} consistency	0.50%
Luminosity consistency between algorithms and luminometers	0.43%
Beam-beam corrections	0.35%
Magnetic non-linearity	0.32%
Scan-to-scan consistency	0.27%
Inner detector length scale	0.24%
Fit model	0.24%
Emittance change correction	0.21%
DCCT calibration	0.20%
Ghost and satellite charge correction	0.17%
Background subtraction method	0.06%
Orbit drift correction (arcBPMs vs DOROS BPMs)	0.06%
Length scale calibration	0.03%
FBCT versus BPTX	0.01%
Statistical uncertainty	0.01%
Subtotal vdM calibration	1.45%
Calibration transfer	1.50%
Calibration anchoring	0.53%
Long-term stability	0.41%
Total uncertainty	2.19%

Table 6.21: *Summary of systematic uncertainties for the full luminosity determination in ATLAS 2022 in percentage.*

7 Measurement of the Run 3 $t\bar{t}$ cross-section and $t\bar{t}/Z$ ratio

The subject of the analysis presented in this thesis is the measurement of the early Run 3 $t\bar{t}$ cross-section and $t\bar{t}/Z$ ratio of cross-sections with the ATLAS experiment at the LHC with proton-proton collisions at a centre-of-mass energy of 13.6 TeV. The final state of the $t\bar{t}$ process in this analysis, shown in figure 7.1, consists of two b -jets, an electron, a muon, and two neutrinos, where the two leptons have opposite electric charge.

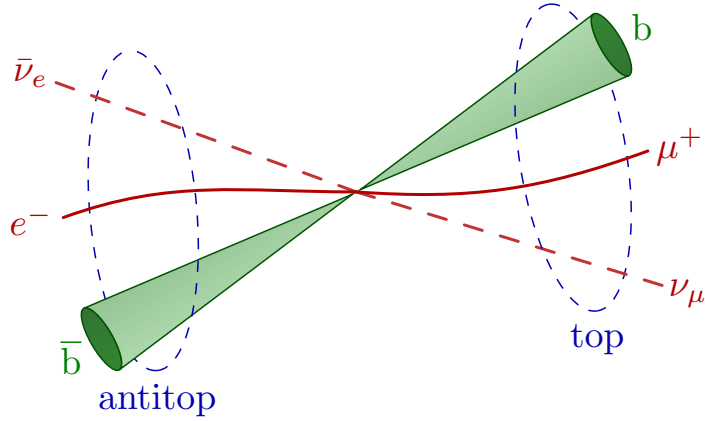


Figure 7.1: Visual representation of the final state for this analysis: two b -jets, two opposite charged leptons with different flavour, and two neutrinos [150].

7.1 Analysis strategy

7.1.1 $t\bar{t}$ cross-section

The $t\bar{t}$ cross-section is measured with the b -jet counting method [151, 152]. The idea behind this method is to count the amount of events passing the event selection ($N_{\geq 0}$), and having exactly one b -tagged jet (N_1), or exactly two b -tagged jets (N_2). Then, through a simultaneous fit of the two regions N_1 and N_2 , the inclusive $t\bar{t}$ cross-section and the b -jet efficiency can be

measured in data. The advantage of this method lies in the in-situ measurements of the b -jet efficiency, since jet and b -tagging related uncertainties are usually large, especially in early measurements, given that precise calibrations are not available early in the data-taking.

7.1.2 Derivation of the method

The methodology of the b -jet counting method is described in this section. The amount of predicted events passing the event selection without any b -jet requirements is given by

$$N_{\geq 0} = \mathcal{L} \sigma_{t\bar{t}} \epsilon_{e\mu}, \quad (7.1)$$

where $\mathcal{L}$ is the integrated luminosity, $\sigma_{t\bar{t}}$ is the predicted cross-section, $\epsilon_{e\mu}$ is the efficiency of selecting an event in the $e\mu$ region determined in MC.

The number of b -jets for a born level signal is given by

$$N_b = (\mathcal{L} \sigma_{t\bar{t}} \epsilon_{e\mu}) \epsilon_b + (\mathcal{L} \sigma_{t\bar{t}} \epsilon_{e\mu}) \epsilon_b = 2 (\mathcal{L} \sigma_{t\bar{t}} \epsilon_{e\mu}) \epsilon_b = N_1 + 2N_2. \quad (7.2)$$

where N_1 is the number of events with exactly one b -jet and N_2 is the number of events with exactly two b -jets. The number of events with exactly two b -jets can be written as

$$N_2 = (\mathcal{L} \sigma_{t\bar{t}} \epsilon_{e\mu}) \epsilon_{bb}, \quad (7.3)$$

where ϵ_{bb} is the efficiency of tagging simultaneously two b -jets.

The number of events with exactly one b -tagged jet is then given by

$$\begin{aligned} N_1 &= N_b - 2N_2 \\ &= 2 (\mathcal{L} \sigma_{t\bar{t}} \epsilon_{e\mu}) (\epsilon_b - \epsilon_{bb}). \end{aligned} \quad (7.4)$$

The efficiency of tagging simultaneously two b -jets (ϵ_{bb}) is not exactly equivalent to tagging two separate b -jets independently from each other (ϵ_b^2). The correlation factor C_b corrects this difference as $C_b = \epsilon_{bb}/\epsilon_b^2$. This correlation factor's value lies close to unity and is obtained from MC simulation. Using C_b , the above equations can be written as

$$\begin{aligned} N_1 &= 2 (\mathcal{L} \sigma_{t\bar{t}} \epsilon_{e\mu}) \epsilon_b (1 - C_b \epsilon_b), \\ N_2 &= (\mathcal{L} \sigma_{t\bar{t}} \epsilon_{e\mu}) C_b \epsilon_b^2. \end{aligned} \quad (7.5)$$

The backgrounds components can be taken into account as

$$\begin{aligned} N_1 &= 2 (\mathcal{L} \sigma_{t\bar{t}} \epsilon_{e\mu}) \epsilon_b (1 - C_b \epsilon_b) + N_1^{\text{bkg}}, \\ N_2 &= (\mathcal{L} \sigma_{t\bar{t}} \epsilon_{e\mu}) C_b \epsilon_b^2 + N_2^{\text{bkg}}, \end{aligned} \quad (7.6)$$

where N_1^{bkg} is the sum of all backgrounds in the first region and N_2^{bkg} is the sum of all backgrounds in the second region. For practical reasons, the free parameter in the fit is the signal strength μ defined as $\mu_{t\bar{t}} = \sigma_{t\bar{t}}^{\text{meas.}} / \sigma_{t\bar{t}}^{\text{pred.}}$ and not the $t\bar{t}$ cross-section. The above equations then become

$$\begin{aligned} N_1 &= \mu_{t\bar{t}} N_{\geq 0}^{\text{pred.}} 2\epsilon_b(1 - C_b\epsilon_b) + N_1^{\text{bkg}}, \\ N_2 &= \mu_{t\bar{t}} N_{\geq 0}^{\text{pred.}} C_b\epsilon_b^2 + N_2^{\text{bkg}}, \end{aligned} \quad (7.7)$$

where $N_{\geq 0}^{\text{pred.}} = \mathcal{L}\sigma_{t\bar{t}}^{\text{pred.}}\epsilon_{e\mu}$.

7.1.3 Z cross-sections

The Z cross-section is measured in the opposite-sign same-flavour channels, i.e. in the ee and $\mu\mu$ channels. For these two signal regions a dilepton mass cut around the Z mass, $66 < m_{ll} < 116$ GeV with $l = e, \mu$, is applied to reduce the background.

The number of events of the Z process in the signal regions are given by

$$\begin{aligned} N_{ee} &= \mathcal{L}\sigma_Z\epsilon_{ee} + N_{ee}^{\text{bkg}}, \\ N_{\mu\mu} &= \mathcal{L}\sigma_Z\epsilon_{\mu\mu} + N_{\mu\mu}^{\text{bkg}}, \end{aligned} \quad (7.8)$$

where N_{ll} is the number of events passing the selection, and ϵ_{ll} is the event selection efficiency. With the Z signal strength $\mu_Z = \sigma_Z^{\text{meas.}} / \sigma_Z^{\text{pred.}}$ the above two equations can be re-written as

$$\begin{aligned} N_{ee} &= \mu_Z N_{ee}^{\text{pred.}} + N_{ee}^{\text{bkg}}, \\ N_{\mu\mu} &= \mu_Z N_{\mu\mu}^{\text{pred.}} + N_{\mu\mu}^{\text{bkg}}, \end{aligned} \quad (7.9)$$

where $N_{ll}^{\text{pred.}} = \mathcal{L}\sigma_Z^{\text{pred.}}\epsilon_{ll}$ with $l = e, \mu$.

7.1.4 $t\bar{t}/Z$ ratio of cross-section

To extract the ratio of $t\bar{t}$ and Z cross-section a combined fit of $t\bar{t}$ and Z regions is performed. This allows to take into account all the correlations between them correctly. Separate fits are also performed to cross-check the uncertainties in the Z regions.

7.2 Statistical analysis

In this section the statistical method used is presented based on the example of a $t\bar{t}$ cross-section only fit. The equations obtained at the end of the b -jet counting method (equation 7.7) have two free parameters, which are the signal strength $\mu_{t\bar{t}}$ and the b -jet efficiency ϵ_b , and N_1 and N_2 are the data yields. In this analysis a profile likelihood fit is performed to find the best-fit parameters of the model.

Likelihood is used to quantify the agreement between the model's prediction and data, or said differently how likely is it to observe the data, given the parameter set of the model. This is expressed as

$$L(\mathbf{d}, \mathbf{M}(\mu, \epsilon_b)) = \prod_{i \in \text{bins}} P(d_i | M_i(\mu, \epsilon_b)), \quad (7.10)$$

where $\mathbf{d}$ is the set of data yields (N_1, N_2), $\mathbf{M}$ are the predicted yields μ, ϵ_b are the free parameters of the model, and P represents a Poisson distribution. This distribution is an exact description of the measurement since yields are measured. For large counting rates it can be well modelled by a Gaussian distribution. The goal is, for a given model, to find the best parameter set to describe the data. This is done by maximizing the likelihood function

$$\max(L(\mathbf{d}, \mathbf{M}(\mu, \epsilon_b))) \Rightarrow \text{best set of parameters.} \quad (7.11)$$

In practice, it is easier to minimize the negative log-likelihood

$$\min(-\ln L(\mathbf{d}, \mathbf{M}(\mu, \epsilon_b))) \Rightarrow \text{best set of parameters.} \quad (7.12)$$

This is equivalent to maximizing the likelihood but numerically more precise. The negative log-likelihood is then

$$-\ln L(\mathbf{d}, \mathbf{M}(\mu, \epsilon_b)) = - \sum_{i \in \text{bins}} \ln(P(d_i | \mathbf{M}(\mu, \epsilon_b))), \quad (7.13)$$

where in this case there are only two bins, N_1 and N_2 . All the bins are simultaneously fit with the same model parameters.

Expanding the prediction into the signal and background yields, $M_i(\mu, \epsilon_b) = \mu s_i(\epsilon_b) + b_i$, equation 7.13 becomes

$$-\ln L(\mathbf{d}, \mathbf{M}(\mu, \epsilon_b)) = - \sum_{i \in \text{bins}} \ln(P(d_i | \mu s_i(\epsilon_b) + b_i)), \quad (7.14)$$

where b_i is the sum of all expected backgrounds in bin i , s_i is the expected signal, and μ is the signal strength.

The last step is to add systematic uncertainties. Systematic uncertainties attempt to describe the limited knowledge of input parameters. These systematic effects are captured in the

nuisance parameters (NP). The signal and background predictions depend on these nuisance parameters. When including systematic uncertainties, the profile likelihood is written as

$$-\ln L(\mathbf{d}, \mathbf{M}(\mu, \epsilon_b, \boldsymbol{\theta})) = - \sum_{i \in \text{bins}} \ln(P(d_i | \mu s_i(\epsilon_b, \boldsymbol{\theta}) + b_i(\boldsymbol{\theta}))), \quad (7.15)$$

where $\boldsymbol{\theta} = \theta_1, \theta_2, \theta_3, \dots$ are the nuisance parameters.

NPs are constrained through a Gaussian distribution. The Gaussians are normalised in the fit to a Gaussian with mean zero and unit variance. The likelihood function is then written as

$$-\ln L(\mathbf{d}, \mathbf{M}(\mu, \epsilon_b, \boldsymbol{\theta})) = - \sum_{i \in \text{bins}} \ln(P(d_i | \mu s_i(\epsilon_b, \boldsymbol{\theta}) + b_i(\boldsymbol{\theta}))) - \sum_{j \in \text{NPs}} \ln(G(\theta_j)), \quad (7.16)$$

where $G(\theta_j)$ is a Gaussian with central value 0 and a width 1.

7.3 Event selections

The event selection starts by choosing the appropriate triggers for the analysis, in this case single-lepton unprescaled triggers are used. The selected triggers with lowest p_T threshold have a threshold at 26 GeV for electrons and 24 GeV for muons. Once the event passes a trigger, the objects are fully reconstructed and required to pass object selection as explained in Chapter 2. Afterwards, an event selection is applied to reject background.

The event selection requires the events to have exactly two leptons with opposite electric charge. For this analysis this means that the possible final states are e^-e^+ , $\mu^-\mu^+$, $e^-\mu^+$ and $e^+\mu^-$. Final states with hadronically-decaying tau leptons are not taken into account and their contribution is estimated to be negligible in this analysis. Leptonically-decaying tau leptons cannot be distinguished from electrons or muons and are thus taken automatically into account.

For the $e\mu$ channel the events are required to have at least one jet with $p_T > 30$ GeV that is b -tagged. The $e\mu$ channel is consequently dominated by $t\bar{t}$ events. The same-flavour regions do not have any jet requirements, but have a cut around the Z mass to reduce background and are consequently dominated by Z signal events. The event selection is summarised in table 7.1.

	$e\mu$ 1b	$e\mu$ 2b	ee	$\mu\mu$
Trigger		Single-lepton unprescaled		
Number of leptons			2	
Opposite-sign leptons			Yes	
Same-flavour leptons		No		Yes
Number of jets		≥ 1		≥ 0
Number of b -tagged jets	= 1	= 2		≥ 0
Other			$66 < m_{ll} < 116$ GeV	

Table 7.1: *Event selection summary.*

7.4 Data and Monte Carlo samples

7.4.1 Data sample

The data analysed in this thesis were taken during 2022 with the ATLAS detector with proton-proton collisions at the centre-of-mass energy of 13.6 TeV. This dataset corresponds to an integrated luminosity of 29 fb^{-1} . The runs used are required to fulfil the ATLAS data quality control requirements [153].

7.4.2 Monte Carlo samples

For all MC samples $m_{\text{top}} = 172.5 \text{ GeV}$ is assumed unless specified differently. In the following sections, MC samples used for modelling of various processes are described in detail. The ME is usually available at LO or NLO. However, sometimes the impact of NNLO on the cross-section is non-negligible. For these cases, a correction factor is used to adjust the scale of the cross-section values.

$t\bar{t}$ samples Three different MC generators are used to simulate nominal $t\bar{t}$ events, POWHEG-BOX v2 [154–157] for the ME calculation, PYTHIA 8.307 [103] for PS, hadronisation and underlying event simulation, and EVTGEN 2.1.1 [106] for modelling the decays of charm and bottom hadrons. POWHEGBOX v2 at NLO with NNPDF3.0NLO PDF set [158] and the h_{damp} parameter set to $1.5m_{\text{top}}$ [159], is interfaced with PYTHIA with parameters set according to the A14 tune [160] using NNPDF2.3LO PDF set [161]. The h_{damp} parameter is a free modelling parameter that is tuned and controls the matching and merging between PS and ME. The $t\bar{t}$ sample is normalised to the predicted cross-section at NNLO in QCD including the resummation of NNLL soft-gluon terms calculated using Top++ 2.0 [32–38]. The predicted cross-section is $\sigma(t\bar{t})_{\text{NNLO+NNLL}} = 924^{+32}_{-40} \text{ pb}$ using the PDF4LHC21 [39] PDF set. The uncertainties include scale variations, α_s variation, and PDF set variations. The calculation of the theoretical uncertainties are described in reference [39].

Z samples $Z \rightarrow ll$ events are simulated using SHERPA 2.2.12 [90] at NLO ME for up to two partons and LO for up to five partons using COMIX [162] and OPENLOOPS [163–165] libraries. The SHERPA PS is matched using the MEPS@NLO prescription [166–169] and the set of tuned parameters developed by the SHERPA authors. The PDF set used is NNPDF3.0NNLO. The cross-sections are normalised to NNLO in QCD and NLO in EW using the PDF4LHC21 [39] PDF set calculated by the MATRIX program [55]. The decays $Z/\gamma^* \rightarrow ee, \mu\mu$ and $\tau\tau$ are simulated. For all, the MC generator and the prediction, leptons before QED radiation are used. The LO Z production Feynman diagram is shown in figure 7.2.

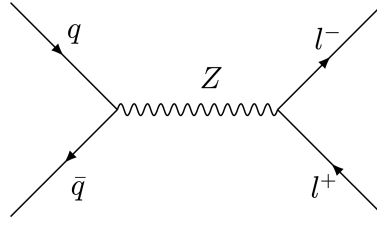


Figure 7.2: The LO Z production diagram starting with a quark-antiquark pair and decaying to a lepton-antilepton pair.

Single top produced in association with a W boson The single top Wt ME is simulated using POWHEGBOX v2 [102, 154–157] at NLO in the five flavour scheme [170] using the NNPDF3.0NLO [171] PDF set. The ME simulation is interfaced with PYTHIA 8.307 [103] using the A14 tune [160] and NNPDF2.3LO [161] PDF set for the PS and hadronisation modelling. The overlap and interference of Wt with the $t\bar{t}$ signal is removed using the diagram-removal scheme [172]. The number of events in the sample is normalised to the N^3 LO in QCD cross-section calculated using the MSTW2008 NNLO PDF set [26]. Wt production diagrams are shown in figure 7.3.

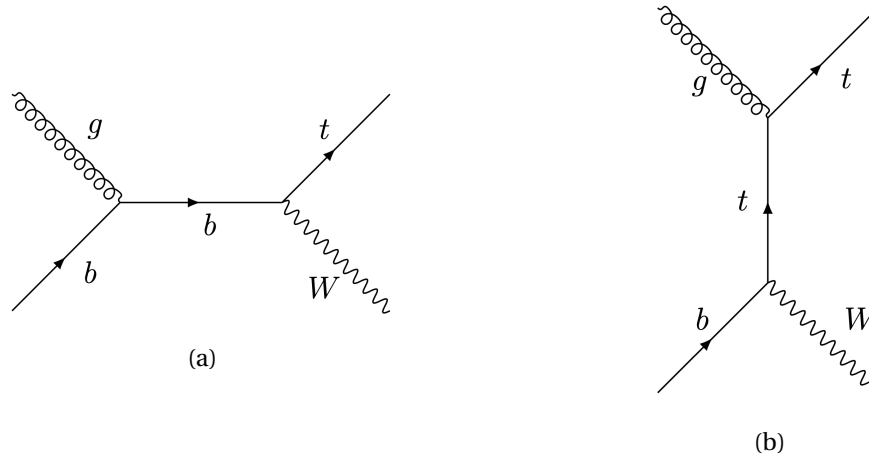


Figure 7.3: Feynman diagrams visualizing the Wt production at LO: (a) shows the s -channel, (b) the t -channel.

Single top samples The single top s - and t -channels MEs are simulated using POWHEGBOX v2 [102, 154–157] at NLO in the four flavour scheme [170] using the NNPDF3.0NLO [171] PDF set. The ME simulation is interfaced with PYTHIA 8.307 [103] using the A14 tune [160] and NNPDF2.3LO [161] PDF set for the PS and hadronisation modelling. The number of events in the samples are normalised to the NNLO in QCD predicted cross-sections using the MSTW2008 NNLO PDF set [26]. As an example the s -channel diagram is shown in figure 7.4.

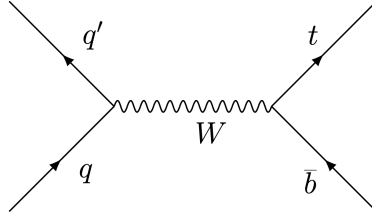


Figure 7.4: Feynman diagrams visualizing the single top production s -channel at LO.

Diboson samples Diboson events are generated using SHERPA 2.2.12 [90], including off-shell effects and Higgs boson contributions where appropriate. The ME is estimated at NLO for up to one additional parton emission and at LO for up to three additional parton emissions. The diboson sample cross-section is normalised to NNLO QCD prediction calculated using the MATRIX program [55]. Examples of LO Feynman diagrams are shown in figure 7.5.

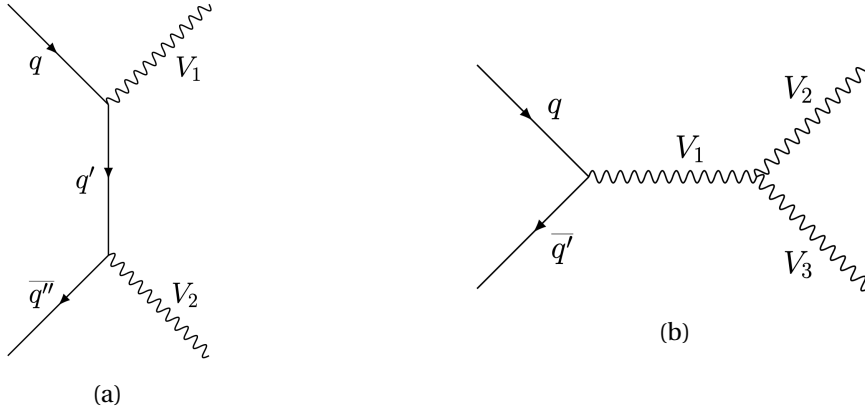
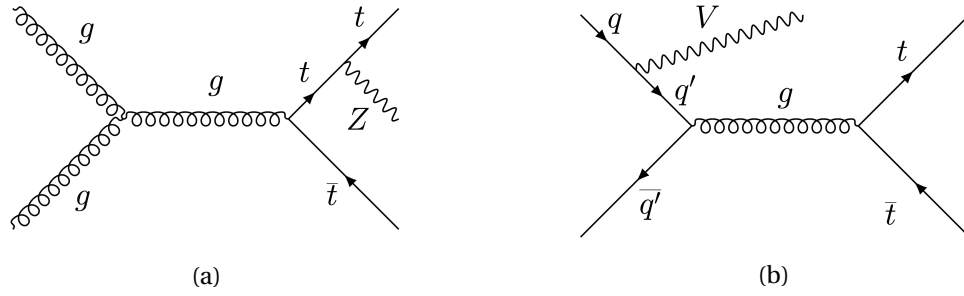


Figure 7.5: Examples of LO Feynman diagrams for the diboson background. (a) t -channel Feynman diagram with $V_1, V_2 \in W^\pm, Z$, (b) s -channel Feynman diagram.

$t\bar{t}V$ samples The $t\bar{t}V$ events are simulated using SHERPA 2.2.12. Example of Feynman diagrams contributing to this background are shown in figure 7.6.

Figure 7.6: Example Feynman diagrams contributing to the $t\bar{t}V$ background.

W+jets samples W+jets background events are simulated using SHERPA 2.2.12 [90] at NLO for up to two partons and LO for up to five partons using COMIX [162] and OPENLOOPS [163–165] libraries. The events are interfered with SHERPA for PS and hadronisation using the MEPS@NLO prescription [166–169]. The PDF set used is the NNPDF3.0NNLO PDF set. The sample is normalised to the cross-section at NNLO in QCD and NLO in EW produced with MATRIX [55] using the PDF4LHC21 [39] PDF set. Examples for Feynman diagrams contributing to this process are shown in figure 7.7.

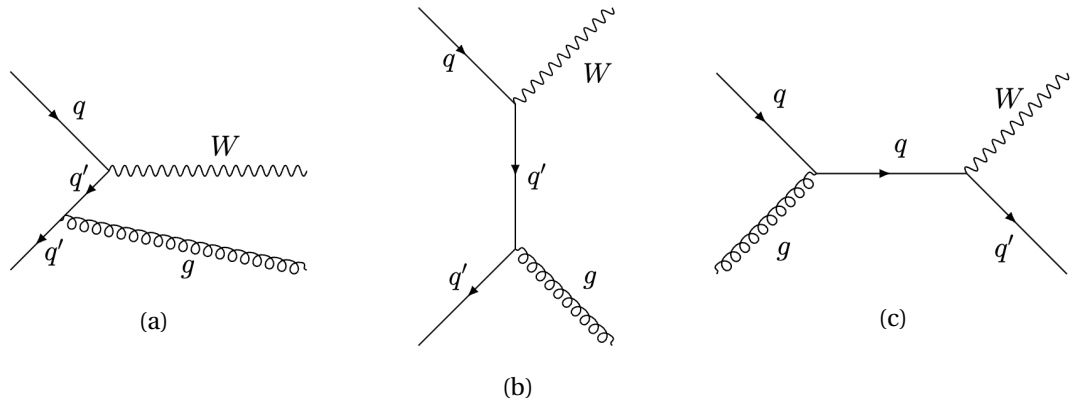


Figure 7.7: Example Feynman diagrams contributing to W+jets.

Pileup samples Multiple proton interactions inside a bunch-crossing are simulated using an overlay [173] of events generated with EPOS 2.0.1.4 [174, 175] using EPOS LHC tune and PYTHIA 8.307 using NNPDF2.3LO set of PDFs with the A3 tune [176]. Pileup reweighting is applied to the simulated samples to match the average number of interactions per bunch-crossing in data.

7.5 Misidentified leptons

Misidentified leptons are fake and non-prompt leptons. Fake leptons are non-leptons that are reconstructed and identified as leptons, an example of fake leptons are charged hadrons reconstructed as electrons. Non-prompt leptons are leptons not originating from the hard interaction but for example from heavy flavour decays.

The contribution of misidentified leptons in data is estimated using MC events with at least one prompt lepton. For every event in MC passing the selection it is checked if the two selected leptons are prompt. Events for which this is not the case are put all together in a *fake lepton* background. This has a small contribution to the total amount of events, only around 1% of events in the $e\mu$ channel and less than 0.1% of events in the same-flavour channels.

7.6 Yields

The signal and background yields for every region of the fit are shown in table 7.2. A better visualisation of the background contribution to the total signal is shown in the pie charts in figures 7.8 - 7.10, for the inclusive $e\mu$, $e\mu$ one b -tagged and $e\mu$ two b -tagged, and same-flavour regions respectively. The $e\mu$ inclusive region has around 22.8% background contribution to the total yield. Note that this region is not used in the analysis.

Process	Region				
	$e\mu$ inclusive	$e\mu$ 1b	$e\mu$ 2b	ee	$\mu\mu$
$t\bar{t}$	$177\,000 \pm 5\,000$	$87\,400 \pm 2\,600$	$52\,700 \pm 1\,600$	$22\,300 \pm 1\,200$	$33\,500 \pm 1\,900$
$Z \rightarrow l\bar{l}$	$13\,100 \pm 600$	270 ± 70	14.2 ± 3.0	$7\,749\,000 \pm 230\,000$	$14\,100\,000 \pm 400\,000$
Wt	$19\,000 \pm 9\,000$	$10\,200 \pm 700$	$1\,720 \pm 290$	$2\,250 \pm 120$	$3\,410 \pm 200$
Diboson	$17\,000 \pm 8\,000$	230 ± 120	5.3 ± 3.0	$9\,000 \pm 5\,000$	$18\,000 \pm 9\,000$
$t\bar{t}V$	220 ± 110	100 ± 50	69 ± 35	240 ± 120	250 ± 130
Misid. leptons	$2\,800 \pm 1\,400$	$1\,100 \pm 500$	500 ± 500	$6\,000 \pm 6\,000$	$6\,000 \pm 6\,000$
Total prediction	$229\,000 \pm 14\,000$	$99\,200 \pm 3\,000$	$55\,000 \pm 1\,700$	$7\,780\,000 \pm 230\,000$	$14\,100\,000 \pm 400\,000$
Data	222711	92385	50956	7812978	14242875

Table 7.2: Predicted and observed event yields in the different dilepton regions after event selection. Systematic uncertainties, representing all considered sources, are shown for the predicted yields.

The main background contribution is from single top Wt followed closely by the diboson background. The one b -tagged region has already much less background contribution to the total yield of only 12.0% and largely dominated by single top Wt . In the two b -tagged $e\mu$ region the background is as low as 4.2% of the total predicted events. The background is even lower for the same-flavour regions, it amounts for both to 0.4% of the total predicted yields.

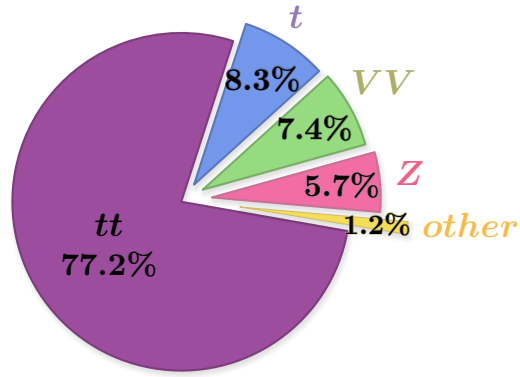


Figure 7.8: Relative contribution of signal and backgrounds in the inclusive $e\mu$ region.

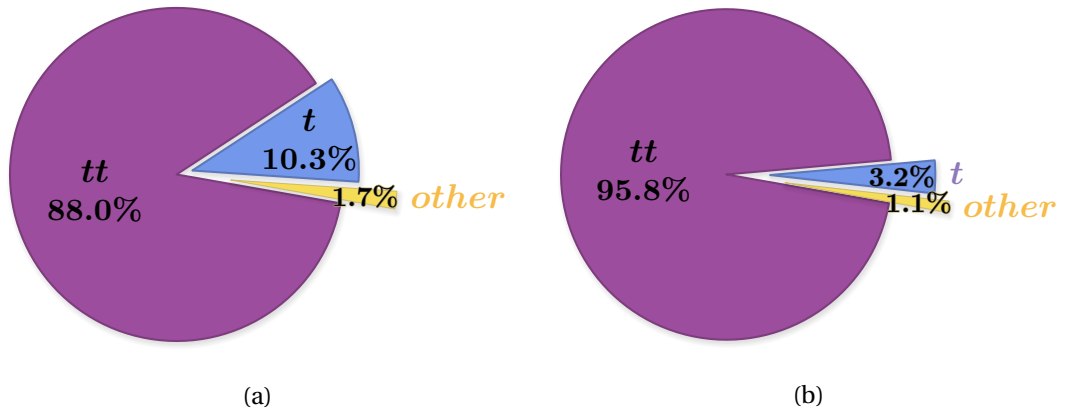


Figure 7.9: Relative contribution of signal and backgrounds in the one b -tagged (a), and two b -tagged (b) regions in the $e\mu$ channel.

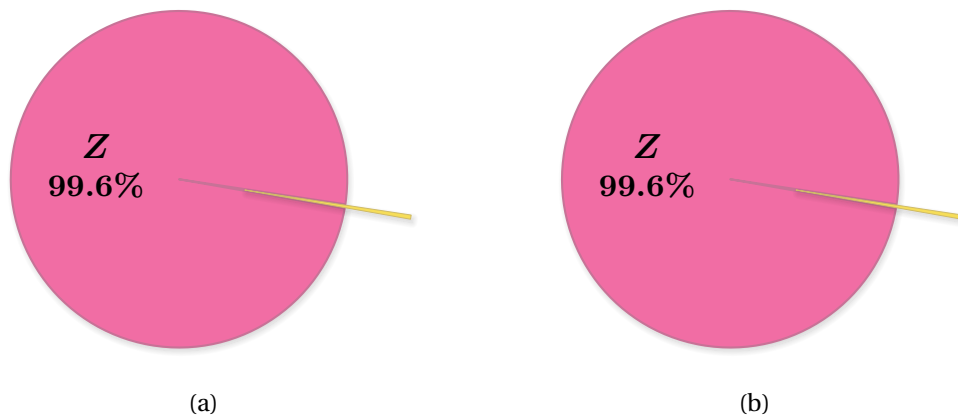


Figure 7.10: Relative contribution of signal and backgrounds in the ee (a), and $\mu\mu$ (b) regions.

7.7 Monte Carlo to data comparisons

In this section several data-to-MC comparisons are shown. Figure 7.11a shows the number of events as a function of number of b -tagged jets with 77% WP. It can be seen that most events are found with exactly one b -tagged jets, this is since not only the b -tag efficiency contributes but also the jet reconstruction efficiency. Notice that the signal dominates over the background in all the bins and that the largest background contribution is found in the 0-tagged region. Figure 7.11b shows the jet multiplicity without b -tagging requirements. Most events have exactly two jets. Figure 7.12 shows six data-to-MC comparison plots. Figure 7.12a shows the leading lepton p_T , i.e. the p_T of the lepton with highest p_T , in the $e\mu$ channel with events that have at least one b -tagged jet.

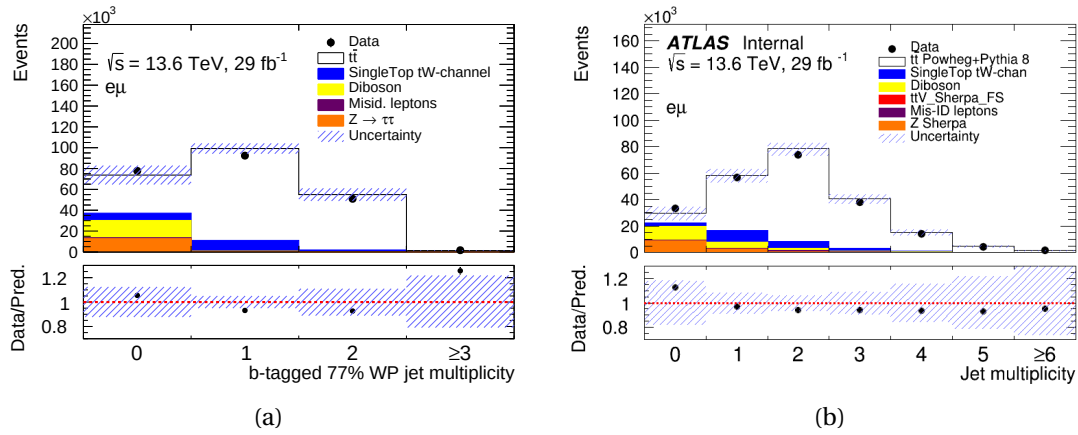
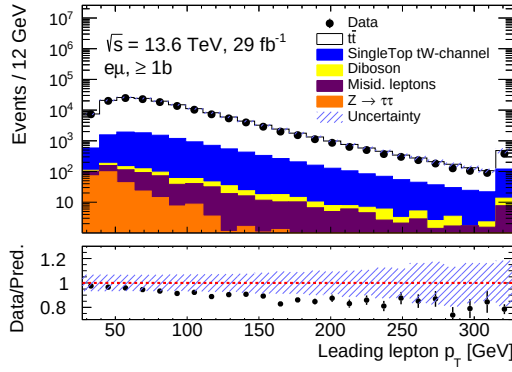
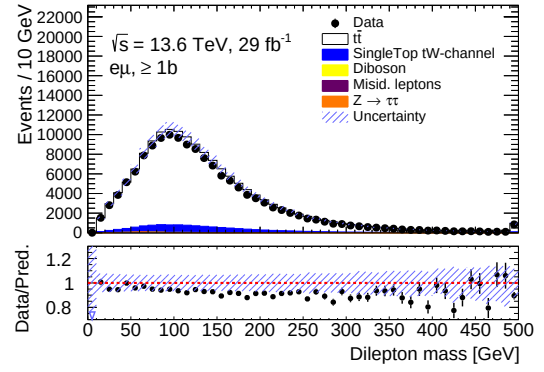


Figure 7.11: Data-to-MC comparison plots. (a) shows the number of b -jets in the event using WP 77%, (b) shows the number of jets in the event.

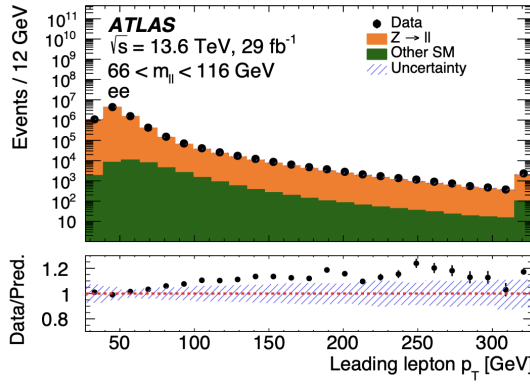
The last bin contains the overflow events. The lower part of the plot shows the ratio of data-to-MC prediction. The number of measured events is a bit lower than the predicted amount and there is a slight slope as a function of p_T . This slope is due to top p_T mis-modelling, which improves when adding higher order corrections. Note that the mis-modelling is covered by the uncertainty band, and that this disagreement is not important for this analysis since most of data lie in the low p_T region which is well modelled [177]. Figure 7.12b shows the dilepton mass distribution in the $e\mu$ channel with at least one b -tagged jet. The next two plots, figure 7.12c and figure 7.12d, show the leading lepton p_T and dilepton mass in the ee channel. This region is dominated $Z \rightarrow ee$ and the background is around three orders of magnitude smaller than the signal. Some data-to-MC discrepancies can be seen at high leading lepton p_T , due to $Z \rightarrow ll$ mis-modelling, which could be due at least in part to missing higher order corrections [178]. Figure 7.12e and figure 7.12f show the same as figure 7.12c and figure 7.12d but for the $\mu\mu$ channel.



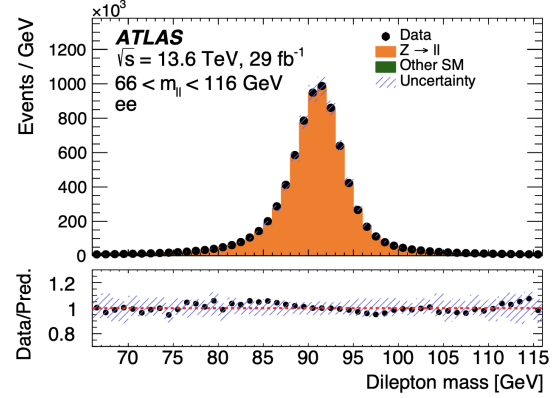
(a) Leading jet p_T in the $e\mu$ region with at least one b -tagged jet.



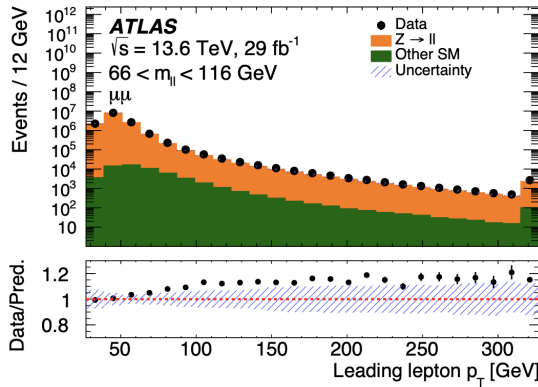
(b) Dilepton mass in the $e\mu$ region with at least one b -tagged jet.



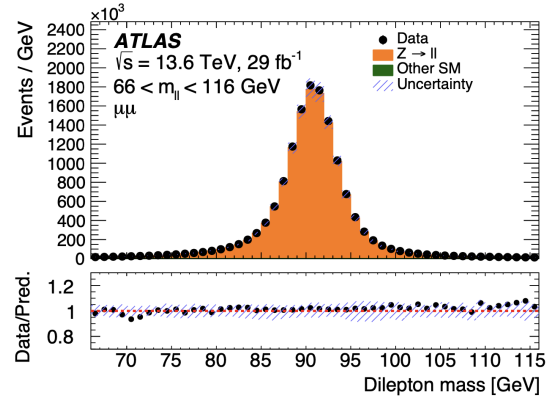
(c) Leading jet p_T in the ee region [179].



(d) Dilepton mass in the ee region [179].



(e) Leading lepton p_T in the $\mu\mu$ region [179].



(f) Dilepton mass in the $\mu\mu$ region [179].

Figure 7.12: Data-to-MC comparison for the different fit regions as a function of leading lepton p_T or dilepton mass.

7.8 Systematic uncertainties

Systematic uncertainties quantify the limited knowledge of input parameters in a measurement that are normally correlated between data-points.

The uncertainties can be divided into two major categories:

- **Experimental uncertainties:** these include luminosity and pileup related uncertainties, object uncertainties due to reconstruction, identification, isolation and calibration, and are described in section 7.8.1,
- **Theoretical uncertainties:** these include all uncertainties related to the computation of the cross-sections and the modelling of processes in MC simulations, as described in section 7.8.2.

The systematic uncertainties are propagated to the likelihood fit through Gaussian-constrained nuisance parameters.

7.8.1 Experimental uncertainties

Experimental uncertainties are defined as uncertainties related to the detector or the accelerator. They include uncertainties due to the calibration of objects, the luminosity precision and the number of average interactions in a bunch-crossing. These uncertainties can affect both the normalisation and the shape of the measured distributions.

Luminosity The preliminary luminosity uncertainty is 2.2% [140], i.e. the dataset corresponds to $(29.0 \pm 0.6) \text{ fb}^{-1}$ integrated luminosity. More details on the luminosity determination can be found in Chapter 6.

Pileup The number of pileup events is not well modelled since the simulation of soft interactions is not exact and an uncertainty in the tuning of the simulation needs to be taken into account. This uncertainty is obtained by varying the number of pileup events by 4% in the simulation.

Lepton uncertainties Lepton uncertainties are related to their trigger, reconstruction, identification, and isolation efficiency calibrations (SF). The calibration SFs have an uncertainty associated that is varied up and down to estimate their uncertainty contribution to the measured value [116, 119, 180]. On top of these, electrons (muons) also have an uncertainty associated with the energy (momentum) scale and resolution calibration.

For electrons, the Run 2 uncertainties on the energy corrections are used by inflating them to take into account the differences between Run 2 and Run 3 [116]. Similarly, the uncertainty on the identification scale factors are also estimated in Run 2 and inflated to use in Run 3.

Conservative uncertainties on the reconstruction and isolation SFs are assumed, which cover the difference between data and the central value of the SFs, which is set to unity for this preliminary calibration. The trigger uncertainties are measured in Run 3 data. For muons, the momentum correction uncertainties were derived using Run 3 data [180]. Muon efficiency calibration SFs have been estimated using Run 3 data following the procedure described in [119].

Jet and flavour tagging uncertainties These uncertainties have to be taken into account for the backgrounds, but are measured in-situ for the signal. Jet kinematics are impacted by JES [181] and JER [182]. These are estimated from Run 2 and any differences between Run 2 and Run 3 are taken into account. The differences between simulation and data in the NNJVT discriminant are taken into account by a 10% uncertainty per jet per event. Flavour uncertainties come from mistagging efficiency uncertainties for charm and light jets amounting to 20% and 40% respectively. The b -jet related uncertainties are only applied to the background processes and not to the $t\bar{t}$ signal since there the b -jet efficiency is measured directly in data.

7.8.2 Theoretical uncertainties

Uncertainties originating from the simulation of the processes used in the analysis are referred to as theoretical uncertainties. They include missing higher order corrections to the theoretical prediction of cross-sections, interference between processes and MC simulation uncertainties.

Parton shower and hadronisation This uncertainty takes into account the approximative PS modelling. The uncertainty is estimated by taking the difference between two generators with different PS models.

ISR and FSR The $t\bar{t}$ and single top ISR modelling uncertainty is estimated by varying the strong coupling constant, the variation of the Var3c A14 tune parameter, the factorisation and the renormalisation scales. The FSR uncertainty is obtained by varying the renormalisation scale used for FSR by changing α_s through the A14 eigentune setting.

$t\bar{t}$ signal The $t\bar{t}$ modelling uncertainty includes parton shower and hadronisation models uncertainties that are obtained by comparing the nominal $t\bar{t}$ sample with an alternative $t\bar{t}$ sample. In this case, the alternative sample is simulated with POWHEGBOX v2 using NNPDF3.0NLO PDF set and is interfaced with HERWIG 7.2.3 with the MMHT2014LO PDF set [183]. The h_{damp} is varied up by a factor 2 and its uncertainty is symmetrised. The top quark p_T mismodelling due to missing higher order corrections is obtained by comparing the nominal $t\bar{t}$ sample and a p_T reweighed sample. The p_T reweighing is done in this case according to the NNLO QCD top p_T prediction, computed with the MATRIX program [55]. This reweighted

sample is not used for the cross-section measurement only for the uncertainty estimation. PDF uncertainty is also part of the $t\bar{t}$ signal uncertainties and is estimated by considering the internal variations of the PDF4LHC21 PDF set [39].

Single top background For the Wt process similarly to the $t\bar{t}$ process, scale variations of the matrix element (i.e. renormalisation and factorisation scale variations), variations of the Var3c parameter and of the FSR are considered. Since no exact modelling is available for the Wt and $t\bar{t}$ processes interference, two approximations, diagram-removal scheme with diagram-subtraction scheme, are compared to estimate an associated uncertainty [184]. Additionally, for the Wt process a normalisation uncertainty of 3.5% is assumed originating from the predicted uncertainty on its cross-section.

Misidentified leptons For the fake and non-prompt lepton background conservative normalisation uncertainties are assumed. Since no dedicated data-driven estimation of this background was performed and the backgrounds are negligible in magnitude. The uncertainties are as follows for the different regions: in $e\mu$ one b -tagged 50%, in $e\mu$ two b -tagged 100%, and in ee and $\mu\mu$ 100%. These uncertainties do not impact significantly the total measured uncertainty since this background has a low contribution to the total yield.

Z sample For the Z sample which is used as Z +jets in the $e\mu$ regions, the ME scale variations and the PDF uncertainties using the PDF4LHC21 PDF set are taken into account [39].

Other backgrounds Other backgrounds that are considered in the analysis are the diboson background which has a conservative normalisation uncertainty of 50%. Similarly for the ttV process a 50% normalisation uncertainty is assumed.

Monte Carlo statistics In the simulation a finite number of events is produced. This gives origin to a statistical uncertainty. In this analysis the statistical uncertainty on MC is considered as a systematic uncertainty. For all fitted bins two NPs are used to take this into account, one for the $t\bar{t}$ signal and one for the backgrounds in the $e\mu$ region and just one NP in the ee and $\mu\mu$ regions.

7.8.3 Pruning and correlation assumption of systematic uncertainties

This analysis has a large amount of NPs, which can lead to numerical instabilities in the profile likelihood minimisation and increases fitting time. Thus, *pruning* is used. Pruning is the action of dropping small enough systematic contributions. The pruning threshold is chosen as the highest threshold possible for which the result does not change compared to no pruning. Different choices of pruning can lead to different pulls and constraints. In this analysis a pruning threshold of 0.0001 is used, i.e. all systematic uncertainties that are less

than 0.01% are dropped in the fit.

In the $t\bar{t}/Z$ ratio fit the PDF variations and detector related uncertainties are assumed to be fully correlated between processes, while the scale variations are assumed to be uncorrelated. A test was made on the correlation assumption for scale variations for $t\bar{t}$ and Wt a negligible impact on the total systematic uncertainty has been found.

7.9 Study of lepton isolation efficiency modelling

In this section, the studies on the dependence of electron and muon isolation efficiency on various kinematic observables, as well as the differences in predicted isolation efficiencies for various generators used to model $t\bar{t}$ and Z production are presented. This is important since in this analysis leptons are required to pass a tight isolation selection Chapter 5.

In the Run 2 $t\bar{t}$ inclusive cross-section measurements, the PS modelling uncertainty contribution was one of the dominant uncertainties, with a significant component of the uncertainty originating from the modelling of the lepton isolation efficiency. The measurements used an in-situ calibration of the efficiency to correct the various MC predictions to data. The isolation efficiency is studied in this analysis to check if this observation holds for Run 3.

The isolation efficiency is defined as

$$\epsilon_{\text{iso}} = \frac{N^{\text{passed iso}}}{N^{\text{total}}}, \quad (7.17)$$

where N^{total} is the total number of prompt leptons passing selection criteria without requirement on isolation and $N^{\text{passed iso}}$ is the total number of leptons passing both selection and isolation criteria.

The analysis involves regions with varying jet multiplicities, thus, the dependency of the isolation efficiency has been compared for various jet multiplicities in nominal $t\bar{t}$ MC sample in the $e\mu$ channel. Events are required to pass the general event selection without any requirement on jets or b -jet multiplicity.

For the $t\bar{t}$ MC samples three different generators are compared: POWHEG+PYTHIA 8 (PP8), POWHEG+HERWIG 7.2.3 (PH7), and AMCATNLO+HERWIG 7.2.3.

As a benchmark, the isolation efficiency is first studied with reprocessed 2018 Run 2 samples. To estimate this in-situ uncertainty in Run 2 AF2 was used. Thus, first a comparison between the ϵ_{iso} obtained in fast and full simulation is performed. The effect of the ϵ_{iso} difference for muons and electrons on the inclusive cross-section is found to be insignificant ($< 0.1\%$). The maximal difference in inclusive ϵ_{iso} between the different generators is found to be $< 0.5\%$. When examining the p_T dependence, the largest difference of $\sim 1\%$ is observed between PP8 and PH7 for low- p_T muons close to the selection threshold.

Initial results of ϵ_{iso} studies in Run 3 show much better agreement between generators than the Run 2 studies.

This difference is found to be due to usage of different HERWIG versions in Run 2 and Run 3: in Run 2, HERWIG 7.1.3 is used and in Run 3 HERWIG 7.2.3. A newer version of HERWIG was tested with Run 2 (Herwig 7.2.1), leading to a drastic reduction of the ϵ_{iso} difference with respect to PP8, thus reducing the differences between Run 2 and Run 3 PS modelling impact on ϵ_{iso} to a negligible level. Figure 7.13 shows isolation efficiency ratios between PP8 and PH7 in Run 2 for the two different HERWIG versions tested.

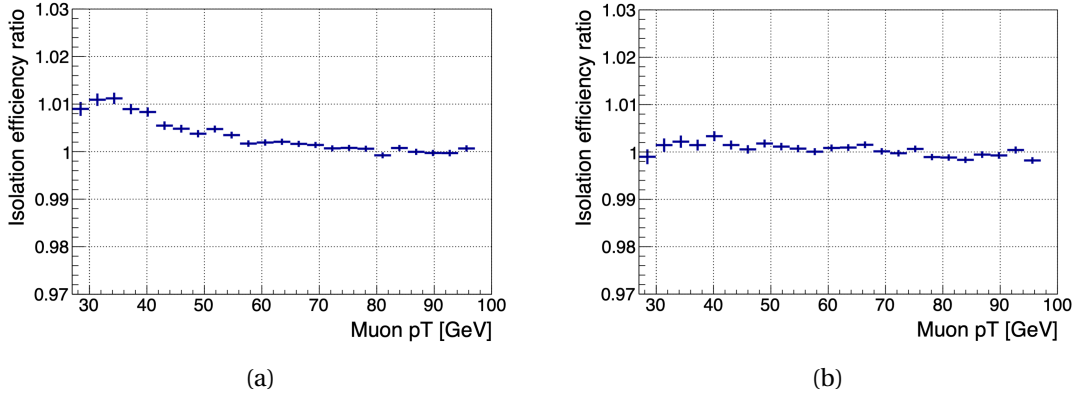


Figure 7.13: Muon isolation efficiency ratio between PP8 and PH7 as a function of muon p_T for Run 2 $t\bar{t}$ samples for HERWIG 7.1.3 (a), and (b) for HERWIG 7.2.1..

FSR and h_{damp} variations of PP8 do not impact the ϵ_{iso} significantly, as can be seen in table 7.3. The differences in inclusive isolation efficiency with respect to the nominal PP8 sample are $< 0.1\%$.

Variation	Ratio to PP8	
	Electrons	Muons
h_{damp}	+0.04%	-0.01%
FSR up	+0.03%	+0.04%
FSR down	-0.03%	-0.08%

Table 7.3: Relative change in inclusive ϵ_{iso} for $t\bar{t}$ PP8 variations with respect to the nominal PP8 prediction.

Figure 7.14 shows the dependency of the lepton isolation efficiency on the inclusive number of b -jets in $t\bar{t}e\mu$ events in Run 3, showing negligible dependence, of the order of $\sim 0.1\%$.

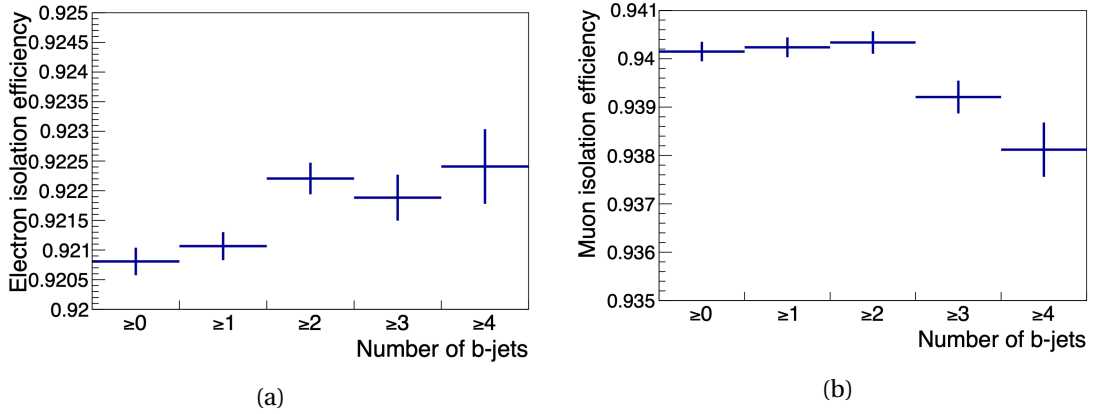


Figure 7.14: Dependence of the simulated electron (a), and muon (b) isolation efficiency as a function of inclusive number of b-jets in $t\bar{t} e\mu$ channel (PP8).

For the $t\bar{t}/Z$ ratio, the generator SHERPA is used for the MC prediction of Z production. It is interesting to check the agreement in isolation efficiency between SHERPA and PP8, since the lepton calibrations are performed assuming PP8 as the nominal MC generator.

The largest difference between Sherpa and PP8 is observed for low- p_T muons in $\mu\mu$ channel of the order of $\sim 2\%$, as can be seen in figure 7.15.

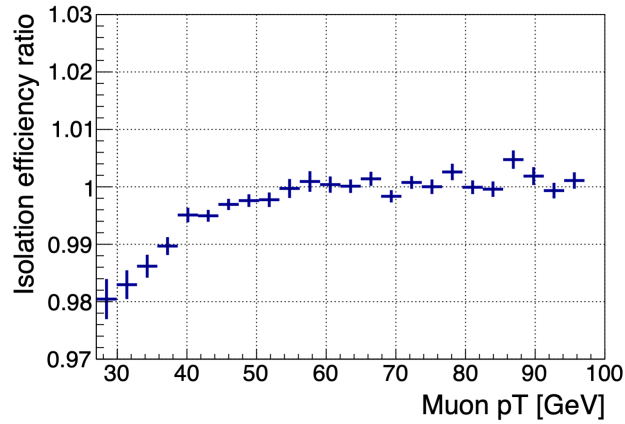


Figure 7.15: The ϵ_{iso} ratio of PP8 to SHERPA for $Z \rightarrow \mu\mu$.

This large difference is concerning since the muon calibrations for the Z MC samples are done based on PP8, while SHERPA is used as the nominal sample for this analysis.

To further understand this difference, the modelling of the isolation variables used by the isolation WP is studied, as shown in figure 7.16 and figure 7.17. The plots show the normalized event ratio between SHERPA and PP8 in two bins, where the first bin includes leptons that pass the isolation WP cut, and the second bin, contains leptons which fail the cut.

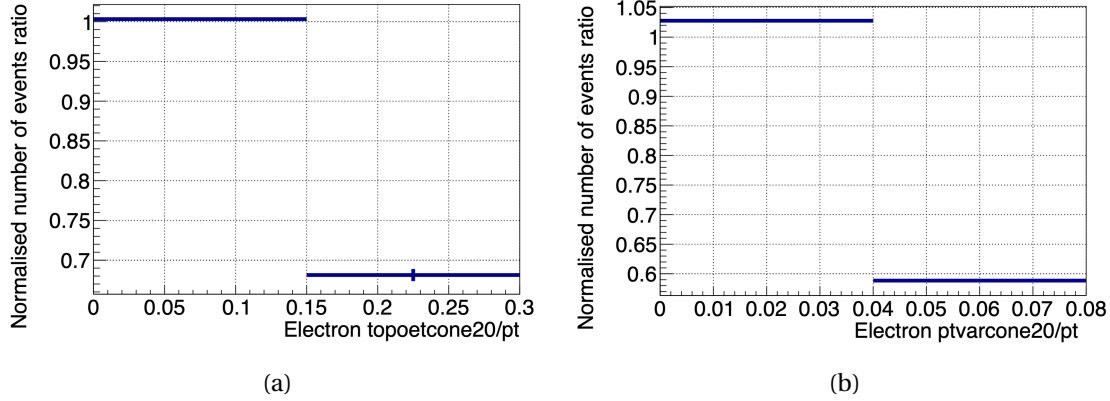


Figure 7.16: SHERPA-to-PP8 ratio of normalised distributions of calorimeter-based (a) and track-based (b) electron isolation variables.

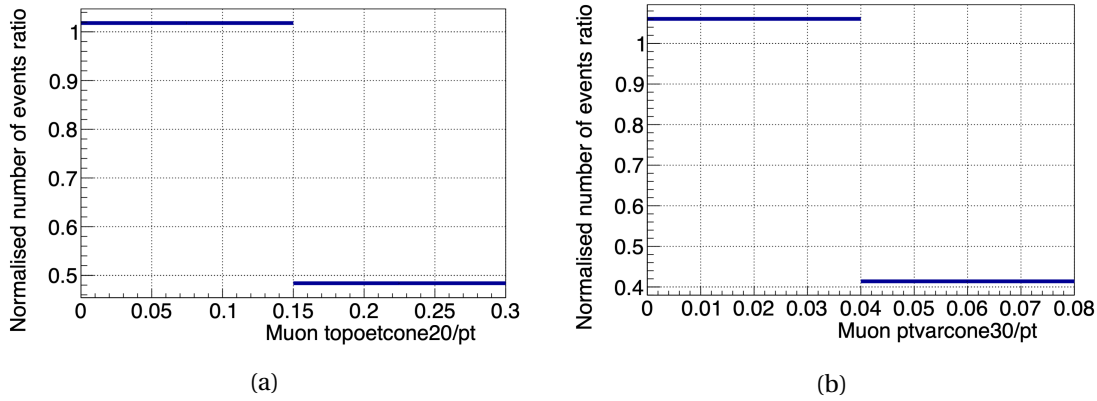


Figure 7.17: SHERPA-to-PP8 ratio of normalised distributions of calorimeter-based (a) and track-based (b) muon isolation variables.

It can be seen that the isolation efficiency difference is induced by differences in modelling of both the calorimetric and the track-based isolation variables. The contribution of the track-based isolation mismodelling is larger. The origin of these differences is under investigation. To account for the PP8 to SHERPA difference of the ϵ_{iso} in Z MC samples in the analysis, MC-to-MC scaling factors are calculated to scale SHERPA ϵ_{iso} prediction to that of PP8. Figure 7.18 shows the MC-to-MC scaling factors as ratio of PP8 over SHERPA, which are directly applied per-lepton in the analysis. The error bars correspond to the statistical uncertainties. The SFs are estimated as a function of lepton p_T only, given the low statistics in the samples. A check of the SF dependency on lepton η was performed, and no significant dependency was found, as is shown in figure 7.19.

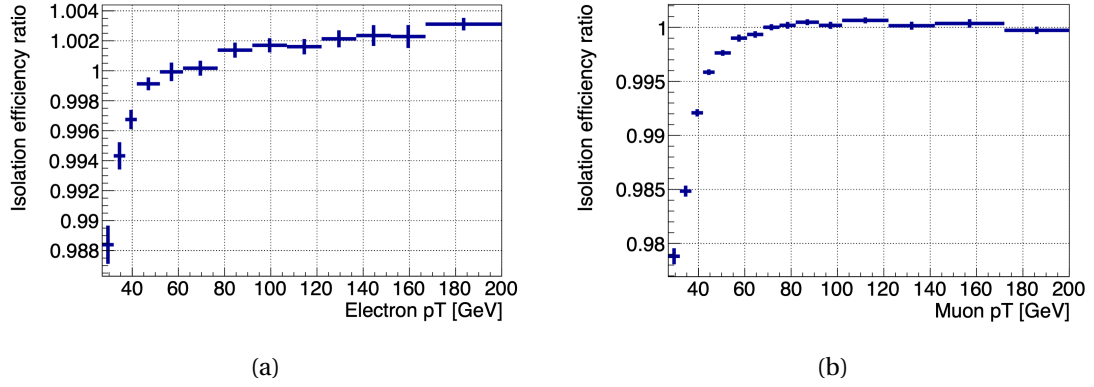


Figure 7.18: MC-to-MC SF (PP8/SHERPA) for electrons in $Z \rightarrow ee$ (a) and muons in $Z \rightarrow \mu\mu$ (b) as a function of the lepton p_T .

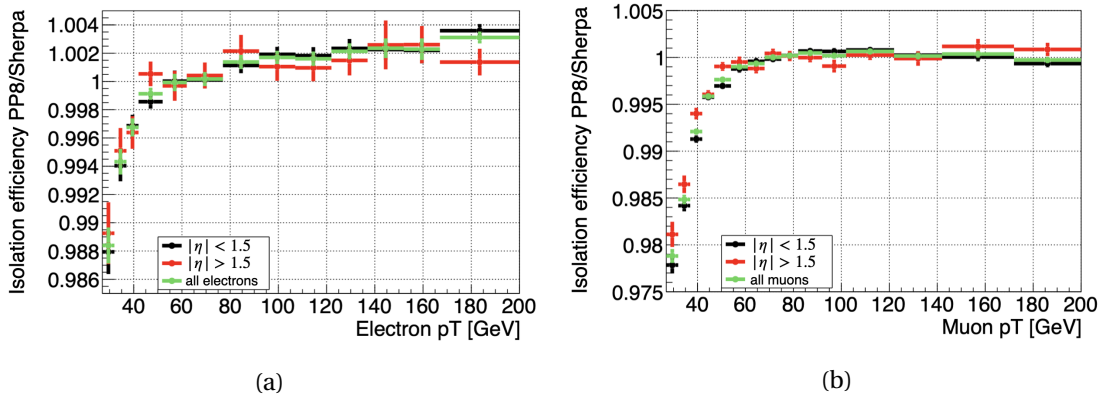


Figure 7.19: MC-to-MC SF (PP8/SHERPA) for electrons in $Z \rightarrow ee$ (a) and muons in $Z \rightarrow \mu\mu$ (b) for different η regions.

7.10 Cross-section measurement results

The event yield for data, signal and backgrounds in the fit regions are shown in figure 7.20. In figure 7.20a the fit regions and the agreement between prediction and data before the fit are shown. It can be seen that in both the $e\mu$ regions the number of predicted events is a bit higher than the measured yield, while for the same-flavour regions the agreement is already very good. The $e\mu$ regions are dominated by the $t\bar{t}$ signal with the leading background being single top Wt , while the same-flavour regions are dominated by the Z signal followed by the $t\bar{t}$ background. In figure 7.20b the same plot after the fit is shown. It can be seen that in the $e\mu$ region the data-to-MC agreement improved, and the uncertainty band is reduced.

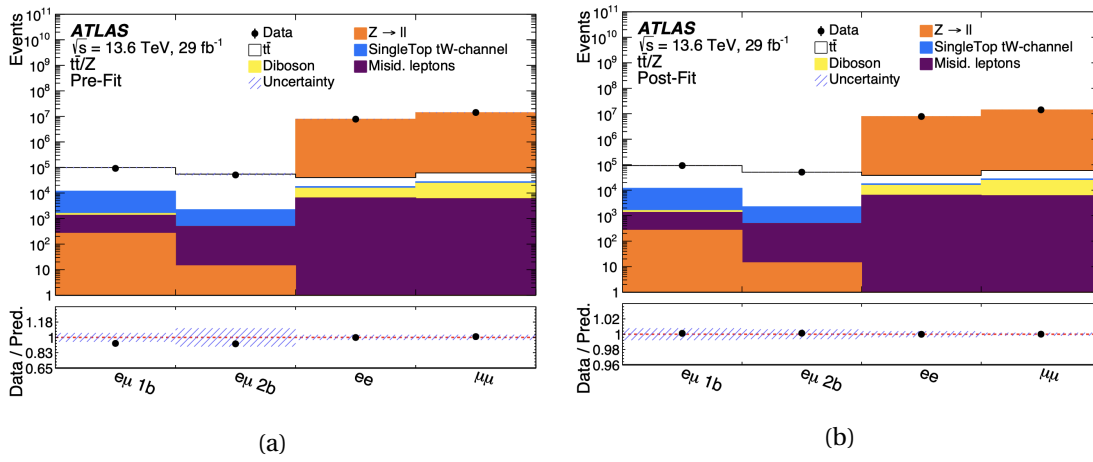


Figure 7.20: Event yield plots for the fitted regions before (a), and after (b) the fit [179].

The measured values extracted from the binned profile likelihood fit are

$$\begin{aligned}
 \sigma_{t\bar{t}} &= 850 \pm 3(\text{stat.}) \pm 18(\text{syst.}) \pm 20(\text{lumi.}) \text{ pb}, \\
 R_{t\bar{t}/Z} &= 1.145 \pm 0.003(\text{stat.}) \pm 0.021(\text{syst.}) \pm 0.002(\text{lumi.}), \\
 \epsilon_b &= 0.544 \pm 0.001(\text{stat.}) \pm 0.004(\text{syst.}) \pm 0.001(\text{lumi.}), \\
 \sigma_{Z \rightarrow ll}^{\text{fid}} &= 744 \pm 11(\text{stat.}+\text{syst.}) \pm 16(\text{lumi.}) \text{ pb}.
 \end{aligned} \tag{7.18}$$

Note that "(syst.)" means all other systematics apart from luminosity. The fiducial phase-space for the Z cross-section measurement is defined by lepton $p_T > 27$ GeV, lepton $|\eta| < 2.5$ and $66 < m_{ll} < 116$ GeV. The Z cross-section has been obtained from a fit to the ee and $\mu\mu$ regions only to understand better the systematic uncertainties originating from same-flavour regions. In the Z cross-section fit, the $t\bar{t}$ background has an additional 5.1% normalisation uncertainty according to the uncertainty on the prediction of the $t\bar{t}$ cross-section value. Given that the ee and the $\mu\mu$ regions are separate, some pulls and constraints can originate from fitting the two regions simultaneously, since it is assumed that $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ have the

same cross-section value. However, the two cross-sections agree better than 0.5σ , and no pulls are observed.

It can be seen that the statistical uncertainty on the $t\bar{t}$ cross-section is negligible compared to the systematic uncertainties. The dominant systematic uncertainty is coming from the luminosity uncertainty. It can also be seen how this uncertainty is as expected not the largest anymore in the ratio of the $t\bar{t}$ cross-section over the Z cross-section.

The corresponding theory predictions with $m_{\text{top}} = 172.5$ GeV and the PDF4LHC21 PDF set are

$$\begin{aligned}\sigma_{t\bar{t}}^{\text{theory}} &= 924_{-40}^{+32}(\text{scale+PDF}+\alpha_s) \text{ pb}, \\ R_{t\bar{t}/Z}^{\text{theory}} &= 1.238_{-0.071}^{+0.063}(\text{scale+PDF}+\alpha_s), \\ \epsilon_b &= 0.5431 \pm 0.0003(\text{MC stat.}), \\ \sigma_{Z \rightarrow ll}^{\text{fid,theory}} &= 746_{-22}^{+21}(\text{scale+PDF}+\alpha_s) \text{ pb},\end{aligned}\tag{7.19}$$

The theoretical prediction of Z cross-section agrees with the measured value within 1σ .

Figure 7.21 shows the inclusive $t\bar{t}$ cross-section as a function of the centre-of-mass energy for the ATLAS, CMS, Tevatron as well as the LHC combinations. A new point has now been added to this plot at 13.6 TeV. It can be seen in the plot that the ATLAS measured value at 13.6 TeV lies a bit lower than the predicted value. The measurement deviates from the prediction by 1.5σ . This is obtained by adding in quadrature the downward uncertainty of the prediction with the uncertainty of the measurement. The CMS measurement [185] also lies slightly below the predicted value but still compatible within 1σ .

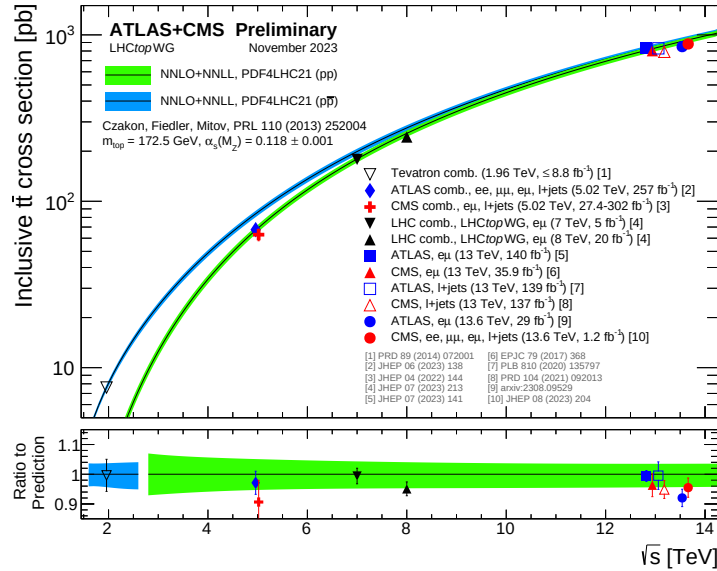


Figure 7.21: Summary of the inclusive $t\bar{t}$ cross-section measurement at different experiments at different centre-of-mass-energies [45].

Figure 7.22 shows the agreement between the measured and predicted $t\bar{t}$ cross-sections. Several predictions are shown for different PDF sets. It can be seen that the measured value is lower than any PDF set prediction although some have a better agreement with the measured value than others.

Figure 7.23 shows the predictions and measurement for the $t\bar{t}/Z$ ratio. Note that the measured value is lower than the average of the predictions using different PDF sets. The fiducial Z cross-section agrees well with theory, this shows that the deviation of the $t\bar{t}$ cross-section cannot be explained by a common error, e.g. luminosity normalisation, impacting both cross-sections to be lower than their predictions. A possible hypothesis could be that the gluon-gluon PDF is wrong while the quark-quark PDF correct.

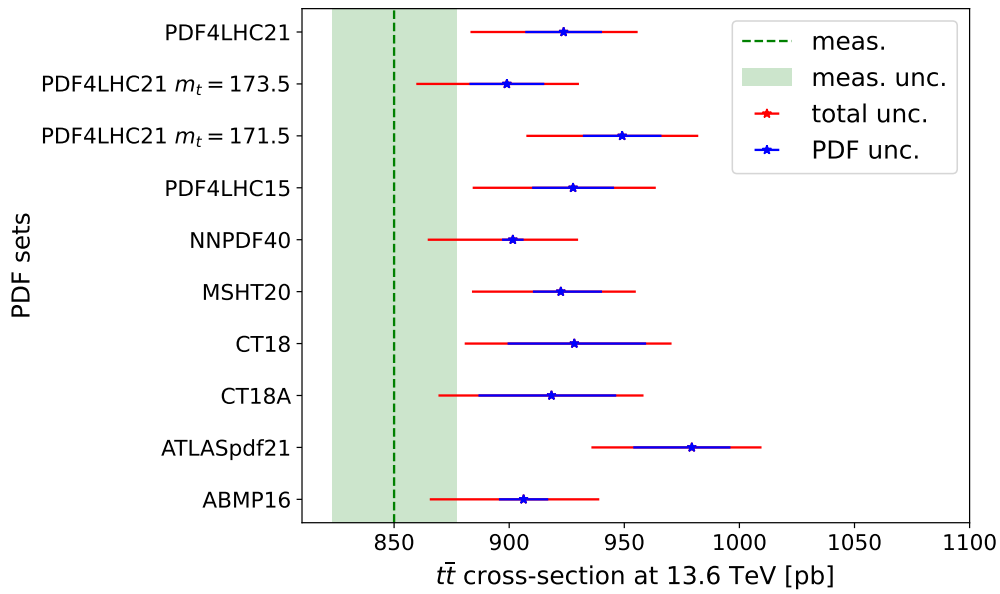


Figure 7.22: Comparison of the measured $t\bar{t}$ cross-section with predictions using different PDF sets.

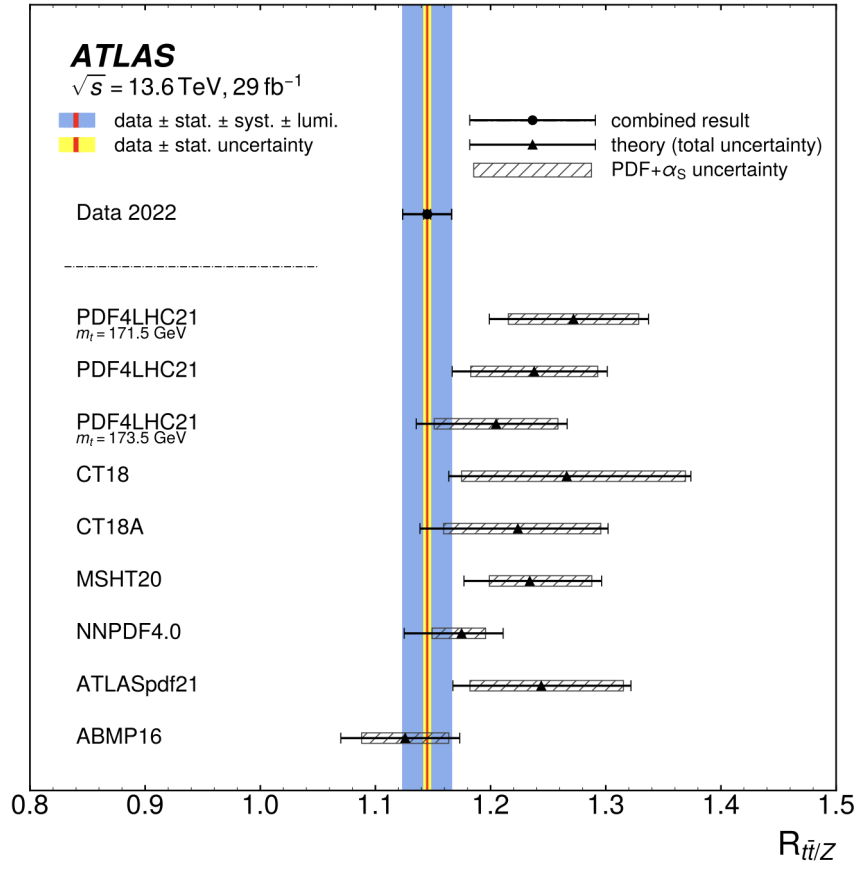


Figure 7.23: Comparison of the measured $t\bar{t}/Z$ ratio with predictions using different PDF sets [179].

7.10.1 Uncertainties

A breakdown of the uncertainties of each measurement is shown in table 7.4. The impact of the uncertainty is estimated by repeating the likelihood fit with the NPs parameters corresponding to the studied uncertainty fixed to their best-fit values. In case of group ranking as shown in table 7.4, all NPs in the group are simultaneously fixed. The so-obtained uncertainty is then subtracted in quadrature from the uncertainty of the full likelihood fit. In this way the contribution of the studied uncertainty can be estimated. In contrast to the full fit, with this procedure correlations between the studied uncertainty and the other uncertainties are not taken into account. Thus, the so-found uncertainty components might be slightly larger than their real contribution in the full fit. This effect has been found to be negligible in this analysis: when summing in quadrature all the ranking plot impacts, a total uncertainty of 3.3% instead of 3.2% is found. The statistical uncertainty is obtained by repeating the fit with all NPs fixed at their best fitted value.

Category		Uncertainty [%]		
		$\sigma_{t\bar{t}}$	$\sigma_{Z\rightarrow\ell\ell}^{\text{fid.}}$	$R_{t\bar{t}/Z}$
$t\bar{t}$	$t\bar{t}$ parton shower/hadronisation	0.9	< 0.2	0.9
	$t\bar{t}$ scale variations	0.4	< 0.2	0.4
	$t\bar{t}$ normalisation	-	< 0.2	-
	top quark p_T reweighting	0.6	< 0.2	0.6
Z	Z scale variations	< 0.2	0.4	0.3
Bkg.	Single top modelling	0.6	< 0.2	0.6
	Diboson modelling	< 0.2	< 0.2	0.2
	$t\bar{t}V$ modelling	< 0.2	< 0.2	< 0.2
Lept.	Fake and non-prompt leptons	0.6	< 0.2	0.6
	Electron reconstruction	1.2	1.0	0.4
	Muon reconstruction	1.4	1.4	0.3
	Lepton trigger	0.4	0.4	0.4
Jets/tagging	Jet reconstruction	0.4	-	0.4
	Flavour tagging	0.4	-	0.3
PDFs		0.5	< 0.2	0.5
Pileup		0.7	0.8	< 0.2
Luminosity		2.3	2.2	0.3
Systematic uncertainty		3.2	2.8	1.8
Statistical uncertainty		0.3	0.02	0.3
Total uncertainty		3.2	2.8	1.9

Table 7.4: Breakdown of uncertainties for each measurement.

The last line in table 7.4 shows the total uncertainty on the measurement in %. The lines above show the systematic and statistic components: the measurements are dominated by the systematic uncertainty, while the statistical uncertainty is an order of magnitude smaller. The largest uncertainty in the cross-section measurements is the luminosity uncertainty, followed by the lepton reconstruction uncertainties, while in the ratio measurement, the luminosity uncertainty plays a subdominant role. The dominant uncertainty in the ratio originates from the $t\bar{t}$ parton shower and hadronisation modelling, followed by the top quark p_T reweighting, the single top modelling and fake and non-prompt lepton estimation. A few uncertainties in the table do not exist for all measurements, they are shown as dashes. Values smaller than 0.2% are not explicitly written since the procedure to obtain these uncertainties is an approximation and uncertainties that are smaller than 0.2% are not reliable. The post-fit NP correlations which are obtained in the process of the likelihood minimization are shown in figure 7.24.

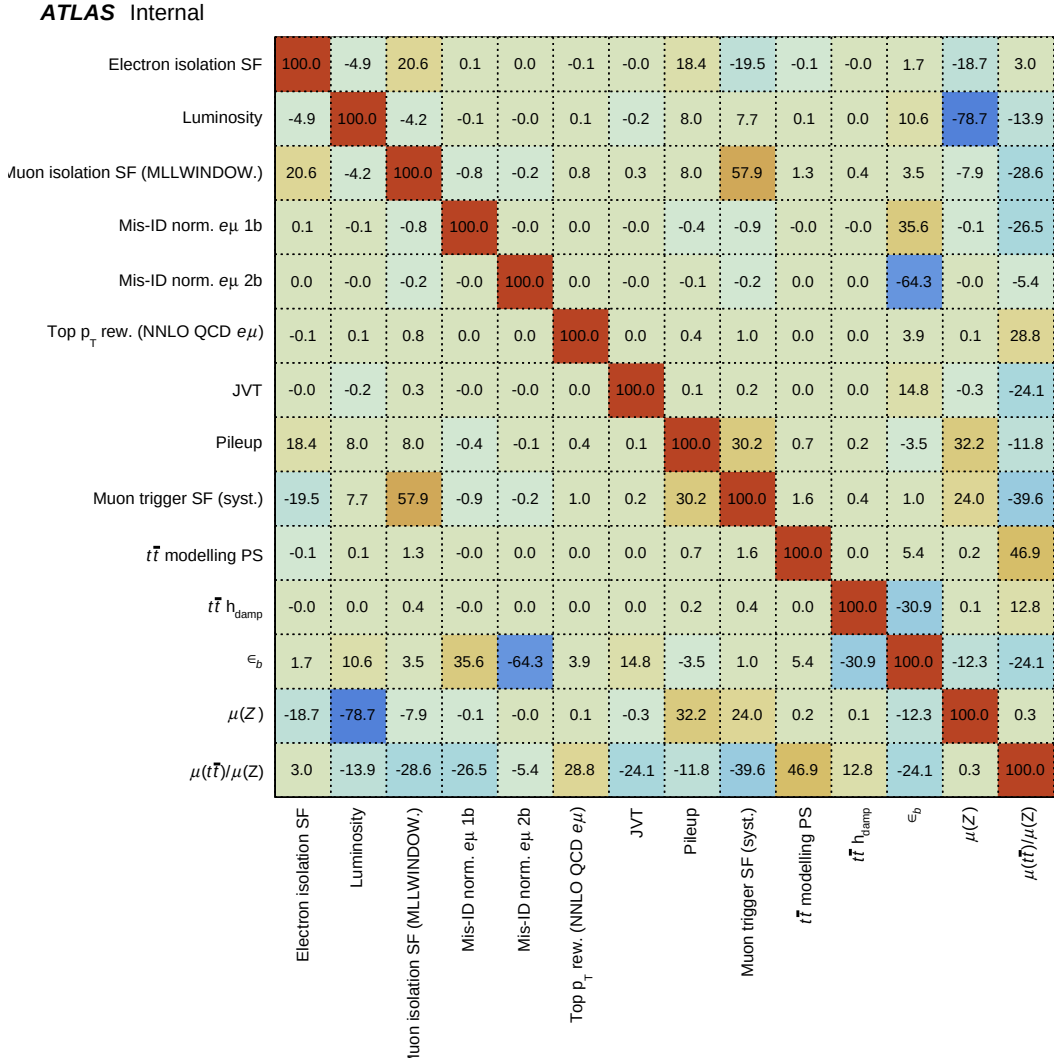


Figure 7.24: Correlation matrix of the fit showing only contributions of at least 20%. Positive correlations are shown in shades of red and negative/anti-correlations are shown in blue.

Another way of visualizing the contribution of the different uncertainties components to the total uncertainty can be obtained from *ranking plots*. The ranking plot for the $t\bar{t}$ cross-section measurement is shown in figure 7.25, the ranking plot for $t\bar{t}/Z$ ratio in figure 7.26, and the ranking plot the for the Z cross-section in figure 7.27. The black dots with uncertainty lines correspond to the bottom axis. The central value shows the pull and the black line the constraint of the NP in the fit. The blue colour bands correspond to the upper axis, they show the contribution of the uncertainty to the total uncertainty of the measured observable. The empty boxes show the pre-fit contribution, while the filled boxes the post-fit contribution.

The ordering of the NPs in the ranking plot is based on the post-fit impact they have on the parameter of interest. If the NPs have asymmetrical impact the larger of the variations is taken in the ordering. Thus, the most contributing uncertainty is shown on top, and the least contributing one on the bottom. Only the ten highest-ranked NPs are shown here.

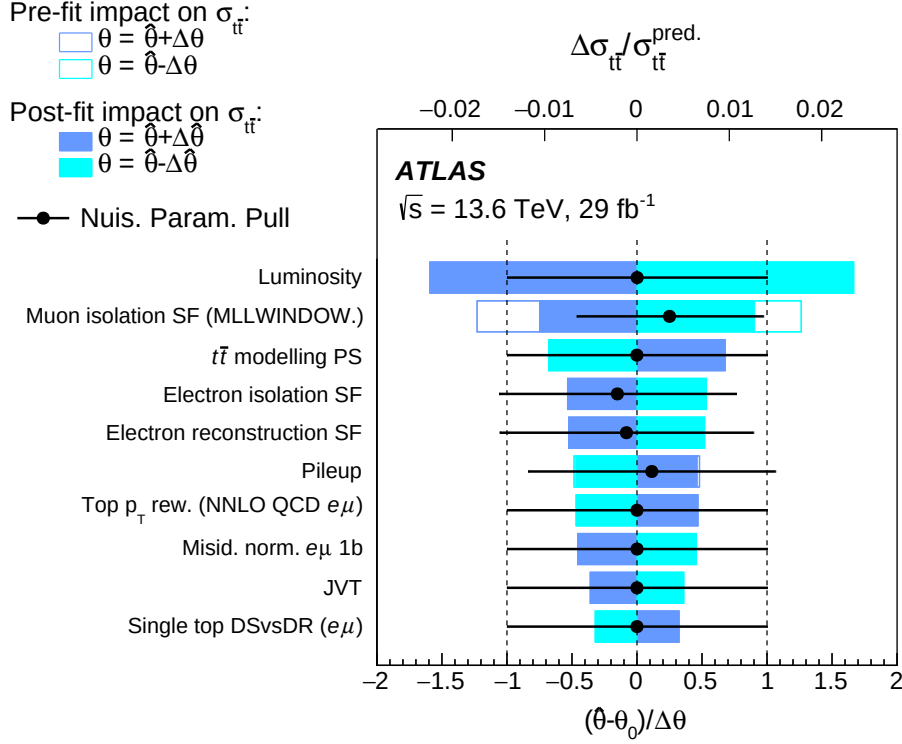


Figure 7.25: $t\bar{t}$ cross-section ranking plot, top 10 contributions. Misid. norm. $e\mu$ 1b is the normalisation uncertainty for fake and non-prompt background in the $e\mu$ one b -tagged region [179].

For every NP the fit is rerun four times, fixing the ranked NP to a value:

$$\begin{aligned}
 \text{NP value} &= \text{pre-fit} + \text{pre-fit uncertainty}, \\
 \text{NP value} &= \text{pre-fit} - \text{pre-fit uncertainty}, \\
 \text{NP value} &= \text{post-fit} + \text{post-fit uncertainty}, \\
 \text{NP value} &= \text{post-fit} - \text{post-fit uncertainty}.
 \end{aligned} \tag{7.20}$$

Note that these values are normalised for the fit. Thus, the pre-fit uncertainty is normalised to 1 and the pre-fit value to 0. The post-fit uncertainty can be constraint and pulled. The difference of the result of these four fits is then compared to the nominal full fit to estimate the impact. This is how the empty and filled blue lines in the ranking plots are obtained.

Figure 7.25 shows again that luminosity is the dominant uncertainty in the $t\bar{t}$ cross-section measurement followed by muon isolation SF and parton shower modelling in the $t\bar{t}$ process.

The only small pull and constraint of the fit is the muon isolation SE. The constraint is about 75% of the pre-fit uncertainty. The muon isolation SFs have large uncertainties. Since electron isolation SFs have smaller uncertainties and the fit is done simultaneously in both regions, the muon isolation uncertainty get constrained. No other significant constraints are present since this measurement is done in four bins with three free parameters.

Figure 7.26 shows that the dominant uncertainty for the ratio measurement is the $t\bar{t}$ modelling of PS. Several uncertainties cancel in this measurement but this modelling uncertainty does not since it only affects $t\bar{t}$. No significant pulls or constraints are observed in this fit.

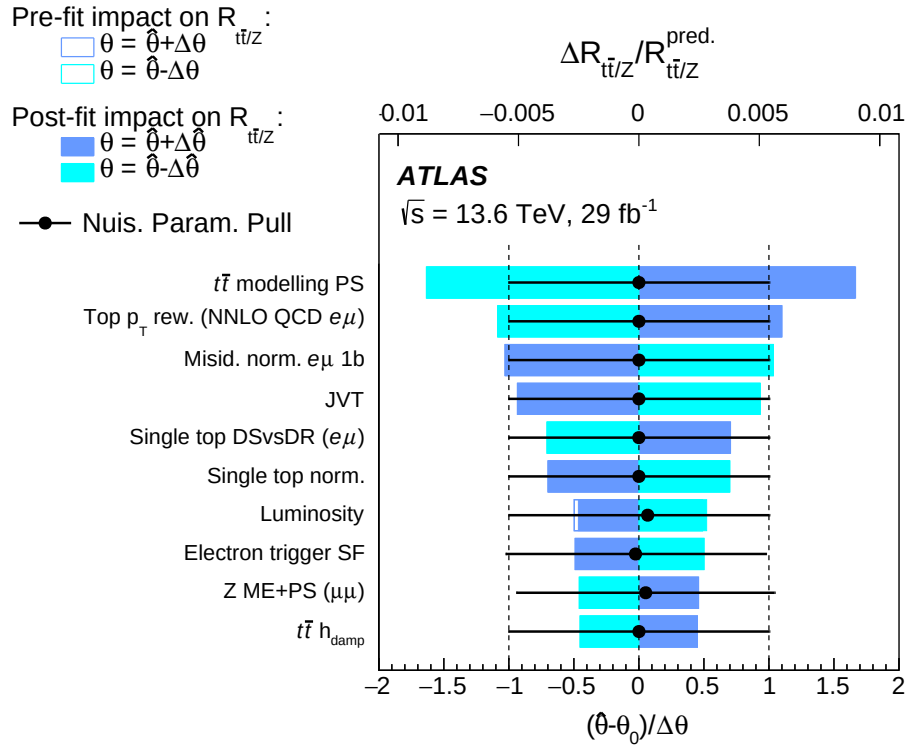
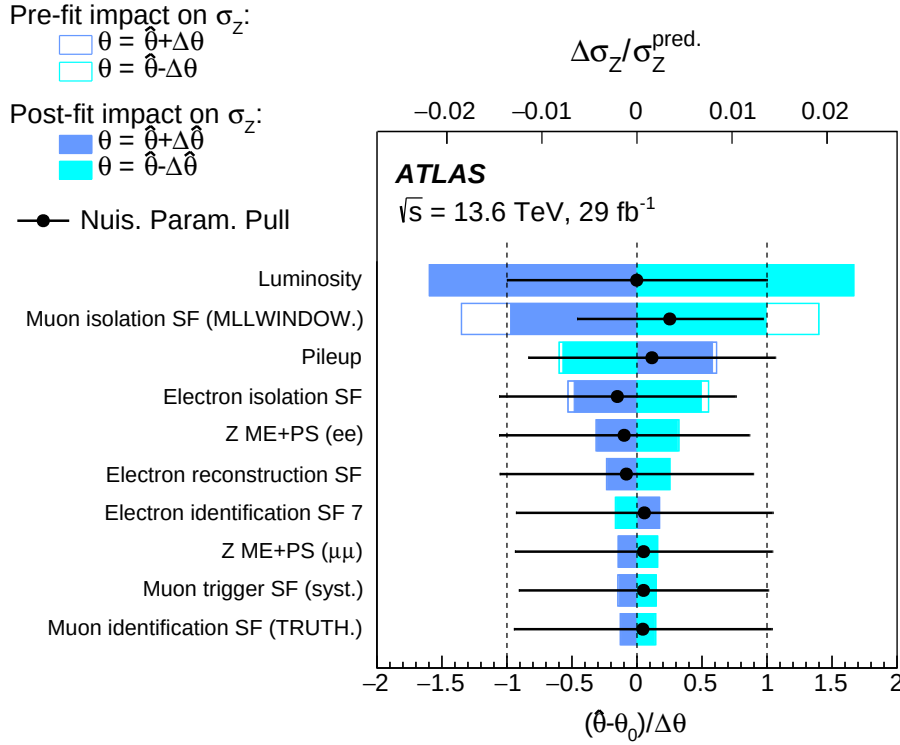


Figure 7.26: $t\bar{t}/Z$ cross-section ratio ranking plot, top 10 contributions [179].

Figure 7.27 shows the top 10 contributions to the Z cross-section measured uncertainty. As in the $t\bar{t}$ cross-section, luminosity is the dominant uncertainty and the only significant pull and constraint in the fit is the muon isolation SE.

Figure 7.27: Z cross-section ranking plot, top 10 contributions [179].

7.11 Ratio of cross-sections at different centre-of-mass energies

It is interesting to measure the ratio of the $t\bar{t}$ cross-section at different energies since it is sensitive to PDFs and since several uncertainties are correlated, the ratio has a better precision than the cross-section measurement alone. In this part, the ratio of the $t\bar{t}$ cross-section at 13.6 TeV to the $t\bar{t}$ cross-section at 13 TeV will be presented. The details on the correlation choice and its impact on the ratio uncertainty will be discussed, and the measured ratio will be compared to different PDF set predictions. The same strategy as in reference [152] is followed.

7.11.1 Predicted energy ratio

The theoretical prediction for the $t\bar{t}$ cross-section is obtained at NNLO in QCD, including the resummation of NNLL soft gluon terms using the Top++2.0 calculator for both Run 2 and Run 3 predictions [32–38]. The prediction detailed in this section is done using the PDF4LHC21 PDF set.

The predicted cross-sections and their uncertainties are

$$\sigma_{t\bar{t}}^{13 \text{ TeV}} = 833.9_{-30.0}^{+20.5}(\text{scale}) \pm 21.0(\text{PDF}+\alpha_s) \text{ pb}, \quad (7.21)$$

$$\sigma_{t\bar{t}}^{13.6 \text{ TeV}} = 923.6_{-33.4}^{+22.6}(\text{scale}) \pm 22.8(\text{PDF}+\alpha_s) \text{ pb}, \quad (7.22)$$

Which results in a central value of

$$R_{13.6/13} = \frac{\sigma_{t\bar{t}}^{13.6 \text{ TeV}}}{\sigma_{t\bar{t}}^{13 \text{ TeV}}} = 1.10759. \quad (7.23)$$

The individual PDF components, α_s uncertainty, and scale variations are fully correlated between the two energies to estimate the uncertainty on the energy ratio, since the same estimation methods and tools are used. The uncertainty in the ratio is calculated as follows.

Scale variations The envelope of the scale variations of the ratio is taken

$$\Delta R_{\text{scale}} = \max\left(\left|R_{13.6/13}^{\text{scale}} - R_{13.6/13}\right|\right) = 0.00017 \longrightarrow \Delta R_{\text{scale}}^{\text{relative}} = \frac{\Delta R_{\text{scale}}}{R_{13.6/13}} = 0.015\%, \quad (7.24)$$

where $\Delta R_{\text{scale}}^{\text{relative}}$ is the relative uncertainty due to scale variations with respect to the predicted ratio central value.

Strong coupling variation The α_s uncertainty is estimated as

$$R_{13.6/13}^{\alpha_s, \text{up}} = \frac{\sigma_{13.6} + \frac{\sigma_{13.6}(\alpha_s=0.119) - \sigma_{13.6}(\alpha_s=0.117)}{2}}{\sigma_{13} + \frac{\sigma_{13}(\alpha_s=0.119) - \sigma_{13}(\alpha_s=0.117)}{2}}, \quad (7.25)$$

$$R_{13.6/13}^{\alpha_s, \text{down}} = \frac{\sigma_{13.6} - \frac{\sigma_{13.6}(\alpha_s=0.119) - \sigma_{13.6}(\alpha_s=0.117)}{2}}{\sigma_{13} - \frac{\sigma_{13}(\alpha_s=0.119) - \sigma_{13}(\alpha_s=0.117)}{2}}. \quad (7.26)$$

The upward and downward uncertainties are

$$\Delta R_{\alpha_s}^{\text{up}} = R_{13.6/13}^{\alpha_s, \text{up}} - R_{13.6/13} = -0.00022, \quad (7.27)$$

$$\Delta R_{\alpha_s}^{\text{down}} = R_{13.6/13} - R_{13.6/13}^{\alpha_s, \text{down}} = -0.00022. \quad (7.28)$$

The uncertainty is symmetrized since $\Delta R_{\alpha_s}^{\text{up}} < \Delta R_{\alpha_s}^{\text{down}}$:

$$\Delta R_{\alpha_s} = \frac{\left|R_{13.6/13}^{\alpha_s, \text{up}} - R_{13.6/13}^{\alpha_s, \text{down}}\right|}{2} = 0.00022 \longrightarrow \Delta R_{\alpha_s}^{\text{relative}} = \frac{\Delta R_{\alpha_s}}{R_{13.6/13}} = 0.020\%. \quad (7.29)$$

PDF variations The uncertainty of the energy ratio coming from the PDF variation is calculated as

$$\Delta R_{\text{PDF}} = \sqrt{\sum_i \left(\frac{F_i^{13.6}}{F_i^{13}} - \frac{F_0^{13.6}}{F_0^{13}} \right)^2} = 0.00086 \rightarrow \Delta R_{\text{PDF}}^{\text{relative}} = \frac{\Delta R_{\text{PDF}}}{R_{13.6/13}} = 0.078\%, \quad (7.30)$$

for the PDF4LHC21 PDF set. The other PDF sets variation is explained in Chapter 2 and shown in figure 7.28.

The total uncertainty in the predicted energy ratio is obtained as the squared sum of the three aforementioned uncertainty components

$$\Delta R_{\text{tot}} = \sqrt{(\Delta R_{\text{scale}})^2 + (\Delta R_{\alpha_s})^2 + (\Delta R_{\text{PDF}})^2}. \quad (7.31)$$

The predicted energy ratio is thus

$$R_{13.6/13} = \frac{\sigma_{t\bar{t}}^{13.6}}{\sigma_{t\bar{t}}^{13}} \quad (7.32)$$

$$= 1.10759 \pm 0.00017(\text{scale}) \pm 0.00022(\alpha_s) \pm 0.00086(\text{PDF}) \quad (7.33)$$

$$= 1.10759 \pm 0.00089. \quad (7.34)$$

The predicted energy ratio for different PDF sets can be seen in figure 7.28. The PDF set predictions agree quite well, and their uncertainties are dominated by the PDF uncertainties.

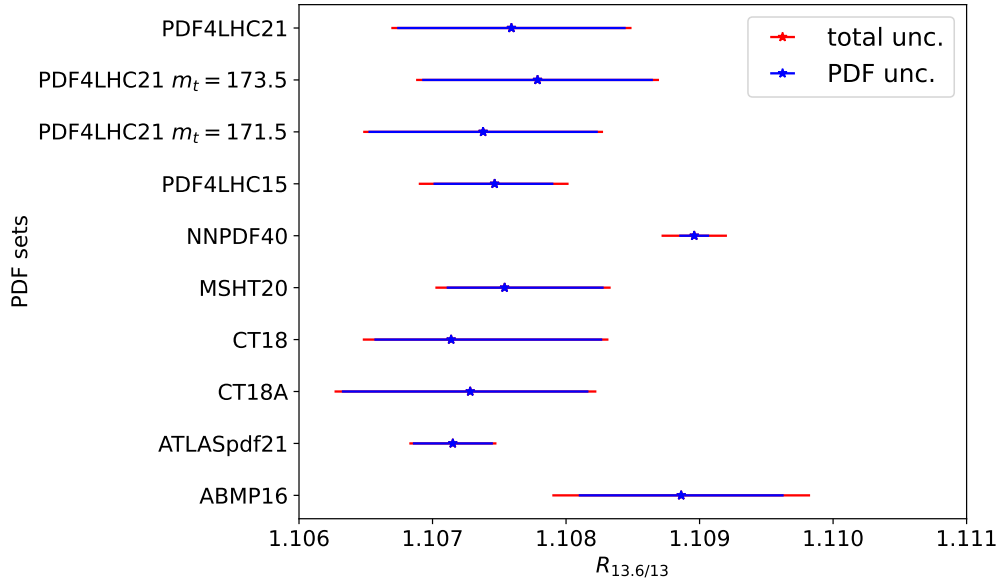


Figure 7.28: Predicted energy ratio for several PDF sets.

7.11.2 $t\bar{t}$ cross-section measurement at 13 TeV

The Run 3 measurement is based on the same methodology and event selection as the Run 2 measurement [177]. The inclusive Run 2 $t\bar{t}$ cross-section at 13 TeV was measured using 140 fb^{-1} of data. The $t\bar{t}$ signal is modelled using POWHEGBOX v2 [102, 154–157] at NLO with the NNPDF3.0 PDF set [171] interfaced to PYTHIA 8.230 [186] with A14 tune [160] using the NNPDF2.3 PDF set [161]. The dominant background, Wt , is simulated using POWHEGBOX v2 [102, 154–157] interfaced with PYTHIA 8.230 [186] and the diagram-removal scheme is used. Diboson events are generated with SHERPA 2.2.2 [90] with the NNPDF3.0 PDF set [171] at NLO for up to one additional parton and at LO for up to three additional partons. $t\bar{t}V$ events are modelled with MADGRAPH5_AMC@NLO [101] interfaced with PYTHIA 8.210 [186] with the A14 tune [160] and the NNPDF2.3 PDF set [161]. Some $t\bar{t}$ events can be produced in association with heavy flavour quarks; a process, which is very difficult to model. These events are studied using the nominal sample with a reweighting applied such that the fraction of events with at least three b -tagged jets at generator level is enhanced by 30% as in reference [152].

The same event selection and *b-jet counting method* as in Run 3 are used, with the difference that for b -tagging the MV2c10 algorithm [187] is used with WP 70%. Pileup is generated with PYTHIA 8.186 [188] using the NNPDF2.3 PDF set and the A3 tune. EVTGEN 1.6.0 [106] is used to simulate the bottom and charm hadron decays. The PDF uncertainty is estimated by using the PDF4LHC15 PDF set [189–191]. The modelling uncertainty of PS and hadronisation is estimated by comparing the nominal $t\bar{t}$ sample with an alternative sample, POWHEGBOX v2 [102, 154–157] interfaced with HERWIG 7.0.4 [104, 105] with the H7UE tune [192] and NNPDF3.0 PDF set [171]. The ME uncertainty is estimated through comparison with the alternative sample generated with MADGRAPH5_AMC@NLO [101] interfaced with PYTHIA 8.230 [186] using the A14 tune [160] and the NNPDF2.3 PDF set [161]. Fake leptons are estimated in a similar way to 13.6 TeV, in the Run 2 measurement in addition a data-driven normalisation using same-sign lepton events is performed. An in-situ lepton isolation efficiency measurement using the tag-and-probe method is performed as well.

The measured inclusive $t\bar{t}$ cross-section amounts to

$$\sigma_{t\bar{t}}^{\text{meas., 13 TeV}} = 829 \pm 1(\text{stat.}) \pm 13(\text{syst.}) \pm 8(\text{lumi.}) \pm 2(\text{beam}) \text{ pb} \quad (7.35)$$

The largest uncertainty is from the luminosity calibration, with relative impact of 0.93%. This is followed by the top p_T reweighting uncertainty, the Wt cross-section prediction uncertainty, and the electron isolation uncertainty estimated in-situ in this measurement. They amount to 0.58%, 0.52% and 0.51%, respectively.

As can be seen in figure 7.29, the measured value is in very good agreement with the predictions of the $t\bar{t}$ cross-section for different PDF sets.

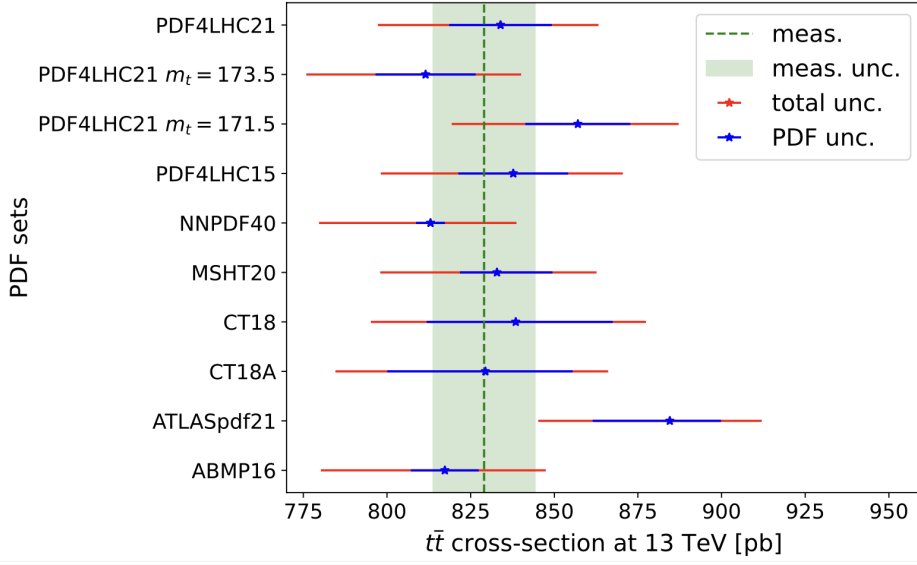


Figure 7.29: Comparison of $t\bar{t}$ cross-section measurement at 13 TeV to the prediction of several PDF sets.

7.11.3 Measured energy ratio

To measure the energy ratio, the uncertainties between the two measurements have to be compared, and assumptions on their correlations have to be made.

The energy ratio is measured using an $e\mu$ regions only fit ($t\bar{t}$ only fit) in Run 3, since the four region fit is too unstable to get the very fine uncertainties which are needed for this measurement, and the Run 2 results from [177].

7.11.3.1 Differences between the two measurements

The grouped uncertainties and their values for the two measurements are shown in table 7.5. The last column shows the best choice of the correlation of an uncertainty between the two measurements.

The systematic uncertainty contributions in the table are obtained differently for the two measurements. In the 13 TeV result, the fit is rerun for every systematic variation separately, while fixing the others at their nominal values. As a consequence, the uncertainties are treated as uncorrelated. In the 13.6 TeV measurement, the uncertainties are input as NPs to the fit and the impact of individual uncertainties is obtained from systematics ranking section 7.10.1. Thus, the correlation between the uncertainties is taken into account. Note that for the Run 3 uncertainties, grouping of several uncertainties is obtained by summing them in quadrature.

Differences in uncertainties between the two measurements The main uncertainty differences between the two measurements are briefly discussed here. The different methods used in the two measurements to estimate the uncertainties listed in table 7.5 are not a problem for the correlation choices since in Run 3 $t\bar{t}$ only fit there are basically no pulls or constraints, and it has been seen that the post-fit correlations are negligible. The parton shower uncertainty has a relatively large difference in magnitude between the two measurements. This can originate from multiple effects. One probable cause could be the different PYTHIA and HERWIG versions used in the two analyses. In the Run 2 measurement, PYTHIA 8.230 compared to HERWIG 7.1.3 is used, while in the Run 3 measurement, PYTHIA 8.307 compared to HERWIG 7.2.3 is used to estimate this uncertainty. Newer versions of generators mean several changes in the simulation. In an ideal scenario, a better motivated PS and hadronisation modelling uncertainty would be available, which was not the case in these measurements. The h_{damp} parameter has a large variation between the two measurements. It is possible that it is due to the utilisation of newer POWHEG and PYTHIA generators for the simulation of the signal. In the Run 3 measurement, lepton-related calibrations are preliminary, resulting in conservative uncertainties, while in the Run 2 measurement they have precise calibrations, resulting in uncertainties that are smaller than preliminary uncertainties due to the extensive studies of lepton performance during the entire Run 2. Notice that in particular, muon isolation has a large difference in magnitude. This is because an in-situ calibration of lepton isolation was used in the Run 2 measurement, which is absent in the Run 3 measurement. The difference in electron isolation uncertainties between the Run 2 and the Run 3 measurements is smaller since it has been seen in the isolation modelling studies section 7.9 that the isolation for electrons is described better by simulation than for muons. When examining the uncertainties related to jet reconstruction and identification, it can be seen that the JVT uncertainty in the Run 3 measurement is an order of magnitude higher than in the Run 2 measurement. This is because, in the Run 3 measurement, no NNJVT correction is applied, and conservative uncertainties are applied due to preliminary studies of JVT modelling in data, whereas in the Run 2 measurement, the full and final calibration is available. Note that the origin of several differences in uncertainties is not clear and its investigation is beyond the scope of this thesis. Since the Run 3 analysis is an early measurement, it is possible that not all uncertainties have been considered to full satisfaction. Nevertheless, considering the large luminosity uncertainty, the outcome would remain mostly unchanged. For luminosity, a preliminary Run 3 calibration with an improved final Run 2 calibration is compared, hence the difference.

Uncertainties not considered in one of the measurements For instance, it is now known that the MADGRAPH5_AMC@NLO interfaced with PYTHIA 8.210 utilised in Run 2 of this comparison contains a bug in matrix element corrections^I, and at the time of the Run 3 analysis a sample with bugfix was not available. As a result, Run 3 does not currently provide

^IInternal ATLAS Top Working Group communication

an estimate of this uncertainty. If the Run 2 uncertainty can be believed, it can be seen that it would be negligible compared to the others. In the early Run 3 measurement, the uncertainty on the production of $t\bar{t}$ associated with a heavy flavour decay was not estimated.

Category		Uncertainty [%]		
		$\sigma_{t\bar{t}}$	$\sigma_{t\bar{t}}$	
	Name	13 TeV	13.6 TeV	Correlated?
Modelling	Matrix Element	0.16	-	No
	$t\bar{t} / Wt$ interference	0.37	0.38	Yes
	Parton Shower and hadronisation	0.22	0.90	Yes
	Wt cross-section	0.52	0.38	Yes
	h_{damp} variation	0.01	0.24	Yes
	Top quark p_T reweighting	0.58	0.59	Yes
	Initial State Radiation	0.37	0.25	Yes
	Final State Radiation	0.35	0.24	Yes
	$t\bar{t}$ + heavy flavour	0.34	-	No
Leptons	Electron energy scale	0.10	0.06	Yes
	Electron reconstruction efficiency	0.37	0.43	Yes
	Electron isolation	0.51	0.41	Yes
	Muon momentum scale	0.13	0.50	Yes
	Muon reconstruction efficiency	0.35	0.28	Yes
	Muon isolation	0.33	1.27	Yes
	Lepton trigger efficiency	0.05	0.34	Yes
Jets	Jet energy scale and resolution	0.10	0.09	Yes
	Jet vertex tagger	0.03	0.52	No
	Flavour tagging	0.07	0.25	Yes
Backgrounds	V+jets modelling	0.05	0.15	Yes
	Diboson modelling	0.34	0.12	Yes
	$t\bar{t}V$ modelling	0.03	0.06	Yes
	Fake and non-prompt leptons	0.32	0.56	Yes
Statistics	Data	0.15	0.30	No
	MC	0.04	-	No
	Beam energy	0.23	-	No
	PDFs	0.43	0.44	Yes
	Luminosity	0.93	2.35	No
	Pileup	-	0.46	No

Table 7.5: The uncertainty grouping for the two measurements and the best choice of their correlations. Dashed uncertainties do not have an equivalent in the given measurement.

The MC statistical uncertainty in the early Run 3 measurement is completely negligible. For the beam energy in the preliminary early measurement, it was decided that this uncertainty was not relevant for the measurement. The Run 2 measurement does not quote an uncertainty due to pileup modelling. However, the potential impact of it should be smaller than in Run 3 since larger pileup is present than in Run 2, and it should be taken into account to a large extent in the isolation in-situ measurement.

As mentioned earlier, it has to be taken into account that Run 3 is an early measurement with preliminary calibrations and conservative uncertainties, while the Run 2 measurement is the state-of-art measurement of the Run 2 cross-section.

7.11.3.2 Correlation model

Modelling All modelling uncertainties are assumed to be correlated since they are dominated by theoretical uncertainties. Exceptions are the ones that do not have a corresponding equivalent in the Run 2 or the Run 3 measurement. This also includes the modelling of backgrounds.

Leptons For leptons in general, it has been chosen to correlate the uncertainties since their extraction is systematically correlated. In particular, for electrons, either SF in Run 2 are used or they are assumed to be equal to unity, with conservative uncertainties covering any difference between Run 2 and Run 3, and data and MC simulations. Thus, the Run 3 uncertainties include the Run 2 uncertainties and the two measurements' uncertainties are chosen to be correlated. However, given the large difference in magnitude between the uncertainty in the two measurements, in particular in the case of muons, the choice of whether to correlate this uncertainty or not does not significantly change the result.

Jets JES and JER in Run 3 are based on a Run 2 in-situ data calibration with conservative uncertainties covering the differences between Run 2 and Run 3. The corresponding uncertainties are thus assumed to be correlated. For the JVT uncertainties, since a new JVT estimation method is used in Run 3, they are taken as uncorrelated. Note that in this uncertainty as well, given the relatively large difference in magnitude between the two measurements, a change in correlation assumption is negligible. The flavour tagging uncertainty is based on the same methodology and is thus assumed to be correlated. Note that all jet and tagging uncertainties mainly originate from their impact on backgrounds since for the signal they get absorbed in the b -jet efficiency.

Luminosity Luminosity is considered to be uncorrelated between the two measurements since the beam conditions usually vary largely from year to year. As a consequence, the

largest uncertainties in the luminosity determination, namely the calibration transfer and the non-factorisation uncertainties, are uncorrelated.

7.11.3.3 Uncertainty correlation studies

Following the correlation model described above, the following result is found

$$R_{13.6/13} = 1.0253 \pm 0.0347. \quad (7.36)$$

The impact of the correlation choices on the energy ratio uncertainty has been estimated by changing the assumption of each uncertainty one-by-one and comparing it to assuming the conservative approach that all uncertainties are uncorrelated. When all uncertainties are assumed to be uncorrelated, the following ratio is found

$$R_{13.6/13} = 1.0253 \pm 0.0383. \quad (7.37)$$

If, on the other hand, all uncertainties that can be correlated between the measurements are correlated, the uncertainty changes to

$$R_{13.6/13} = 1.0253 \pm 0.0312. \quad (7.38)$$

In table 7.6 the correlation variations are listed. The first column shows the different uncertainties; the second column shows, in percentage, the change in the uncertainty on the ratio compared to the uncertainty under the assumption of no correlations between the measurements; and the last column shows the total uncertainties on the ratio.

It can be seen from the table that the only correlation assumption that has a strong enough impact on the total ratio uncertainty to change the second significant digit in the uncertainty is the luminosity uncertainty.

If luminosity is uncorrelated, and all other possible-to-correlate uncertainties are correlated, the following uncertainty is obtained

$$R_{13.6/13} = 1.0253 \pm 0.0347. \quad (7.39)$$

Thus, the same result as in the chosen correlation model.

Category	Change in uncertainty of the ratio [%]	Total uncertainty on the ratio
Luminosity	8.16	0.0352
Muon isolation	1.51	0.0377
p_T reweighting	1.23	0.0378
Electron isolation	0.75	0.0380
PS and hadronisation	0.71	0.0380
Wt cross-section	0.71	0.0380
PDFs	0.68	0.0381
Misidentified leptons	0.64	0.0381
Electron efficiency	0.57	0.0381
Wt interference	0.50	0.0381
Muon efficiency	0.35	0.0382
ISR	0.33	0.0382
FSR	0.30	0.0382
Muon momentum scale	0.23	0.0382
Data statistics	0.16	0.0383
Diboson	0.15	0.0383
Lepton trigger efficiency	0.06	0.0383
Flavour tagging	0.06	0.0383
JVT	0.06	0.0383
JES and JER	0.03	0.0383
V+jets	0.03	0.0383
Electron energy scale	0.02	0.0383
h_{damp}	0.01	0.0383
$t\bar{t}V$	0.01	0.0383

Table 7.6: *Relative change and total uncertainty on the ratio for changes in correlation assumptions for individual uncertainty sources.*

Figure 7.30 visualises more clearly the magnitude of the change in the uncertainty on the ratio.

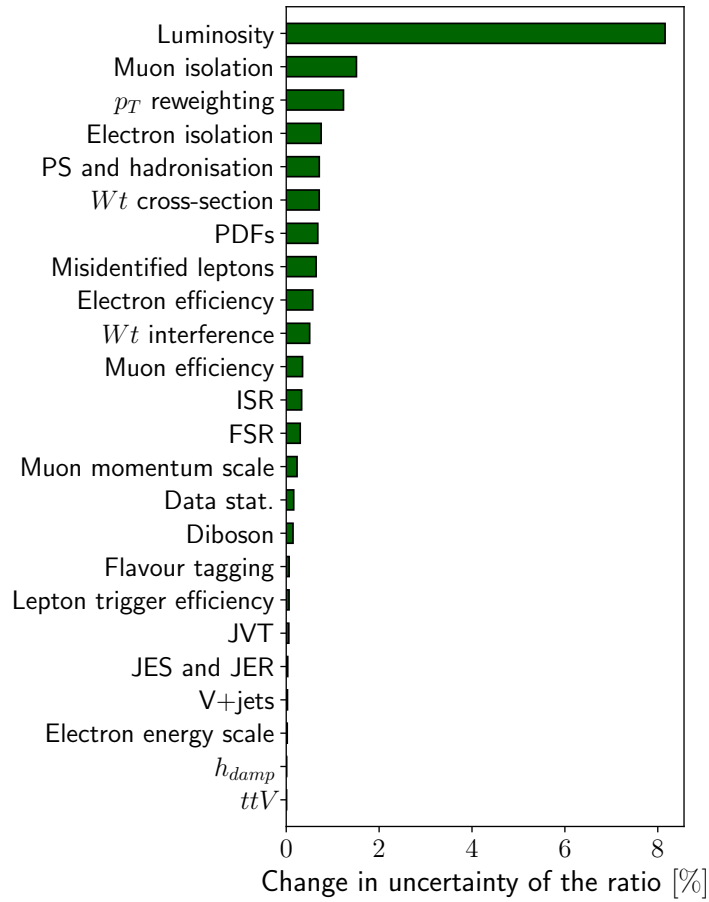


Figure 7.30: *Uncertainty change when the corresponding uncertainty is assumed to be correlated compared to the case where all uncertainties are uncorrelated.*

7.11.4 Energy ratio measurement results

With the assumed correlation model, the measured energy ratio is found to be

$$R_{13.6/13} = 1.0253 \pm 0.0347 \quad (7.40)$$

This value agrees within 2.4 standard deviations with the predicted value.

The measured value is compared to the prediction of different PDF sets in figure 7.31. It can be seen that the measured value lies consistently lower than any of the PDF set predictions.

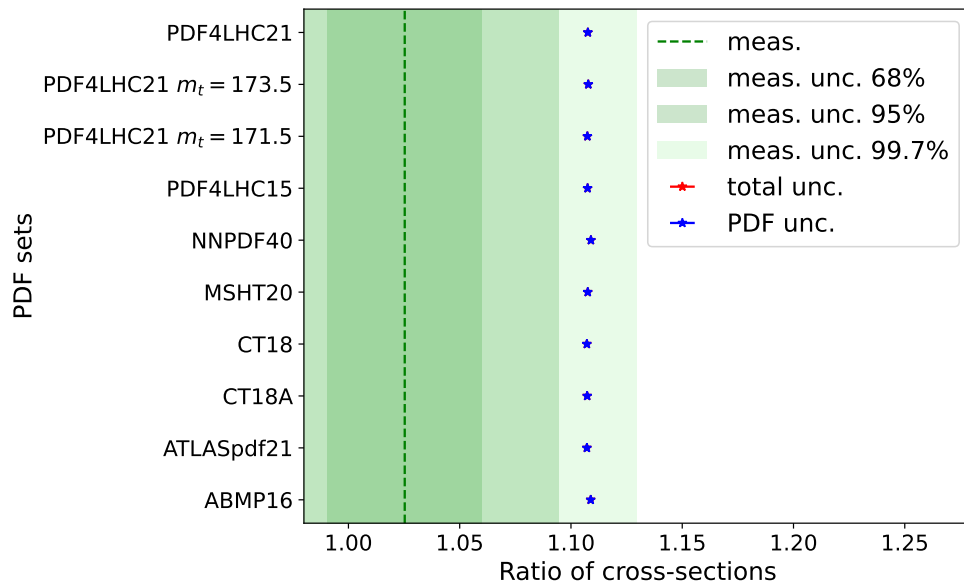


Figure 7.31: Measured energy ratio and the corresponding predicted value for several PDF sets. The size of the error bars is comparable or smaller than the marker size. The three bands show the $1/2/3\sigma$ bands of the measured uncertainty.

8 Conclusion

In this thesis the measurement of the inclusive $t\bar{t}$ cross-section at 13.6 TeV using 29 fb^{-1} of data recorded with the ATLAS detector at the LHC in 2022 was presented. The largest uncertainty of this measurement is the luminosity uncertainty. The preliminary luminosity calibration for 2022 has an uncertainty of 2.2%. In this thesis, the luminosity calibration and in particular the van der Meer scan calibration has been presented in detail. The two main contributions to the luminosity uncertainty come from the preliminary calibration transfer amounting to 1.5% and the beam's factorisability being 1.07%.

The measured cross-section is $\sigma_{t\bar{t}} = 850 \pm 3(\text{stat.}) \pm 18(\text{syst.}) \pm 20(\text{lumi.}) \text{ pb}$, while the prediction is $\sigma_{t\bar{t}}^{\text{theory}} = 924^{+32}_{-40}(\text{scale+PDF}+\alpha_s) \text{ pb}$. A slight discrepancy with the predicted value is found at the level of 1.5 standard deviations. Additionally, the investigation into the $t\bar{t}/Z$ cross-section ratio unveiled a similar trend of the measured values being marginally lower than the predicted values. The measured value being $R_{t\bar{t}/Z} = 1.145 \pm 0.003(\text{stat.}) \pm 0.021(\text{syst.}) \pm 0.002(\text{lumi.})$, while the prediction gives $R_{t\bar{t}/Z}^{\text{theory}} = 1.238^{+0.063}_{-0.071}(\text{scale+PDF}+\alpha_s)$. Finally, the inclusive $t\bar{t}$ cross-section ratio between 13.6 TeV and 13 TeV centre-of-mass energy was performed and found to be $R_{13.6/13} = 1.0253 \pm 0.0347$. Tests of correlation assumptions were performed and the result is robust against the choice of the assumptions. Theory predictions for different PDF sets are compared to the measurements. Overall the predictions agree well with each. The agreement between the measurement and the prediction is at the level of 2.4 standard deviations.

To understand the deviation further a differential cross-section measurement of the $t\bar{t}$ cross-section could be performed. In this way, the agreement with the prediction can be better understood through studies of the kinematic dependence of the cross-section. Furthermore, the Run 3 analysis was done with very preliminary calibrations and therefore more final calibrations are needed to improve the precision of this measurement and understand if the discrepancy with the prediction is real or maybe due to potential calibration-related issues. To sum up, this thesis has explored the complex field of $t\bar{t}$ cross-section measurements, which is an important test of perturbative QCD at heavy scales. The search for even-more precise $t\bar{t}$ cross-section measurement is important for perturbative corrections in QCD and to help constrain backgrounds in searches for new physics.

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Appendix

A LUCID list of algorithms

The following LUCID algorithms are used in this analysis:

- lucBiPMTcxx: hit counting algorithms for PMT xx on side C
- lucBiPMTAxx: hit counting algorithms for PMT xx on side A
- lucBiHitORA: counts the number of hits in the 4 (A3, A7, A11, A15) PMTs on side A divided by the number of tubes
- lucBiHitORC: counts the number of hits in the 4 (C3, C7, C11, C15) PMTs on side C divided by the number of tubes
- lucBiHitOR: counts the number of hits in the 8 (A3, A7, A11, A15, C3, C7, C11, C15) PMTs divided by the number of tubes
- lucBi2HitORA: counts the number of hits in the 4 (A4, A8, A12, A16) PMTs on side A divided by the number of tubes
- lucBi2HitORC: counts the number of hits in the 4 (C4, C8, C12, C16) PMTs on side C divided by the number of tubes
- lucBi2HitOR: counts the number of hits in the 8 (A4, A8, A12, A16, C4, C8, C12, C16) PMTs divided by the number of tubes
- lucBiEvtA: count an event if there is at least 1 hit in 1 of the 4 (A1, A5, A9, A13) PMTs on side A during a bunch crossing
- lucBiEvtC: count an event if there is at least 1 hit in 1 of the 4 (C1, C5, C9, C13) PMTs on side C during a bunch crossing
- lucBiEvtAND: AND between lucBiEvtA and lucBiEvtC

- lucBiEvtOR: registers an event if any of the 8 (A1, A5, A9, A13, C1, C5, C9, C13) PMTs registers an event
- lucBi2EvtA: count an event if there is at least 1 hit in 1 of the 4 (A4, A8, A12, A16) PMTs on side A during a bunch crossing
- lucBi2EvtC: count an event if there is at least 1 hit in 1 of the 4 (C4, C8, C12, C16) PMTs on side C during a bunch crossing
- lucBi2EvtAND: AND between lucBi2EvtA and lucBi2EvtC
- lucBi2EvtOR: registers an event if any of the 8 (A4, A8, A12, A16, C4, C8, C12, C16) PMTs registers an event

B BCM list of algorithms

The following BCM algorithms are used in this analysis:

- bcmAXP: event counting algorithm for side A BCM channel in the x plane
- bcmAXM: event counting algorithm for side A BCM channel in the x plane
- bcmAYP: event counting algorithm for side A BCM channel in the y plane
- bcmAYM: event counting algorithm for side A BCM channel in the y plane
- bcmCXP: event counting algorithm for side C BCM channel in the x plane
- bcmCXM: event counting algorithm for side C BCM channel in the x plane
- bcmCYP: event counting algorithm for side C BCM channel in the y plane
- bcmCYM: event counting algorithm for side C BCM channel in the y plane
- bcmHORA: OR of X plane BCM channels on side A (bcmAXP, bcmAXM)
- bcmHORC: OR of X plane BCM channels on side C (bcmCXP, bcmCXM)
- bcmVORA: OR of Y plane BCM channels on side A (bcmAYP, bcmAYM)
- bcmVORC: OR of Y plane BCM channels on side C (bcmCYP, bcmCYM)
- bcmHEvtOR: OR between bcmHORA and bcmHORC
- bcmVEvtOR: OR between bcmVORA and bcmVORC

- bcmTEvtOR: OR between bcmHEvtOR and bcmVEvtOR
- bcmHEvtAND: AND between bcmHORA and bcmHORC
- bcmTEvtAND: AND between bcmVORA and bcmVORC