
Calibration of the Liquid Argon Calorimeter and Search for Stopped Long-Lived Particles

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Abstract

This thesis dives into the three main aspects of today's experimental high energy physics: detector operation and data preparation, reconstruction and identification of physics objects, and physics analysis. The symbiosis of these is the key to reach a better understanding of the underlying principles of nature. Data from proton-proton collisions at a centre-of-mass energy of $\sqrt{s}=13$ TeV collected by the ATLAS detector during 2015–2018 are used.

In the context of detector operation and data preparation, the data quality assessment for the Liquid Argon calorimeter of the ATLAS experiment is improved by an adaptive monitoring of noisy channels and mini noise bursts allowing an assessment of their impact on the measured data at an early stage. Besides data integrity, a precise energy calibration of electrons, positrons and photons is essential for many physics analyses and requires an excellent understanding of the detector. Corrections of detector non-uniformities originating from gaps in between the Liquid Argon calorimeter modules and non-nominal high voltage settings are derived and successfully recover the homogeneity in the energy measurement. A further enhancement is reached by introducing the azimuthal position of the electromagnetic cluster in the calibration algorithm. Additionally, a novel approach to exploit tracking information in the historically purely calorimeter-based energy calibration for electrons and positrons is presented. Considering the track momentum results in an about 30% better energy resolution for low- p_T electrons and positrons. The described optimisation of the energy calibration is especially beneficial for precision measurements which are one way to test and challenge our current knowledge of the Standard Model of particle physics. Another path is the hunt for new particles, here presented by a search for stopped long-lived particles suggested by many theoretical models. This analysis targets gluinos which are sufficiently long-lived to form quasi-stable states and come to rest in the detector. Their eventual decay results in large energy deposits in the calorimeters. The special nature of the expected signature requires the exploration of non-standard datasets and reconstruction methods. Further, non-collision backgrounds are dominant for this search which are investigated in detail. In the context of simplified supersymmetric models an expected signal sensitivity of more than 3σ for gluinos with a mass up to 1.2 TeV and a lifetime of $100\mu s$ is achieved.

Kurzfassung

Die vorgestellte Arbeit befasst sich mit den drei Hauptaspekten der modernen experimentellen Hochenergiephysik: Detektorbetrieb und Datenaufbereitung, Rekonstruktion und Identifikation physikalischer Objekte, sowie der Datenanalyse. Die Symbiose dieser ist der Schlüssel zu einem besseren Verständnis der zugrunde liegenden Naturgesetze. Es werden Daten von Proton-Proton-Kollisionen bei einer Schwerpunktsenergie von $\sqrt{s} = 13$ TeV verwendet, die vom ATLAS-Detektor im Zeitraum 2015–2018 aufgenommen wurden.

Im Rahmen des Detektorbetriebs und der Datenaufbereitung wird die Bewertung der Datenqualität für das Flüssig-Argon-Kalorimeter des ATLAS Experimentes durch eine dedizierte Überwachung von Detektorrauschen verbessert, um diese Ursachen für eine Beeinträchtigung der gemessenen Daten frühzeitig zu beheben. Neben der Datenintegrität ist eine präzise Energiekalibrierung von Elektronen, Positronen und Photonen für viele Analysen unerlässlich und erfordert ein gutes Verständnis des Detektors. Korrekturen von Detektorungleichmäßigkeiten, die durch Lücken zwischen den Flüssig-Argon-Kalorimetermodulen und anomalen Hochspannungseinstellungen verursacht werden, werden bestimmt und stellen die Homogenität der Energiemessung erfolgreich wieder her. Eine weitere Verbesserung wird erreicht, indem die azimutale Position des elektromagnetischen Clusters in den Kalibrierungsalgorithmus eingeführt wird. Zusätzlich wird ein neuartiger Ansatz zur Verwendung von Spurinformatoren bei der bislang rein kalorimeterbasierten Energiekalibrierung für Elektronen und Positronen vorgestellt. Unter Berücksichtigung des Spurimpulses wird eine um etwa 30 % bessere Energieauflösung für Elektronen und Positronen mit niedrigem p_T erzielt. Die beschriebenen Optimierungen der Energiekalibrierung sind besonders vorteilhaft für Präzisionsmessungen, die eine Möglichkeit darstellen unser derzeitiges Wissen über das Standardmodell der Teilchenphysik zu testen und zu hinterfragen. Ein anderer Weg ist die Suche nach neuen Teilchen, wie die präsentierte Suche nach gestoppten langlebigen Teilchen, die von vielen theoretischen Modellen vorhergesagt werden. Diese Analyse fokussiert sich auf Gluinos, die langlebig genug sind, um quasi-stabile Zustände zu bilden und im Detektor zur Ruhe zu kommen. Ihr letztendlicher Zerfall führt zu großen Energiedepositionen in den Kalorimetern. Die ungewöhnliche Signatur des erwarteten Signals erfordert die Verwendung von nicht standardmäßigen Datensätzen und Rekonstruktionsmethoden. Darüber hinaus dominieren für diese Suche nicht kollisionsbedingte Untergründe, die im Detail untersucht werden. In der Interpretation von vereinfachten supersymmetrischen Modellen wird eine erwartete Signalsensitivität von mehr als 3σ für Gluinos mit einer Masse von bis zu 1.2 TeV und einer Lebensdauer von $100 \mu s$ erreicht.

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Chapter 1

Introduction

In the pursuit of an understanding of every aspect of the universe, from the infinitely small to the infinitely vast, i.e. a *Theory of Everything*, the *Standard Model of particle physics* is a crucial stepping stone. It summarises our current knowledge of particle physics including the building blocks of everyday matter surrounding us and the interactions between them. Continuously tested in various experiments over the past fifty years and currently by the LHC¹ and the ATLAS² and CMS³ experiments among others, it has been proven correct in successfully describing many aspects of particle physics. Despite these successes it is confined in its boundaries and cannot explain all observed phenomena, e.g. gravity and Dark Matter, and is constantly challenged by experimental results which reveal possible discrepancies and hint towards new physics beyond the Standard Model, e.g. flavour universality tests in $R_{K^{(*)}}$ [1, 2] by the LHCb⁴ experiment. It is evident that the Standard Model is only one puzzle piece and its extension is imperative. The key to achieve this is a two-fold approach: Searches for new particles in un- and under-explored phase space on the one side and precise scrutiny of the Standard Model parameters on the other side. Pursuing both directions is vital, not only for experimental particle physics but also theoretical particle physics as new inputs allow refining existing models and designing new models which in turn provide new impulse for the experimental field. A brief overview of the theoretical concepts is given in Section 2, including an introduction of *Supersymmetry* as one of the possible extensions of the Standard Model.

The experimental success relies on the symbiosis of the technical setup and operation of the detector, data acquisition and preparation, reconstruction and identification of physics objects, and analysis of the provided data exploiting the available tools to their fullest. Section 3 introduces the ATLAS detector as an example of a state-of-the-art particle physics experiment with the focus on one of its sub-detectors, the Liquid Argon Calorimeter and its dedicated data quality assessment. The measurements of this sub-detector are particularly essential for studies involving electrons, positrons and photons which are often featured in precision measurements. Their energy calibration is one of the indispensable ingredients and is discussed in Section 4 including several improvements. On the final stage of the analysis chain lie searches for new particles. A search for stopped long-lived particles in the scope of supersymmetric extensions of the Standard Model is presented in Section 5. For this search a distinct understanding of the detector, the data quality assessment and the reconstruction of physics objects is critical. A brief discussion of potential future improvements is given in Section 6.

Whether it is absent or present, the search for new physics will give us valuable information and guidance towards a deeper understanding of nature. Only the persistent endeavour to expand our horizons and tap new technological possibilities by exploring new paths and

¹Large Hadron Collider

²A Toroidal LHC ApparatuS

³Compact Muon Solenoid

⁴Large Hadron Collider beauty

scrutinising given procedures will allow physics to evolve.

Chapter 2

Theoretical Foundations

The foundations of modern particle physics are summarised by the *Standard Model of particle physics* (SM). It is a mathematical description of the observations made in experiments and describes the nature of elementary particles and their interactions. The SM, outlined in Section 2.1, represents our current knowledge of particle physics. Despite its success, it is not a complete theory and might evolve in the future. Although the SM gives an excellent description of many precision measurements, it fails to include some experimental observations, of which a few are touched at the end of Section 2.1. Hence, a plethora of extensions of the SM exists aiming to cover the open questions and contradictions. The concept of *Supersymmetry* (SUSY) gives rise to many such theories, including models featuring long-lived particles, and is discussed in Section 2.2.

The SM and any extension of it provide many interesting physics processes to study and to search for with existing and future experiments. In order to analyse experimentally obtained data in the scope of a specific theoretical model, the simulation of the expected signatures is crucial. Section 2.3 gives a brief introduction in the simulation of physics processes.

2.1 Standard Model of Particle Physics

The *Standard Model of particle physics* [3–17] gives a mathematical description of the elementary particles and the fundamental forces which drive interactions between them.¹ Initially, the SM was born from experimental observations of interactions between elementary particles and transformations of compound states. Motivated by the similarities and differences of the studied particles and their interplay, they were categorised and their quantitative characterisation allowed a mathematical formulation. Based on this the developed model grew further and not only described the experimental status at the time, but predicted new particles and interactions. The current formulation of the SM is rather complete, very capable to describe the experimental observations and builds the foundation for modern particle physics.

A schematic overview of the SM is depicted in Figure 2.1.1. It summarises all particles which are currently known to exist and considered to be elementary states. They can be separated into two categories based on their intrinsic property of *spin* and the spin-statistic theorem. The spin defines the behaviour of a particle under relativistic space-time transformation and differs greatly depending on whether it is integer or half-integer value.

Particles with half-integer spin are called *fermions* as they follow the Fermi-Dirac statistics. They are also labelled matter particles as any kind of known matter is a compound of them. An anti-particle can be assigned to each fermion with the identical properties besides opposite

¹With the exception of gravity which is covered by general relativity [18].

charges, increasing the total count of fermions to 24.^{2,3} By analogy they are the building blocks of anti-matter. Fermions can be split into three generations: The first generation contains the building blocks for stable, everyday matter; the second and third generation can be seen as heavier copies of the first generation with similar characteristics. However, they cannot form any stable matter as they eventually transform into particles of the first generation, but they can be created in particle collisions.

Particles with integer value spins are called *bosons* as they are subject to the Bose-Einstein statistics. They are often referred to as force carriers or mediators as they mediate the interaction between the fermions. Three fundamental types of interactions are described by the SM: the weak, the electromagnetic and the strong interaction; but not every particle succumbs to each force. Only those particles which carry a charge corresponding to the type of the force participate in its interactions.

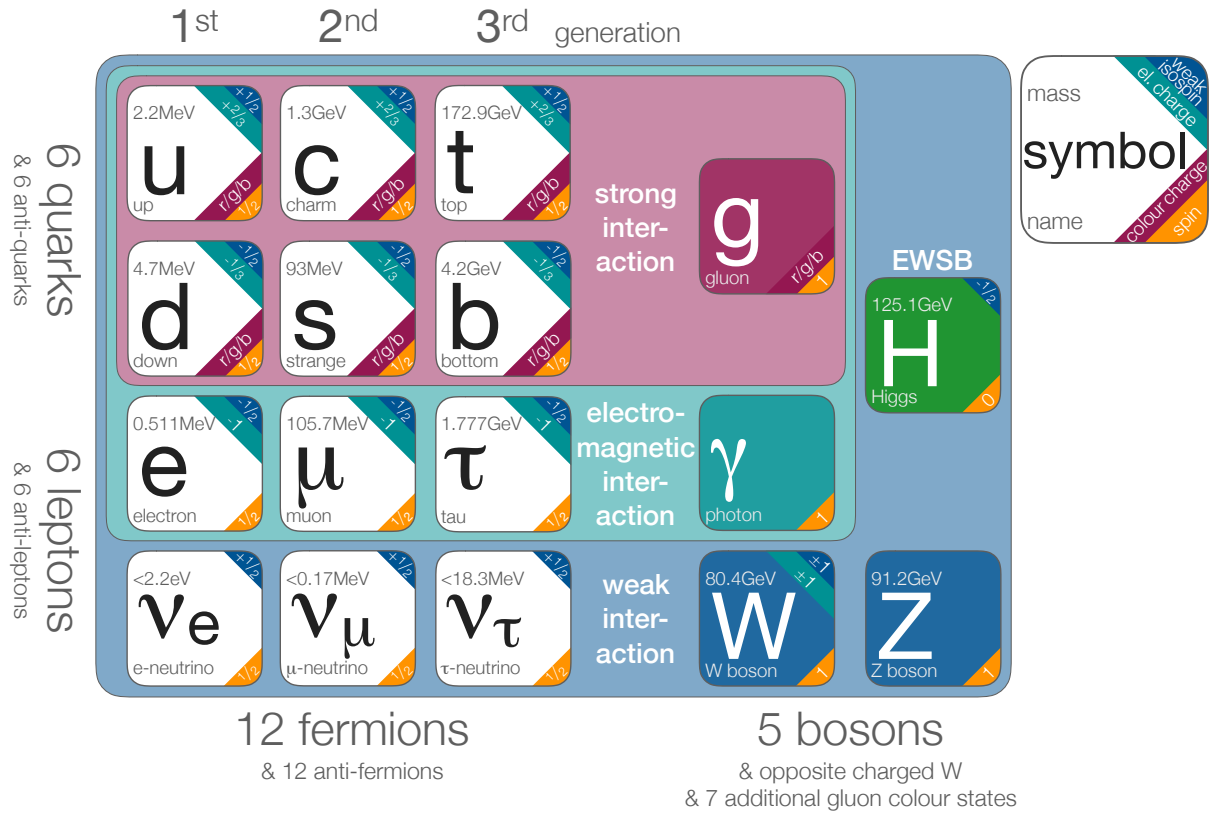


Figure 2.1.1: Schematic overview of the Standard Model of particle physics.

The mathematical representation of the SM as a *Quantum Field Theory* (QFT) is given by the local gauge symmetry group

$$SU(3)_C \times SU(2)_L \times U(1)_Y . \quad (2.1.1)$$

It features three symmetry groups which correspond to the three fundamental interactions mentioned above. The fermions are excitations of fermion fields while the bosons are associated to gauge fields. To each group generator a gauge field is assigned to ensure invariance under local transformation of the fermion fields. Based on the Noether Theorem every continuous symmetry gives rise to a conserved quantity, i.e. the aforementioned charges.

²Currently it is not clear whether neutrinos have anti-particles or whether they are their own anti-particles, i.e. Majorana particles.

³Colour states of the quarks are neglected.

The strong interaction is represented by the $SU(3)_C$ group and field theory of *Quantum Chromodynamics* (QCD). The index C stands for its intrinsic property, the colour charge. As the $SU(3)_C$ has eight generators, eight gluon fields, G^i , exist which all can be identified with the gluons as particles. However, it comes with eight different colour charges, or more precisely colour charge combinations. As the underlying group is non-abelian it gives rise to self-interaction of gluons. The only fermions that carry a colour charge, i.e. the only fermions participating in strong interactions, are quarks. The running of the strong coupling constant, α_s , causes two phenomena unique to QCD. One is the asymptotic freedom which is present at small distances when α_s approaches zero. As a result quarks and gluons can be considered free particles at very high energies and small distances and interact directly with each other which is exploited at collider experiments. At the other end of the spectra, at larger distances and small energies, quarks are only observed as bound states of two (mesons), three (baryons) or five (pentaquarks) quarks with a net colour charge of zero. This is called *confinement*.

The electro-weak interaction is the unification of the electromagnetic and weak force and represented by the $SU(2)_L \times U(1)_Y$ gauge group. It has four generators, therefore four gauge fields: $W^{1\dots 3}$ and B .

The physically observed states, the W and Z bosons as well as the photon, arise from a mixing of these gauge fields. Contrary to $SU(3)_C$, the $SU(2)_L \times U(1)_Y$ symmetry group is broken by *spontaneous symmetry breaking* (SSB) and only the abelian $U(1)_Q$ remains as a symmetry of the ground state.

The SSB is realised via the *Higgs-Brout-Englert mechanism* [13–16], introducing a new scalar spin-0, the Higgs field, which can be represented as a complex isospin doublet and the Higgs potential with a non-trivial vacuum expectation value. Three of the four associated degrees of freedom, corresponding to the four real scalar fields, are absorbed as the longitudinal polarisation components of the W and Z bosons according to the Goldstone theorem [19, 20]. Hence, they receive their mass in a consistent way, while the photon stays massless. The remaining degree of freedom is identified with the physical scalar Higgs field and its excitation, the Higgs boson.

The photon, the gauge boson of the electromagnetic interaction, cannot self-interact as $U(1)_Q$ is abelian and the photon carries no electric charge. All fermions, besides neutrinos, carry an electrical charge and engage in electromagnetic interactions through the photon. Hence, neutral leptons, i.e. neutrinos, solely interact via the weak interaction. The only interaction all fermions participate in is the weak interaction as every fermion has a weak isospin. Due to the non-abelian character of the $SU(2)_L \times U(1)_Y$ gauge group, its mediators, the Z and W bosons, can self-interact. By construction left-handed fermions and right-handed anti-fermions are grouped in $SU(2)_L$ doublets, while right-handed fermions and left-handed anti-fermions only come as singlets. Hence, the quarks of the first generation form the doublet $(u, d)_L^T$ and the singlets u_R and d_R . While, the leptons of the first generation form the doublet $(\nu_e, e)_L^T$ and the singlet e_R . As a consequence, the SM contains no right-handed neutrino. The particles of the second and third generation form doublets and singlets accordingly.

So far only the masses of the weak gauge bosons and the Higgs boson are derived but not for the fermion fields, although it is well known that all fermions are massive. The fermion masses are a result of the Yukawa coupling to the Higgs field.⁴

For reasons of renormalisation, the fundamental parameters of the SM can be defined by a finite number of measurements. The SM is fully described by 19 parameters:

- three gauge couplings,
- six Yukawa couplings for quarks (corresponding to six quark masses),
- three Yukawa couplings for leptons (corresponding to three lepton masses⁵),

⁴For neutrinos this is only true if they are pure Dirac fermions; if they are Majorana fermions, beyond SM mass terms are necessary.

⁵Neutrinos are massless in the original SM.

- one CP-phase and three mixing angles of the CKM matrix,
- one Higgs mass,
- one Higgs self-coupling constant, and
- one QCD vacuum angle (θ_{QCD}).

The precise determination of these parameters at a certain energy scale, allows making predictions and validating the evolution of the SM at an arbitrary energy scale.

Into the Unknown of the SM

The SM has an impressive track record of describing observed and formerly unseen physics. However, in its current state it cannot explain all observed phenomena [21] and it is apparent that it needs to be modified, extended or embedded in a more complex higher level theory. Most of the free parameters of the SM are determined with exceptional precision and continuous efforts are made to reach similar or even better results for all of them, like the progressively improving determination of the Higgs boson mass. These measurements are not only made out of self-serving purpose but also to give vital input for the mentioned extended or superior models. In its lifetime of about five decades, the SM has stood several trials and proven to be a reliable theory within its scope. It is still challenged by various studies, e.g. $R_{K^{(*)}}$ measurements [1, 2], as any discrepancy might give a hint to approach the unexplained and unknown.

One of the apparent shortcomings of the SM is that neutrinos remain massless. This is in conflict with the experimentally observed neutrino oscillations which require, albeit not necessarily large, but non-zero masses [22].

Further, the SM fails to explain the imminent abundance of matter compared to anti-matter. Based on theories describing the origin of the universe and its evolution, matter and anti-matter should have been produced in equal amounts. Eventually, this would have lead to the annihilation of both which is obviously not the case.

Another observed but not yet explained phenomenon is summarised under the term *Dark Matter* (DM) [23, 24]. It was introduced to explain the discrepancies between the theoretically assumed and measured dependence of the circular velocity of galaxies on their radii. Based on classical Newtonian physics an increasing mass density is required in order to explain the measured flat velocity for large radii. This defies other observations which state a decrease with large radii. DM could bridge the gap as it contributes the needed mass but would be invisible for us as it does not participate in electromagnetic interactions. The existence of DM is further supported by gravitational lensing effects and anisotropies in cosmic microwave background measurements. From current studies it is known to be a form of non-baryonic matter which makes up about 27 % [21, 24, 25] of the total energy content of the universe. The SM neutrino initially served as a possible DM particle candidate but due to its small mass it only would have an unsatisfying contribution.

Dark matter is not the only form of energy along visible matter. In fact most of the energy content in the universe, 68 %, is assumed to be a not yet found form of energy, called *Dark Energy* [24]. It is needed to explain the ever accelerating expansion of the universe. Its existence could explain the QFT-based estimation of the vacuum energy density which is at least 40 orders of magnitude too large compared to the observed bounds. However, not much is known about the characteristics of Dark Energy.

Another, issue arises from the SM itself: the hierarchy problem [26]. The large difference of the electro-weak and Planck scale leads to large higher order loop corrections to the Higgs mass, and thus requires a fine-tuning of the bare Higgs mass to 30 digits. Albeit it is not an obvious lack of the SM, such large adjustments are considered to be unnatural and motivate the assumption that new physics would yield a more natural explanation.

The separation of the strong and electro-weak interaction is unsatisfying as it was possible to unify the electromagnetic and weak interaction. Their coupling constants depend on the energy scale at which the interaction takes place and are similar at very high energies but still too far apart to realise a unification of all three fundamental forces. Assuming that the SM gauge group is embedded in a higher order broken symmetry, allows the couplings to be unified at a very high energy scale but accommodate the separation at the so far explored phase space. This scenario is referred to as *Grand Unified Theory* (GUT).

As appealing the concept of GUT is, it has one apparent flaw: the contempt of gravity. Although gravity can be neglected at energy scales much smaller than the Planck scale, the pursuit of one theory that describes everything is captivating. However, it would require the conjunction of general relativity and QFT which appear to be incompatible and hence certainly demands a new theoretical framework.

These and several unmentioned unanswered questions give rise to a plethora of new concepts and models. One of the most appealing concepts is the principle of Supersymmetry which will be addressed in the following section.

2.2 A Supersymmetric Long-Lived Approach

Various theories aim to overcome the shortcomings of the SM outlined at the end of Section 2.1. Some of the most favoured theories arise from the concept of Supersymmetry [27] and are described in this section with the focus on representations which give rise to *long-lived particles* (LLPs). The existence of LLPs is featured in many *beyond Standard Model* (BSM) theories [28–34]. Although several searches for long-lived particles were already conducted at the LHC’s predecessors, the apparent absence of any new physics signatures gives further rise to LLP scenarios.

The proper lifetime, τ , of a particle is defined as

$$\tau^{-1} = \Gamma = \frac{1}{2m_X} \int d\Pi_f |\mathcal{M}(m_x \rightarrow p_f)|^2, \quad (2.2.1)$$

with m_X as the particle mass, $\mathcal{M}$ as the matrix element of its decay into the decay products p_f , and $d\Pi_f$ representing the Lorentz-invariant phase space for the decay. Three ways to reach long lifetimes can be derived based on this definition:

- small couplings lowering the probability for a decay to happen,
- a nearly mass degenerated spectrum reducing the available phase space, or
- scale suppression leading to highly virtual intermediate states.

These are generic features of many BSM theories, including various SUSY models.

SUSY is a principle which describes a symmetry between bosons and fermions based on a supersymmetric transformation. It proclaims that each particle has a supersymmetric partner, a so-called *sparticle*, with identical characteristics but a difference in spin of $1/2$. Hence, every degree of freedom of a fermionic SM particle has a bosonic partner, a *sfermion*, and each bosonic SM particle has a fermionic counterpart, a *gaugino*, respectively *higgsino*. This is achieved by introducing anti-commuting spinor operators which transform fermion into boson fields and vice versa. Corresponding particles and sparticles are combined in *super multiplets* and participate in the fundamental interactions in the same manner. However, this basic formulation of SUSY requires the sparticles to have the exact same mass as their SM partners. This has been disproved experimentally as otherwise they would have been discovered by now. Thus, SUSY must be a broken symmetry which allows the sparticles to have significantly higher masses than their SM counterparts. One way to realise this is via *soft symmetry breaking*, e.g. at an energy scale close to 1 TeV. The *Minimal Supersymmetric Standard Model* (MSSM) [35] is a benchmark candidate

which satisfies these needs. It follows the same underlying gauge symmetry as the SM and the particle content grows only by a minimal number. Mainly the Higgs sector is significantly expanded in order to avoid gauge anomalies and inconsistencies. The MSSM features a total of five Higgs bosons: one light neutral state (the experimentally confirmed SM-like Higgs boson), one CP-even neutral heavy state, one CP-odd neutral heavy state and two electrically charged heavy Higgs bosons. Although the MSSM reduces the number of free parameters drastically from 105 to eight, it is still not feasible to scan the entire parameter space. Hence, several benchmark scenarios are introduced to further restrict the parameter space.

Divergences in the fermionic loop corrections to the Higgs mass can be reduced by introducing superpartners. However, a certain fine-tuning remains as the particle and sparticle masses are not identical. Under the assumption that the breaking of SUSY occurs around 1 TeV, the running of the coupling constants changes such that a unification of the fundamental forces can be achieved. Further, the *lightest SUSY particle* (LSP) serves as a promising DM candidate, as a stable neutral, weakly interacting particle with non-negligible mass is favoured.

However, a major caveat of the MSSM is that it permits interactions violating the conservation of lepton and baryon number, and thus leads to the decay of the proton in a rather short time span which is experimentally excluded. This inconvenience is mitigated by introducing a new quantum number called *R-Parity* and defined as

$$P_R = (-1)^{2s+3(B+L)}, \quad (2.2.2)$$

where s is the spin and L and B are the lepton and baryon number of the particle. By enforcing the conservation of R-Parity the decay of the proton is prevented. As a consequence sparticles can only be produced in pairs and their decay results in a remaining sparticle in the final state. However, it is worth noting that R-Parity is not necessarily conserved in all SUSY models giving rise to interesting new signatures [36–39].

One of the R-parity conserving scenarios, which features LLPs, is *split-SUSY* [40, 41]. Split-SUSY is mainly guided by the unification of the gauge couplings and DM, but omits to resolve the hierarchy problem and resorts to fine-tuning. The breaking of SUSY can occur at a high energy scale resulting in heavy sleptons and squarks. The latter suppress the decay of the gluino as it is only possible through a virtual squark. Consequentially, the gluino is long-lived. Figure 2.2.1 shows a Feynman diagram of the production of a long-lived gluino in a hadron collision and its subsequent decay via a virtual squark in the split-SUSY model [42].

If SUSY breaking takes place at an energy scale, m_S , much larger than 1000 TeV, all scalars, except the SM-like Higgs boson, would be extremely heavy while fermionic particles, like the gluino, can have masses at the electro-weak scale. In this scenario the gluino lifetime is long enough such that it hadronises and binds with SM quarks and gluons to form a meta-stable state, called *R-hadron*. In R-parity violating scenarios similar R-hadron states can be realised for squarks.

In case of $m_S > 10^6$ GeV, the R-hadron can travel a macroscopic distance before it decays. For $m_S > 10^7$ GeV the decay typically takes place outside of the detector.⁶ If SUSY is broken at an even higher energy scale, R-hadrons begin to affect nucleosynthesis in the early universe ($m_S > 10^9$ GeV) and eventually would be considered stable as their lifetime would exceed the age of the universe ($m_S > 10^{13}$ GeV).

The gluino in an R-hadron can be regarded as a non-interacting spectator surrounded by a cloud of quarks or gluons which interact with the surrounding material. While moving through a detector, the R-hadron loses its energy through hadronic scattering and ionisation if it carries an electrical charge. This results in intriguing detector signatures such as displaced or delayed decays [44, 45]. In the first case the LLP travels notably slower than SM particles and thus takes much longer to reach detector layers further away from the collision point, like the calorimeters

⁶Under the assumption of the current layouts of the LHC detectors.

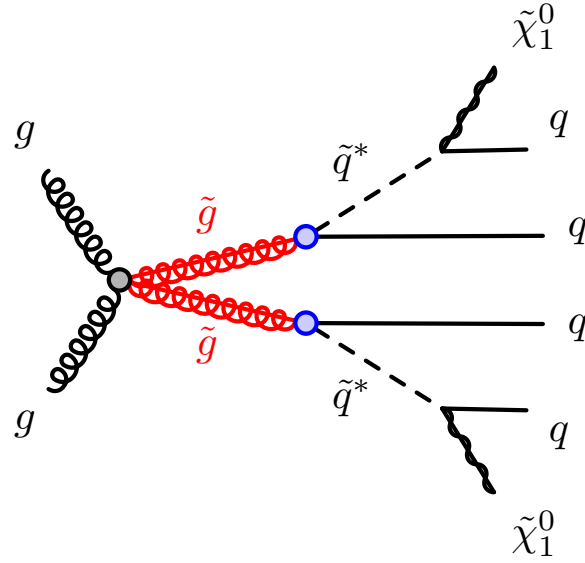
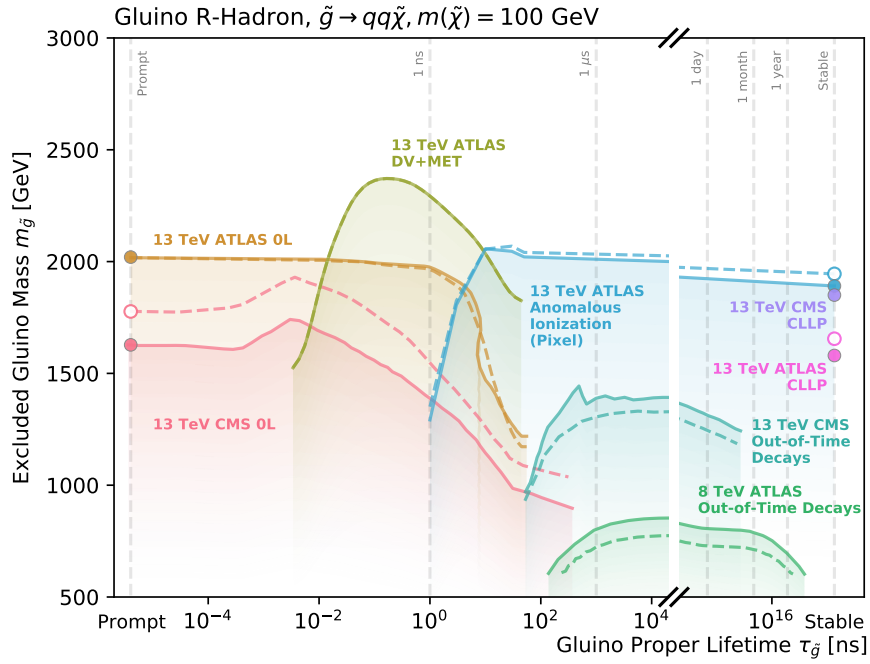


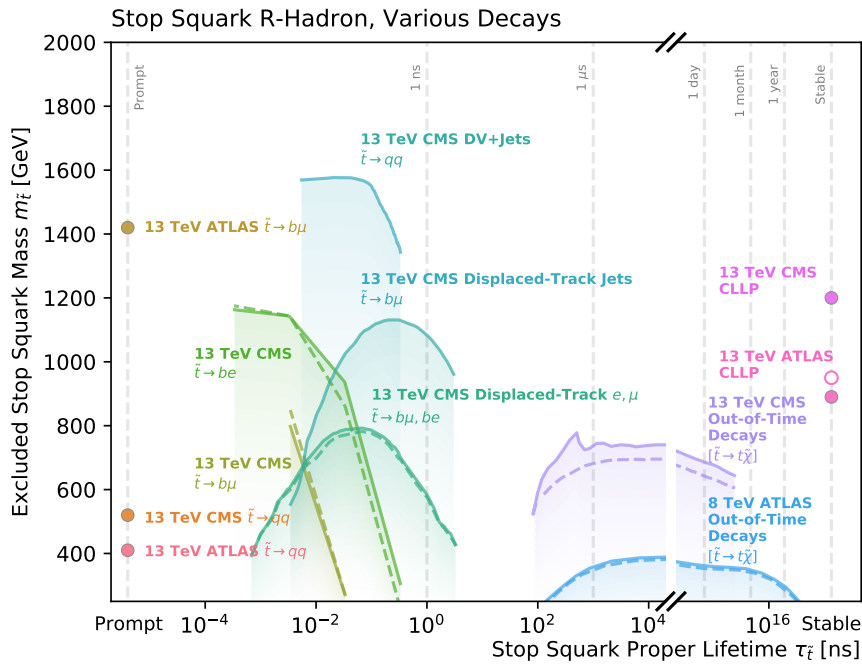
Figure 2.2.1: Production of a long-lived gluino in a hadron collision and its subsequent decay via a virtual squark in the split-SUSY model [43].

or muon spectrometer, where it eventually decays. A delayed decay of an LLP might occur significantly later than its production and cannot be associated to a collision any longer and hence might be misidentified or lost entirely. However, by exploiting times during which no collisions take place a unique opportunity to explore such out-of-time signature is provided and is discussed exhaustively in Section 5.

The current limits on gluino and stop squark R-hadron masses and live times are summarised for various final states in Figure 2.2.2. For the analyses of out-of-time decays published by the ATLAS collaboration limits of the gluino and stop mass have been set at 800 GeV and 380 GeV, respectively, for various lifetimes ranging between $10 \mu\text{s}$ and 1000 s [46]. These limits have been increased by the CMS collaboration to 1380 GeV and 740 GeV for gluinos and stops, respectively [47].



(a)



(b)

Figure 2.2.2: A broad range of limits on the mass vs. lifetime of the gluino (a) and stop squark (b) is obtained from a number of searches [46–61]. When available, dashed lines and open circles denote the expected limits given the experimental sensitivity, while solid lines and filled circles represent the limits that were actually observed in the experiment. Circles at lifetime values labelled as prompt denote a search based on a prompt signature, rather than a long-lived one. [43]

2.3 Event Simulation

In order to confirm or disprove a theory, it needs to be represented by quantities which can be measured within an experiment. Therefore, it is essential to predict the signatures that are induced in a detector by simulating how a theoretical event takes place in a physical setup. On the one hand, this gives indispensable guidance for searches for new physics but also for the design of future experiments. On the other hand, physics simulations are a valuable reference to estimate and improve the performance of reconstruction, identification and calibration methods and design new algorithms.

Monte Carlo (MC) generators are exploited to randomly generate events based on theoretical predictions. The first stage is the event generation during which event generators simulate the initial, intermediate and final states of a physics process from its matrix element. This stage is also called the *hard scattering* and is based on perturbative QCD. In case the process takes place in a proton-proton collision, like the data study in this thesis, it is crucial to factor *parton density functions* (PDFs) in. One caveat of the PDFs is that they cannot be calculated by first principles but must be measured. Therefore, data from various current and past experiments are combined to achieve the most accurate description.

Afterwards, follows the step of *parton showering* which simulates the decay cascades of quarks into quarks and gluons and of gluons into pairs of quarks until they are stopped randomly or their energy is below a certain cut-off value. The final shower products are hadronised subsequently for reasons of confinement.

In addition, initial and final state radiation are modelled. Further, *pile-up* events, i.e. proton-proton interactions happening simultaneously to the hard scattering, are simulated separately as minimum-bias events. Similarly, non-interacting partons or beam remnants are simulated and overlaid as underlying events.

All steps can be performed with the **Athena** software framework [62] in combination with third party software packages. The latter are dedicated programmes which perform one or several of the aforementioned steps. For example PYTHIA [63] can be used to simulate the hard scattering as well as the parton showering. Eventually, the interaction with the detector and the detector response needs to be simulated which is discussed in Section 3.2.8. The final results of the simulation process allow the predict of cross sections and the extraction of distributions of the final state observables which can be compared to data measurements.

Chapter 3

The LHC and the ATLAS Detector

Particle colliders play a key role in the aim to deepen our understanding of the universe and address the questions raised in Chapter 2. The largest and most powerful hadron-hadron collider ever built is the *Large Hadron Collider* (LHC) at CERN. In order to allow the precise study of known interactions and the search for not yet discovered particles, sophisticated detectors are essential. Driven by the high demands of fundamental particle physics research, various computational and technological breakthroughs have been achieved hand in hand with major scientific advancements. The data analysed within the scope of this thesis are based on proton-proton collisions recorded with the ATLAS detector, one of the four main experiments installed at the LHC.

The LHC and the associated collider chain of CERN is outlined in Section 3.1 followed by a detailed discussion of the ATLAS experiment in Section 3.2.

3.1 The Large Hadron Collider

The LHC [64–67] is part of CERN’s extensive accelerator complex outlined in Figure 3.1.1. Although the LHC is capable to accelerate different types of particles, most of the time protons are the focus of attention. To create the protons, hydrogen atoms are inserted in a duoplasmatron and ionised by electrons from a cathode filament creating a plasma. The plasma is passed through a series of charged grids which strip the valence electrons off and leave a pure proton beam. The first part in the accelerator chain is the linear accelerator *LINAC2* where the protons gain an energy of 50 MeV. Following that, they enter a series of circular accelerators starting with the *Proton Synchrotron Booster* (PSB) where they cycle until exceeding 1.4 GeV. At the next stage, the protons are fed into the *Proton Synchrotron* (PS) which they exit with 25 GeV. After another ramp in energy to 450 GeV in the *Super Proton Synchrotron* (SPS), the proton beam is split into two and injected via separate transfer tunnels in to the LHC.

The LHC is situated in a tunnel about 100 m underground the Franco-Swiss border and spans a circumference of 26.7 km. It is separated into eight arcs connected by eight straight sections. One of the latter is equipped with two series of 400 MHz superconducting radio-frequency cavities to accelerate the two proton beams with alternating electric fields to almost the speed of light. These cavities operate at a temperature of 4.5 K with a voltage of 20 MV each resulting in an accelerating field of 5 MV/m. Based on this accelerating concept the beams are separated into several bunches rather than a continuous flow of particles. The same principle is exploited in the pre-accelerators; hence the structuring of the beam is already defined by the PS.¹ Each bunch is filled with up to 1.6×10^{11} protons and separated from the subsequent one by 25 ns. 3564 bunch positions are defined per beam but due to technical restrictions related to the pre-accelerators

¹The bunch separation induced by LINAC2 is dissolved by the PSB which divides the protons over four stacked rings to reduce the repulsive effect of the Coulomb force in between the protons which is non-negligible at these energies.

and filling, the number of proton-filled bunches is limited to 2808. The filled bunches are grouped into trains with larger gaps in between them. Although the remaining bunches in these gaps are unfilled, they nevertheless contain up to 10^8 protons due to contamination debunching and trailing ghost bunches. Based on the proton population, a *Bunch-Crossing Identification* (BCID) is assigned. The combination of two filled bunches from each beam is called *paired*. If only one bunch is filled the term *unpaired* is used. BCIDs with two unfilled bunches are denoted as *empty* since the likelihood of proton-proton collisions is negligible given the low proton density.

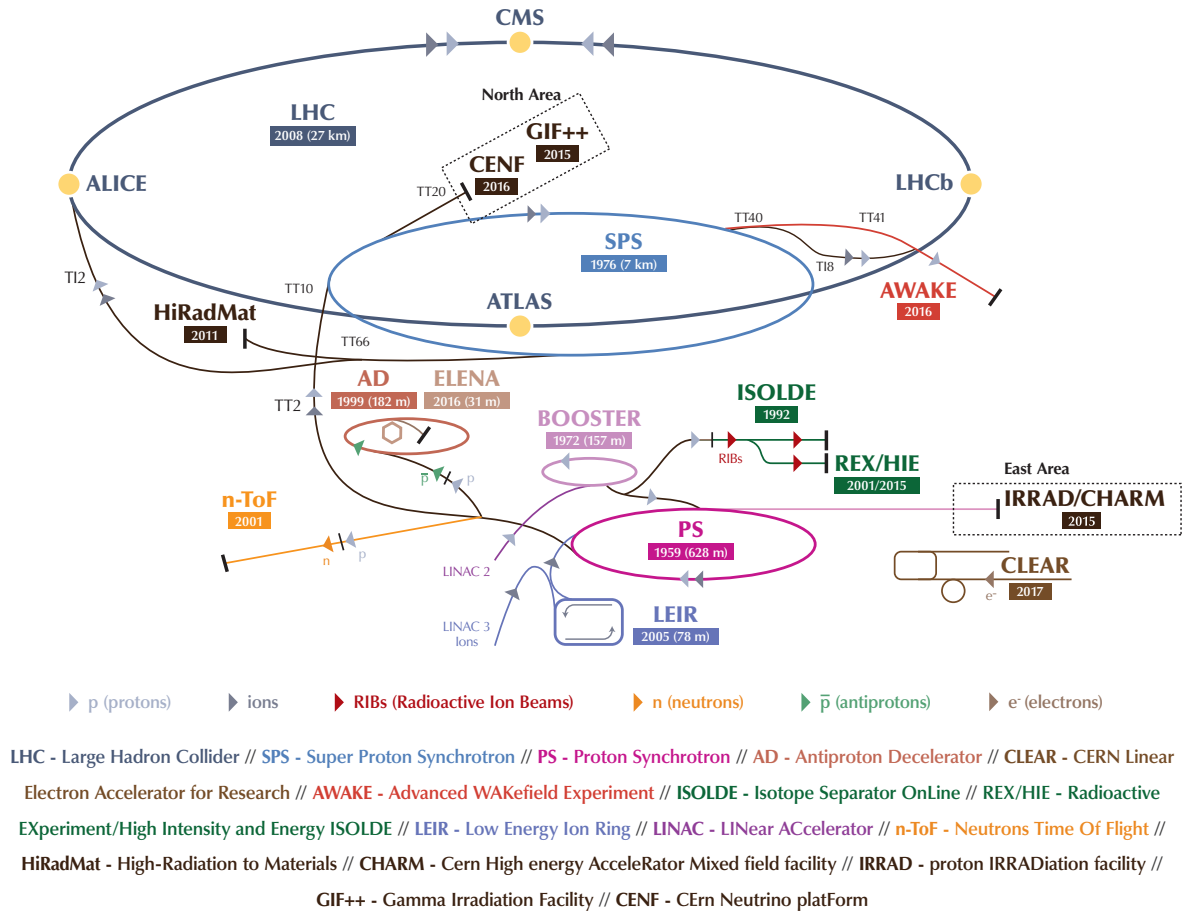


Figure 3.1.1: Schematic overview of the accelerator complex at CERN (adapted) [68].

To allow an uninterrupted passage of the protons and prevent any energy losses due to collisions with gas molecules, an ultra-high vacuum of 10^{-10} to 10^{-11} mbar is maintained in the beam pipes. At four of the straight intersections the two counter-circulating beams can be crossed-over and brought to collision. Particles created over the course of these collisions are observed by the four large LHC experiments.

The arcs are equipped with 1232 dipole magnets to constrain the proton beams on circular trajectories based on the Lorentz force. Therefore, a magnetic field of up to 8.33 T is required and contrary to the pre-accelerators which rely on conventional electromagnets, this can only be realised with superconducting coils made of niobium-titanium cables which need to be kept at a temperature of 1.9 K to allow a resistance free flow of electricity. Due to the limited space in the tunnel a twin-bore magnet design has been chosen, coupling both beam pipes surrounded by the magnet coils and an iron yoke embedded in a bath of superfluid liquid helium. The same technology is exploited in various higher order correction and focusing magnets which

are distributed strategically along the accelerator to preserve the beam integrity. Quadrupole magnets are installed in an alternating focusing and defocusing configuration (FODO cells) on both sides of each detector to keep the transverse spread of the bunches small while increasing the proton density. Protons which drift too far away from the centre of their respective bunch are captured by collimators such that they cannot pose any risk to the sensitive detectors. In addition, several setups to monitor the beam position and profile are in place to guarantee the best beam quality.

The four main detectors at the LHC are ALICE, ATLAS, CMS and LHCb. ATLAS (*A Toroidal LHC ApparatuS*) [69] and CMS (*Compact Muon Solenoid*) [70] are two multi-purpose detectors which have a similar physics programme but rely on different detector technologies, such that each can validate the observations of the other one. ALICE (*A Large Ion Collider Experiment*) [71] focuses on collisions of lead ions which are accelerated instead of protons for a distinct period of time, e.g. to study the quark-gluon-plasma, a state which existed shortly after the Big Bang. The forward spectrometer LHCb (*Large Hadron Collider beauty*) [72] examines a broad b -physics spectrum, e.g. CP violation. The main experiments are accompanied by three smaller experiments: LHCf [73], MoEDAL [74] and TOTEM [75]. LHCf measures neutral particles in the very forward region of LHC collisions at ATLAS to calibrate the hadron interaction models used in extremely high-energetic cosmic ray research. The purpose of TOTEM is to determine the total proton-proton cross section and to study elastic scattering and diffractive dissociation. MoEDAL searches for magnetic monopoles and other highly ionising (pseudo-) stable massive particles.

The data presented in the following chapters were collected during Run 2 of the LHC which started in 2015 and finished by the end of 2018 with 149 fb^{-1} [76] of data collected at a centre-of-mass energy of 13 TeV. Run 2 was preceded by Run 1 (2009–2012) during which 21.7 fb^{-1} (5.3 fb^{-1}) [76] were recorded at a centre-of-mass energy of 8 TeV (7 TeV). Until 2021 the LHC will be in *Long Shutdown 2* (LS2) and undergo several upgrades to reach higher luminosities and energies in the upcoming Run 3 opening an opportunity for new discoveries thanks to increased production cross sections.

Considering a physics process with a cross section, σ_{process} , the mean number of produced events per second, N_{event} , is given by

$$N_{\text{event}} = \mathcal{L} \sigma_{\text{process}} , \quad (3.1.1)$$

with $\mathcal{L}$ as integrated luminosity

$$\mathcal{L} = \int L \, dt . \quad (3.1.2)$$

L refers to the instantaneous luminosity which only depends on beam parameters when assuming a Gaussian beam profile, according to

$$L = \frac{N_b^2 n_b f_{\text{rev}} \gamma_r}{4\pi \epsilon_n \beta^*} \cdot F \quad \text{with} \quad F = \left(1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*} \right)^2 \right)^{-\frac{1}{2}} , \quad (3.1.3)$$

where the number of particles per bunch, N_b , and the mean number of bunches per beam, n_b , are considered as well as the revolution frequency, f_{rev} . Furthermore, ϵ_n , β^* and γ_r refer to the normalised transverse beam emittance, the beta function at the collision point and the relativistic gamma factor, respectively. The geometrical luminosity reduction factor, F , depends on the crossing angle, θ_c , of the colliding beams at the interaction point (IP), the root mean square (RMS) of the bunch length, σ_z , and transverse RMS of the beam size at the IP, σ^* . Considering the operational parameters of the LHC in 2018 a peak luminosity of $2.14 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ was reached which excelled the design value of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$.

3.2 The ATLAS Detector

The ATLAS detector, shown in Figure 3.2.1, is with 44 m in length and 25 m in diameter the largest LHC experiment. It features a cylindrical shape covering almost 4π to capture all remnants of a collision. It is composed of several sub-detectors which are arranged concentrically around the IP where the proton-proton collisions take place. Different technologies are exploited to serve their respective task best. An illustration of various particles traversing ATLAS is depicted in Figure 3.2.2.

The innermost layers form the tracking system which allows a precise measurement of tracks of charged particles including their momenta, and the reconstruction of primary and secondary vertices. Next follow the calorimeters to determine particle energies. Finally, the detector is enclosed by the muon spectrometer, installed to measure the trajectories of muons and anti-muons.² The sub-detectors are arranged such that ATLAS is forward-backward symmetric and invariant under discrete rotation around the beam axis, with the exception of the muon spectrometer due to the supporting structures of the detector. The calorimeters and muon system further serve for trigger purposes. Given the high bunch crossing rate of 40 MHz and limited data storage, an outstanding trigger system is critical to select only interesting events for recording.

All detector parts as well as the trigger system are vital for any physics analysis, either for the direct reconstruction of the particles of interest and their decay products or for background studies and suppression of misidentification. For the presented analyses the calorimeters play a key role but the tracking system and the muon spectrometer are equally vital for the studies presented in Chapters 4 and 5, respectively. A description of each sub-system is given in the following sections.

ATLAS uses a right handed coordinate system with its origin in the nominal IP which is equal to the centre of the detector. The z -axis points in beam direction; hence the x - y -plane is transverse to the beamline. Thereby, the positive x -axis points towards the centre of the LHC and the positive y -axis upwards. Along the z -axis the detector is divided into an A-side (positive z) and a C-side (negative z).

Based on the concentric design of the detector around the beamline, many measured quantities are expressed in cylindrical coordinates, with the azimuthal angle, ϕ , around the beam axis and the polar angle, θ , with respect to the beam axis. Hence, the x - y -plane can also be denoted as r - ϕ -plane with r as radius. Positive ϕ values corresponds to the upper half of the detector while negative ϕ values are assigned in the lower half. An important quantity in hadron collider physics is the rapidity, y , due to the invariance of particle production as a function of y under longitudinal boosts. The rapidity is defined as

$$y = \frac{1}{2} \cdot \ln \frac{E + p_z}{E - p_z} , \quad (3.2.1)$$

where E denotes the particle energy and p_z its momentum component along to the beamline. For massless particles it reduces to the pseudorapidity, η :

$$\eta = -\ln \tan \frac{\theta}{2} . \quad (3.2.2)$$

Further, the spacial distance, ΔR , of two objects in the η - ϕ -plane is given by:

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} . \quad (3.2.3)$$

Positive and negative η values corresponds to the A and C side of the detector. Particular attention is given to transverse quantities since the longitudinal momentum of the initial partons

²Throughout the rest of the thesis the term “muon” is used referring to both, muon and anti-muon.

cannot be determined a priori. Only the vector sum of momenta in the transverse plane is zero at vanishing beam crossing angles. Highly important for physics analyses are the transverse momentum, p_T , the transverse energy, E_T , and the missing transverse energy, E_T^{miss} , which are defined in the r - ϕ -plane.

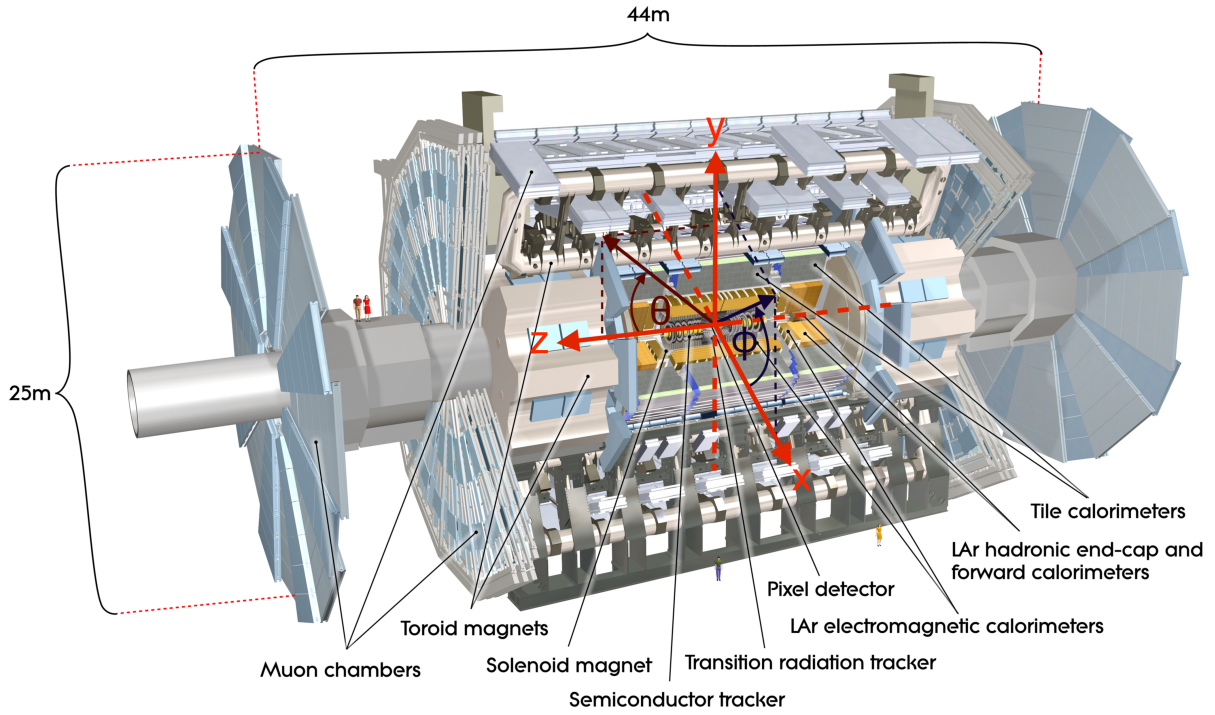


Figure 3.2.1: Cut-away view of the ATLAS detector and coordinate system (adapted) [77].

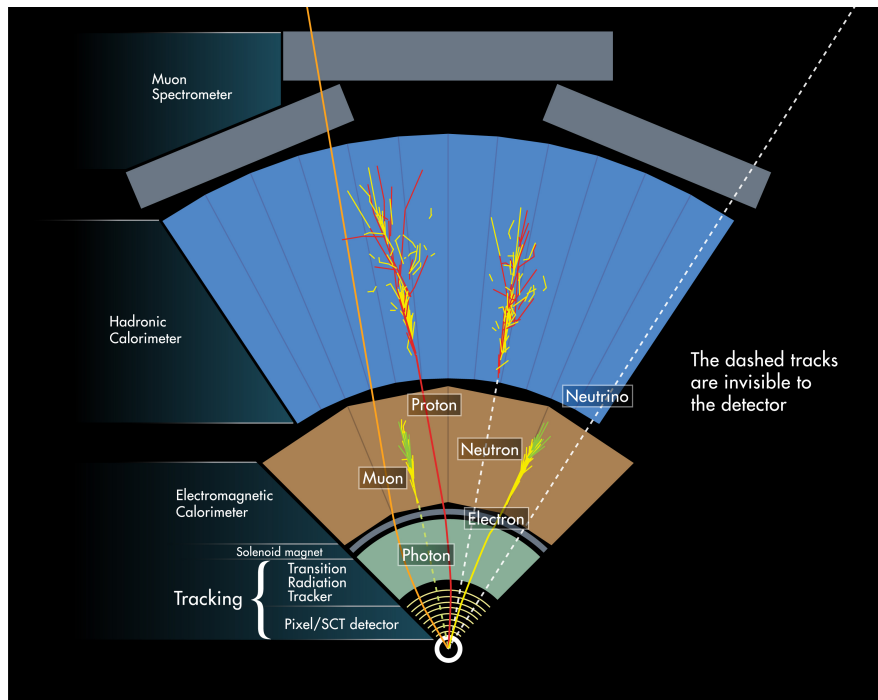


Figure 3.2.2: Illustration of particles traversing the ATLAS detector [78].

3.2.1 Inner Detector

The detector part closest to the IP is the *Inner Detector* (ID) [79, 80], a tracking device shown in Figure 3.2.3. It encloses the beam pipe and extends 2.1 m and 6.2 m in transverse and longitudinal direction, respectively. The ID covers an absolute pseudorapidity range up to 2.5. It measures the trajectories of charged particles and their vertex of origin with remarkably high precision. It is composed of three dedicated sub-detectors surrounded by a 2 T solenoid magnet. A major challenge for the design is to minimise the material in front of the calorimeter system and the impact on the energies of the traversing particles.

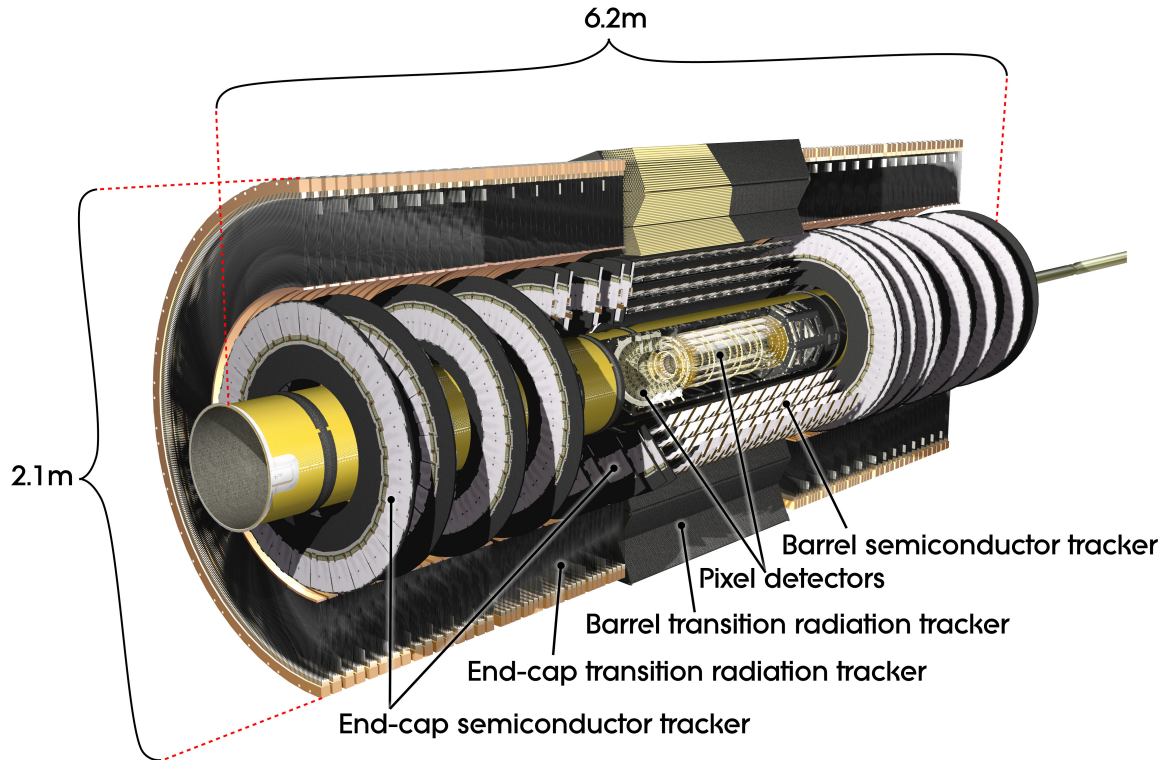


Figure 3.2.3: Cut-away view of the inner detector [69].

The first tracking sub-system, the **Pixel Detector**, expands over 1.3 m in longitudinal direction and consists of four cylindrical barrel layers with radii ranging from 5.05 cm to 12.25 cm and three end-cap disks with an outer radius of 15 cm. It features n-type silicon wafer pixel sensors with a size of $50 \times 300 \mu\text{m}^2$ and a thickness of $250 \mu\text{m}$. Each pixel combines a junction diode depleted by a bias voltage as active sensor and a read-out chip. If a particle passes through a pixel, electron-hole pairs are created. The electrons migrate to a cathode where they are collected by tiny bump bonds and converted into a measurable current. The sensors are arranged in a matrix layout offering over 92 million read-out channels which allow a highly granular measurement in both coordinates in the layer plane and provides an excellent impact parameter resolution and vertex reconstruction. The intrinsic resolution of the Pixel detector reaches $10(10) \mu\text{m}$ in the r - ϕ -plane and $115(150) \mu\text{m}$ in z -direction in the barrel (end-cap) region.

This high precision is only surpassed by the **Insertable b-Layer** (IBL) which is not only the innermost but also the youngest part of the Pixel detector and was installed during LS1 to improve the reconstruction of jets originating from b -quarks. It is directly mounted on the beam pipe at a radius of 31 mm and consists of silicon pixels with a size of $50 \times 250 \mu\text{m}^2$. Given this, the IBL achieves a longitudinal and transverse resolution of $8.5 \mu\text{m}$ and $47 \mu\text{m}$, respectively.

About 1000 charged particles traverse the Pixel detector per bunch crossing hitting in average three to four sensors each. This results in a severe radiation damage over time such that the entire system needs to be replaced in 2024 and make way for a tracking device capable to cope with the increased particle rates expected at the High-Luminosity LHC.

The **Semi-Conductor Tracker** (SCT) follows outwards the tracking system. It is built of eight barrel layers and nine disks in each end-cap with radii from 30 cm to 52 cm and 28 cm to 56 cm, respectively. The same physics concept as for the Pixel detector is exploited but the cathodes have the form of strips which reduces the number of read-out channels to approximately 6.3 million. Each sensor is composed of 768 active strips of silicon wafers with a thickness of $285\text{ }\mu\text{m}$. Four layers of sensors with a size of $64.0 \times 63.6\text{ mm}^2$ and a strip-pitch of $80\text{ }\mu\text{m}$ are placed in separated modules in the central and innermost part of the SCT. As caveat of the strip arrangement, each strip misses position information in one direction. In order to recover a two-dimensional trajectory measurement, two active sensor layers are wire bound and rotated by a small angle of 40 mrad to each other. Albeit the granularity of the SCT is notably coarser than the one of the Pixel detector, it still reaches a compatible precision to determine vertex, track momenta and impact parameters of charged particles. The SCT's intrinsic resolution is $17\text{ }\mu\text{m}$ and $580\text{ }\mu\text{m}$ in transverse and longitudinal direction, respectively.

The **Transition Radiation Tracker** (TRT) is the outermost shell of the tracking system. With an extension over $2.5 \times 5.3\text{ m}^2$ it only covers an absolute pseudorapidity range up to 2.0. Contrary to the Pixel detector and the SCT the underlying detector technology is different: Straw tubes of 4 mm diameter are filled with a gas mixture of 70 % xenon, 27 % carbon dioxide and 3 % oxygen.³ About 50000 straw tubes are grouped in 73(160) layers of 144(37) cm length each one surrounded by polypropylene fibres (foils) in the barrel (end-cap) region. Every tube houses a $31\text{ }\mu\text{m}$ thin gold-plated tungsten-rhenium wire under high voltage in its centre. When a charged particle enters the gas is ionised and the freed electrons drift with a constant velocity towards the cathode. Due to the high electric field close to the cathode, avalanching is induced and finally leads to a measurable electric signal. Since the drift time is well known, the location of the entry point can be calculated. Further, a particle passes through various boundaries with different refractory indices such that ultra-relativistic particles ($\gamma > 1000$) emit transition radiation in a small angle with respect to the direction of flight at the layer boundaries. The lost energy still contributes to the measured current thanks to xenon's a high absorption efficiency for photons due to its high atomic number. Although the TRT has only 351000 read-out channels and is the least precise of the tracking devices, it still reaches an intrinsic resolution of $130\text{ }\mu\text{m}$ per straw tube.

Finally, a **Solenoid Magnet** completes the ID. To reach a magnetic field strong enough to bend the trajectories of ultra-relativistic particles and allow an efficient momentum measurement, superconducting aluminium-copper-niobium-titanium wire coils with a length of 5.3 m and a diameter of 2.4 m are required. With a current of 7.73 kA a magnetic field of 2 T is reached but comes with the cost of intense cooling. The solenoid magnet and the barrel parts of the calorimeter share the same cryostat to keep the material in front of the calorimeter and the deterioration of the energy measurements at a minimum.

3.2.2 Calorimeter System

The ATLAS calorimeter system is divided into several sub-calorimeters which all aim to absorb and measure the energy of charged and neutral particles and finally to stop them with exceptions for muons and neutrinos. Thanks to a high hermiticity the missing energy of the latter can be

³In some regions xenon had to be replaced by argon to mitigate the costs caused by a gas leak.

reconstructed as negative vectorial sum of all energy deposits. The underlying detector principle of all calorimeters of ATLAS is an alternating arrangement of passive and active material layers, whereby traversing particles interact with the passive layers creating showers of secondary particles which in turn lose their energy in the active material resulting in a measurable signal which is proportional to the deposited energy. The sum of the energy deposits in all sampling layers gives the energy of the initial particle. Depending on the particle type the induced showers differ. Electrons, positrons⁴ and photons cause electromagnetic (EM) showers, whereas hadrons result in hadronic showers with an electromagnetic component. As electromagnetic showers are less penetrating than hadronic showers, a division into an electromagnetic (ECAL) and hadronic (HCAL) calorimeter is useful. In ATLAS this is realised by using different materials, namely liquid argon (LAr) and plastic scintillators for the active layers. The first is utilised for both, the ECAL and HCAL components while the second is only featured in HCAL devices. Figure 3.2.4 shows a schematic of the calorimeter system.

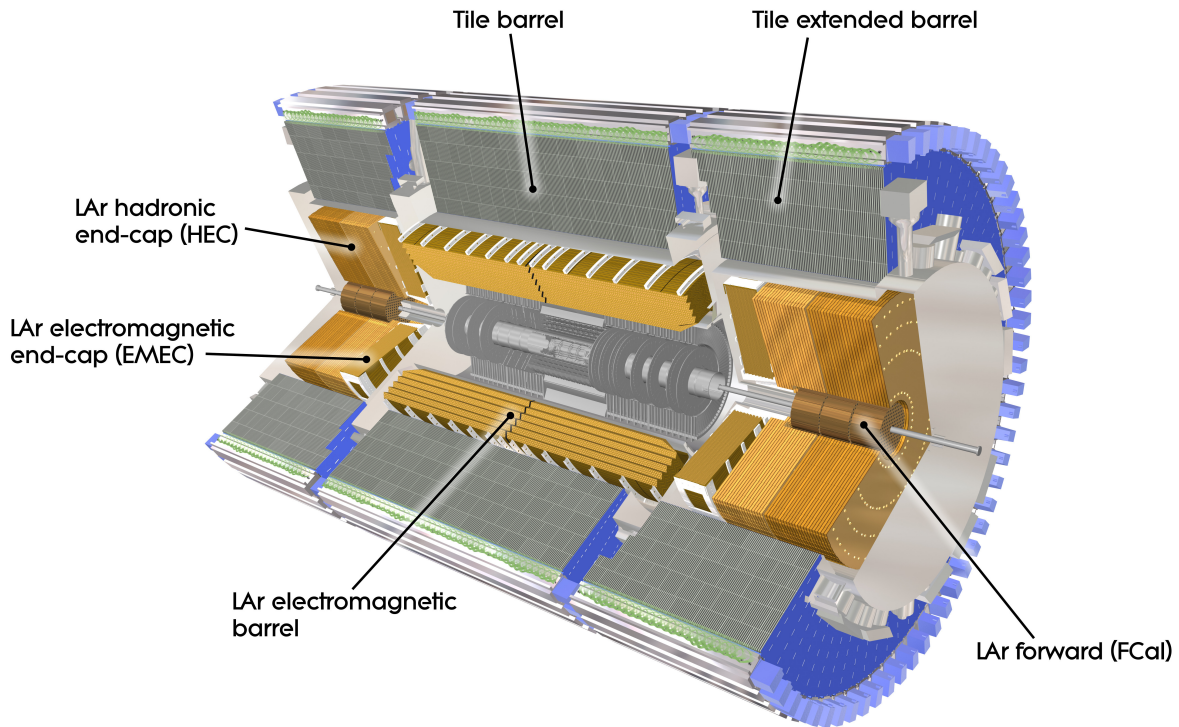


Figure 3.2.4: Cut-away view of the LAr and Tile calorimeters [69].

Liquid argon qualifies as an excellent choice for an active material thanks to its inherent linearity and radiation hardness; furthermore it allows a fast read-out. The LAr calorimeter (LArCalo) [81] consists of four sub-systems: electromagnetic barrel and end-caps, hadronic end-caps and the forward calorimeters. The **Electromagnetic Barrel** (EMB) and **End-caps** (EMECs) cover a range of $|\eta| < 1.52$ and $1.375 < |\eta| < 3.2$, respectively, and hence overlap to guarantee a smooth transition. The EMB is segmented into two wheels of 16 modules each and the EMEC is segmented into eight wedges per end-cap wheel. Both consist of three longitudinal layers with lead as absorber arranged in an accordion geometry to allow perfect azimuthal coverage without any cracks with the exception of a 6 mm gap at $z = 0$ for technical reasons.

⁴Throughout the rest of the thesis the term “electron” is used referring to both, electron and positron.

Figure 3.2.5(a) gives an outline of an EMB module displaying the accordion structure. Additionally, a presampler (PS) is installed in $|\eta| < 1.8$ which accounts for energy loss upstream since EM showers tend to start in front of the first calorimeter layers. However, the main energy fraction is deposited in the second layer, while the shower tail expands in the third layer. The EMB and EMECs have in total 173312 read-out channels, a detailed list including the granularity of each layer is given in Table 3.2.1. All layers combined account for more than 22 radiation lengths, X_0 , but only 1.5 nuclear radiation lengths which makes the EMB and EMECs almost transparent for most of the hadronically interacting particles.

The **Hadronic End-caps** (HECs) and **Forward Calorimeters** (FCALs) also rely on LAr as active material, though they feature different designs. For the HECs which cover $1.5 < |\eta| < 3.2$, a sandwich structure over four longitudinal layers in two wheels per end-cap was chosen. Plates of copper are employed as passive layers. Both HEC wheels together provide 5632 channels housed in 32 wedge shaped modules each. In the high pseudorapidity range, $3.1 < |\eta| < 4.9$, the FCAL serves as EM and hadronic calorimeter simultaneously. Cylindrical 0.25 mm to 0.5 mm wide gaps filled with LAr are arranged in copper (first layer) and tungsten (second and third layer) absorber matrices with electrode groups connected to the read-out channels. Tungsten is a good choice in order to cope with the high activity in the forward region. However, EM showers are too narrow in tungsten and cannot be measured uniformly; thus copper is used in the first layer instead. Its total depth accounts for approximately 10 nuclear interaction lengths. The FCAL houses 3524 channels in three modules per end-cap.

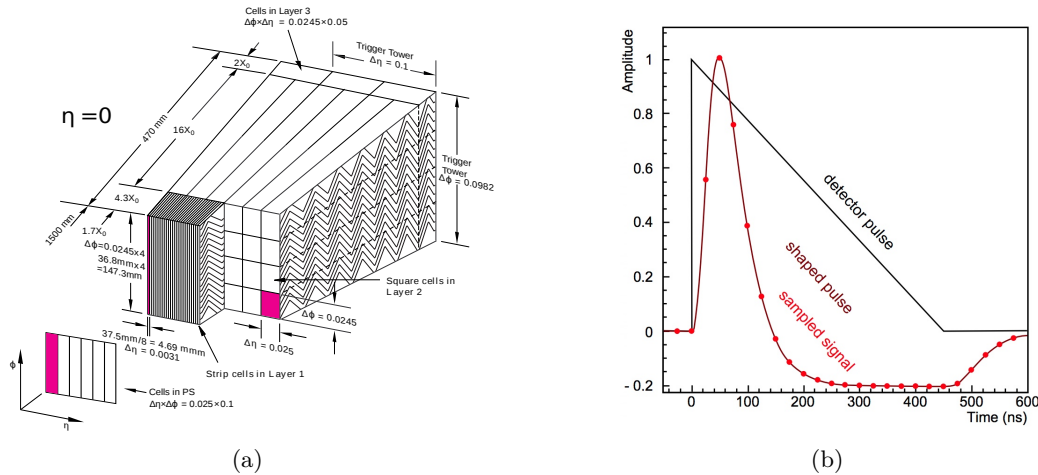


Figure 3.2.5: Left: Sketch of a barrel module of the LArCalo [69]. Right: Detector (black) and shaped (red line) pulse of the LArCalo. The sampled signal is depicted as red points along the shaped pulse [82].

If an electron or a photon enters the calorimeter it will lose its energy by interacting with the absorber material either via bremsstrahlung or e^+e^- -pair-production, respectively. As the secondary particles are photons or electrons as well, they interact in the same manner and an electromagnetic shower emerges eventually. The charged shower particles ionise the LAr. The ions and electrons created, drift to the absorber and electrode, respectively, due to a high electric field applied in the LAr-filled gap. The induced current is collected by the copper read-out electrodes. This signal is amplified and shaped by the Front-End Board (FEB) using three gain levels. The signal is sampled at 40 MHz and stored in analogue memory awaiting the trigger decision. If a positive trigger decision is made the optimal gain (low, medium or high) is selected and the associated four samples are digitised with one sample every 25 ns. The sampled signal amplitude is evaluated by exploiting optimal filtering to compute the energy, signal time and

quality factor with respect to the ideal pulse shape. In order to extract the raw cell energy several calibration constants have to be taken into account. These are determined in daily and weekly calibration runs in which a well defined calibration signal is injected and the electronics response is measured. Following this procedure, the electronics gain, pedestal shift and noise can be extracted. Further, the calibration pulse shape is measured and transformed into the physics pulse shape allowing the determination of the *optimal filtering coefficients* (OFCs). Due to the bi-polar pulse shape the integral over the full pulse is zero (c.f. Figure 3.2.5(b)). Hence, positive and negative amplitude contributions from in-time and out-of-time pile-up cancel for infinite bunch trains. To guarantee a smooth operation, a precise timing of the read-out electronics is crucial to measure out-of-time signals, veto cosmic- and beam-induced background and enable searches for long-lived particles. A fine adjustment of the FEBs is performed based on beam splashes and early collision data. Further, the liquid argon has to be constantly monitored to verify its purity and temperature stability. A change in the LAr temperature results in a change of the LAr density and drift time. A 1 K variation in temperature leads to a change of the energy scale of -2% . In a similar way the purity of the LAr can impact the signal measurement. Impurities like O_2 molecules can capture drifting electrons which results in a degradation of the signal measurement. The LAr temperature and purity are controlled by 508 and 30 monitoring probes, respectively.

The relative energy resolution for the LAr calorimeters is parametrised as:

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c, \quad (3.2.4)$$

where a is the sampling term related to shower fluctuations, b the electronic noise term and c the constant term. Parameters a and b can be extracted by comparing the J/ψ mass in data and simulation and calibration runs, respectively. The constant term is extracted directly from the width of the Z mass peak measured in collision data. The sampling term, a , is dominant at low energies of a few GeV, at lower energies the noise term, b , becomes more relevant, while the constant term, c , is predominant at very high energies.

The **Tile Calorimeter** (TileCalo) [83] is located directly behind the LArCalo and dedicated to the measurement of hadronic showers. It is composed of plastic scintillators as active component and steel absorber plates in a sampling arrangement over three layers. The central and extended barrel span a range of $|\eta| < 1.7$ and 9.7 hadronic interactions lengths in the central transverse region. If a hadronic shower evolves in the TileCalo, the charged particles stimulate the scintillators which in turn emit relaxation light which is guided to photo multipliers via wave length shifting fibres. Further, the TileCalo suppresses punch-through into the muon system, i.e. jets are not stopping in the calorimeter but enter the muon system.

	Barrel	End-cap
EM calorimeter		
Number of layers and $ \eta $ coverage		
Presampler	1 $ \eta < 1.52$	1 $1.5 < \eta < 1.8$
Calorimeter	3 $ \eta < 1.35$	2 $1.375 < \eta < 1.5$
	2 $1.35 < \eta < 1.475$	3 $1.5 < \eta < 2.5$
		2 $2.5 < \eta < 3.2$
Granularity $\Delta\eta \times \Delta\phi$ versus $ \eta $		
Presampler	0.025×0.1 $ \eta < 1.52$	0.025×0.1 $1.5 < \eta < 1.8$
Calorimeter 1 st layer	$0.025/8 \times 0.1$ $ \eta < 1.40$	0.050×0.1 $1.375 < \eta < 1.425$
	0.025×0.025 $1.40 < \eta < 1.475$	0.025×0.1 $1.425 < \eta < 1.5$
		$0.025/8 \times 0.1$ $1.5 < \eta < 1.8$
		$0.025/6 \times 0.1$ $1.8 < \eta < 2.0$
		$0.025/4 \times 0.1$ $2.0 < \eta < 2.4$
		0.025×0.1 $2.4 < \eta < 2.5$
		0.1×0.1 $2.5 < \eta < 3.2$
Calorimeter 2 nd layer	0.025×0.025 $ \eta < 1.40$	0.050×0.025 $1.375 < \eta < 1.425$
	0.075×0.025 $1.40 < \eta < 1.475$	0.025×0.025 $1.425 < \eta < 2.5$
		0.1×0.1 $2.5 < \eta < 3.2$
Calorimeter 3 rd layer	0.050×0.025 $ \eta < 1.35$	0.050×0.025 $1.5 < \eta < 2.5$
Number of read-out channels		
Presampler	7808	1536 (both sides)
Calorimeter	101760	62208 (both sides)
LAr hadronic end-cap		
$ \eta $ coverage		$1.5 < \eta < 3.2$
Number of layers		4
Granularity $\Delta\eta \times \Delta\phi$		0.1×0.1 $1.5 < \eta < 2.5$
		0.2×0.2 $2.5 < \eta < 3.2$
Read-out channels		5632 (both sides)
LAr forward calorimeter		
$ \eta $ coverage		$3.1 < \eta < 4.9$
Number of layers		3
Granularity $\Delta x \times \Delta y$ (cm)		FCAL1: 3.0×2.6 $3.15 < \eta < 4.30$
		FCAL1: $\sim$ four times finer $3.10 < \eta < 3.15,$ $4.30 < \eta < 4.83$
		FCAL2: 3.3×4.2 $3.24 < \eta < 4.50$
		FCAL2: $\sim$ four times finer $3.20 < \eta < 3.24,$ $4.50 < \eta < 4.81$
		FCAL3: 5.4×4.7 $3.32 < \eta < 4.60$
		FCAL3: $\sim$ four times finer $3.29 < \eta < 3.32,$ $4.60 < \eta < 4.75$
Read-out channels		3524 (both sides)

Table 3.2.1: Segmentation of the LAr calorimeter [69].

3.2.3 Muon System

The majority of muons at LHC energies behave as minimal ionising particles, only those with energies below 5 GeV are stopped in the calorimeters. Hence, the *Muon Spectrometer* (MS) [84], shown in Figure 3.2.6, is installed as an outer shell to allow the determination of the direction, charge and momentum of muons. Therefore, a magnetic field of 4 T is generated by a **Toroid Magnet** composed of eight superconducting air-core coils in the barrel and each end-cap. The circular field expands radially symmetric around the beam pipe and provides a local bending power of 1.5 Tm to 5.5 Tm in the barrel part ($|\eta| < 1.4$) and 1 Tm to 7.5 Tm in the end-caps ($1.6 < |\eta| < 2.4$). The system is powered by 20.5 kA and needs to be kept at 4.7 K. Besides all similarities to the Solenoid Magnet of the ID, the Toroid Magnet forces a bending in η instead of ϕ which grants the unique opportunity of two independent momentum measurements. The four sub-systems of the MS are divided into tracking and trigger devices and feature different technologies, whereby none severely distorts the trajectory or stops the muons.

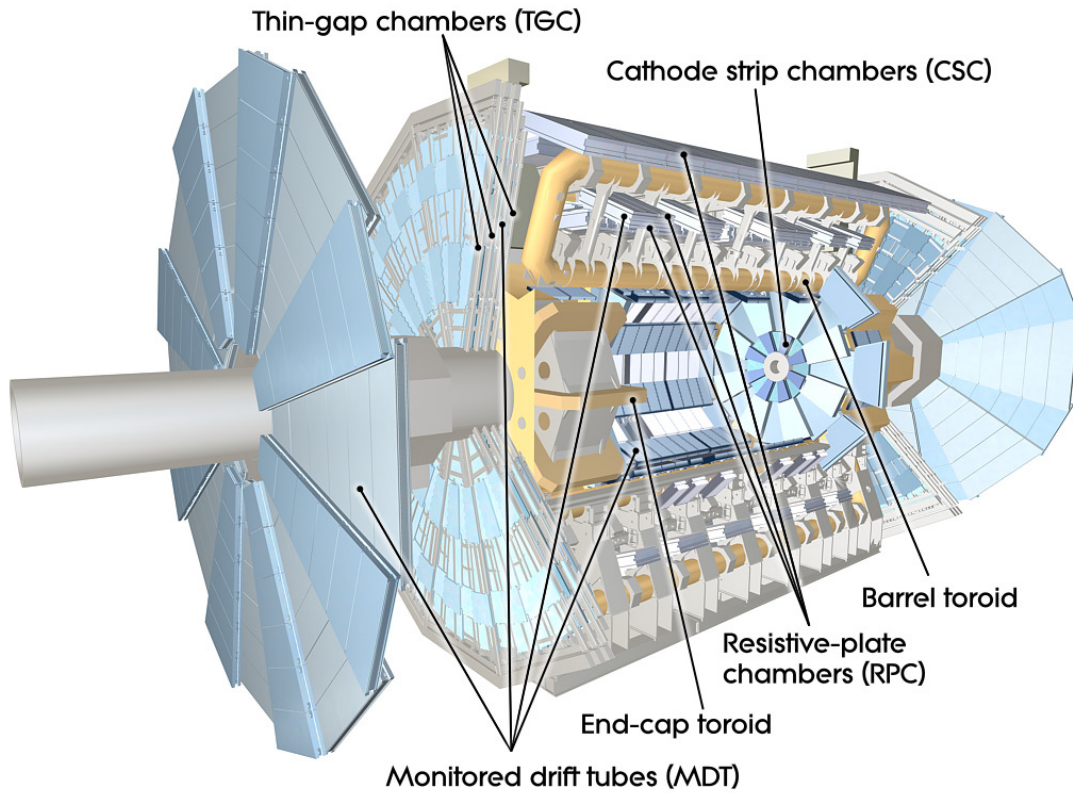


Figure 3.2.6: Cut-away view of the muon system [69].

The **Monitoring Drift Tubes** (MDTs) serve as main detector for precision tracking. They are made of cylindrical pressurised aluminium drift tubes filled with a gas mixture of argon and carbon dioxide embedding a tungsten-rhenium alloyed aluminium wire in the centre. The gas is ionised when a muon passes through and the applied high voltage forces the freed electrons towards the wire anode resulting in an electric signal. The tubes are grouped in chambers and increase in size with growing distance from the IP to ensure a perfect coverage. In the barrel part 16 of these chambers are added in each of the three layers and slightly overlap to prevent any cracks. The single layers are installed as far as 5, 7.5 and 10 m away from the IP and cover a range of $|\eta| < 2.7$ ($|\eta| < 2.0$ in case of the inner layer). In the end-caps four wheels are mounted at a distance of 7.4, 10.8, 14, and 21.5 m from the IP whereby the second is limited to $1.0 < |\eta| < 1.5$ due to the Toroid end-caps.

The other tracking component are the **Cathode Strip Chambers** (CSCs) which are multi-wire proportional chambers with tungsten-rhenium anode wires in a gas mixture of 50 % carbon dioxide, 30 % argon and 20 % carbon tetra-fluoride. The CSCs rely on the same physics principle as the MDTs. The modules are trapeze-shaped with two cathode strips per plane. They are mounted orthogonal to each other in the innermost end-cap wheel and offer a higher rate capability and time resolution at $2.0 < |\eta| < 2.7$. The CSCs provide a tracking precision of $40\ \mu\text{m}$ and 5 mm in the bending and transverse plane, respectively.

Since interesting proton-proton collisions are often accompanied by highly energetic muons, they are suitable candidates to trigger on. However, the MDTs and CSCs are too slow to accomplish this task; hence they are supported by the **Resistive Plate Chambers** (RPCs) and **Thin Gap Chambers** (TGCs) which allow a fast read-out and provide an intrinsic time resolution of 1.5 ns and 2.4 ns, respectively. The RPCs are located outermost of the detector and above and below the middle MDT layer up to $|\eta| < 1.05$. They are equipped with two parallel resistive plates separated by a gap of 2 mm, filled with gas which gets ionised if a muon traverses. The signal is enhanced by an avalanching effect in a high electric field. Thanks to their good resolution of 10 mm in longitudinal and transverse direction, the RPCs can further be exploited to reject cosmic muons by a coincidence measurement. In the end-cap region ($1.05 < |\eta| < 2.4$) the MS is equipped with four TGC layers, one in front of the innermost precision tracking chambers and three surrounding the third MDT chambers of the inner wheel. The technology employed is similar to a multi-wire proportional chamber but provides a radial and azimuthal segmentation as well, resulting in a good trigger signal as well as a transverse and radial resolution of 3 to 7 mm and 2 to 6 mm, respectively. The RPCs and TGCs are used to trigger on muons with different transverse momentum thresholds and give additional information for the high level triggers.

3.2.4 Forward Detectors

In the forward direction of the ATLAS detector four specialised devices to measure luminosity and beam conditions are installed. At $z = \pm 184\text{ cm}$ and $\eta = \pm 4.2$ the BMCs (*Beam Condition Monitors*) are the closest to the IP. They allow the measurement of the bunch-per-bunch luminosity as well as beam halo contributions to react on occurring beam anomalies in order to prevent the ATLAS detector from potential damage. Furthermore, they give valuable information for analyses relying on the bunch structure and per-bunch luminosity.

LUCID (*Luminosity measurement using Cherenkov Integrating Detector*) is located at $z = \pm 17\text{ m}$ and $|\eta| \sim 5.8$, providing a relative luminosity measurement by inelastic proton-proton scattering. As ATLAS' main luminosity detector it is used for online monitoring.

ALFA (*Absolute Luminosity for ATLAS*), installed at $z = \pm 240\text{ m}$, is a device that can be used to determine the total proton-proton cross section and hence the absolute luminosity. Scintillating fibre trackers inside of roman pots are inserted in the beam pipe up to 1 mm distance to the beam to measure elastic proton-proton scattering. The resulting amplitude is linked with the total cross section and absolute luminosity via the optical theorem.

In between the two luminosity detectors the ZDC (*Zero Degree Calorimeter*) is located at $z = \pm 140\text{ m}$ and $|\eta| > 8.3$, which analyses the centrality of heavy-ion collisions by observing neutral particles generated within these collisions. It features quartz and tungsten as active and passive material.

3.2.5 Trigger System & Data Acquisition

With more than 2808 bunches and a bunch spacing of 25 ns as many as 40 million bunch crossings can occur per second. Given this event rate of 40 MHz and an average event size of

1.3 MB approximately 50 TB of data are produced every second, far too much for any data centre to store or process. Therefore, a two level trigger system [85] is in place to reduce the data rate to a tolerable size by rejecting background events while preserving events interesting for physics analyses. The trigger workflow is outlined in Figure 3.2.7. The first stage, the *Level 1* (L1) trigger, is fully hardware based and decreases the data rate to 100 kHz. With a latency of $2.5 \mu\text{s}$ a decision needs to be made quickly and thus can only be based on minimal isolated energy deposits and thresholds on transverse momenta and energies of single physics objects. Simple event topology selections can be applied with the *L1Topo* system which was installed during LS1. In addition to the information from the RPCs and TGCs, hits in trigger towers installed in the calorimeter are considered to address photons, electrons, taus and jets separately and estimate E_T^{miss} as the negative sum of transverse energies. The information provided by the L1Topo further serves as input on the event topology which is taken into account at the second trigger stage. The final L1 decision is made by the *Central Trigger Processor* (CTP) which combines the trigger information and operates on the base of a look-up table. A *Region of Interest* (RoI) is in the η - ϕ -plane defined and passed on to the *High Level Trigger* (HLT). The HLT can build upon a latency of 40 ms and thus the full detector granularity in the RoI and a reconstruction similar to the offline algorithms can be performed. It further includes the information of the tracking system to apply more sophisticated cuts to reduce the event rate to 1 kHz.

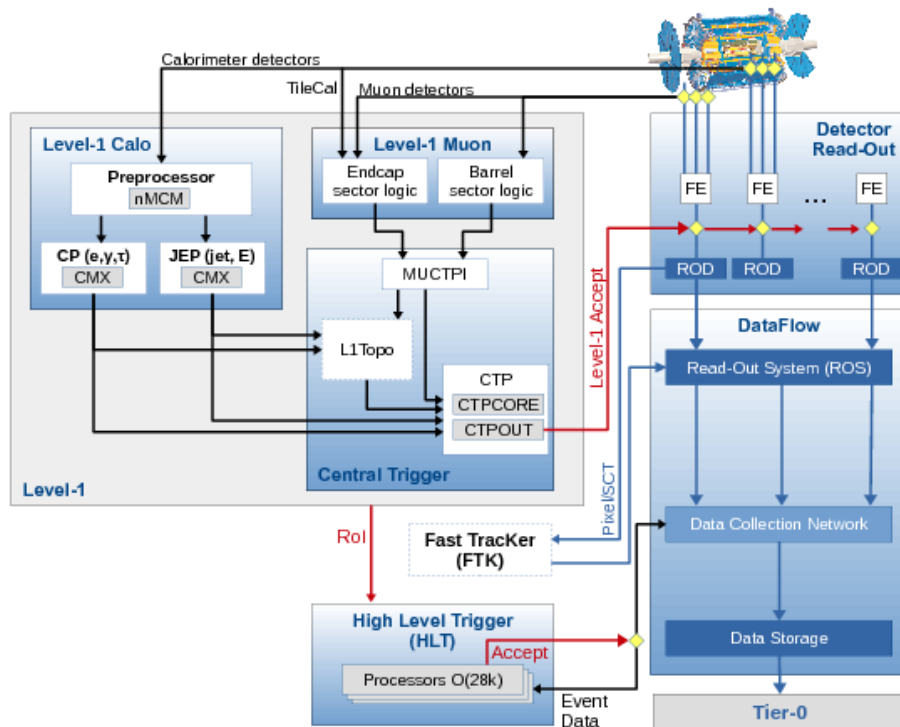


Figure 3.2.7: Workflow of the trigger and data acquisition system of ATLAS [85].

The trigger menu consists of over 2000 triggers grouped into several streams depending on their usages. Each trigger item is composed of a L1 seed and a HLT trigger and name specific thresholds, objects, types of identification, isolation, reconstruction algorithms and geometrical regions. The composition and thresholds are optimised over several luminosity ranges in order to maximise the physics output given the constraints on the bandwidth, rate as well as on the online and offline computational capacities. Albeit the trigger system reduces the data rate significantly, it is not always sufficient. Some triggers are very loose, e.g. to gather data of low-momentum electrons or muons, and thus many events pass the requirements. In order to enable these triggers online and still meet the rate restrictions of the trigger system, a prescale is

applied, i.e. given a prescale of i only every i -th event is recorded. Contrary to that, unprescaled triggers record all events that passed the selection. Prescales can be applied on L1, HLT and stream level. For some triggers they are predefined or set automatically based on the detector activity but can also be regulated manually if needed. In case a prescaling is not sufficient a disabling of single triggers can be considered as last measure.

The triggers can further be categorised in *primary triggers* which are the main input for physics analyses and *support triggers* for monitoring, efficiency and performance studies. They are accompanied by *backup triggers* with a tighter selection and *alternative triggers* which feature new and experimental algorithms. All triggers, except the primary triggers, are usually prescaled and their rate is kept low. Only *calibration triggers* are operated at high rate since they feature partial event building, i.e. only the necessary information for calibration, monitoring and detector performance studies is recorded. Most triggers that target specific final state signatures, e.g. EM clusters, jets, muons or E_T^{miss} , in paired BCIDs are recorded in the **physics_Main** stream, the input for most physics analyses. On average 10 Hz are dedicated for the so-called **physics_express** stream which is reconstructed promptly and plays a key role for the data quality assessment (c.f. Section 3.2.7). However, other streams, like **physics_Late** or **physics_CosmicCalo**, focus on unpaired or empty BCIDs allowing dedicated background and data quality studies, but also provide a unique opportunity to analyse signals from long-lived particles which decay after a significant delay. One of these special analyses is discussed in Chapter 5.

3.2.6 Data-Taking Conditions in Run 2

During Run 2 a centre-of-mass energy of $\sqrt{s} = 13$ TeV and an integrated luminosity of 158 fb^{-1} have been delivered by the LHC. In the period from 2015 to 2018 149 fb^{-1} of collision data have been collected by the ATLAS experiment reaching a data-taking efficiency of about 94 % (c.f. Figure 3.2.8(a)). The main filling scheme which was used throughout Run 2, was composed of 2544 paired BCIDs with a bunch spacing of 25 ns. Slightly different schemes have been used depending on the operational conditions. Due to difficulties arising from a LHC dipole magnet which prevented the LHC to run with a higher fraction of filled bunches, the so-called 8b4e filling scheme was used over a longer period in 2017. Two commonly operated bunch group schemes are shown in Figure 3.2.9. They consist of various bunch groups based on paired, unpaired and empty BCIDs. However, the names of the bunch groups cannot always be identified with the BCIDs of the same name. The bunch group **empty** does not contain all empty BCIDs but only those which are separated by five BCIDs from the preceding and following filled BCID. The five empty BCIDs closest to the filled bunches serve as a safety margin to account for the afterglow of the proton-proton collisions. They form a bunch group themselves called **firstempty** or **emptyBeforeAfterPaired**. Further, the bunch group scheme differs for special data-taking conditions, e.g. van-der-Meer scans for luminosity calibration or enhanced minimum-bias runs for trigger rate prediction studies. In these cases the trigger menu needs to be adjusted appropriately as well.

As depicted in Figure 3.2.8(b), on average 34.2 proton-proton interactions occur during a single bunch crossing but up to 80 have been observed in 2017. Usually, only one of them is considered as the hard interaction and results in a detector signature worth to be studied. The other interactions are so-called pile-up events. Pile-up arises in the same bunch crossing but also extends to the following ones and hence can be categorised into in-time and out-of-time pile-up depending on their timing with respect to the nominal crossing.

A typical proton-proton fill of the LHC lasts for up to 24 hours but can differ strongly depending on the conditions of the LHC and its pre-accelerators. ATLAS records these data in “ATLAS runs” which are frequently, but not always, comprising full LHC fills. In general, runs can also expand over an interval without any collisions, e.g. so-called *cosmic runs* and *calibration runs* during which data on cosmic muons are gathered or the sub-detectors are calibrated and

aligned, respectively. A single run can further be divided into *luminosity blocks* (LBs) which last for about one minute of data-taking. Several runs are grouped into “periods” with the same detector settings and similar conditions.

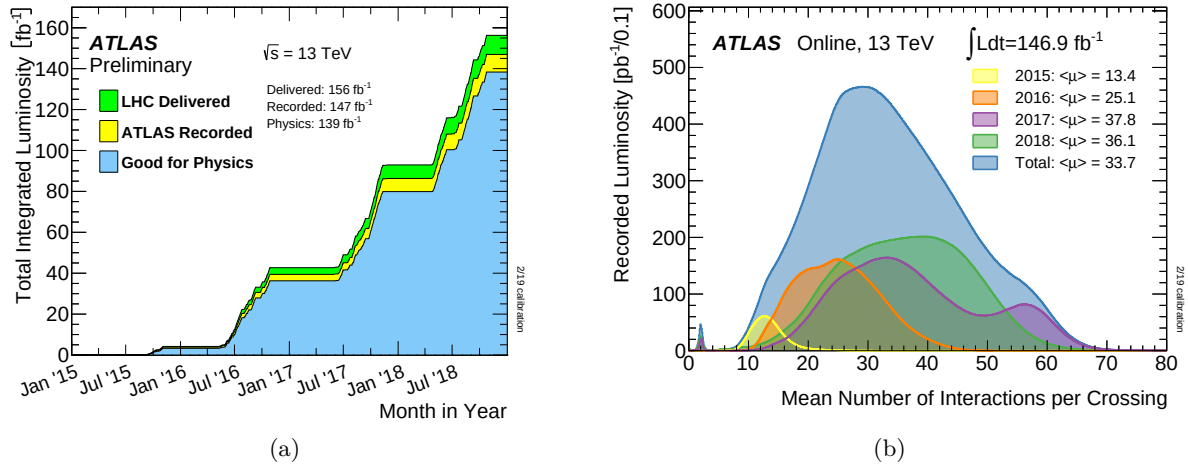


Figure 3.2.8: (a) The total integrated luminosity delivered (green), recorded (yellow) and checked to be good for physics analyses (blue) during stable beams for proton-proton collisions at 13 TeV centre-of-mass energy in Run 2. (b) Luminosity-weighted distribution of the mean number of interactions per bunch-crossing for Run 2 proton-proton collisions at 13 TeV centre-of-mass energy. The mean μ values are given in the legend [86].

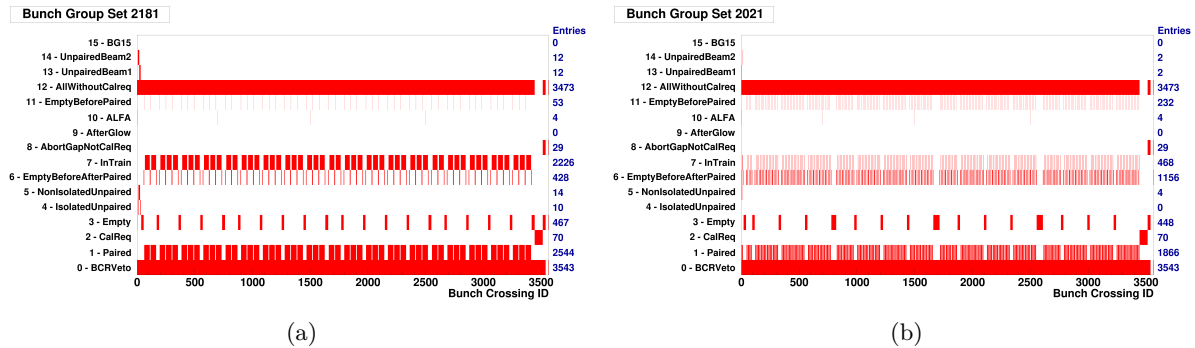


Figure 3.2.9: Exemplary bunch group schemes frequently used in Run 2: (a) 2544b [87] and (b) 8b4e [88].

3.2.7 Data Quality

Precise knowledge of the quality of the recorded data is crucial for all physics analyses. The main goals of the *data quality* (DQ) assessment are to eliminate any detector related problems which can affect the reliability of data and log relevant information in dedicated databases. Therefore, defects are assigned to *intervals of validity* (IoV), i.e. representations of a time interval in the ATLAS database environment. Two types of defects are defined, *intolerable defects* which imply the systematic rejection of the IoV for physics analyses, and *tolerable defects* which mainly serve for information and bookkeeping purpose but the affected data are still suitable for physics analyses. In order to properly address all upcoming issues, the work is shared by DQ sub-groups according to the detector sub-systems (Pixel, SCT, TRT, LAr, Tile, MS) on one side and the signature motivated combined performance groups (ID global, b -tagging, caloCombined,

muonGlobal) on the other side. They are completed by the general luminosity and trigger groups. The ATLAS DQ workflow is outlined in Figure 3.2.10 and described in more detail in [89].

A so-called *Good Runs List* (GRL) is compiled for all runs including only the LBs without intolerable defects and must be applied in any physics analysis to ensure the sanity of the analysed data. The GRL is a powerful and flexible tool and comes in different versions depending on the use case. The most commonly used GRL is labelled “allGood” indicating that DQ information from all sub-systems was considered. For few dedicated studies GRLs which ignore non-relevant defects might be used.

Defects are called primary defects if they are linked to a uniform time period with the same software conditions or reprocessing campaign. These defects are either set explicitly by the DQ shifters or automatically by continuously running jobs. Virtual defects arise from the logic that specifies whether a defect is tolerable or intolerable and are independent of the primary defects.

In a first step an online assessment is performed in the control room with the focus on spotting detector failures as quickly as possible and limiting the amount of unrecoverable data due to severe losses of coverage, timing shifts or data corruption. Due to the time constraints only a rough assessment can be performed; hence a detailed DQ examination is performed offline shortly after a run has finished. Therefore, the *first express processing* (ES1) of the `physics_express` and calibration streams, starts promptly after a run started and monitoring histograms are produced simultaneously. The latter undergo a post-processing featuring dedicated DQ algorithms and are posted on a central ATLAS webpage. The `physics_express` stream, containing about 10 % of the data, is of special interest as it provides a proper mix of various triggers gathering information on all sub-detectors and physics objects. During ES1 the conditions database is updated to store a complete picture of the detector status for each run as well as the calibration constants as a function of time. These tasks have to be completed typically within a 48 hours window, the so-called *calibration loop*. After the calibration loop expired the processing of all physics streams starts, picking up the information from the updated databases. This *bulk processing* (Bulk) lasts for a couple of hours or days. After the Bulk is concluded the processed data need to be examined under a DQ focus before it can be used for physics analyses. In this final step of the DQ assessment, it is validated that all problems spotted in ES1 have been dealt with properly by the conditions updates. Any remaining issues must be addressed and an additional update of the conditions database might be required. However, these changes can only be incorporated in the next reprocessing which might happen months later. If severe issues are observed, they can be addressed immediately by removing the affected LBs in the GRL. The average DQ efficiency of ATLAS in Run 2 is 95.6 % [89].

LAr DQ

In the scope of the LAr DQ assessment [82] various software and hardware related issues need to be addressed. To facilitate an efficient evaluation a dedicated LAr web interface is provided summarising the relevant information from the central ATLAS webpage in an easily accessible format. Data not suitable for physics analyses are dealt with by two complementary means: on the one hand, LBs (≈ 1 minute) can be rejected, on the other hand, shorter periods ($\ll 1$ minute) can be vetoed.

One key element is the treatment of **noisy cells**.⁵ For this purpose inter-train data recorded in the `physics_CosmicCalo` and `calibration_LArCellEmpty` streams are analysed by an automated procedure and validated manually to identify isolated noisy cells. These two streams are crucial as the detector occupancy should be limited since no collisions happened. In case the pulse quality factor Q with respect to the ideal pulse shape is very high, which indicates that a signal does not stem from a normal ionisation signal in the LAr gaps, cells are flagged

⁵The denotation “cell” is used synonymously for “channels”.

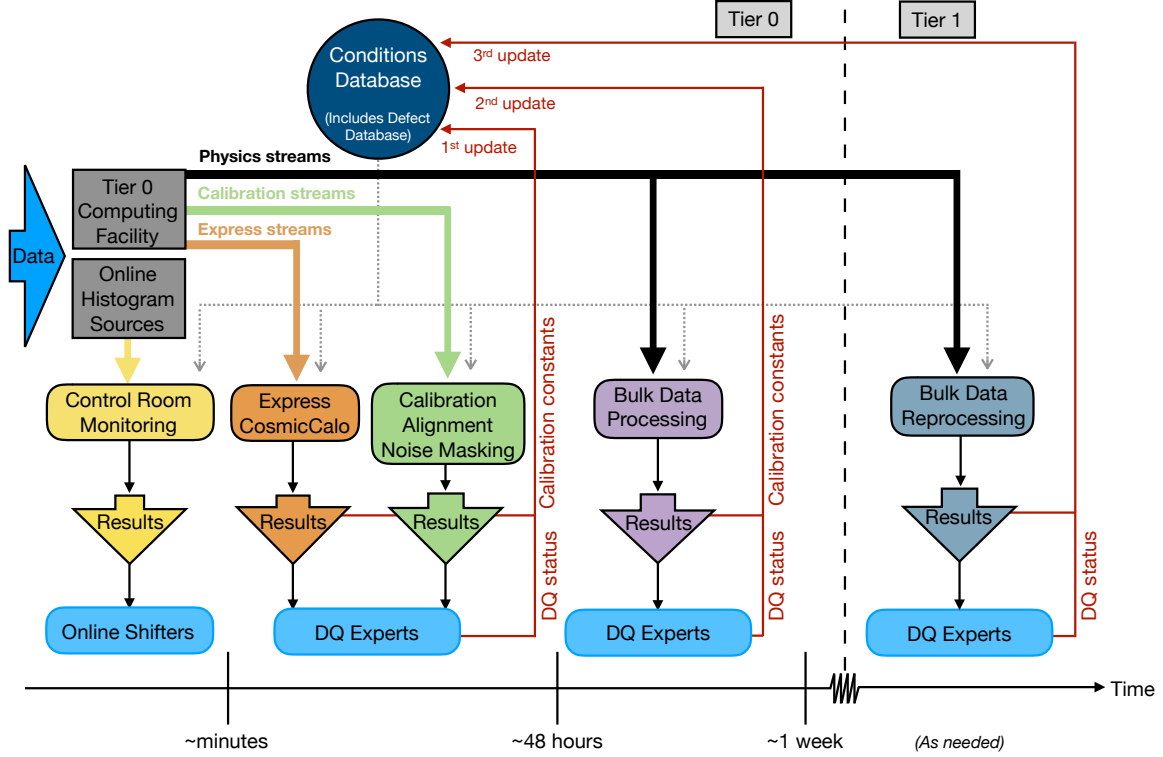


Figure 3.2.10: Overview of the data quality workflow of ATLAS [89].

and masked and their energy is extrapolated from neighbouring cells. Q is defined as

$$Q = \sum_{i=1}^4 (s_i - ped - A(g_i - \tau g'_i))^2, \quad (3.2.5)$$

where s_i are the four digitised samples, ped denotes the electronics baseline value, τ is the pulse peak time and g_i and g'_i are the normalised ionisation pulse shape and its derivative with time, respectively. For the masking two flag options exist: a selective masking which is only applied in case $Q > 4000$ or a permanent masking which lasts for the entire run; they are denoted as “sporadicBurstNoise” (spBN) and “highNoiseHighGain” (hnHG), respectively. The former is in general preferred since the cell is still partially taken into account for energy computation but the latter might be necessary to deal with persistent noise. In rare cases, single cells are masked for more than one run, e.g. in case they are constantly noisy throughout many consecutive runs and might overshadow other less but still severely noisy cells. As a drawback of the cell masking, a “hole” can be created if too many close-by cells are affected which can lead to a miscalculation of various physics quantities, e.g. E_T^{miss} . In order to prevent this, a dedicated tool was developed within the scope of this thesis. For each individual run the list of cells proposed for masking are clustered into groups of close-by cells according to the cell clustering algorithm. If at least five cells flagged as spBN or two cells flagged as hnHG are close-by, the cluster is considered to be prone to cause a hole and requires dedicated treatment. To support the shifters with this task, the information about every problematic cluster and the corresponding cells is compiled in an overview table. Further, they are visualised in η - ϕ -maps per layer; an example is shown in Figure 3.2.11(a). A colour code according to the proposed flag is applied. In addition to the cells proposed for masking in ES1 or Bulk stage, cells which are permanently flagged in the database can be considered as well. A simplified version of these maps, like in Figure 3.2.11(b), is also published to the LAr web interface, where the colouring differs for cells that were flagged in ES1 or Bulk. It is explicitly highlighted in case the flag proposal has changed between the

ES1 and Bulk stage.

If a short noise event is not efficiently cleaned by cell masking, a LB veto is considered, especially if that noise is also visible in the `physics_Main` data at the Bulk stage. Noisy cells account for 0.07 % of data loss in Run 2 [90].

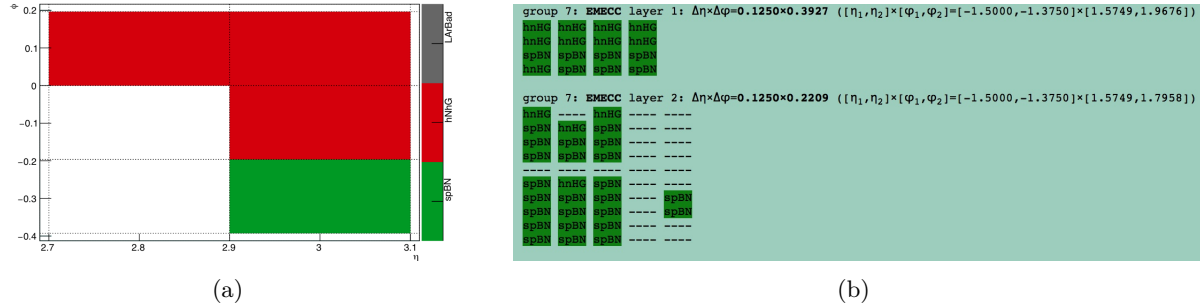


Figure 3.2.11: (a) Map of a cluster of three cells flagged as hnHG (red) and one cell flagged as spBN (green); no cell is permanently flagged in the database (LARBad, grey). (b) A simplified map of a cluster of various spBN and hnHG flagged cells expanding over two layers. The highlighting in green indicates that they are masked at ES1 stage. “— — —” are used for cells which are not flagged. This kind of maps is published on the LAr DQ web interface.

Noise Bursts (NBs) and **Mini Noise Bursts** (MNBs) are phenomena of coherent noise occurring in the LAr calorimeter. NBs expand over a large region in the calorimeter end-caps, an example is shown in Figure 3.2.12. They last for a very short time period of about $1 \mu\text{s}$ up to 1 ms if the burst is very long. On the contrary, MNBs are repeated bursts of noise which are concentrated to smaller regions in the barrel of the calorimeter. Usually about ten cells of one FEB are affected over a time period of less than $1 \mu\text{s}$. The reason for these bursts of noise is not identified, yet. In order to cope with them the Q factor of the affected cells is taken into account since in both cases a high number of cells with large quality factors has been observed. Based on this, affected events are marked with a standard or saturation flag. The former is assigned if there are more than 30 cells in at least three FEBs with $Q > 4000$ and the latter is assigned if the Q factor is saturated for more than 20 cells. If a noisy candidate event is found, a time window is defined around it. Such a time window typically lasts less than 1 ms and includes an additional safety margin before and after the noisy event to account for any tails. The time window veto is an effective approach to reject unreliable data by avoiding the rejection of good quality data recorded in the same LB. An example of an MNB event before and after time window cleaning is depicted in Figure 3.2.13(a) and (b), respectively. The entire LB is rejected only if there are too many NB candidate events found in one LB. It was observed that MNBs occur repeatedly in the same FEBs but also evolve over time. Therefore, a continuous monitoring of the frequently affected FEBs improves the treatment of MNBs. Within the scope of this thesis a tool was developed to facilitate this. Any range of runs can be examined by the tool based on the information provided by the algorithm used to identify MNB candidates. The run occurrence for every FEB is summarised in an η - ϕ -map for various thresholds on the cell occupancy. Further, the cell occupancy development over several runs is visualised for every single FEB. An example is shown in Figure 3.2.14. NBs and MNBs account for 0.08 % and 0.01 % of data loss in Run 2 [90], respectively.

At the beginning of Run 2 **High Voltage trips** caused 0.37 % of data loss and hence were one of the most often occurring reasons for data loss. Every high voltage (HV) line installed at the LArCalo is constantly monitored and information about it is stored in the conditions database. The HV applied on the drift gap has a direct impact on the amount of signal which is collected by the electrodes and thus on the energy computation. A HV trip is characterised by an abrupt decrease of voltage such that the applied correction factor is not reliable which

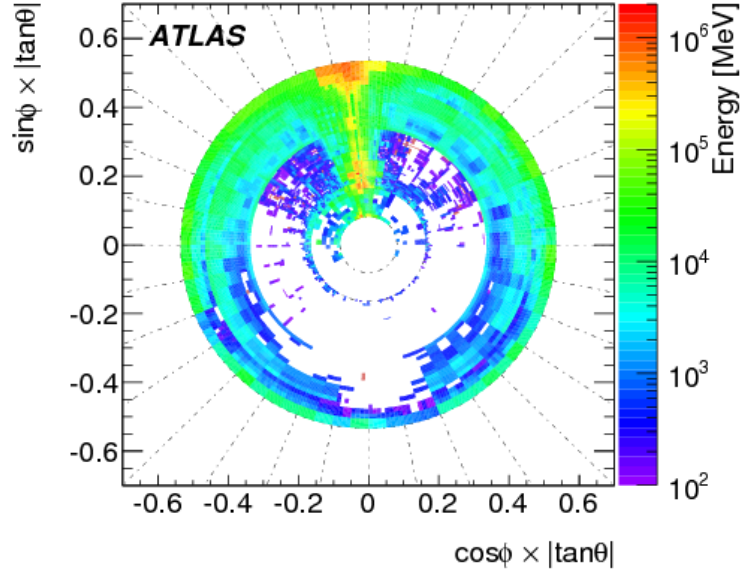


Figure 3.2.12: Energy deposits in the x - y -plane in the LAr calorimeter from an NB event [82].

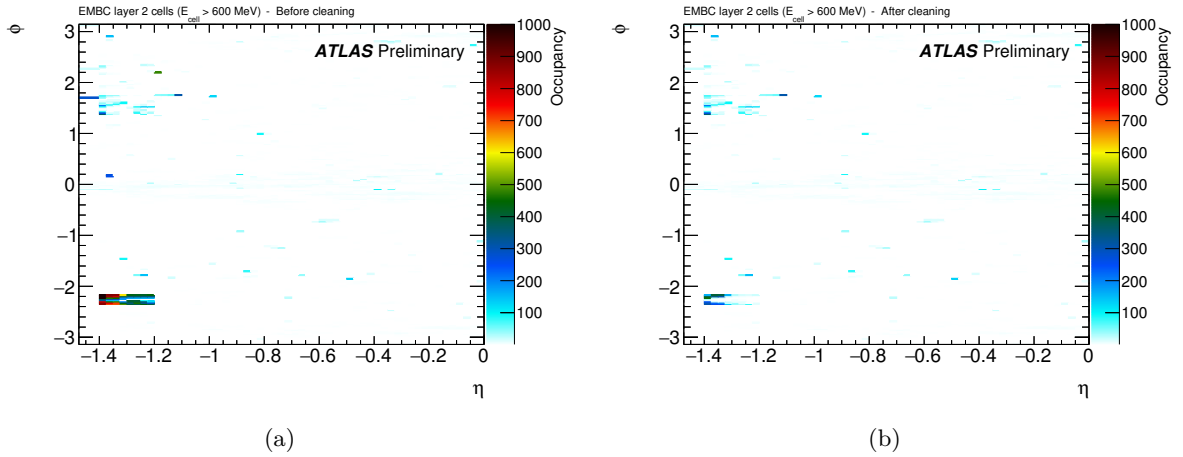


Figure 3.2.13: The cell occupancy in the second EMBC layer shown in the η - ϕ -plane for $E_{cell} > 600$ MeV in 455 pb^{-1} of data recorded in the `physics_CosmicCalo` stream from run 306310 in 2016. A region affected by and MNB confined to a single FEB is clearly visible in the left bottom corner of the left plot and efficiently cleaned by the time window veto as depicted on the right. [91]

usually leads to an underestimation of the measured energy. During data-taking HV trips might occur and are usually automatically recovered. However, the LBs in which a trip happened must be rejected, whereas the LBs spanning the ramp-up phase are usually not removed per se. Ramping HV can induce noise in the affected calorimeter cells and can be treated well by applying a time window veto. During each winter shutdown new high voltage supplies have been installed in various locations, replacing supplies which tended to trip often in the past. These new supplies can temporarily draw a maximum current to avoid a trip. This current-controlled state is kept until the trip is over and the module auto-recovers. In this way the trip is much less severe and cause less data loss. Thanks to this improvement the associated data loss was significantly reduced from 0.31 % in 2015 to 0.02 % in the following years [90].

The luminosity loss due to defect assignment and the time window veto in Run 2 are sum-

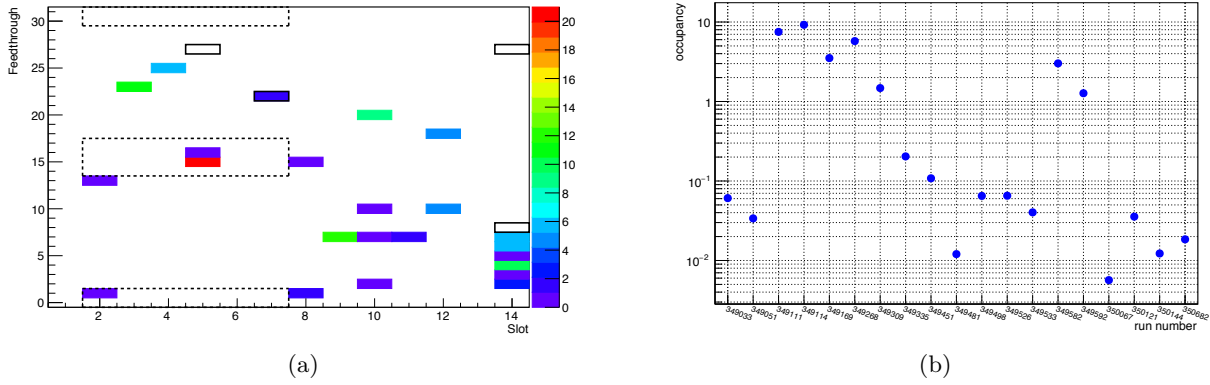


Figure 3.2.14: (a) Map of FEBs (feedthrough-slot) in EMEBC exceeding 0.075 occupancy filled for several runs. Solid lines mark FEBs which were affected in the past and dashed lines FEBs which are affected by beam halo noise and thus likely to reach higher occupancy. (b) Occupancy development of a single FEB (feedthrough 20, slot 10) over several runs.

marised in Figure 3.2.15. Other issues addressed in the LAr DQ assessment are data corruption, data integrity and energy computation errors as well as mis-synchronisation are included, too. These issues arise from various sources, like FEB errors, malfunction of gain selectors or mis-timed cells or FEBs. They can mainly be treated by the time window veto but LB rejection might be necessary in case the former is not efficient enough.

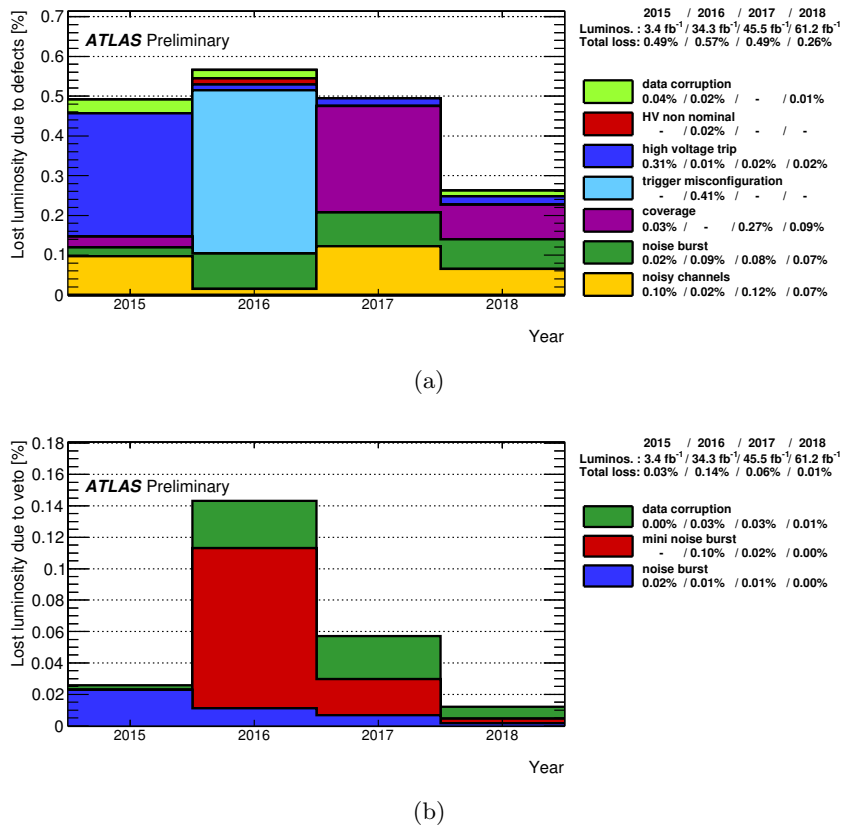


Figure 3.2.15: LAr DQ inefficiency in Run 2 due to defect (a) and veto (b) rejection. [91]

3.2.8 Detector Simulation

In order to make predictions based on simulated processes and final state particles described in Section 2.3, their interaction with the detector and its response need to be simulated. Therefore, the toolkit **GEANT4** [92] is used exploiting the information about the detector model, alignment and run conditions which are stored in a database for this purpose. First, hits and energy deposits are simulated and digitised in **Athena**, where one digit corresponds to an energy deposit exceeding a predefined voltage or current threshold in a certain time window. These raw data objects store the event and generator information, the so called *truth level information*. Finally, the same trigger, reconstruction and calibration as in the processing of recorded data are applied on the final state particles, providing the *reconstruction-level information*. Further, pile-up events, i.e. proton-proton interactions happening simultaneously to the main hard scattering, are simulated separately as minimum-bias events and their energy depositions are superimposed to the main event and taken into account during digitisation. The full detector simulation is very complex and consumes a huge number of CPU hours, e.g. for a single event the simulation chain can take as long as 15 minutes. To save computing resources a fast simulation, FastCaloSim [93], with a reduced calorimeter granularity can be used if feasible. However, for the studies presented in Chapter 4 and 5 the full detector simulation was exploited.

Chapter 4

Physics with Electrons

Electrons play a key role in many physics analyses, may it be precision measurements, like the determination of the W boson mass [94] or Higgs couplings [95], or searches for new physics ranging from low energies of a few GeV to high energies of several TeV, like lepton flavour universality tests in $R_{K^{(*)}}$ [1, 2] and the Z' resonance search [96], respectively.

The EM calorimeter is, besides the ID, the most important sub-detector for the reconstruction and identification of electrons. Electrons from decays of Z boson are used for the calibration of the energy measurement of the EM calorimeter owing to their distinct detector signature.

A summary of the essential steps of the reconstruction and identification of electrons is given in Section 4.1, followed by a comprehensive discussion of the energy calibration procedure in Section 4.2. The latter includes an update on the uniformity correction on the calibrated energy. The final section of this chapter, Section 4.4, is dedicated to detailed studies on possible improvements of the raw energy calibration.

4.1 Reconstruction & Identification

Cell Clustering

The electromagnetic calorimeter is a key component in the reconstruction and identification of electrons because both rely on the energy deposits in this sub-detector. Therefore, the EM calorimeter is divided in the η - ϕ -space in a grid of $N_\eta \times N_\phi = 200 \times 256$ elements or “towers” with a size of $\Delta\eta^{\text{tower}} \times \Delta\phi^{\text{tower}} = 0.025 \times 0.025$ each, adopted from the calorimeter granularity. The tower energy is given by the sum of all energies of its cells over all longitudinal layers including the PS. An initial cluster of cells is formed by the sliding-window algorithm [97] which scans across all elements with a 3×5 fixed-size window in steps of 0.025 in either η or ϕ direction. The energy within that window is the sum of the energy of all towers covered by it. If the energy exceeds 2.5 GeV, i.e. a local maximum is identified, a rectangular seed cluster is formed around the seed position which is a layer-dependent barycentre of the position of the energy deposits. In case two seed clusters overlap within an area of $\Delta\eta \times \Delta\phi = 5 \times 9$ units, only the cluster with the highest E_T is kept if the transverse energies of the two clusters differ by at least 10%, otherwise the cluster with the highest- E_T central tower is retained. The energy-weighted barycentre in η and ϕ in the second calorimeter layer (L2), the so-called pre-cluster barycentre, is reevaluated after the clustering is done and all cells have been added. It further is used as seed for the clustering in the first and third EM calorimeter layers. Whereas for the PS, the barycentre is derived from the energy distribution in the first layer.

The dimensions of the final cluster must be large enough to contain most of the energy deposits of the electromagnetic shower but at the same time not too vast to avoid including electronic and pile-up noise. In Run 2 a cluster size of $N_\eta^{\text{tower}} \times N_\phi^{\text{tower}} = 3 \times 7 (5 \times 5)$ was chosen in the barrel (end-cap) region of the EM calorimeter. In the barrel region the azimuthal extension

is larger in order to cope with bremsstrahlung and photon conversion which broaden the shower in ϕ due to the bending of the solenoid magnet.

The efficiency of the fixed-size sliding-window clustering algorithm depends on $|\eta|$ and E_T , ranging from 65 % at $E_T = 4.5$ GeV, to 96 % at $E_T = 7$ GeV, to 99 % above a transverse energy of 15 GeV as can be seen in Figure 4.1.1(a).

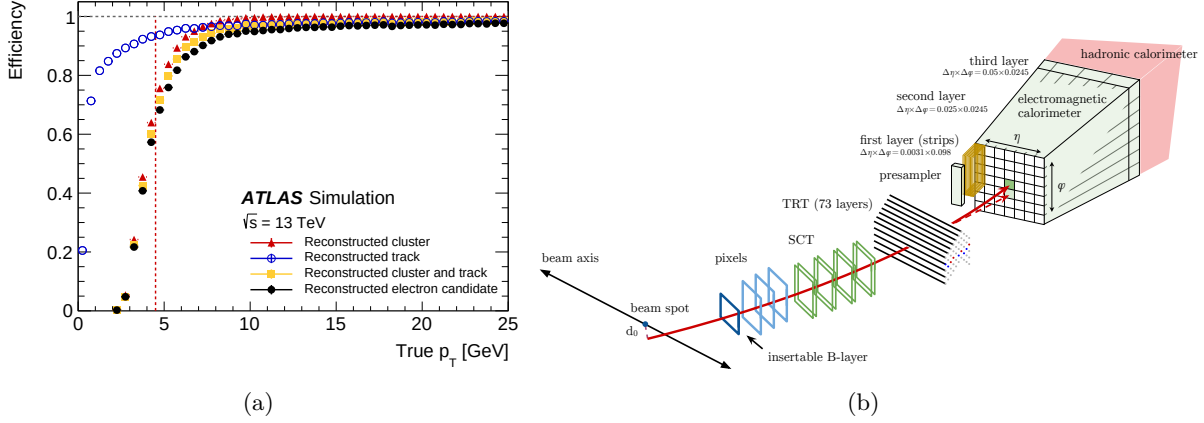


Figure 4.1.1: Left: Reconstruction efficiency for electrons from a simulated single-electron sample as function of the true generator p_T . It is shown for the different steps of the reconstruction algorithm: the seed-cluster reconstruction as red triangles, the track reconstruction using the global χ^2 Track Fitter [98] as blue open circles, the combination of the seed-clustering and the track reconstruction using the GSF tracking as yellow squares and the final reconstructed electron candidate as black closed circles. Right: Schematic illustration of the path of an electron through the ATLAS detector. The red solid line indicates the hypothetical trajectory of the electron. The path of a photon that was radiated due to the interaction of the electron with the detector material is shown as dashed red line. [99]

Reconstruction

The elements that contribute to the reconstruction of electrons are illustrated in Figure 4.1.1(b). As an electron does not only leave a signature in the EM calorimeter but the inner detector too, ID tracks with $p_T > 1$ GeV are loosely matched to the seed cluster. Hence, the reconstruction and identification method described here are dedicated to the central detector region ($|\eta| < 2.47$) owing to the acceptance of the ID. For a track to qualify as “loosely matched”, the spatial difference of its extrapolation to the second EM calorimeter layer and the cluster must fulfil $|\Delta\eta| < 0.05$ and $-0.1 < \Delta\phi_{\text{res}} < 0.05$. $\Delta\phi_{\text{res}}$ is defined as the azimuthal separation of the seed cluster position and the position in the second EM calorimeter layer based on the extrapolation from the perigee after its momentum was rescaled to the cluster energy, multiplied by the electric charge q assigned to the track. This asymmetric requirement on the azimuthal matching accounts for the bending of negative and positive electrically charged tracks in the magnetic field of the solenoid in positive and negative ϕ direction, respectively.

As the trajectory of an electron can change significantly due to bremsstrahlung, a dedicated counter measure, the so-called *Gaussian Sum Filter* (GSF) [100], is embedded in the track fitting and extrapolation algorithm. The GSF is a series of Kalman filters [101] running in parallel and are eventually combined to a weighted sum of Gaussian functions to approximate material-induced energy losses on the track parameters. All loosely matched tracks are refitted and the final matching with the seed cluster and the momentum of the electron candidate is computed. This procedure is especially beneficial for low- p_T electrons where the four-momentum resolution of the track parameters is strongly dominated by bremsstrahlung effects.

The radiation of bremsstrahlung and subsequent conversion of the photon can lead to several collimated tracks matched to the same cluster. In this case the track with the smallest ΔR between the impact point in the calorimeter and the seed cluster is chosen as the primary track of the electron candidate. Except if the separation between the tracks is below $\Delta R = 0.1$, in such a case the track with the most hits in the Pixel detector is preferred.

All track-matched seed clusters with a primary track with at least four hits in the silicon layers are considered as electron candidates. In order to reduce the number of electron candidates that can be associated to conversion photons and secondary particles, a compatibility requirement to the primary vertex (PV) is adopted. Hence, the deviation is restricted by

$$\frac{d_0}{\sigma_{d_0}} < 5 \quad \text{and} \quad \Delta z_0 \sin \theta < 0.5 \text{ mm} , \quad (4.1.1)$$

where σ_{d_0} is the uncertainty on the impact parameter d_0 , and Δz_0 is the difference between the track and the PV in z -direction. The final cluster is rebuilt within a window of an extended size of 3×7 (5×5) cells in the barrel (end-cap) of the EM calorimeter.

The energy of the electron candidate is identified as the energy of the final cluster calibrated at the EM-scale. Its four-momentum is calculated based on the final cluster and the best matched track of the initial seed cluster. Whereas, η and ϕ directions are extracted solely from the track parameters.

The reconstruction efficiencies extracted from simulated single-electron events are shown in Figure 4.1.1(a) for different stages of the reconstruction. The total efficiency varies from 97 % to 99 % above $p_T = 15$ GeV.

At the time of this thesis, a novel approach of dynamical, topological cell clustering is deployed in order to recover bremsstrahlung loss, e.g. by combining the seed cluster of an electron and the satellite cluster of the radiated photon to a “super-cluster”. However, the results presented in this thesis are based on the fixed-size algorithm. A more detailed description of the dynamical, topological cell clustering-based approach can be found elsewhere [102].

Identification

An identification algorithm is needed to distinguish electrons from photons and hadronic jets which can leave similar signatures in the EM calorimeter. A multivariate likelihood (LH) based algorithm is featured to assign a probability to each electron candidate to be background-like or electron-like. The LH approach combines cluster and track properties as well as the quantities evaluating the track-cluster matching. They are described in Table 4.1.1.

The overall probability density functions (PDFs) for signal and background are based on the PDFs for the individual variables. Prompt electrons from simulated $Z \rightarrow e^+e^-$ and $J/\psi \rightarrow e^+e^-$ events serve as signal input, while the background contribution are jets that mimic electrons, conversion electrons and non-prompt electrons from heavy flavour decays. An exemplary log-transformed LH discriminant is depicted in Figure 4.1.2(a).

Through a specific cut selection on the LH discriminant three different inclusive working points with increasing background rejection power but decreasing signal efficiency are provided: *Loose*, *Medium* and *Tight*. For each electron candidate a discriminant value can be calculated; hence it can be classified in the three categories or if none of the cuts are met it is considered to have failed the identification as electron.

As an EM calorimeter cluster can be reconstructed as both, electron and photon, it is crucial that the identification algorithm disentangles this ambiguity. Contrary to electrons, photons do not leave a track signature in the ID but it has to be considered that they can convert to an electron-positron pair which may result in two ID tracks emerging in the SCT or TRT. In the latter case a conversion vertex can be reconstructed but not necessarily both of the outgoing tracks. Hence, an electron candidate is required to have a track with at least two hits in the Pixel detector and seven hits in both silicon detectors, and must not have a conversion vertex

Type	Name	Description
Track conditions	$\Delta p/p$	Momentum lost by the track between the perigee and the last measurement point divided by the momentum at perigee
	$ d_0/\sigma_{d_0} $	Significance of the transverse impact parameter
	d_0	Transverse impact parameter relative to the beamline
TRT	eProbabilityHT	LH probability based on the transition radiation in the TRT
Track-cluster matching	$\Delta\eta_{S1}$	$\Delta\eta$ between the cluster position in the 1 st layer and the extrapolated track
	$\Delta\phi_{\text{res}}$	$\Delta\phi$ between the cluster position in the 2 nd layer and the momentum-rescaled track extrapolated from the perigee, multiplied by its charge q
1 st layer of EM calorimeter	E_{ratio}	Ratio of the energy difference between the maximum and the 2 nd largest energy deposit in the cluster to the sum of these energies
	f_1	Ratio of the energy in the 1 st layer and the total energy in the EM calorimeter
2 nd layer of EM calorimeter	$w_{\eta 2}$	Lateral shower width, $\sqrt{(\sum E_i \eta_i^2)/(\sum E_i) - ((\sum E_i \eta_i)/(\sum E_i))^2}$, where E_i and η_i are the energy and pseudorapidity of cell i , respectively, the sum is calculated within a window of 3×5 cells
	R_ϕ	Ratio of the energy in 3×3 cells over the energy in 3×7 cells centred at the electron candidate cluster position
	R_η	Ratio of the energy in 3×7 cells over the energy in 7×7 cells centred at the electron candidate cluster position
3 rd layer of EM calorimeter	f_3	Ratio of the energy in the 3 rd layer to the total energy in the EM calorimeter (only used for $E_T < 80$ GeV and $ \eta > 2.37$)
Hadronic leakage	R_{had1}	Ratio of E_T in the 1 st layer of the hadronic calorimeter to E_T of the EM cluster (only used for $ \eta < 0.8$ and $ \eta > 1.37$)
	R_{had}	Ratio of E_T in the hadronic calorimeter to E_T of the EM cluster (only used for $0.8 < \eta < 1.37$)

Table 4.1.1: Type and description of the variables used in the electron LH identification [99].

associated. For the *Medium* and *Tight* working point one of the Pixel hits needs to be in the innermost layer in order to reduce the contribution from photon conversions. In case the track is matched to a conversion vertex but the two affiliated tracks do not both have hits in the silicon detectors or only one of them has hits in the Pixel detector, the electron candidate can still be identified as electron. If no tracks, fulfilling the requirements above, are matched to the cluster or none of the tracks associated to a matched conversion vertex have any hits in the Pixel layers, the electron candidate is considered to be a photon. In case none of these requirements is met or $E_{\text{cl}}/p_{\text{track}} > 10$ and $p_{\text{track}} < 2$ GeV, no distinction can be made and the track-matched cluster is identified as both, electron and photon.

The efficiency of the electron identification is measured with a tag-and-probe method from $Z \rightarrow e^+e^-$ and $J/\psi \rightarrow e^+e^-$ data events, with one electron tagged as *Tight* while the other one is the probe. The efficiencies extracted from $Z \rightarrow e^+e^-$ events for the three working points is shown in Figure 4.1.2(b). Considering $J/\psi \rightarrow e^+e^-$ events in the extraction of the PDFs allows

taking electron candidates down to $p_T = 4.5$ GeV into account. The sudden rise in efficiency towards these low transverse momenta is due to mismodelling of the input variables in the simulation.

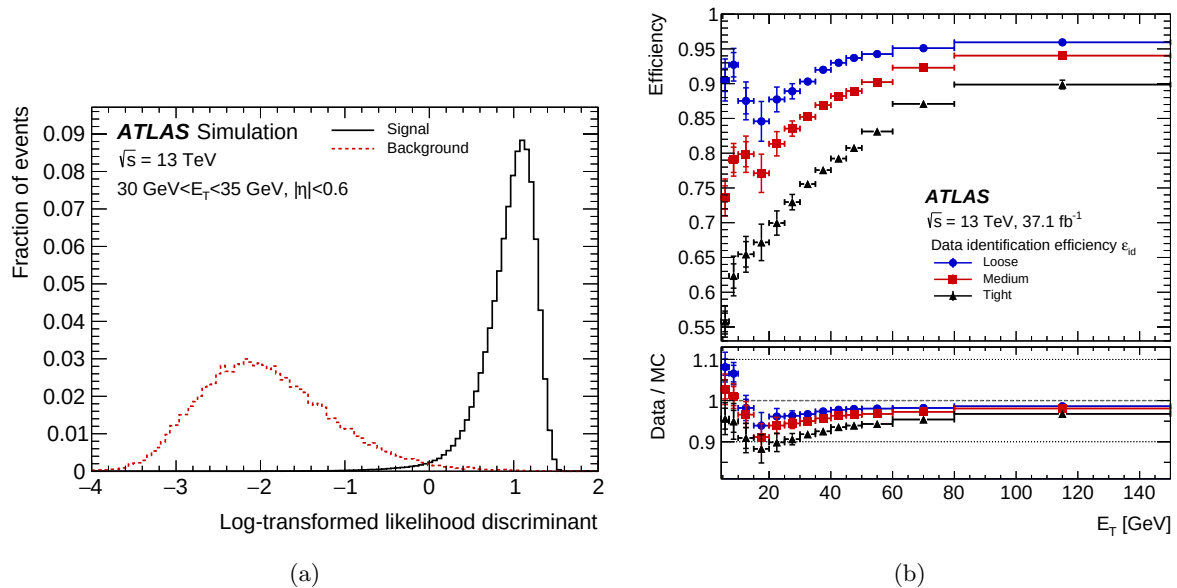


Figure 4.1.2: Left: Log-transformed LH discriminant for reconstructed electron candidates with good quality tracks with $30 \text{ GeV} < E_T < 35 \text{ GeV}$ and $|\eta| < 0.6$. The signal distribution, obtained from prompt electrons from simulated $Z \rightarrow e^+e^-$ events is shown in black. The red dashed line represents the background which is composed of simulated generic two-to-two processes. Right: LH electron identification efficiency measured in $Z \rightarrow e^+e^-$ events as function of E_T for the three working points *Loose* (blue circles), *Medium* (red squares) and *Tight* (black triangle). The inner and outer vertical uncertainty bars represent the statistical and total uncertainties, respectively. The data-to-simulation ratio is shown below. [99]

4.2 Energy Calibration

The energy of an electromagnetic object is identified by the sum of the energy deposits in the corresponding EM calorimeter cluster [103, 104]. Despite thorough alignment and calibration of the detector and the read-out electronics, this energy can differ significantly from the actual energy of the incoming particle. Various sources can be addressed to explain this deviation, like limitations of the finite cluster size, detector non-uniformities or unaccounted bremsstrahlung losses to name a few. Thus, the cluster energy scale and resolution needs to be calibrated following a multi-step scheme summarised in Figure 4.2.1. The core step is the simulation-based calibration of the EM cluster energy which is discussed in Section 4.2.1. Several data-driven corrections need to be applied on data before and after the simulation-based calibration. Most of them are summarised in Section 4.2.2 while the improved uniformity corrections are described in more detail in Section 4.3. The final steps of the calibration chain, the extraction and validation of the energy scale and resolution smearing, is addressed in Section 4.2.3. Section 4.4 is dedicated to improvements on the simulation-based calibration.

4.2.1 Simulation-based Calibration

The simulation-based energy calibration chain aims to recover the energy losses outside of the finite electron or photon cluster and in passive material upstream and inside the calorimeter. To

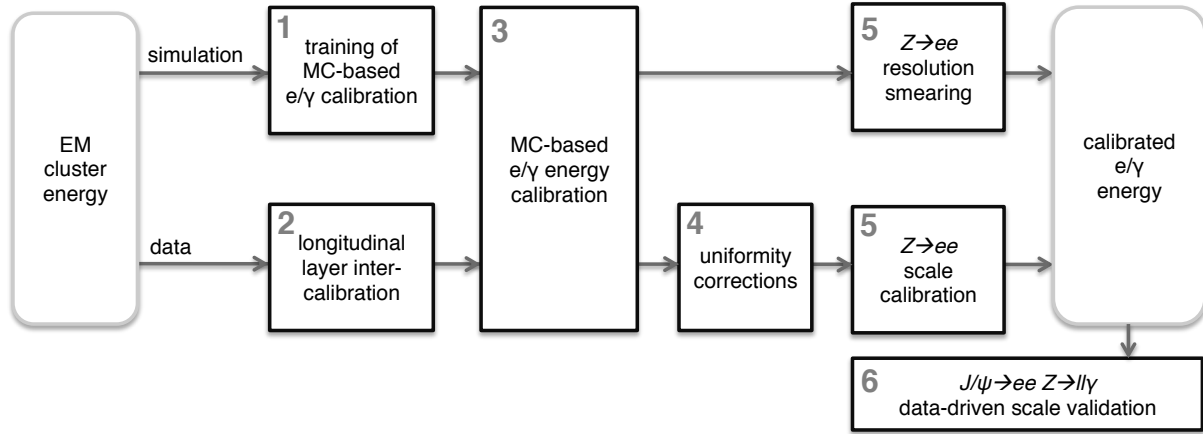


Figure 4.2.1: Schematic overview of the individual steps of the calibration of the energy response of simulated and measured electrons and photons [103].

estimate these losses the raw energy response reconstructed in simulated single-electron (single-photon) events is compared to the generated true energy. Single-particle samples with up to 40 million electron (photon) events are generated by a **GEANT**-based particle gun and passed through a full **GEANT4** detector simulation. No pile-up or underlying events are added to allow a clean extraction of the energy response. The generated E_T spectrum covers a wide range from 1 GeV up to 3 TeV with enhanced statistics between 7 GeV and 200 GeV. Figure 4.2.2 shows the generated E_T spectrum of simulated signal-electron events up to 500 GeV. The electrons (photons) have to fulfil the loose ID requirement, albeit this restriction is lifted for absolute pseudorapidities ranging from 1.37–1.52 and 2.47–2.5 as the efficiency of the identification is rather low and too few particles would be available.

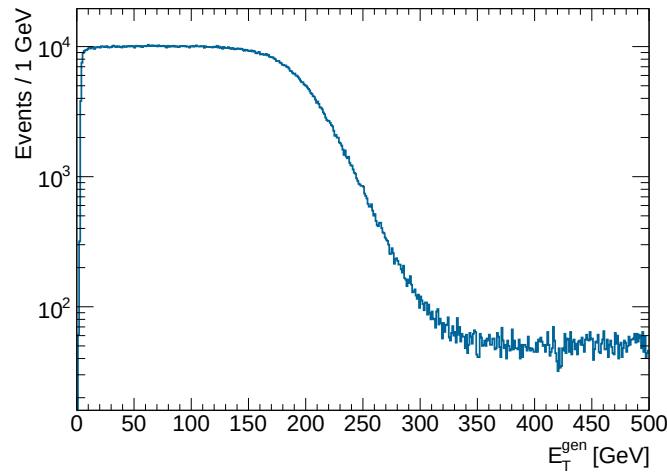


Figure 4.2.2: Generated E_T spectrum up to 500 GeV of simulated single-electron events.

A multivariate regression algorithm based on a boosted decision tree with gradient boosting [105] is trained on the simulated single-particle events. For the technical implementation the ROOT-integrated *Toolkit for Multivariate Analysis* (TMVA) framework [106, 107], which allows training and evaluation of classification and regression problems, is chosen. The aim of the regression is to minimise the RMS of the ratio of the true generated energy and the energy reconstructed in the accordion calorimeter, E_T^{gen}/E_T^{acc} .

The latter is parametrised by a set of variables sensitive to the energy of the shower devel-

opment. They are described in Table 4.2.1. Thanks to the multivariate approach correlations between these variables can be exploited. Further, the configurable implementation via TMVA allows varying the setup easily. As the shower development is different for electrons, unconverted and converted photons, the training is performed separately for these particle types. Especially for converted photons the input variable set is further optimised by including information on the conversion vertex and emerging tracks.

Type	Name	Description	Usage	
			e & unconv. γ	conv. γ
EM calorimeter	E^{acc}	Sum of the uncalibrated energy deposits in the cells in the accordion layers (strip (S1), middle (S2), back (S3)), $E^{\text{acc}} = E_{\text{S1}}^{\text{raw}} + E_{\text{S2}}^{\text{raw}} + E_{\text{S3}}^{\text{raw}}$	•	•
	$E_{\text{S0}}^{\text{raw}}/E^{\text{acc}}$	Ratio of the presampler (S0) to accordion energy (only for $ \eta < 1.8$)	•	•
	$E_{\text{S1}}^{\text{raw}}/E_{\text{S2}}^{\text{raw}}$	Ratio of the energies in the first and second accordion layer	•	•
	η_{cl}	Pseudorapidity of the cluster in the ATLAS frame	•	•
	$\eta_{\text{calo}}/\Delta\eta$	Cell index; with η_{calo} measured in the calorimeter frame and $\Delta\eta=0.025$ as the size of a middle layer cell	•	•
	η_{mod}	η with respect to the cell edge; η_{calo} modulo $\Delta\eta$, with the size of a middle layer cell of $\Delta\eta=0.025$	•	•
	ϕ_{mod}	ϕ with respect to the cell edge; ϕ_{calo} modulo $2\pi/1024$ ($2\pi/768$), ¹ the periodicity of the lead sheets in the barrel (end-cap) region	•	•
Conversion tracks	r_{conv}	Conversion radius (only tracks with $p_{\text{T}} > 3$ GeV are considered)		•
	$E_{\text{T}}^{\text{acc}}/p_{\text{T}}$	Ratio of the conversion p_{T} to the E_{T} in the accordion calorimeter, with $E_{\text{T}}^{\text{acc}} = E^{\text{acc}}/\cosh(\eta_{\text{cl}})$		•
	$p_{\text{T}}^{\text{lead}}/\Sigma p_{\text{T}}^{\text{conv}}$	Fraction of the conversion p_{T} carried by the highest- p_{T} track		•
Transition region ($1.4 < \eta < 1.6$)	$E_{3 \times \text{E4}}/E^{\text{acc}}$	Ratio of the energy in three consecutive E4 scintillators to the accordion energy	•	•
	$\Delta\phi_{\text{cl-E4}}$	$\Delta\phi$ between the cluster and the E4 scintillators, $\Delta\phi_{\text{cl-E4}} = \phi_{\text{cl}} - \phi_{\text{E4}}$	•	•

Table 4.2.1: Type, description and usage of the variables used in the electron and photon MVA calibration [104].

As the behaviour of the input variables varies with pseudorapidity and energy, the training is performed in bins of $|\eta_{\text{cl}}| \times E_{\text{T}}$, which are listed in Table 4.2.2. The covered $|\eta|$ range corresponds to the highly segmented region of the EM calorimeter and the fiducial volume of the ID. The $|\eta_{\text{cl}}| \times E_{\text{T}}$ grid is comprised of 10×9 rectangular bins plus a set of special bins close to the edges of calorimeter modules at η close to 0, 1.37 and 2.5 (3×6) and the transition region between the barrel and the end-cap calorimeters (3×1).

The transition region is handled separately to mitigate the effect of inactive material which

¹The denominators 1024 and 768 reflect the azimuthal segmentation in the barrel and end-cap calorimeter, respectively.

MVA calibration binning		
$ \eta_{\text{cl}} $	“normal”	0.05–0.65, 0.65–0.8, 0.8–1.0, 1.0–1.2, 1.2–1.37, 1.6–1.74, 1.74–1.82, 1.82–2.0, 2.0–2.2, 2.2–2.47
	“special”	0–0.05, 1.37–1.4, 2.47–2.5
	“transition”	1.4–1.46, 1.46–1.52, 1.52–1.6
$E_{\text{T}}^{\text{acc}}$	“normal”	0–10 GeV, 10–20 GeV, 20–40 GeV, 40–60 GeV, 60–80 GeV, 80–120 GeV, 120–500 GeV, 500–1000 GeV, 1000–50000 GeV
	“special”	0–25 GeV, 25–50 GeV, 50–100 GeV, 100–500 GeV, 500–1000 GeV, 1000–50000 GeV
	“transition”	0–10000 GeV
Energy shift binning		
$E_{\text{T}}^{\text{acc}}$	$0 < \eta_{\text{cl}} < 1.4$, $1.6 < \eta_{\text{cl}} < 2.5$	0–5 GeV, 5–7 GeV, 7–10 GeV, 10–15 GeV, 15–30 GeV, 30–50 GeV, 50–80 GeV, 80–3000 GeV
	$1.4 < \eta_{\text{cl}} < 1.46$	0–15 GeV, 15–45 GeV, 45–160 GeV, 160–10000 GeV
	$1.46 < \eta_{\text{cl}} < 1.52$	0–17 GeV, 17–25 GeV, 25–500 GeV
	$1.52 < \eta_{\text{cl}} < 1.6$	0–100 GeV, 100–350 GeV, 350–1000 GeV

Table 4.2.2: $E_{\text{T}}^{\text{acc}}$ and $|\eta_{\text{cl}}|$ bins used in the MVA calibration (top) and to calculate and apply the energy shift (bottom) [104].

is far more abundant here than in the rest of the EM calorimeter (5 to 10 radiation lengths). Therefore, information provided by the E4 scintillators of the intermediate tile calorimeter (ITC) is taken into account. The ITC is a group of four cells (E1 to E4) which is solely composed of active material and squeezed in the gap in between the long and extended tile barrel. It covers the entire ϕ range in the region $1.4 < |\eta| < 1.6$ and offers a granularity of 0.1 in ϕ . The fraction of energy deposited in the E4 scintillators, $E_{3 \times \text{E4}}/E^{\text{acc}}$, and the azimuthal difference between the cluster and E4 scintillators, $\Delta\phi_{\text{cl-E4}}$, are included in the set of MVA input variables.

As the distribution of the target variable, $E^{\text{gen}}/E^{\text{acc}}$, is not perfectly Gaussian and the MVA tends to minimise the RMS of the target, the mean of the calibrated energy, E^{calib} , is close but not equal to E^{gen} . Thus, a set of shifts is applied in some η - E_{T} regions on top of the MVA calibration such that the mean of $E^{\text{calib}}/E^{\text{gen}}$ within the smallest interval containing 10 % of the entries is equal to unity. These shifts differ significantly for some adjacent E_{T} bins, especially in the low- E_{T} region for which the binning is refined. To smooth the dependence of the shifts on E_{T} , a linear interpolation between the barycentres of adjacent E_{T} bins is performed. Finally, the simulation-based multivariate calibration is applied to data as well as simulation.

In order to evaluate the performance of the MVA energy calibration, the linearity and resolution of its response is studied, as well as the dependency on the input variables. The linearity is determined by the behaviour of the peak of $E^{\text{calib}}/E^{\text{gen}}$ as a function of E^{gen} , with the peak being obtained for each calibration bin from the mean of a Gaussian fit of the distribution truncated to $[-1, 2]$ standard deviations to avoid any bias from the tails. The resolution is defined

by the interquartile range of $E^{\text{calib}}/E^{\text{gen}}$, which is the distance between the first and the third interquartiles, according to

$$\text{IQE} = \frac{Q_3 - Q_1}{2\phi^{-1}(0.75)} , \quad (4.2.1)$$

where Q_1 and Q_3 are the first and third quartile of the distribution and ϕ^{-1} represents the inverse of a cumulative distribution function of the Normal function. The scaling factor of 0.75 ensures that an IQE of 1 is equivalent to that of a unity-width Gaussian function. The IQE is insensitive to outliers and commonly used as an estimator for the resolution.

4.2.2 Data-driven Corrections

Since the MVA energy calibration is solely based on simulated single particle events without pile-up, several detector related effects are unaccounted for. This section covers the inter-calibration of the first and second calorimeter layers as well as the calibration of the PS. However, no dedicated calibration of the third EM calorimeter layer is performed as only a small fraction of energy of electrons and photons is deposited in it. Further, effects originating from pile-up are discussed.

Any residual miscalibration due to non-uniformity in the detector response are addressed in Section 4.3 including dedicated studies to mitigate the related effects.

Inter-Calibration of the First and Second EM Calorimeter Layers

Electronics miscalibration and cross talk effects affect the individual calorimeter layer response and thus the overall energy measurement. To account for this an inter-calibration of the first and second layer is performed by comparing the energy deposits of muons from $Z \rightarrow \mu^+\mu^-$ events in data and simulation. Muons are preferred as they are minimal ionising particles at typical LHC energies of 27–100 GeV and thus are insensitive to upstream material and their energy loss scales only with the layer depth.

A correction factor $\alpha_{1/2}$ is extracted as a double ratio of the most probable values (MPVs) of the energy deposits in the first (E_1) and second (E_2) calorimeter layer in data and simulation, $\langle E_{1/2}^{\text{data}} \rangle = \langle E_1^{\text{data}}/E_2^{\text{data}} \rangle$ and $\langle E_{1/2}^{\text{MC}} \rangle = \langle E_1^{\text{MC}}/E_2^{\text{MC}} \rangle$, respectively, according to

$$\alpha_{1/2} = \frac{\langle E_{1/2}^{\text{data}} \rangle}{\langle E_{1/2}^{\text{MC}} \rangle} . \quad (4.2.2)$$

This correction is derived in several bins in η as shown in Figure 4.2.3(a). $\alpha_{1/2}$ is applied on the energy measurement of the second layer in data prior to the MVA calibration.

Presampler Calibration

The PS is especially sensitive to upstream material and thus material mismodelling has a considerable impact on its energy measurement. In order to mitigate these effects a dedicated presampler energy scale, α_{PS} , is derived using electrons from $Z \rightarrow e^+e^-$ events by exploiting the correlation between the shower development and the amount of material in front of the PS.

The PS energy scale is defined by the ratio of the energy deposited in the PS (E_0) in data and simulation multiplied by a correction factor following

$$\alpha_{\text{PS}} = \frac{E_0^{\text{data}}}{E_0^{\text{MC}}} \cdot \frac{1}{1 + A \cdot \left(\frac{E_{1/2}^{\text{data}}}{E_{1/2}^{\text{MC}}} \cdot \frac{1}{b_{1/2}} - 1 \right)} . \quad (4.2.3)$$

A denotes a correlation factor between E_0 and $E_{1/2}$ under variation of upstream material and is estimated based on alternative simulated samples with distorted geometries. $b_{1/2}$ is a correction

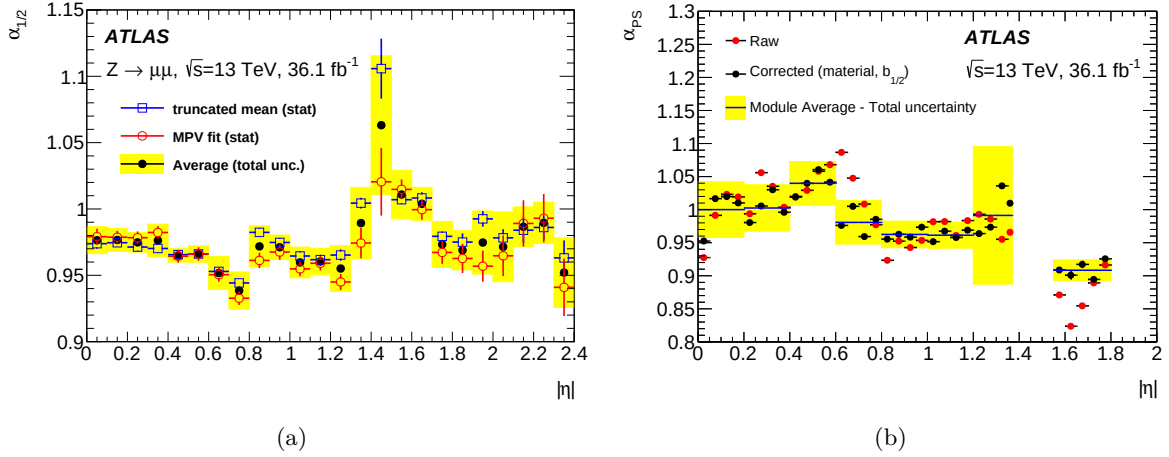


Figure 4.2.3: Left: $\alpha_{1/2}$ as a function of $|\eta|$, obtained from the study of the muon energy deposits in the first two layers of the calorimeters. The results including statistical uncertainties are shown for two different methods: the truncated mean method (blue squares) and MPV fit (red circles). The final averaged measurement is shown with its total uncertainty including the statistical and systematic uncertainties (black dots). Right: α_{PS} as a function of $|\eta|$ before and after the material and $b_{1/2}$ corrections depicted as red and black dots, respectively. The values averaged per PS module are shown as blue lines together with the total uncertainties as yellow bands. [104]

factor on the double ratio of $E_{1/2}$ in data and simulation, accounting for mismodelled material between the PS and the EM calorimeter. It is derived from unconverted photons from $Z \rightarrow e^+e^-\gamma$ events,² as photons are insensitive to material in the ID. α_{PS} is derived in several bins in η as shown in Figure 4.2.3(b) and needs to be applied on the energy measurement of the PS before the MVA calibration.

Pile-up Energy Shift

The bi-polar pulse shapes of the signal measured with the LAr calorimeter is designed such that in an ideal case energy deposits from in- and out-of-time pile-up cancel. However, due to finite bunch trains and bunch-to-bunch variations in the luminosity a residual energy shift remains which depends on the position inside of the bunch train as well as the instantaneous luminosity. The deviation can reach up to $E_T = 500$ MeV for an electron or photon cluster but can be almost fully compensated by a pedestal correction extracted from zero-bias events.

First, the average pile-up energy shift is computed as a function of bunch position in the full LHC, whereby the instantaneous luminosity and the expected pulse shape as a function of time are taken into account as well. This factor is subtracted on a cell-by-cell level and reduces the shift to about 30 MeV. This deviation is mainly due to inaccuracies in the pulse shape predictions as they are based on a drift time corresponding to a high voltage of 2000 V in the LAr gap. However, in 2016 it was lowered to 1200 V in the PS to reduce frequent sporadic bursts of noise. Thus, an additional cluster-level correction on each EM calorimeter layer is applied as a function of η and average interactions per bunch crossing. This reduces the shift in transverse energy to less than 10 MeV.

The linearity and resolution of the MVA response as a function of pile-up reveals a remaining small dependency, especially for low- E_T and increasing pile-up, but this effect is fully covered

²A veto on photons with energy deposits in the PS is applied to reject any conversions occurring in between the end of the ID and the end of the PS.

by uncertainties. In $Z \rightarrow e^+e^-$ events it was observed that the energy response is stable within 0.05 % integrated over η [104].

4.2.3 Energy Scale & Resolution

After the application of the simulation-based calibration and data-driven corrections, a residual disagreement in the energy scale and resolution may be present between simulation and data. The energy scale factor, α , shifts the absolute energy scale of each electron (photons) in data, and an additional constant term, c' , is added to the energy of simulated electrons (photons).

Both factors are derived with a template fit method from $Z \rightarrow e^+e^-$ events. The template fit method exploits a χ^2 minimization to obtain α and c' as function of η .

The deviation of the energy measured and calibrated in data, E^{data} , and the optimal calibrated energy in simulation, E^{MC} , is defined as

$$E^{\text{data}} = E^{\text{MC}}(1 + \alpha_i) , \quad (4.2.4)$$

where α_i denotes the energy scale factor for a given pseudorapidity region i .

The relative energy resolution is parameterised by Equation 3.2.4 (see Section 3.2.2). Only the constant term, c , needs to be estimated solely from data under the assumption that the simulation models data well up to an effective constant term c' :

$$\left(\frac{\sigma(E)}{E} \right)^{\text{data}} = \left(\frac{\sigma(E)}{E} \right)^{\text{MC}} \oplus c' . \quad (4.2.5)$$

c' is applied on the simulated energy to emulate the larger resolution in data, according to

$$E^{\text{data}} = E^{\text{MC}}[1 + c'_i \times N(0, 1)] , \quad (4.2.6)$$

with $N(0, 1)$ being a Normal distributed random number.

The template fit method relies on the invariant di-electron mass measured in $Z \rightarrow e^+e^-$ events where both electrons are in different η regions. Hence, the di-electron mass is parameterised with correction factors on both electron energies and compared to the invariant di-electron mass distribution in simulation. By minimising the χ^2 of the difference between these two, α and c' can be extracted as a function of pseudorapidity. The energy scale factor and effective constant term are binned in 68 and 24 η regions, respectively. Both are shown in Figure 4.2.4.

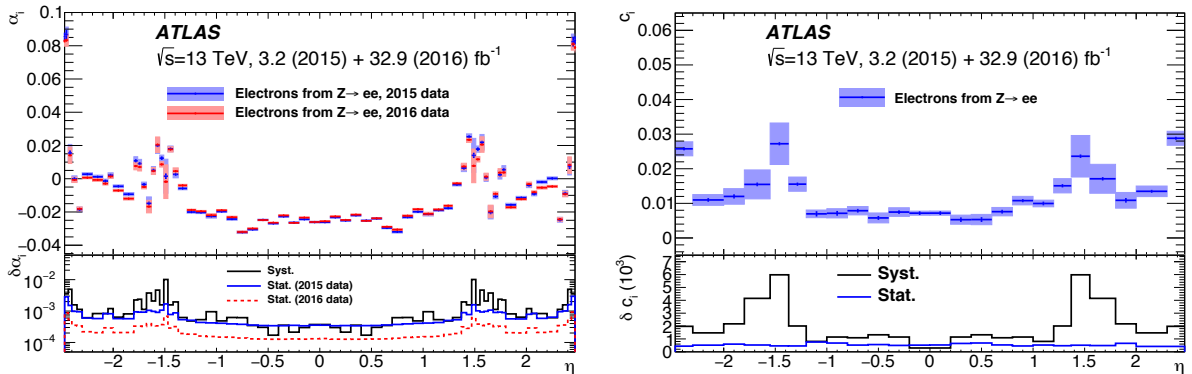


Figure 4.2.4: Results of the data-to-MC calibration from obtained $Z \rightarrow e^+e^-$ events for the energy scale corrections, α_i , (left), and the energy resolution corrections, c_i , (right), as a function of η . The systematic and statistical uncertainties are shown separately in the bottom panels. [104]

Uncertainties

Several systematic uncertainties affect the energy scale and resolution of electrons and converted and unconverted photons. In total 64 and 9 independent systematic uncertainties are obtained on the scale and resolution, respectively.

The uncertainties on the energy scale arise from the layer calibration, non-linearity of the cell energy measurement, material in front of the calorimeter, modelling of the lateral shower shape and pile-up. They vary strongly with transverse energy and pseudorapidity, reaching a minimum of less than 0.001 % for electrons with a transverse energy of about 40 GeV and never exceed a few per mille [104].

The dominant contributors to the resolution uncertainties are residual non-uniformities, fluctuation of the energy loss in front and in the calorimeter and impact of pile-up and electronics noise. For electrons with E_T of 30–60 GeV the uncertainties range from 5 % to 10 % and rise to 50 % towards high energies [104].

Validation

The calibration and data-driven corrections mostly rely on electrons originating from $Z \rightarrow e^+e^-$ events. The scale and resolution as well as their uncertainties are constrained for electrons with transverse energies typical for Z boson decays. In order to validate the extrapolation to lower energies and photons other measures need to be taken. While, the average transverse energy of electrons from $Z \rightarrow e^+e^-$ ranges from 40 GeV to 50 GeV, $J/\psi \rightarrow e^+e^-$ and $Z \rightarrow \ell^+\ell^-\gamma$ ($\ell = e, \mu$) events are used to expand the reach towards transverse energies of electrons of 10 GeV and photons of 25 GeV, respectively.

After the application of the full calibration chain including the nominal corrections of the scale and constant term, the residual difference of the energy scale and resolution is extracted by the minimisation of an unbinned log-likelihood fit of the invariant di-electron mass distributions.

The deviation from and the nominal value of the energy scale agree within 1 % and 0.3 % for low-energy electrons from $J/\psi \rightarrow e^+e^-$ and photons from radiative Z boson decays, respectively [104].

4.3 Uniformity Corrections

Although the LAr calorimeter has a good spatial homogeneity in the η - ϕ -plane, small non-uniformities are sufficient to degrade the accuracy that is needed for precision measurements. Even after the MVA calibration and all corrections described in Section 4.2.2 and 4.2.3 are applied, the energy response measured in data varies for different impact points of electron (photon) showers in the calorimeter. One of these effects originates from the liquid argon gaps in between the barrel modules which are slightly larger than the gaps within the modules resulting in an underestimation of the measured energy. Another source for discrepancies is related to the high voltage applied in the liquid argon gap. Some regions of the calorimeter are operated at a high voltage different from the nominal value, e.g. to prevent intermittent short circuits that would affect detector operation and data quality. Both effects need to be dealt with by correction factors that are extracted from data.

The studies related to the degradation due to the gaps in between the modules and non-nominal high voltage settings are addressed thoroughly in Section 4.3.1 and 4.3.2, respectively. The former is referred to as the *intermodule-widening* (IMW) effect and its correction is assessed and adapted before the HV correction. Electrons that hit the detector in η - ϕ regions overlapping with sectors that are subject to HV corrections have been excluded prior to the extraction of the IMW correction factor to avoid any bias. Both corrections are applied after the MVA-based calibration but prior to the determination of the energy scale and resolution (c.f. Figure 4.2.1).

4.3.1 Intermodule-Widening Correction

The EM calorimeter consists of 16 modules in the barrel part and 8 in the end-caps with a size of $\Delta\phi \approx 0.4$ and 0.8 , respectively [81]. The gap between absorbers increases slightly at the boundaries between modules, which leads to a reduced energy response. The size of the gaps and hence the impact on the energy measurement varies along ϕ . Due to gravity-induced sagging of the calorimeter these intermodule-gaps are further altered. Thus, the gaps in between the modules of the top half of the detector are wider, while those in the bottom hemisphere are compressed.

To mitigate the IMW effect, the ratio of the electron energy and its track momentum is studied as a function of ϕ . As the momentum measurement relies solely on the ID it is insensitive to non-uniformities such as the intermodule-widening effect, while the energy is obtained from the calorimeter and thus prone to its inhomogeneities. Under the assumption of a perfect reconstruction and calibration, the ratio of the electron energy and its momentum, E/p , should be unity.³ In reality it might vary but it still is close to unity and should be flat along ϕ . Any deviation can be related to detector inhomogeneities. Figure 4.3.1 shows the E/p profile of electrons from $Z \rightarrow e^+e^-$ events measured in data and simulation as a function of their relative ϕ position folded over all barrel modules. The azimuthal position, $\phi_{\text{calo}}^{\text{module}}$, defined as:

$$\phi_{\text{calo}}^{\text{module}} = \phi - \left\lfloor \frac{\phi}{2\pi/16} \right\rfloor \cdot \frac{2\pi}{16} + \left(\frac{1 - \text{sgn}(\phi)}{2} \right) \cdot \frac{2\pi}{32}, \quad (4.3.1)$$

is shown relative to the module centre; thus the intermodule-gap is located at the centre of the represented ϕ range. While the distribution is flat for simulated events, a pronounced dip of about 2 % is clearly visible at $\phi_{\text{calo}}^{\text{module}} = \pi/16$ which is associated to the intermodule-gaps and is not included in the simulation of the detector geometry. Thus, a data-driven correction needs to be derived to mitigate this effect. Thanks to the high number of electrons originating from Z boson decays in data taken in 2015 and 2016, it is possible to extract a cleaner signature compared to Run 1 when electrons from W boson decays were utilised [108]. Further, the increased statistics allow the study of each intermodule-gap individually, contrary to Run 1, when four modules within four ϕ regions had to be folded. Hence, more precise correction factors are extracted for Run 2.

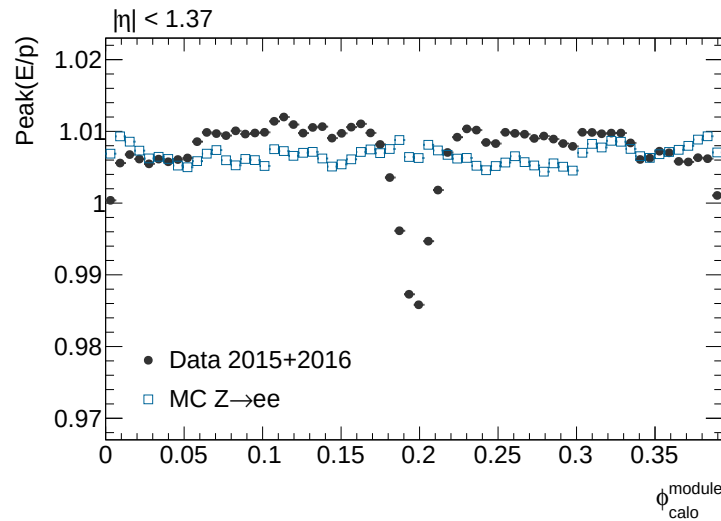


Figure 4.3.1: E/p profile for electrons from a $Z \rightarrow e^+e^-$ selection in data collected in 2015 and 2016 (black dots) and simulated $Z \rightarrow e^+e^-$ events (blue squares) as function of the relative ϕ position in the barrel calorimeter modules when all 16 modules are averaged.

³Assuming that the mass of the electron can be ignored.

To extract the peak position of the E/p distribution a Crystal Ball fit is exploited. For the profiling along $\phi_{\text{calo}}^{\text{module}}$ a ϕ -size binning of $2\pi/1024$ ⁴ was chosen in order to access the cell structures in detail. The dips at the intermodule-gaps are fitted with a Double-Fermi-Dirac function to extract the correction factors. This function is described by:

$$f(\phi_{\text{calo}}^{\text{module}}) = A - B \cdot \frac{1}{1 + e^{C \cdot (\phi_{\text{calo}}^{\text{module}} - 2\pi/32)}} \cdot \frac{1}{1 + e^{-D \cdot (\phi_{\text{calo}}^{\text{module}} - 2\pi/32)}} , \quad (4.3.2)$$

with A being the average value on either side of the gap and B the gap depth. C and D denote the gap width to the left and right, as the shape of the dip can be asymmetric. The relative azimuthal dip position is set to its actual value of $2\pi/32$. The Double-Fermi-Dirac fit provides a set of four coefficients for each module. A scale independent correction factor, $f_{\text{corr}}(\phi_{\text{calo}}^{\text{module}})$ is defined by

$$f_{\text{corr}}(\phi_{\text{calo}}^{\text{module}}) = \frac{f(\phi_{\text{calo}}^{\text{module}})}{A} . \quad (4.3.3)$$

The final corrected energy of electrons and photons alike is given by $E \cdot f_{\text{corr}}(\phi_{\text{calo}}^{\text{module}})^{-1}$.

The results of the fit as well as the corrected energy response are shown in Figure 4.3.2 and 4.3.3 for each individual module. The fit parameters for each intermodule-gap are listed in Table 4.3.1. The strength of the effect varies from 1 % to 4 % in modules in the bottom and top hemisphere, respectively. In Figure 4.3.4 the final correction factors f_{corr} are depicted as a function of ϕ_{calo} .

ϕ range	A	B	C	D
$[-1 \cdot \pi, -7 \cdot \pi/8]$	1.0051	0.1092	176.1656	190.3224
$[-7 \cdot \pi/8, -6 \cdot \pi/8]$	1.0062	0.0600	171.8869	234.8213
$[-6 \cdot \pi/8, -5 \cdot \pi/8]$	1.0064	0.0600	148.0816	140.2255
$[-5 \cdot \pi/8, -4 \cdot \pi/8]$	1.0044	0.0586	169.2064	247.3744
$[-4 \cdot \pi/8, -3 \cdot \pi/8]$	1.0085	0.0534	179.1729	200.0
$[-3 \cdot \pi/8, -2 \cdot \pi/8]$	1.0069	0.0677	146.0761	243.8578
$[-2 \cdot \pi/8, -1 \cdot \pi/8]$	1.0074	0.0877	133.3117	167.4158
$[-1 \cdot \pi/8, 0]$	1.0062	0.0954	128.4704	151.0013
$[0, 1 \cdot \pi/8]$	1.0038	0.1171	172.7186	236.2191
$[1 \cdot \pi/8, 2 \cdot \pi/8]$	1.0053	0.1178	191.3666	200.0
$[2 \cdot \pi/8, 3 \cdot \pi/8]$	1.0067	0.1301	159.1135	166.4980
$[3 \cdot \pi/8, 4 \cdot \pi/8]$	1.0060	0.1566	163.260	134.320
$[4 \cdot \pi/8, 5 \cdot \pi/8]$	1.0040	0.1666	181.2413	169.1742
$[5 \cdot \pi/8, 6 \cdot \pi/8]$	1.0036	0.1127	128.6864	154.9979
$[6 \cdot \pi/8, 7 \cdot \pi/8]$	1.0046	0.140	193.0130	198.9917
$[7 \cdot \pi/8, \pi]$	1.0041	0.1005	200.0	177.1375

Table 4.3.1: Fit parameters of the Double-Fermi-Dirac fit used to parameterise the dip in the energy profile with respect to $\phi_{\text{calo}}^{\text{module}}$ associated to the intermodule-gaps.

⁴1024 electrodes are deployed over the full azimuthal range of 2π .

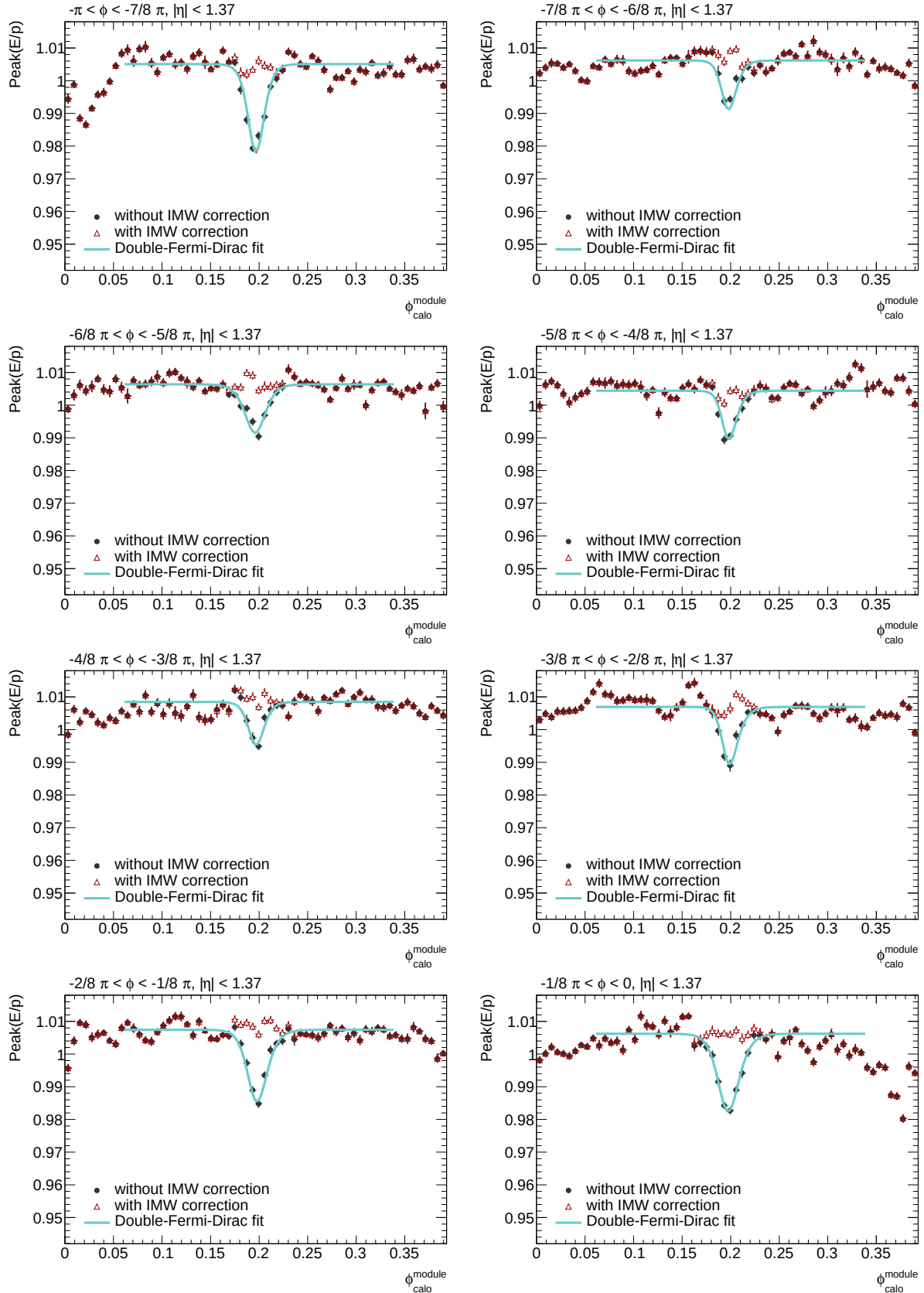


Figure 4.3.2: E/p profiles for electrons from a $Z \rightarrow e^+e^-$ selection in data collected in 2015 and 2016 as function of the relative ϕ position in the lower barrel calorimeter modules for each individual module before (black dots) and after (red triangles) applying of the IMW correction. The turquoise line depicts the Double-Fermi-Dirac fit which was used to extract the correction.

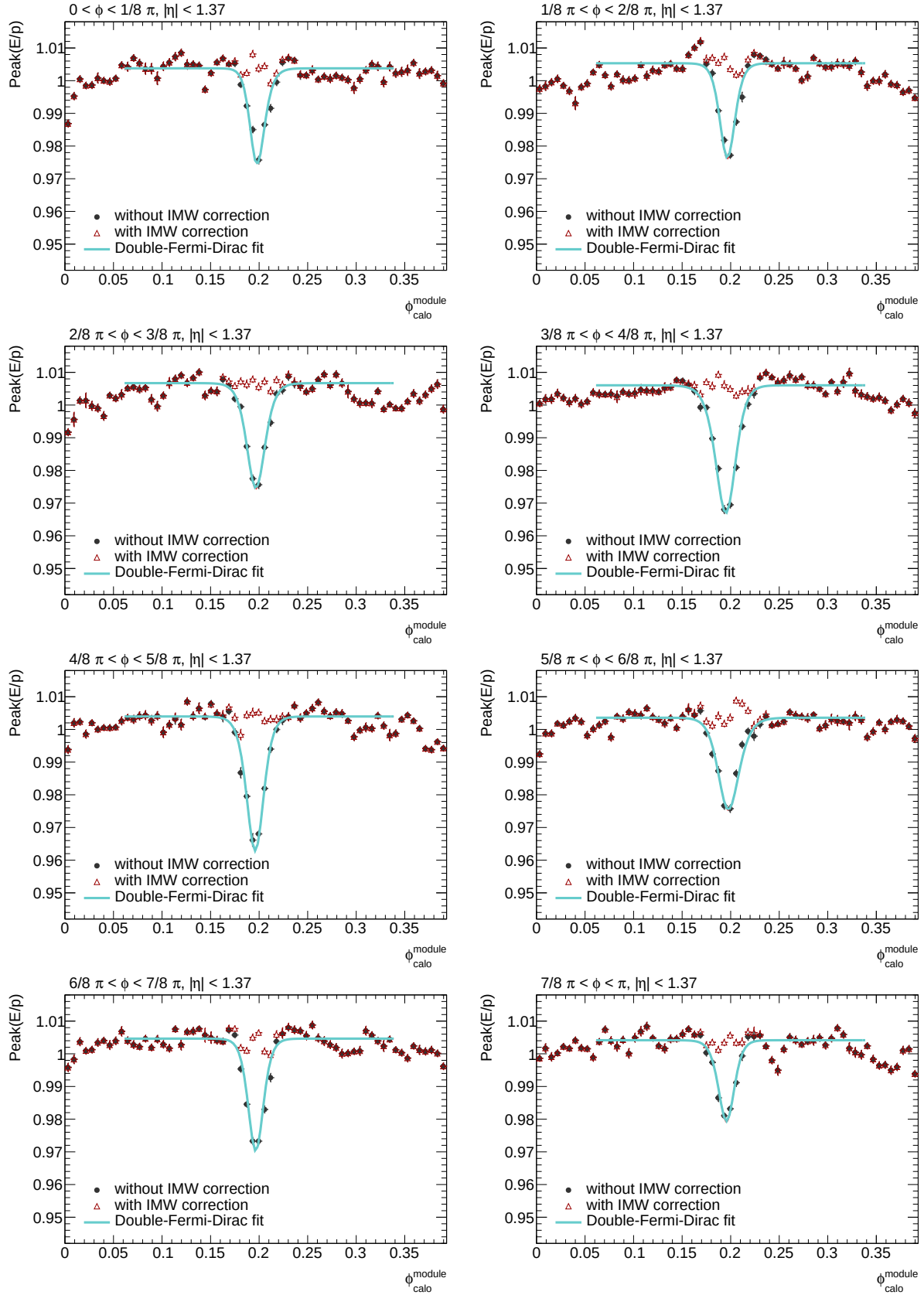


Figure 4.3.3: E/p profiles for electrons from a $Z \rightarrow e^+e^-$ selection in data collected in 2015 and 2016 as function of the relative ϕ position in the upper barrel calorimeter modules for each individual module before (black dots) and after (red triangles) applying of the IMW correction. The turquoise line depicts the Double-Fermi-Dirac fit which was used to extract the correction.

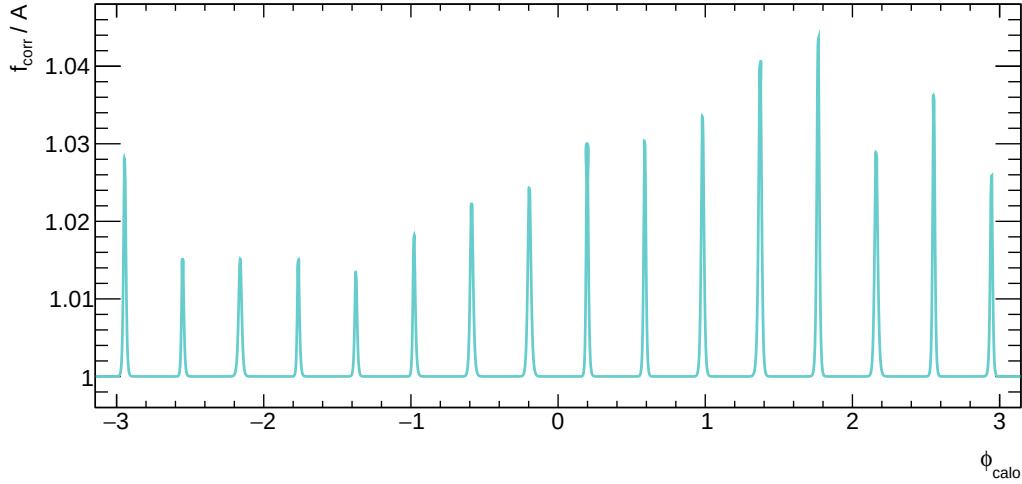


Figure 4.3.4: Size of the impact of the IMW correction on the energy as a function of ϕ .

While so far only the barrel modules have been addressed, the IMW effect has also been investigated in the end-caps. However, no similar effect can be observed as shown in Figure 4.3.5, whereby the distributions for all eight modules in the two end-caps are folded to obtain enough statistics and decrease the impact of fluctuations. Separate investigations of the two end-caps have not revealed any notable effects either (c.f. Appendix A.1.1). The absence of the degeneration in the energy at the intermodule-gaps is thanks to the different construction of the support structure in the end-caps compared to the barrel. Hence, no IMW correction is applied for electrons or photons detected in the end-cap calorimeters.

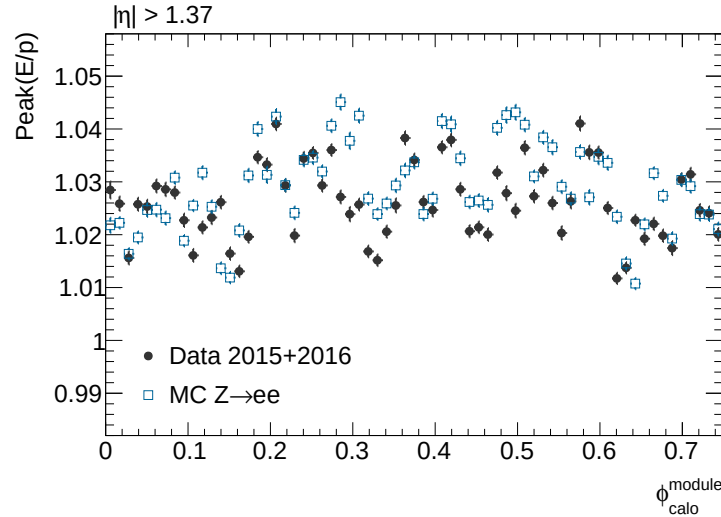


Figure 4.3.5: Folded E/p profile with respect to $\phi_{\text{calo}}^{\text{module}}$ of all calorimeter modules in the end-caps. $Z \rightarrow e^+e^-$ events selected in data collected in 2015 and 2016 and simulated $Z \rightarrow e^+e^-$ events are depicted as black dots and blue squares, respectively.

The impact of the IMW effect can be observed in the reconstructed invariant di-electron mass of $Z \rightarrow e^+e^-$ events. The peak of the invariant di-electron mass obtained by a truncated Gaussian fit as a function of $\phi_{\text{calo}}^{\text{module}}$ is shown in Figure 4.3.6 with and without the correction factors applied. Figure 4.3.7 depicts a shift in the inclusive invariant di-electron mass which is evaluated to be 0.1%.

It has been observed that the strength of the IMW effect scales with the transverse momen-

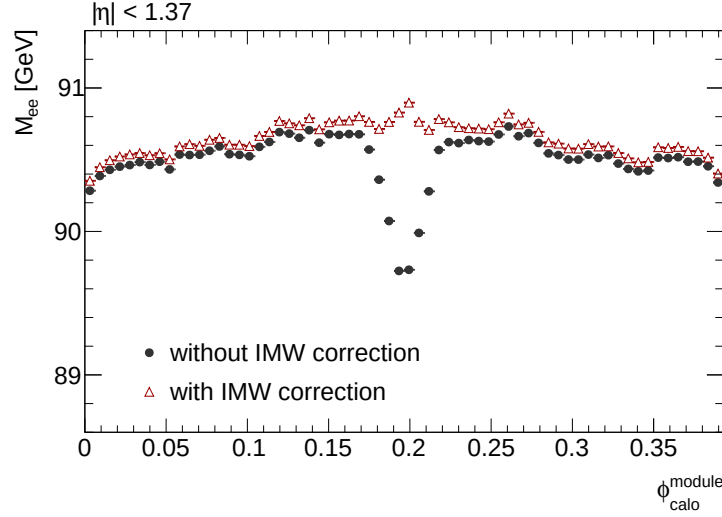


Figure 4.3.6: Invariant di-electron mass of $Z \rightarrow e^+e^-$ events selected in data collected in 2015 and 2016 with respect to $\phi_{\text{calo}}^{\text{module}}$ with (red triangles) and without (black dots) the IMW correction applied. All electrons with an $|\eta| < 1.37$ enter the distribution. The distribution is folded over all 16 barrel modules.

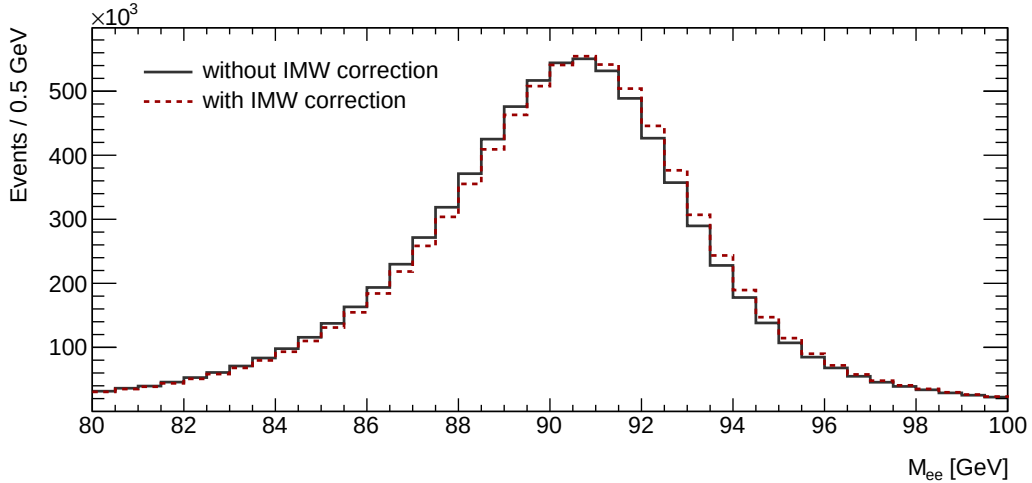


Figure 4.3.7: Invariant di-electron mass of $Z \rightarrow e^+e^-$ events selected in data collected in 2015 and 2016 with (red) and without (black) the IMW correction applied. All electrons with an $|\eta| < 1.37$ enter the distribution.

tum of the particle which hits the gap. Since the method to extract the IMW correction relies on $Z \rightarrow e^+e^-$ events for which the energy of the vast majority of the decay products ranges between 40 GeV and 50 GeV, the derived correction factors are optimised for this energy range. For the low energy end of the spectrum $J/\psi \rightarrow e^+e^-$ events provide electrons with energies of 5 GeV and 40 GeV.⁵ Combining the events from a $J/\psi \rightarrow e^+e^-$ and $Z \rightarrow e^+e^-$ selection in the data recorded in 2015 and 2016 allows the study of the energy dependence of the IMW effect. Therefore, the combined sample is split depending on the energy of the electrons in subsets containing roughly the same number of electrons. To ensure sufficient statistics in the low energy bins the IMW effect is studied for all modules folded such that one correction function is derived per energy bin. The results are shown in Figure 4.3.8. The amplitude of the correction function

⁵The absence of any well known sources of electrons with higher energies prohibits to perform this study beyond the Z boson kinematics.

reaches its maximum for energies between 20 GeV and 39 GeV and decreases towards both ends of the energy spectrum.

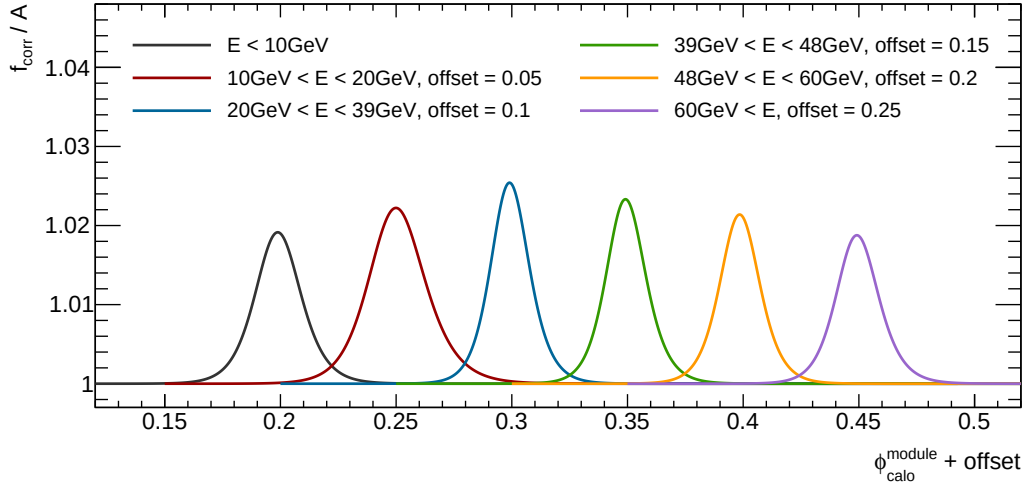


Figure 4.3.8: Size of the impact of the IMW correction on the energy as a function of $\phi_{\text{calo}}^{\text{module}}$ for different energy ranges. For easier visibility an offset on $\phi_{\text{calo}}^{\text{module}}$ is applied.

The behaviour at higher energies is related to the size of the shower induced by the electron. As the shower grows in width and depth with increasing energies, the fraction of the shower that overlaps with the intermodule-gap shrinks. Thus, the amplitude of the correction factor declines as well.

For lower energies the influence of the magnetic field of the solenoid magnet on the electron trajectory is more relevant. The lower the electron energy is, the stronger the curvature of its trajectory. As a result the angle between the EM shower and the intermodule-gap becomes non-negligible. The effect is illustrated by Figure 4.3.9 which shows the difference in the electron ϕ based on the ID track and the calorimeter cluster versus the electron energy. The correlation follows a falling exponential function and supports that the effect is dominant for energies below 20 GeV. Due to the inclination the fraction of the shower overlapping with the intermodule-gap is minimised for lower energies, and hence the amplitude of the IMW correction factor is smaller as well. At the time when this study was conducted the recorded number of electrons at low and high energies was not sufficient to evaluate the observed energy dependence of the IMW effect for each module separately.

Independently of the IMW effect two other features were observed in the scope of this study. First, the slight curvature in the E/p and invariant di-electron mass profiles which is lowest at the module centre and highest at the position of the gap. The origin for this is not identified, yet. It might be related to the PS modules which are finer segmented in ϕ , i.e. two PS modules are within the range of one accordion module. Similar to the intermodule-gaps of the accordion modules, the gaps in between the PS modules, which are at the centre of the accordion modules, are slightly larger than the LAr gaps inside each PS module and hence can lead to an underestimation of the measured energy. However, as this was not proven and the effect on the overall energy scale is considered to be negligible, no further investigations have been pursued. Second, the E/p profiles for the ϕ ranges of $[-2\pi/16, 0]$ and $[-\pi, -7\cdot 2\pi/16]$ show a deviation in the measured energy close to $\phi = -2\pi/16$ and $\phi = -7\cdot 2\pi/16$. The effect is of the same order as the one induced by the intermodule-widening but is of different origin and is discussed in Section 4.4.1.

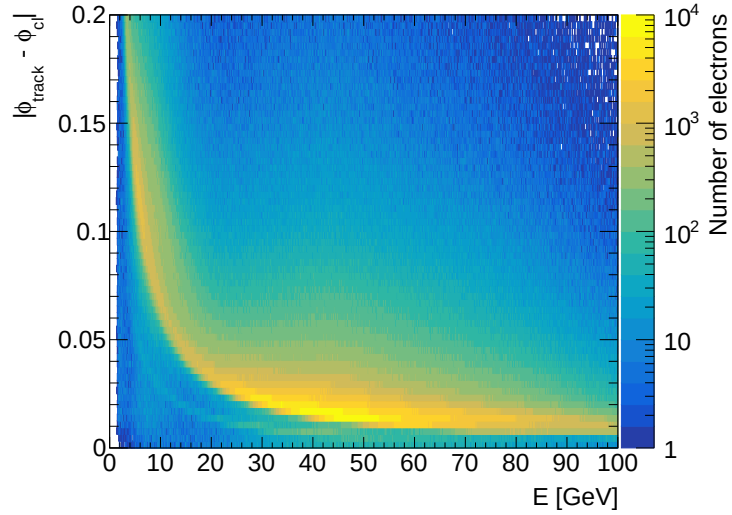


Figure 4.3.9: Azimuthal deviation between the electron ϕ based on the track measured in the ID and ϕ of the associated cluster in the calorimeter versus the electron energy. A combination of $J/\psi \rightarrow e^+e^-$ and $Z \rightarrow e^+e^-$ events selected in data collected in 2015 and 2016 is represented.

4.3.2 High Voltage Correction

Each read-out electrode of the LAr calorimeter cells has two independent HV supplies for redundancy. 32 electrodes, i.e. cells, are summarised in a sector supplied by the same two HV lines on each side of the electrodes. The dimension of the cells and sectors differ for the barrel and end-cap of the accordion calorimeter, they are summarised in Table 4.3.2.

	HV sector size		Cell size	
	$\Delta\eta$	$\Delta\phi$	$\Delta\eta$	$\Delta\phi$
Barrel	0.2	$\frac{2\pi}{32}$	0.025	$\frac{2\pi}{256}$
End-cap	0.2	$\frac{2\pi}{32}$	0.025	$\frac{2\pi}{256}$
	0.1 for $ \eta = [2.0, 2.1]$ and $ \eta = [1.5, 1.6]$	$\frac{2\pi}{32}$	0.025	$\frac{2\pi}{256}$

Table 4.3.2: Sizes of HV sectors and cells of the accordion calorimeter in η and ϕ (excluding the crack region).

The nominal HV is 2000 V in the barrel accordion and varies between 1000 V and 2500 V in the end-caps depending on the calorimeter region. However, high leakage currents in the LAr gap prevent some HV lines to be operated at their nominal values. In such case the HV applied on one or both sides of an electrode needs to be lowered. The reason for such lowering is manifold, e.g. to prevent short circuits, high voltage trips or mitigate noisy channels. As a consequence of these non-nominal conditions, the electric field within the gap is weaker and thus the drift velocity of the ionisation electrons is smaller affecting the measured signal amplitude. Hence, the detector performance is deteriorated and causes non-uniformities in the energy measurement in η - ϕ -space.

At first order this is corrected on reconstruction level by applying a HV dependent correction on the cell-level calibration in the affected regions as described in [109]. However, imperfect corrections, e.g. if large currents are drawn, lead to local fluctuations of the energy scale.

Residual effects can be observed, e.g. in the invariant di-electron mass in $Z \rightarrow e^+e^-$ events, and need to be addressed by a particle-level correction factor.

With the start of Run 2 several changes in the HV system have been made and the correction factors derived in Run 1 [103] had to be reassessed. First, the changes in sectors which are at non-nominal settings have to be identified. The HV settings are constant most of the time but might vary throughout a long data-taking period. Temporary deviations are negligible and would be impossible to study due to the lack of statistics. Figure 4.3.10(a) and (b) show η - ϕ -maps⁶ of the HVs applied to the two half gaps of a sector for data taken in run 311287 which stands exemplary for the entire Run 2. Several sectors operating at non-nominal HV can be easily identified. As the average HV in an affected sector is smaller than the overall average, the energy of the shower induced by an electron which overlaps with that sector is underestimated. However, not in all cases short-circuits are the origin. For some the reason is unknown and they are covered by energy calibration uncertainties. Only sectors for which short-circuits are the cause of a lower HV are considered in this study. To assess if short-circuits are the origin, the current leaking into the electrodes has been studied. In nominal running conditions it should be null but it is raised when a short-circuit happens. Figure 4.3.10(c) and (d) show the η - ϕ -maps of the leakage current for the two half gaps.

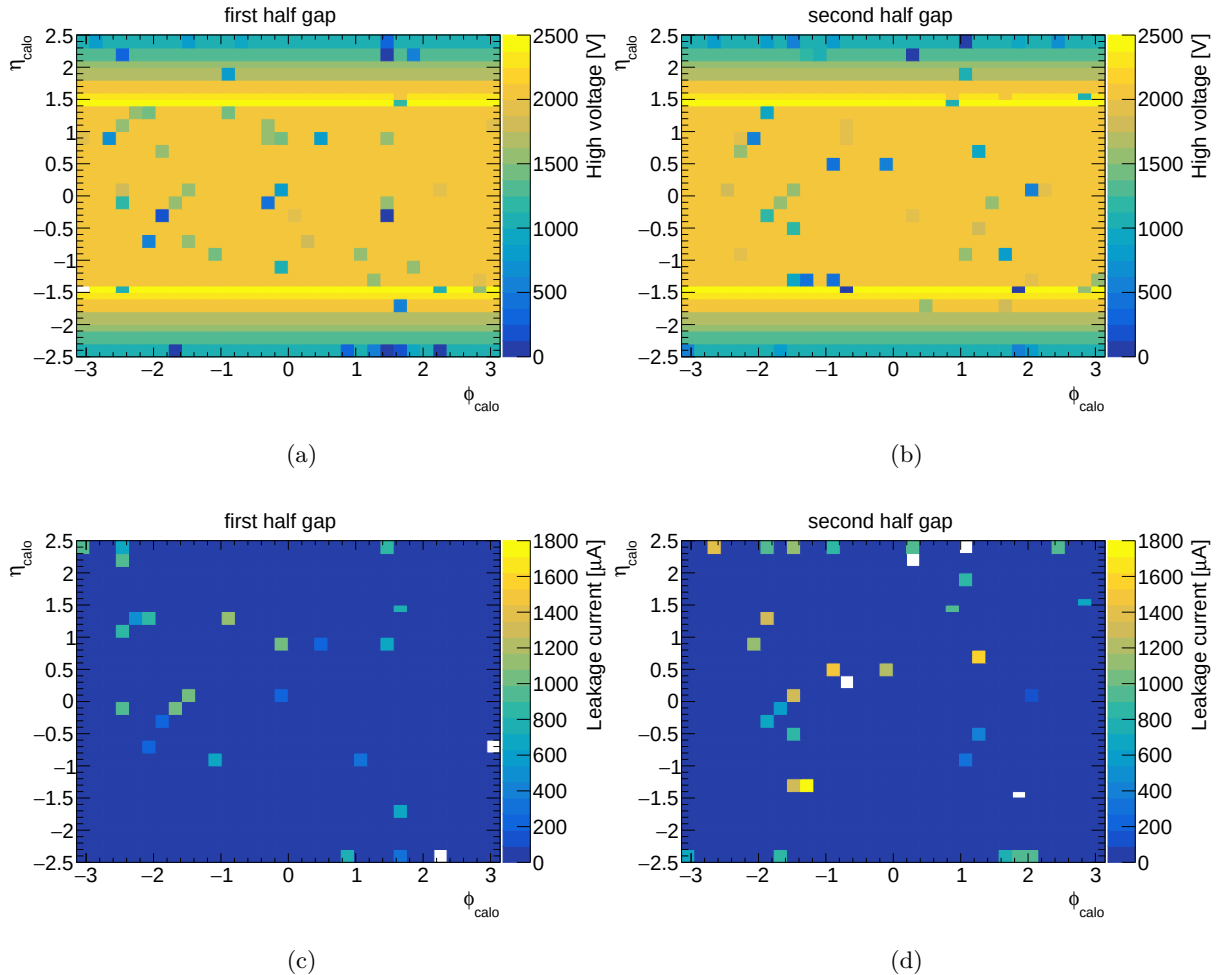


Figure 4.3.10: η - ϕ -maps of the HV and the leakage current for the two half gaps extracted from run 311287 (no significant differences have been observed for other runs).

⁶A few sectors have been further split to operate at different HV, extending the sizes of the HV sectors mentioned in Table 4.3.2.

In order to study the impact of short-circuits on the measured energy $Z \rightarrow e^+e^-$ events serve as optimal probe as the Z boson mass is very well known as 91.1876 ± 0.0021 GeV [22] and should be the same in every part of the detector if it is operated at nominal conditions. However, any inhomogeneities in the HV caused by short-circuits lead to an underestimation of the invariant di-electron mass if one of the decay particles hits an affected sectors. Figure 4.3.11 shows the distribution of the invariant di-electron mass of $Z \rightarrow e^+e^-$ events in the η - ϕ -space with a binning based on the HV sectors, whereby the η - ϕ -positions of both decay particles are considered. Various fluctuations can be spotted whereby most are only within 1 % while the overall spread ranges from 86 GeV to 92 GeV. When comparing the η - ϕ -maps of the HV and the leakage current to the one of the invariant di-electron mass of $Z \rightarrow e^+e^-$ events the sectors with a lower than average invariant di-electron mass can be related to a non-nominal HV accompanied by large leakage currents. A total of 17 sectors have been identified, listed in Table 4.3.3, and are further investigated.

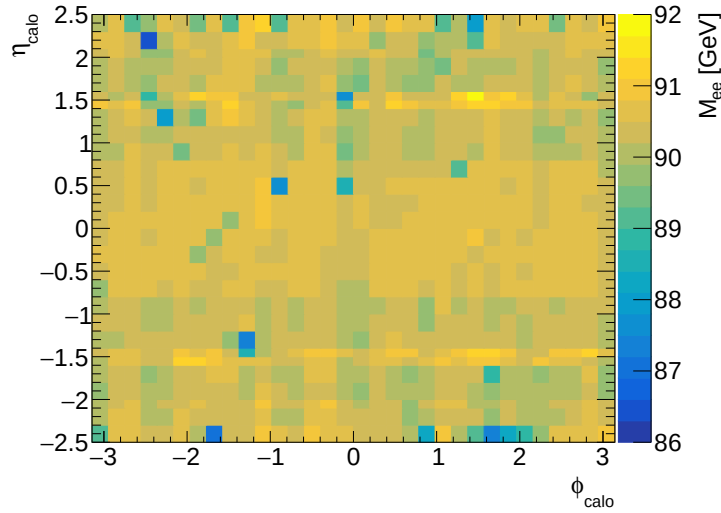


Figure 4.3.11: η - ϕ -map of the invariant di-electron mass of $Z \rightarrow e^+e^-$ events collected in 2015 and 2016. The peak position in each bin was derived with a truncated Gaussian fit. The histogram is filled per decay particle.

Therefore, the E/p profile of electrons from Z boson decays are used. Contrary to the IMW effect where the relative ϕ position with respect to the module centre was used and the entire barrel range was covered, now the profiling is along the entire ϕ range while only an η slice corresponding to the HV sector segmentation is selected. As before, the ratio of the energy measured in the calorimeter and the momentum measured based on the track information are expected to be equal to unity if no inhomogeneities are present. Figures 4.3.12 to 4.3.15 show the E/p profiles of the affected slices in η .⁷ Some fluctuations are apparent between sectors but also for electrodes within a sector. However, a correction factor is only extracted for the 17 sectors with non-nominal HV and high leakage currents. Those sectors, highlighted by the green shaded areas, can easily be spotted in the E/p profiles in Figures 4.3.12 to 4.3.15, some of them are within the same η slice. To extract an empirical correction factor for the individual sectors, the peak values of the E/p distribution obtained with a double-sided Crystal Ball fit for each individual electrode are averaged over all sectors. The correction factors are then calculated as the ratio of these averaged peak values for the sectors with non-nominal and nominal HV settings. Each correction factor is only applied to the corresponding sector with non-nominal HV settings. The values of the corrections, listed in Table 4.3.3, are typically 1 % to 7 % and affect 2 % of the calorimeter acceptance for $|\eta| < 2.5$.

⁷The binning represents the deployed electrodes.

HV sector in bins of $\eta \times \phi$ range			Correction factor
$[-2.5, -2.3]$	$\times$	$[-9 \cdot \frac{2\pi}{32}, -8 \cdot \frac{2\pi}{32}]$	1.025
$[-2.5, -2.3]$	$\times$	$[4 \cdot \frac{2\pi}{32}, 5 \cdot \frac{2\pi}{32}]$	1.036
$[-2.5, -2.3]$	$\times$	$[8 \cdot \frac{2\pi}{32}, 9 \cdot \frac{2\pi}{32}]$	1.053
$[-2.5, -2.3]$	$\times$	$[9 \cdot \frac{2\pi}{32}, 10 \cdot \frac{2\pi}{32}]$	1.026
$[-2.5, -2.3]$	$\times$	$[10 \cdot \frac{2\pi}{32}, 11 \cdot \frac{2\pi}{32}]$	0.994
$[-1.8, -1.6]$	$\times$	$[8 \cdot \frac{2\pi}{32}, 9 \cdot \frac{2\pi}{32}]$	1.027
$[-1.4, -1.2]$	$\times$	$[-7 \cdot \frac{2\pi}{32}, -6 \cdot \frac{2\pi}{32}]$	1.065
$[-0.4, -0.2]$	$\times$	$[-10 \cdot \frac{2\pi}{32}, -9 \cdot \frac{2\pi}{32}]$	1.017
$[-0.2, 0.0]$	$\times$	$[-13 \cdot \frac{2\pi}{32}, -12 \cdot \frac{2\pi}{32}]$	1.008
$[-0.2, 0.0]$	$\times$	$[-9 \cdot \frac{2\pi}{32}, -8 \cdot \frac{2\pi}{32}]$	1.014
$[0.0, 0.2]$	$\times$	$[-8 \cdot \frac{2\pi}{32}, -7 \cdot \frac{2\pi}{32}]$	1.018
$[0.4, 0.6]$	$\times$	$[-5 \cdot \frac{2\pi}{32}, -4 \cdot \frac{2\pi}{32}]$	1.063
$[0.4, 0.6]$	$\times$	$[-1 \cdot \frac{2\pi}{32}, 0]$	1.041
$[0.6, 0.8]$	$\times$	$[6 \cdot \frac{2\pi}{32}, 7 \cdot \frac{2\pi}{32}]$	1.028
$[1.2, 1.4]$	$\times$	$[-12 \cdot \frac{2\pi}{32}, -11 \cdot \frac{2\pi}{32}]$	1.051
$[1.2, 1.4]$	$\times$	$[-10 \cdot \frac{2\pi}{32}, -9 \cdot \frac{2\pi}{32}]$	1.020
$[2.1, 2.3]$	$\times$	$[-13 \cdot \frac{2\pi}{32}, -12 \cdot \frac{2\pi}{32}]$	1.071

Table 4.3.3: Affected η - ϕ -regions affected by HV inhomogeneities and corresponding correction factors.

Albeit at first order it can be expected that the correction factors are larger than unity, this is not the case for the sector at $[-2.5, -2.3] \times [10 \cdot 2\pi/32, 11 \cdot 2\pi/32]$. Usually the correction applied in the reconstruction is not sufficient to recover the underestimation of the measured energy but in rare cases it can be too high leaving an excess. Subsequently, the correction factors at the stage of the electron energy calibration need to mitigate this overshoot. In Figures 4.3.12 to 4.3.15 the E/p profiles after the application of these correction factors are depicted as well and show that the deteriorations are well recovered. A few residual deviations remain in the most forward end-cap region due to low statistics.

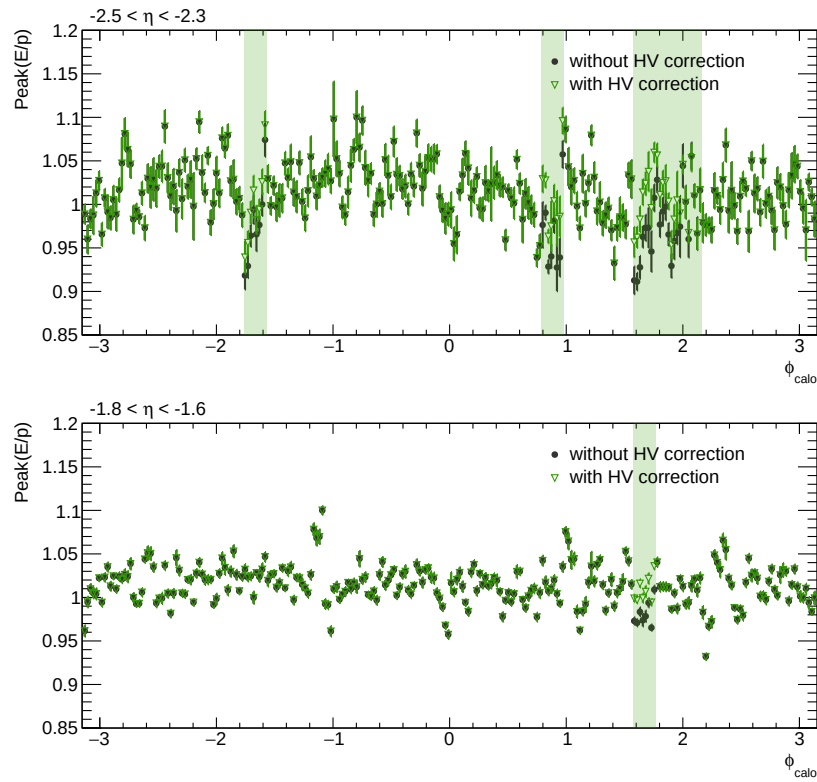


Figure 4.3.12: E/p profiles along ϕ in bins of η in the end-cap on the C side, before (black dots) and after applying the HV correction (green triangles). Affected regions are highlighted by the green shaded areas. The peak of the E/p distributions in each ϕ bin is obtained from a double-sided Crystal Ball fit. The distributions are based on electrons taken from a $Z \rightarrow e^+e^-$ selection in data recorded in 2015–2016.

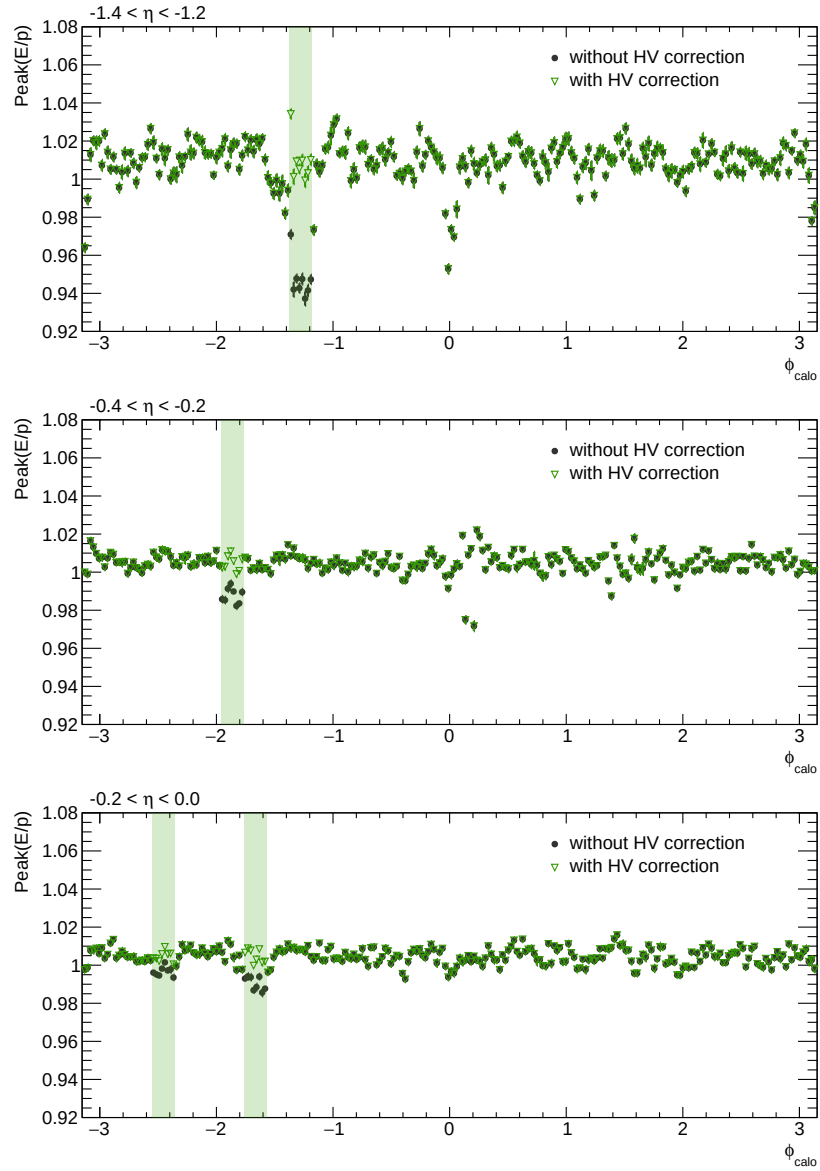


Figure 4.3.13: E/p profiles along ϕ in bins of η in the barrel on the C side before (black) and after applying the HV correction (green triangles). Affected regions are highlighted by the green shaded areas. The peak of the E/p distributions in each ϕ bin is obtained from a double-sided Crystal Ball fit. The distributions are based on electrons taken from a $Z \rightarrow e^+e^-$ selection in data recorded in 2015–2016.

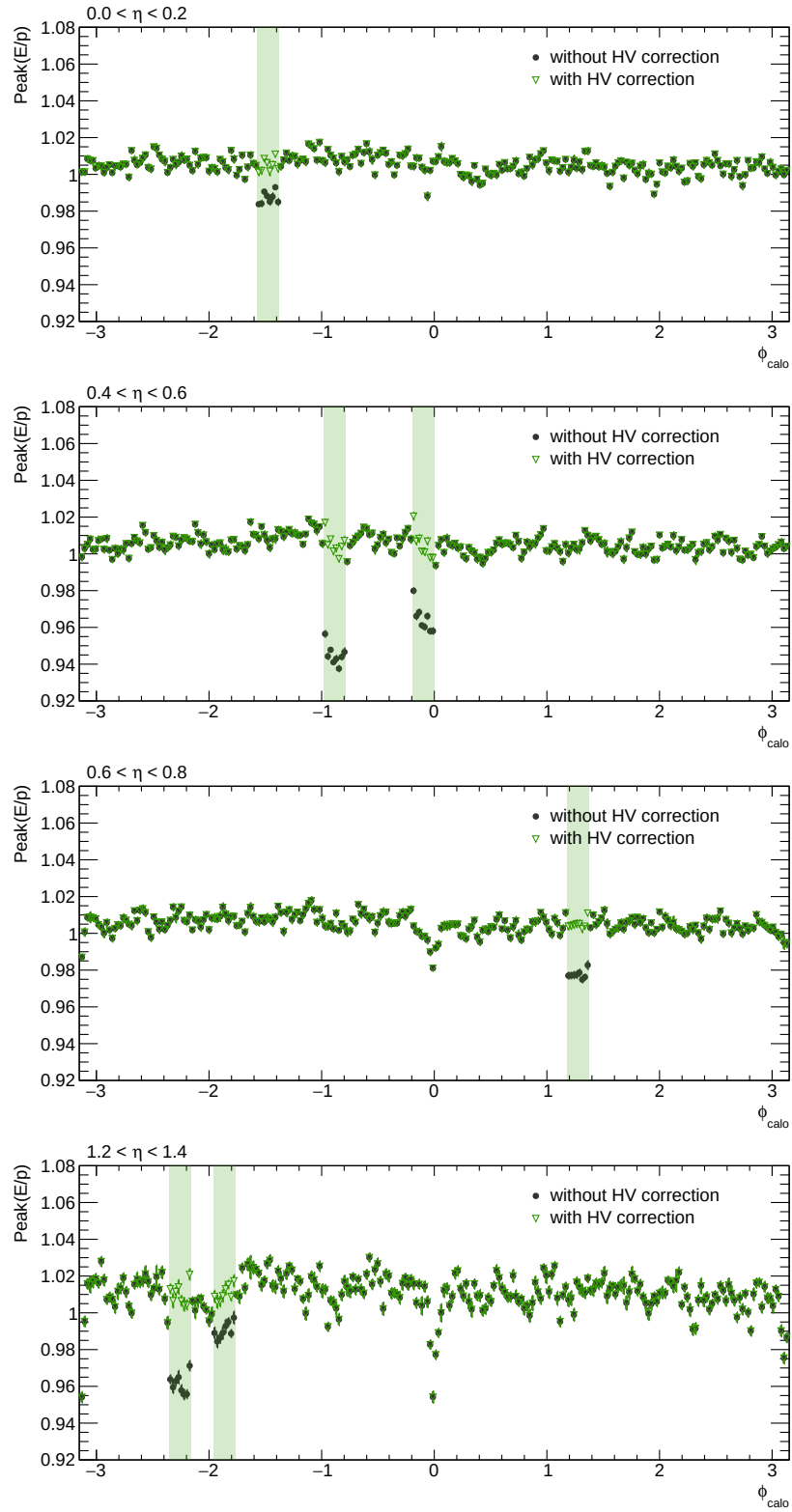


Figure 4.3.14: E/p profiles along ϕ in bins of η in the barrel on the A side before (black) and after applying the HV correction (green triangles). Affected regions are highlighted by the green shaded areas. The peak of the E/p distributions in each ϕ bin is obtained from a double-sided Crystal Ball fit. The distributions are based on electrons taken from a $Z \rightarrow e^+e^-$ selection in data recorded in 2015–2016.

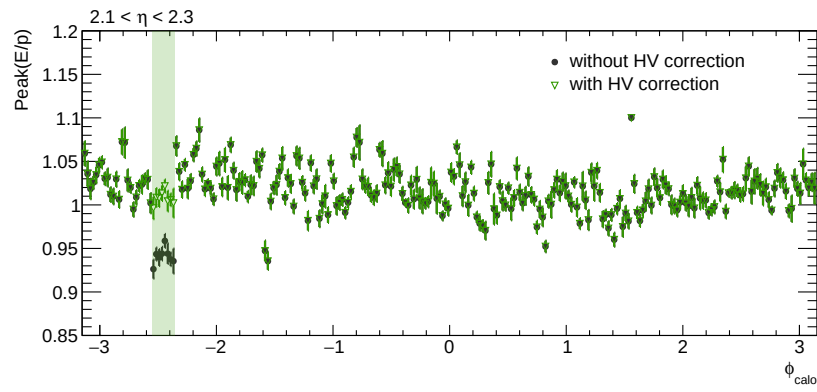


Figure 4.3.15: E/p profile along ϕ in bins of η in the end-cap on the A side before (black) and after applying the HV correction (green triangles). Affected regions are highlighted by the green shaded areas. The peak of the E/p distributions in each ϕ bin is obtained from a double-sided Crystal Ball fit. The distributions are based on electrons taken from a $Z \rightarrow e^+e^-$ selection in data recorded in 2015–2016.

The validity of the correction factors is once again evaluated by profiling the invariant di-electron mass of $Z \rightarrow e^+e^-$ events along ϕ for the same slices of η . The peak of the invariant di-electron mass distribution of each electrode is extracted with a truncated Gaussian fit. The profiles of the concerned η slices are shown in Figures 4.3.16 to 4.3.19 before and after the HV correction factors are applied. All deviations due to non-nominal HV settings caused by short-circuits are flattened which proves the effectiveness of the derived correction factors. As aforementioned, the correction is less effective in the most forward end-cap region. Figure 4.3.20 depicts the shift in the inclusive invariant di-electron mass which is evaluated to be around 0.1 %.

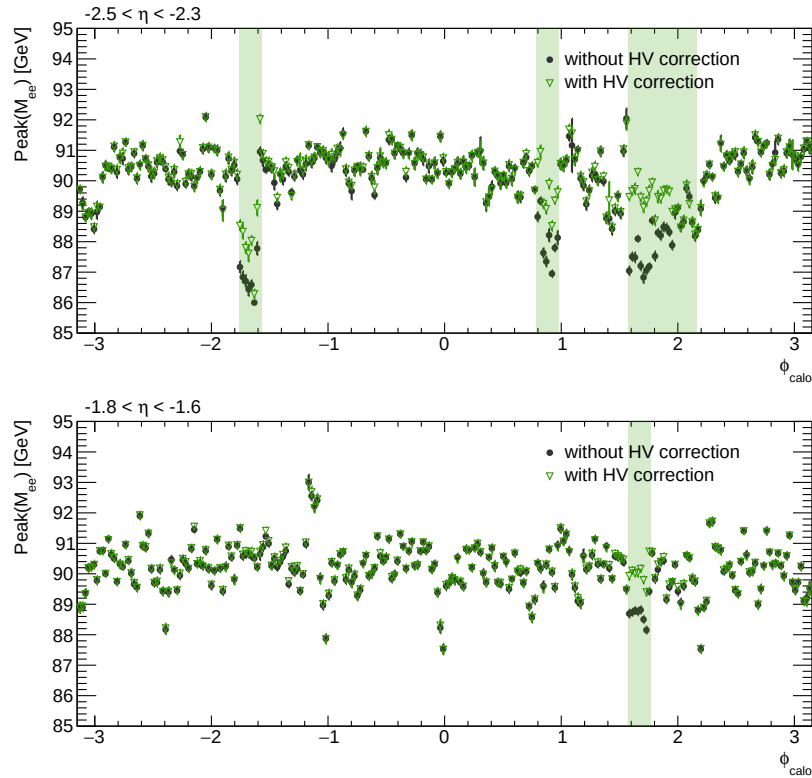


Figure 4.3.16: Profile of M_{ee} along ϕ in bins of η in the end-cap on the C side before (black) and after applying the HV correction (green triangles). Affected regions are highlighted by the green shaded areas. The peak of the M_{ee} distributions in each ϕ bin is obtained from a truncated Gaussian fit. The distributions are based on events from a $Z \rightarrow e^+e^-$ selection in data recorded in 2015–2016.

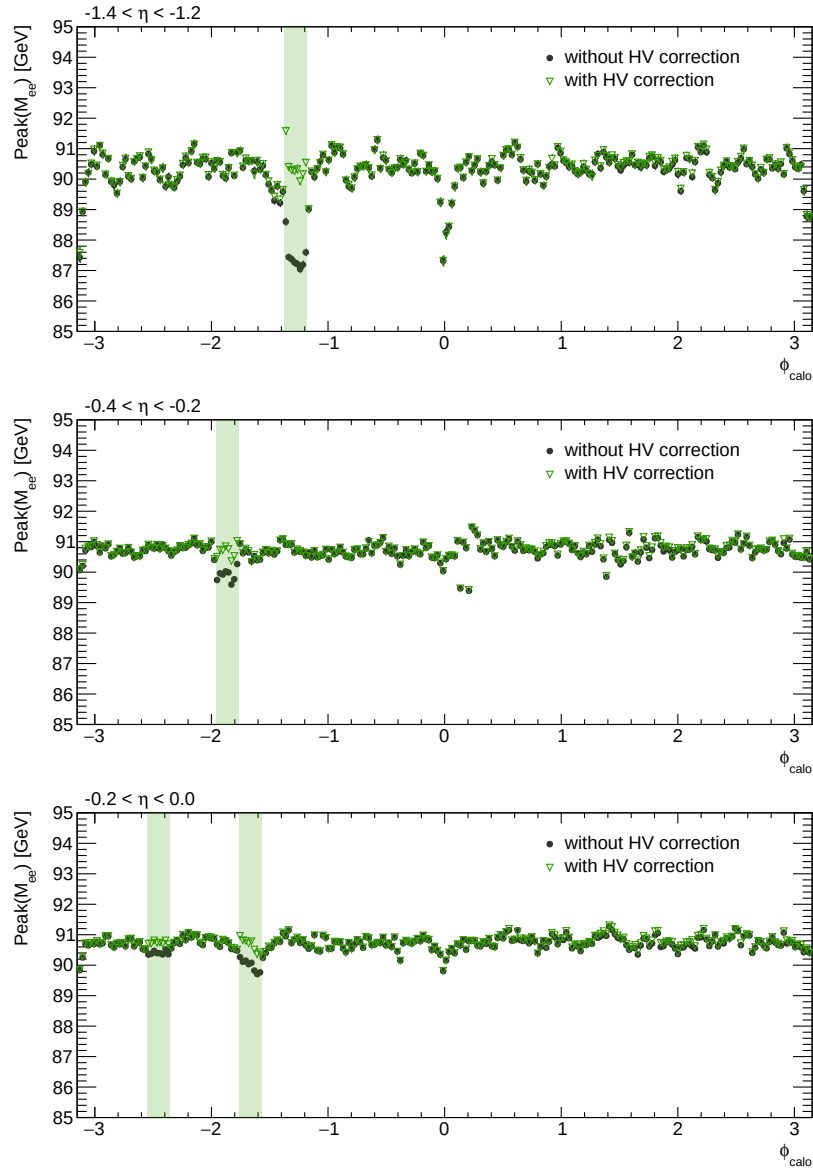


Figure 4.3.17: Profile of M_{ee} along ϕ in bins of η in the barrel on the C side before (black) and after applying the HV correction (green triangles). Affected regions are highlighted by the green shaded areas. The peak of the M_{ee} distributions in each ϕ bin is obtained from a truncated Gaussian fit. The distributions are based on events from a $Z \rightarrow e^+e^-$ selection in data recorded in 2015–2016.

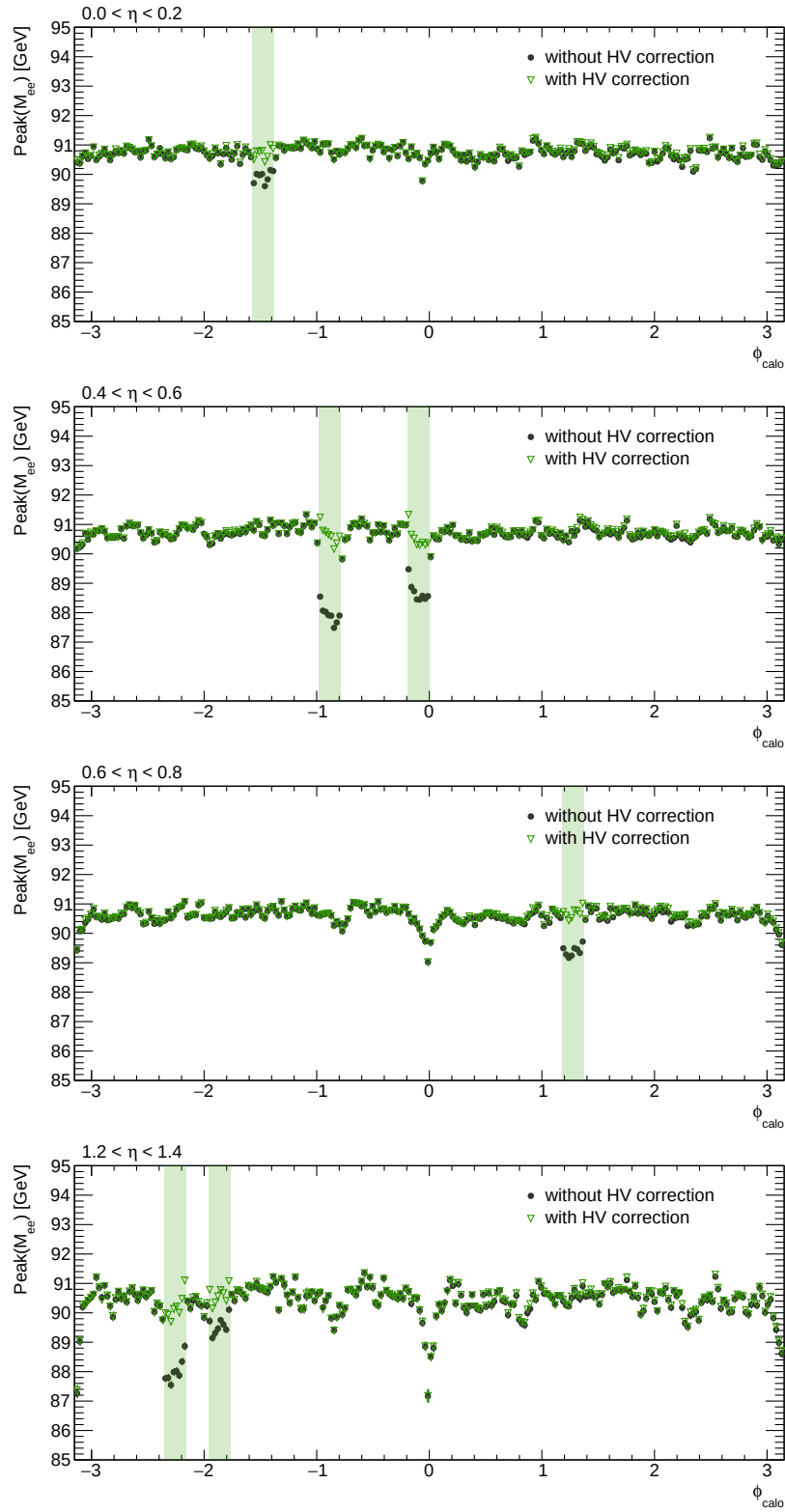


Figure 4.3.18: Profile of M_{ee} along ϕ in bins of η in the barrel on the A side before (black) and after applying the HV correction (green triangles). Affected regions are highlighted by the green shaded areas. The peak of the M_{ee} distributions in each ϕ bin is obtained from a truncated Gaussian fit. The distributions are based on events from a $Z \rightarrow e^+e^-$ selection in data recorded in 2015–2016.

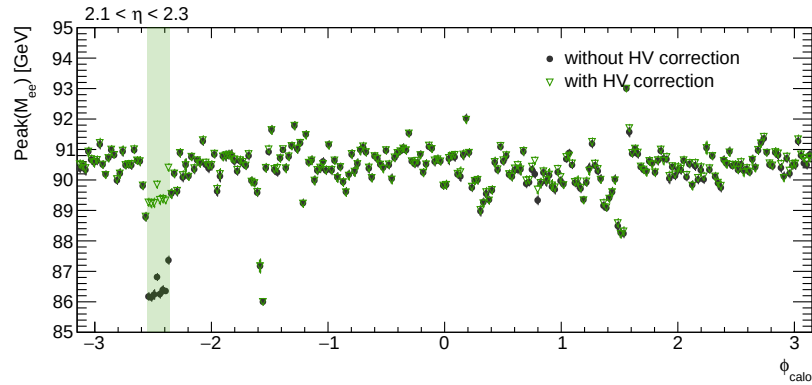


Figure 4.3.19: Profile of M_{ee} along ϕ in bins of η in the end-cap on the A side before (black) and after applying the HV correction (green triangles). Affected regions are highlighted by the green shaded areas. The peak of the M_{ee} distributions in each ϕ bin is obtained from a truncated Gaussian fit. The distributions are based on events from a $Z \rightarrow e^+e^-$ selection in data recorded in 2015–2016.

Finally, the E/p and M_{ee} profiles further reveal a feature that was already touched in the end of Section 4.3.1, namely deviations from the overall average at $\phi=0$ and $\pm\pi$. They are not related to the HV settings of the LAr calorimeter and are discussed in Section 4.4.1.

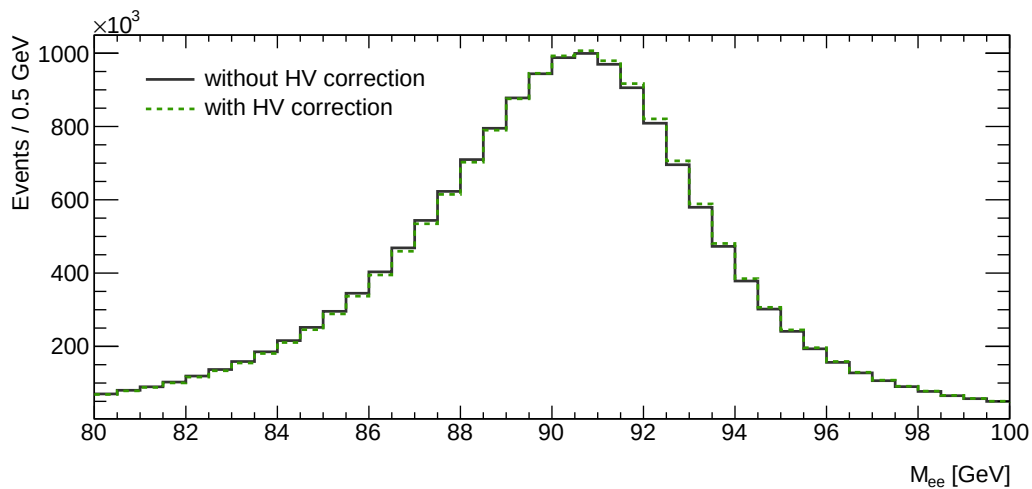


Figure 4.3.20: Distribution of the invariant di-electron mass measured in $Z \rightarrow e^+e^-$ events recorded in 2015 and 2016 before (black) and after (green) the application of the HV corrections.

4.4 Improvements of the MVA Calibration

Although the energy calibration of electrons already yields a very good performance, it still has room to improve pushing the limits of precision even further. Various reasons can motivate a modification of several steps of the calibration procedure, such as a better understanding of the detector gained throughout Run 1 and early Run 2 or changing demands from physics analyses. This section is dedicated to possible improvements on the MVA-based energy calibration by expanding the set of input variables.

Section 4.3.1 and 4.3.2 briefly touched the observed degradations in the energy measurement with respect to ϕ which remain even after the application of the IMW and HV correction. They are caused by detector inhomogeneities and can be mitigated at the stage of the MVA calibration

by including the measured azimuthal angle of the calorimeter cluster. Section 4.4.1 discusses the related studies in detail.

Further, Section 4.4.2 is dedicated to a study of considering tracking variables as input to the MVA which would benefit physics analyses using low- and medium-energy electrons in their final states. However, the MVA calibration currently used still solely relies on calorimeter based input variables.

4.4.1 Cluster ϕ

In the scope of the reassessment of the non-uniformities in the energy response related to the intermodule-gaps (c.f. Section 4.3.1) and non-nominal high voltage settings (c.f. Section 4.3.2) a notable deviation in the energy measurement has been observed in the barrel calorimeter for ϕ close to 0 and $-\pi$. The source for these degradations has been identified to be part of the support structure of the ID rails, called wedges. These wedges are passive material in which the electrons (photons) passing through lose a fraction of their energy which is unaccounted for. Figure 4.4.1 shows a sketch of the EM barrel calorimeter cryostat with the ID wedges highlighted. Their location aligns with the ϕ positions of the dips in energy. Fortunately, these wedges are included in the detector simulation and hence simulated electrons suffer the same energy loss as electrons measured in data. In order to mitigate the effect a correction factor could be derived from simulated events or the azimuthal angle of the calorimeter cluster, ϕ_{cl} , can be included in the input variable set for the MVA calibration. The latter has the benefit that an additional step in the calibration procedure can be avoided and thus is favoured. Further, any other detector non-uniformities in ϕ are addressed as well as long as they are considered in the detector simulation.

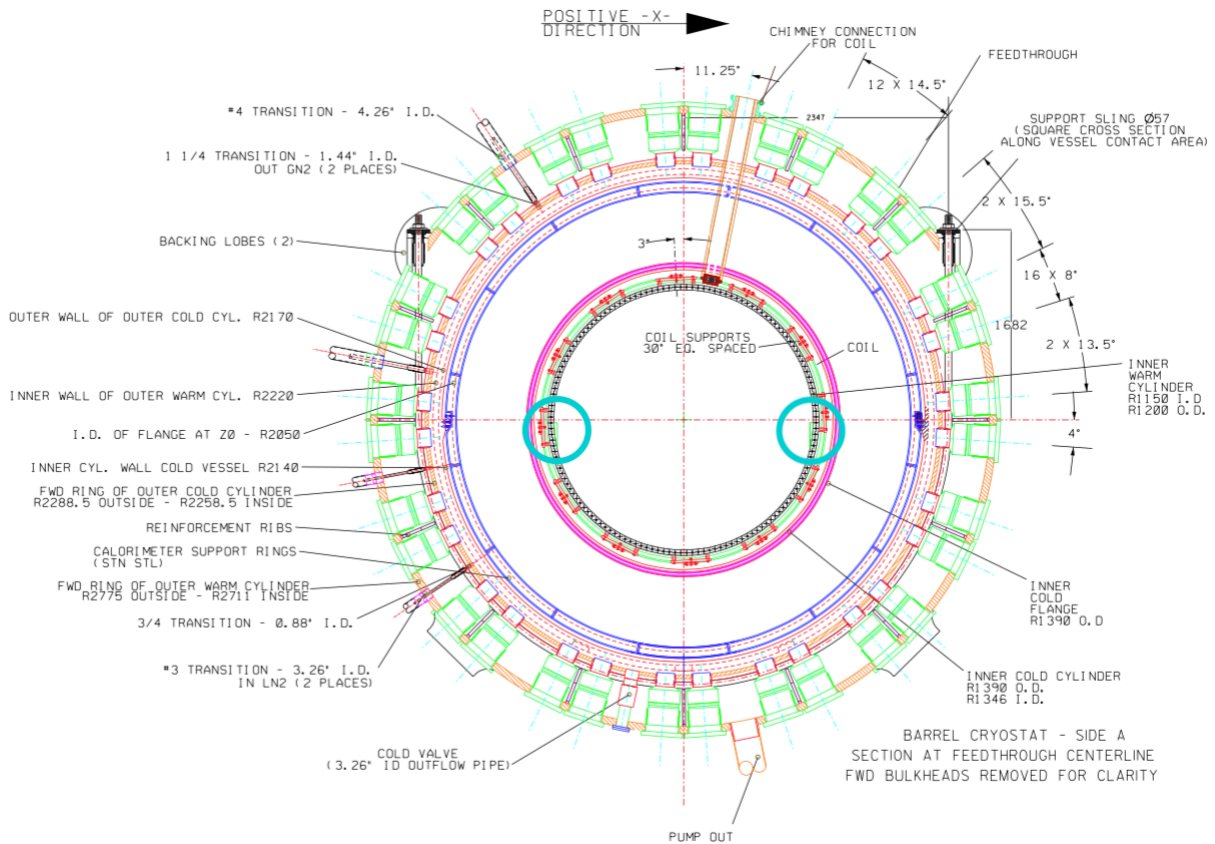


Figure 4.4.1: Barrel cryostat of the EM calorimeter of ATLAS. The support wedges of the ID are encircled in light blue. Adopted from [81].

To ensure that no unwanted dependencies are introduced by including ϕ_{cl} , the behaviour of E/E^{gen} with respect to ϕ_{cl} is investigated and shown in Figure 4.4.2 for the nominal and the extended variable set. As reference the distribution of ϕ_{cl} itself is depicted as well. The E/E^{gen} profile is derived from the peak position of a truncated Gaussian fit function applied to the E/E^{gen} distribution in a single ϕ_{cl} bin.⁸ The peak position is close to unity with notable deviations for the nominal variable set. These deviations are successfully recovered by exploiting the information provided by ϕ_{cl} . The improvements are especially notable for ϕ_{cl} close to 0 and $-\pi$ where the ID wedges are located. This is proven in more detail by Figure 4.4.3 which shows the E/E^{gen} profiles with respect to $\phi_{\text{calo}}^{\text{module}}$ for the two regions where the ID support structure is situated. An underestimation of up to 1 % is apparent and is almost fully recovered by considering ϕ_{cl} in the MVA calibration.

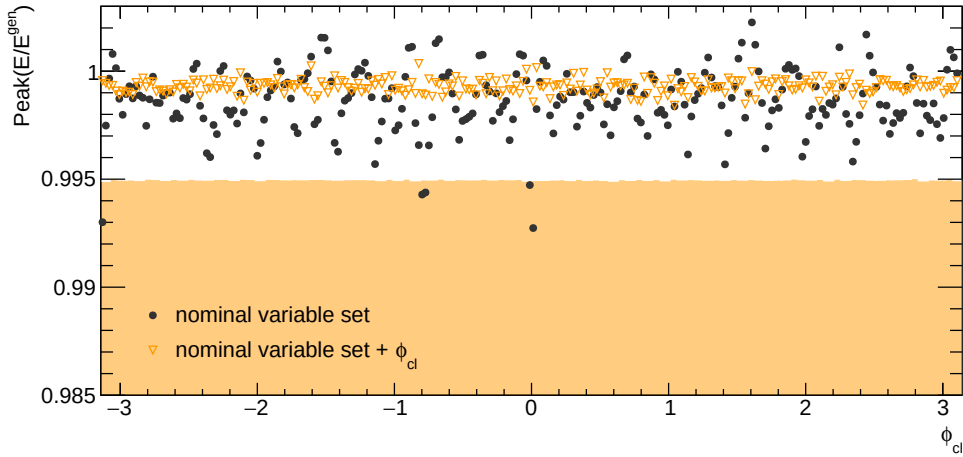


Figure 4.4.2: E/E^{gen} profile with respect to ϕ_{cl} for simulated single electrons calibrated with the nominal variable set (black dots) and calibrated with the variable set extended by ϕ_{cl} (orange triangles). The profile is extracted from the peak position of a truncated Gaussian fit of the E/E^{gen} distribution in each ϕ_{cl} bin. The ϕ_{cl} distribution is shown as orange shaded area.

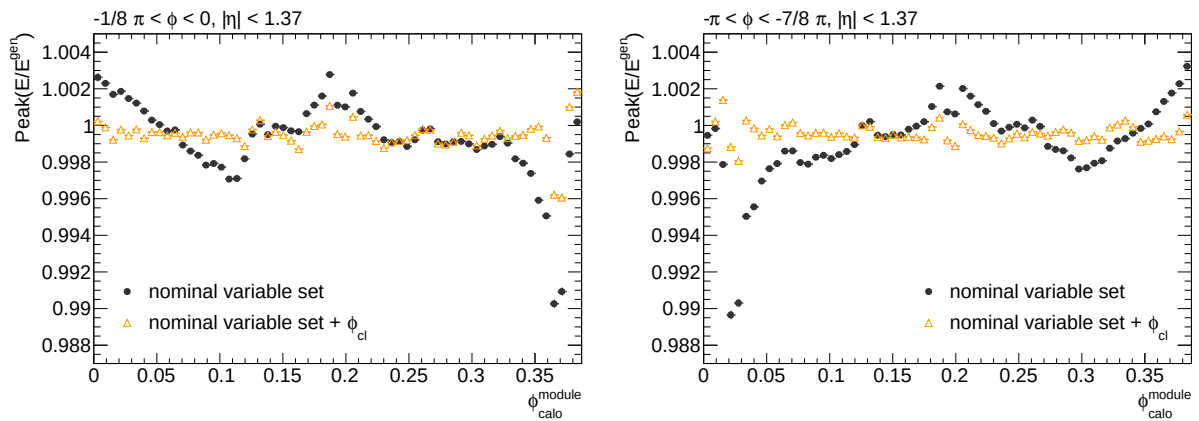


Figure 4.4.3: E/E^{gen} profiles with respect to $\phi_{\text{calo}}^{\text{module}}$ for simulated single electrons calibrated with the nominal variable set (black dots) and calibrated with the variable set extended by ϕ_{cl} (orange triangles). The profile is extracted from the peak position of a truncated Gaussian fit of the E/E^{gen} distribution in each $\phi_{\text{calo}}^{\text{module}}$ bin. Only the regions where the ID support wedges are located are shown.

⁸The ϕ_{cl} binning is motivated by the number of read-out electrodes.

The linearity and resolution of the MVA response as functions of p_T and η show excellent results as can be seen in Figure 4.4.4 and 4.4.5, respectively. The profiled peak position of E/E^{gen} is similar to or better than the one obtained with the nominal variable set. The linearity with p_T is especially improved for lower energies. Also the resolution, evaluated with the IQE profile of the E/E^{gen} distribution, is improved by about 2% over the entire p_T range above 10 GeV and up to 5% for the outer barrel and end-cap calorimeter. These results confirm that including ϕ_{cl} does not introduce any biasing dependencies or degradations of the MVA response.

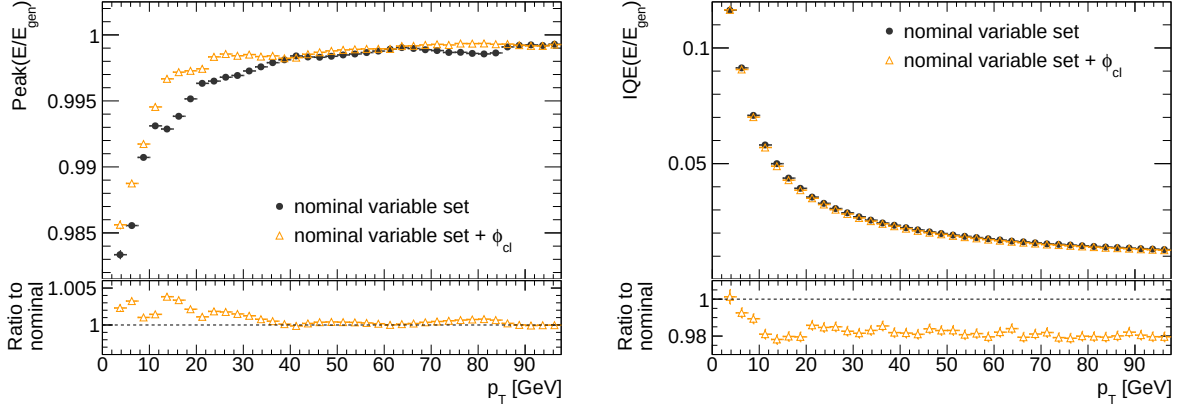


Figure 4.4.4: E/E^{gen} profiles with respect to p_T for simulated single electrons calibrated with the nominal variable set (black dots) and calibrated with the variable set extended by ϕ_{cl} (orange triangles). The profile of the peak position of the E/E^{gen} in each p_T bin is extracted from a truncated Gaussian fit and shown on the left. The profile of the IQE of the E/E^{gen} in each p_T bin is shown on the right.

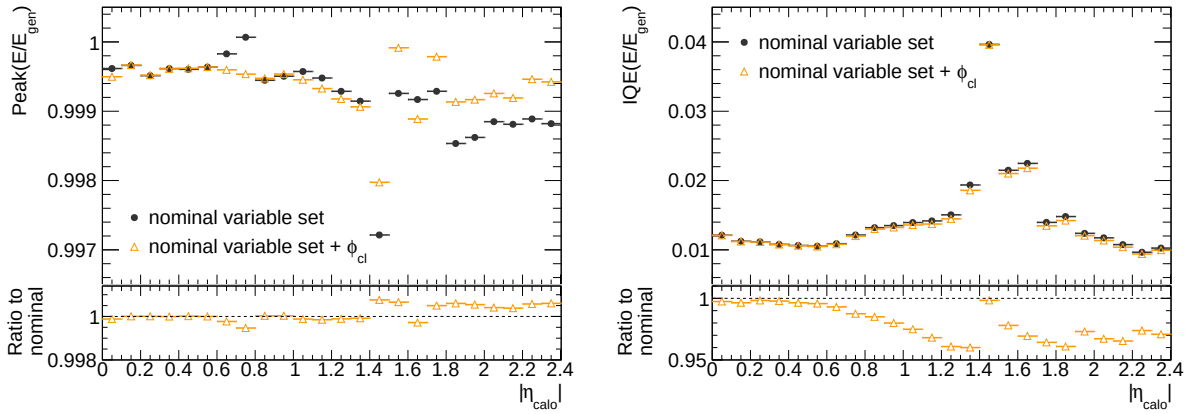


Figure 4.4.5: E/E^{gen} profiles with respect to η for simulated single electrons calibrated with the nominal variable set (black dots) and calibrated with the variable set extended by ϕ_{cl} (orange triangles). The profile of the peak position of the E/E^{gen} in each η bin is extracted from a truncated Gaussian fit and shown on the left. The profile of the IQE of the E/E^{gen} in each η bin is shown on the right.

Finally, the impact of a variable set extended by ϕ_{cl} is studied in a $Z \rightarrow e^+e^-$ selection in data recorded in 2015 and 2016. The invariant di-electron mass ratios as functions of the $\phi_{\text{calo}}^{\text{module}}$ for the regions dominated by the ID wedges are depicted in Figure 4.4.6 and show a similar effect as seen in the single-particle sample. This has also been investigated in the E/p profiles with respect to $\phi_{\text{calo}}^{\text{module}}$ and can be found in Appendix A.2.1. Note that the IMW correction discussed in Section 4.3.1 is not applied. The linearity and resolution based on the invariant di-electron mass ratio as functions of pile-up is slightly improved as well as presented by Figure 4.4.7. The

behaviour of the MVA response measured in data with respect to η can be seen in Figure A.2.2.

Overall the inclusion of ϕ_{cl} in the MVA-based calibration is widely beneficial even beyond its initially motivated purpose and mitigates various deviations in the energy response due to detector non-uniformities.

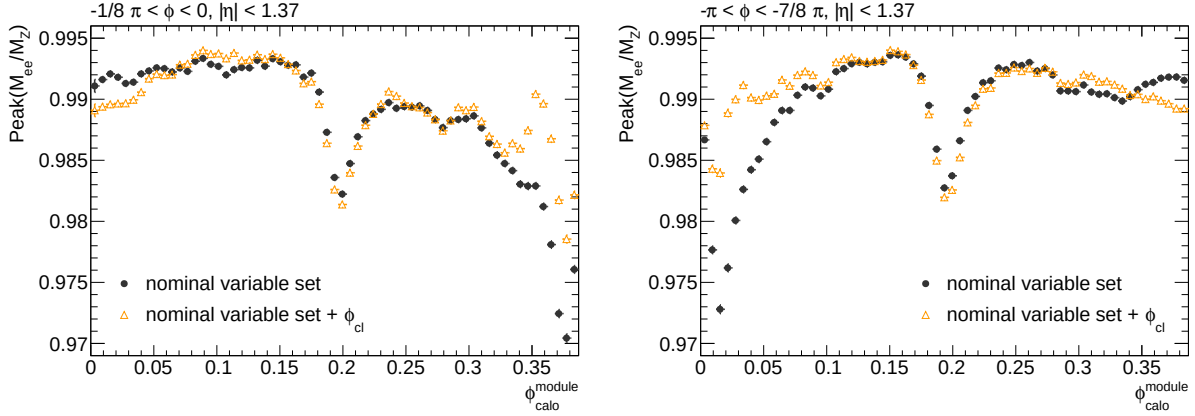


Figure 4.4.6: M_{ee}/M_Z profile with respect to $\phi_{\text{cal}}^{\text{module}}$ for electrons from a $Z \rightarrow e^+e^-$ selection in data calibrated with the nominal variable set (black dots) and calibrated with the variable set extended by ϕ_{cl} (orange triangles). The profile is extracted from the peak position of a truncated Gaussian fit of the M_{ee}/M_Z distribution in each $\phi_{\text{cal}}^{\text{module}}$ bin. Only the regions where the ID support wedges are located are shown.

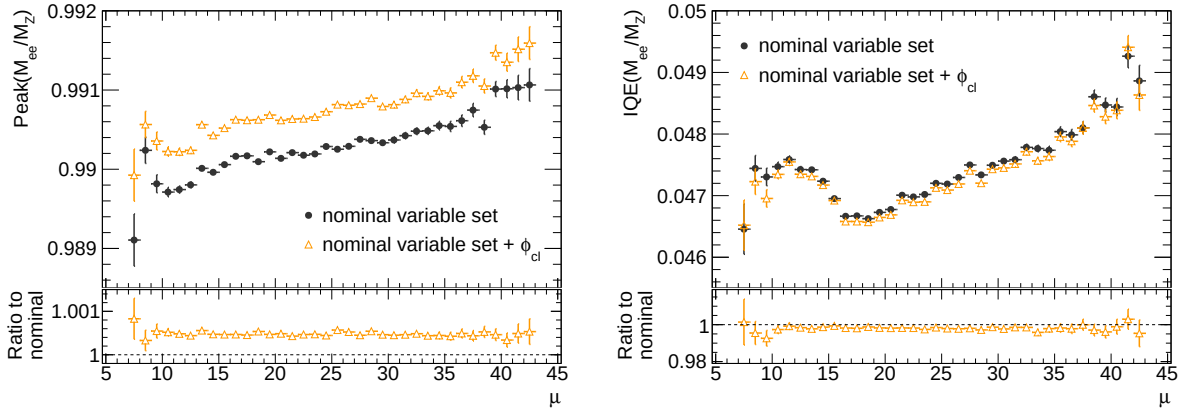


Figure 4.4.7: M_{ee}/M_Z profile with respect to the average number of interactions per bunch crossing, μ , for electrons from a $Z \rightarrow e^+e^-$ selection in data calibrated with the nominal variable set (black dots) and calibrated with the variable set extended by ϕ_{cl} (orange triangles). The profile of the peak position of the M_{ee}/M_Z in each μ bin is extracted from a truncated Gaussian fit and shown on the left. The profile of the IQE of the M_{ee}/M_Z in each μ bin is shown on the right.

4.4.2 Tracking Information

The MVA-based calibration for electrons described in Section 4.2.1 relies solely on calorimeter-based variables. Albeit the resolution of the EM calorimeter is remarkable for electrons with medium to high energies, it falls short towards low energies compared to what is achievable with the ID. Hence, considering tracking variables can potentially improve the energy scale and resolution for low-energy electrons, like those from the measurements of $R_{K^{(*)}}$, or those originating from $J/\psi \rightarrow e^+e^-$ or $H \rightarrow ZZ^{(*)} \rightarrow \ell^+\ell^-e^+e^-$ ($\ell = e, \mu$). Another motivation arises

from bremsstrahlung losses, as tracking variables provide information which is not accessible with calorimeter variables. Further, tracking information is already successfully implemented for the MVA-based calibration of photons to deal with conversions. Various variables, listed in Table 4.4.1, have been investigated with the focus on improving the linearity and resolution of the MVA response. The most promising two, p_{track} and $\Delta\phi_2$, are further discussed in this section.

Name	Description
p_{track}	Momentum measured from the ID track
$\Delta\phi_2$	Difference between the ϕ of the calorimeter cluster and the ϕ of the impact point in the second calorimeter layer of the extrapolation of the track from the perigee
$\Delta\phi_{\text{LM}}$	Difference between the ϕ of the calorimeter cluster and the ϕ of the impact point in the second calorimeter layer of the extrapolation of the track from its last measurement in the ID
ΔR_2	ΔR between the calorimeter cluster and the impact point in the second calorimeter layer of the extrapolation of the track from the perigee
$\Delta\phi_{\text{FM-LM}}$	Difference in ϕ between first and last track measurement
$\Delta\phi_{\text{FM-LM}} \times p_{\text{T}}^{\text{track}}$	Difference in ϕ between first and last track measurement times $p_{\text{T}}^{\text{track}}$
$\Delta p_{\text{T}}^{\text{FM-LM}} \times p_{\text{T}}^{\text{track}}$	Difference in $p_{\text{T}}^{\text{track}}$ between the first and the last track measurement times $p_{\text{T}}^{\text{track}}$
$\Delta\phi_{\text{FM-LM}} \times \Delta p_{\text{T}}^{\text{FM-LM}}$	Combination of $\Delta\phi_{\text{FM-LM}} \times p_{\text{T}}^{\text{track}}$ and $\Delta p_{\text{T}}^{\text{FM-LM}} \times p_{\text{T}}^{\text{track}}$

Table 4.4.1: Variables that have been investigated as potential extension to the MVA input variable set.

$\Delta\phi_2$ is defined as the difference between the ϕ measured in the second calorimeter layer based on the calorimeter cluster and the extrapolation of the track from the perigee. In case an electron radiates a photon, the electron trajectory is altered which leads to a larger $\Delta\phi_2$ as opposed to when no bremsstrahlung occurred. Hence, this variable is especially sensitive to bremsstrahlung losses and useful to recover the energy which was carried away by the radiated photon. The E/E^{gen} profile of the energy response with respect to $\Delta\phi_2$ is shown in Figure 4.4.8(a) for the calibration with and without this variable. If $\Delta\phi_2$ is not considered in the MVA calibration a dependence towards very low and high values of the energy response is visible which vanishes if $\Delta\phi_2$ is taken into account. However, the dependency is especially strong in the tails of the $\Delta\phi_2$ distribution where it is populated by only very few electrons.

The second variable of interest is the momentum measured from the electron track, p_{track} ; hence a variable purely based on tracking information which can be exploited to recover linearity and resolution of the MVA response. Profiling E/E^{gen} against p_{track} indicates that stability and linearity can be improved slightly for p_{track} below 60 GeV and significantly below 20 GeV as depicted in Figure 4.4.8(b). Besides this, no dependency is visible and hence p_{track} can be added safely to the MVA input variable set.

To explore the full potential of both variables a separate MVA has been trained which

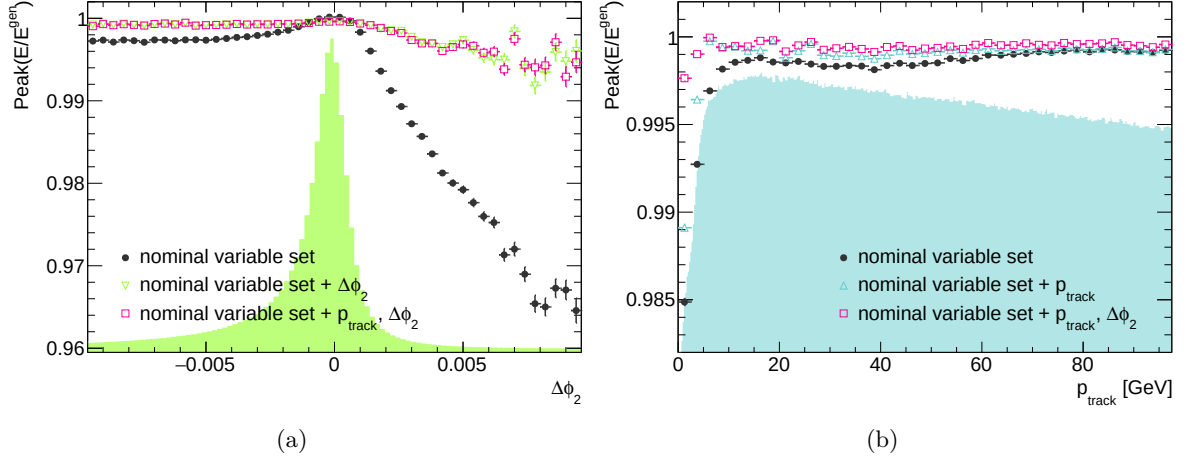


Figure 4.4.8: E/E^{gen} profiles with respect to $\Delta\phi_2$ (left) and p_{track} (right) for simulated single electrons calibrated with a variable set extended by $\Delta\phi_2$, p_{track} and both are depicted in green, blue and pink, respectively. As reference the profile for the nominal calibration is included as black dots. The profile is extracted from the peak position of a truncated Gaussian fit of the E/E^{gen} distribution in the respective variable bin. The $\Delta\phi_2$ and p_{track} distribution are shown as green and blue shaded area in the left and right plot, respectively.

includes both, $\Delta\phi_2$ and p_{track} , at once. The linearity of the energy response with respect to these two variables is included in Figure 4.4.8 as well. A significant improvement is observed mainly for electrons with very low track p_T of ≈ 7 GeV).

The linearity and resolution of the calibration response is studied with respect to p_T and η to estimate the enhancement achievable by including p_{track} and $\Delta\phi_2$ separately or combined in the MVA training. The linearity, shown in Figure 4.4.9, is improved for p_T below 60 GeV, whereby the impact is the stronger the lower the electron p_T . Still only about 1 % can be gained with all three variable extensions performing almost equally well. For the resolution on the other hand an improvement of almost 30 % is achievable by including p_{track} and $\Delta\phi_2$ in the calibration for electrons with p_T below 5 GeV. At a p_T of 20 GeV the resolution is still 7 % better compared to the nominal variable set. This is mainly driven by p_{track} .

The linearity with η is conserved very well with only minor deviations in the transition region as can be seen in Figure 4.4.10. The resolution is slightly improved by about 2.5 % over the entire η range, whereby the impact in the end-cap is most notable and driven by the information provided by $\Delta\phi_2$.

Further, the behaviour with pile-up is evaluated in data which have been collected in 2015 and 2016. Therefore, events from a $J/\psi \rightarrow e^+e^-$ and $Z \rightarrow e^+e^-$ selection in data are combined to enhance the number of electrons with low p_T as these are the main target of the MVA calibration with p_{track} and $\Delta\phi_2$. Hence, E/p is used rather than a mass ratio to study the linearity and resolution of the MVA response. Figure 4.4.11 shows that both are as stable for the extended variable sets as for the nominal one. Only for $\mu < 10$ fluctuations of a few per mille occur which are due to the lack of statistics, still a slightly better performance is achieved by exploiting p_{track} in the MVA. The overall resolution as function of pile-up is improved by about 4-5 % for the variable sets which include p_{track} . The performance of the variable set with $\Delta\phi_2$ is similar to the nominal configuration. The behaviour of the MVA response measured in data as function of η can be found in Figure A.3.1.

Finally, Figure 4.4.12 shows the invariant di-electron mass peak measured in events from a $J/\psi \rightarrow e^+e^-$ selection in data with the electrons calibrated with the nominal and extended variable sets. The peak position evaluated with a truncated Gaussian fit is improved by maximal two per mille in case of the variable sets including p_{track} . However, the resolution is reduced by

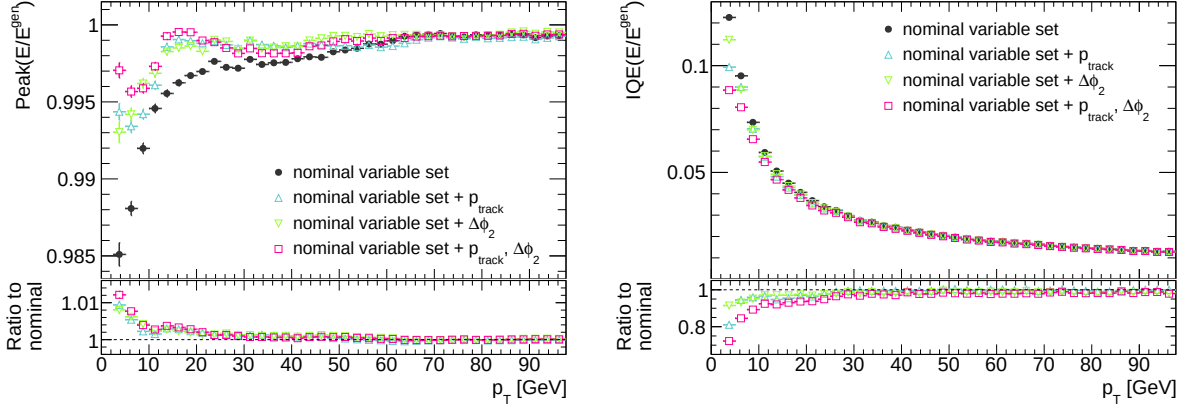


Figure 4.4.9: E/E^{gen} profiles with respect to p_T for simulated single electrons calibrated with a variable set extended by $\Delta\phi_2$, p_{track} and both are depicted in green, blue and pink, respectively. As reference the profile for the nominal calibration is included as black dots. The profile of the peak position of the E/E^{gen} distribution in each p_T bin is extracted from a truncated Gaussian fit and shown on the left. The profile of the IQE of the E/E^{gen} distribution in each p_T bin is shown on the right.

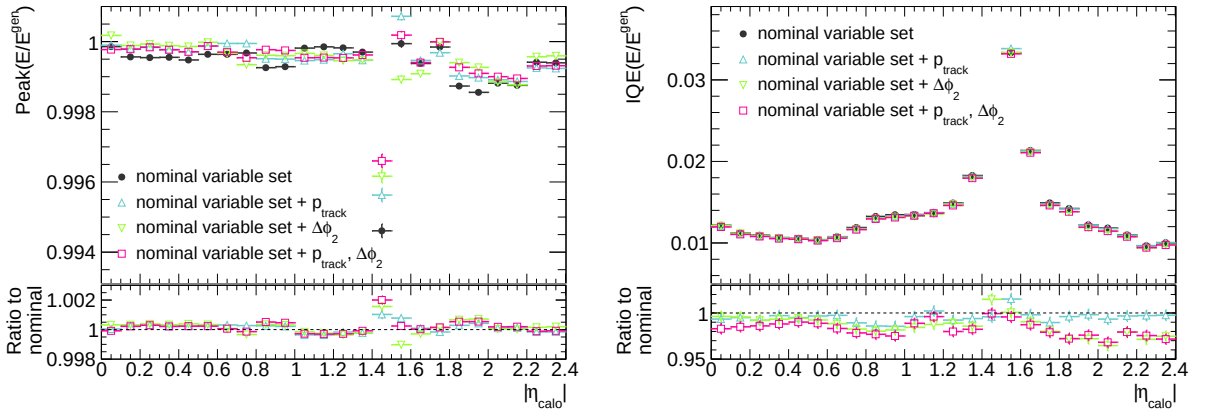


Figure 4.4.10: E/E^{gen} profiles with respect to η for simulated single electrons calibrated with a variable set extended by $\Delta\phi_2$, p_{track} and both are depicted in green, blue and pink, respectively. As reference the profile for the nominal calibration is included as black dots. The profile of the peak position of the E/E^{gen} distribution in each η bin is extracted from a truncated Gaussian fit and shown on the left. The profile of the IQE of the E/E^{gen} distribution in each η bin is shown on the right.

3 % and 15 % for MVA calibrations with $\Delta\phi_2$ and p_{track} from 148 MeV to 143 MeV and 128 MeV, respectively. The performance of the variable sets including both variables and solely p_{track} are equally well.

A different approach used in $H \rightarrow ZZ^{(*)} \rightarrow \ell^+ \ell^- e^+ e^-$ is the so-called E - p -combination [110] which combines the cluster energy and track momentum using a likelihood method and is applied separately on top of the nominal calibration chain. Performance measurements on the J/ψ mass yield comparable results to the study presented here.

As aforementioned, exploiting track based variables provides valuable information to the MVA-based energy calibration leading to significant improvements in the low- p_T region. Especially including the momentum measured from the track directly in the MVA turned out to be successful without introducing any unwanted dependencies with transverse momentum or pseudorapidity and eventually allow dropping the necessity of the E - p -combination step.

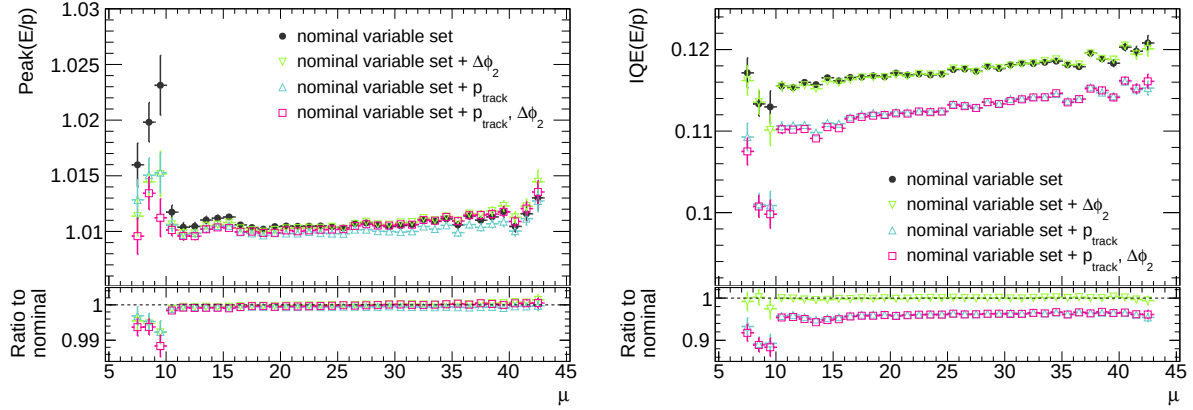


Figure 4.4.11: E/p profiles with respect to the average number of interactions per bunch crossing, μ , for electrons from a combined $J/\psi \rightarrow e^+e^-$ and $Z \rightarrow e^+e^-$ selection in data calibrated with a variable set extended by $\Delta\phi_2$, p_{track} and both are depicted in green, blue and pink, respectively. As reference the profile for the nominal calibration is included as black dots. The profile of the peak position of the E/p distribution in each μ bin is extracted from a double-sided Crystal Ball fit and shown on the left. The profile of the IQE of the E/p distribution in each μ bin is shown on the right.

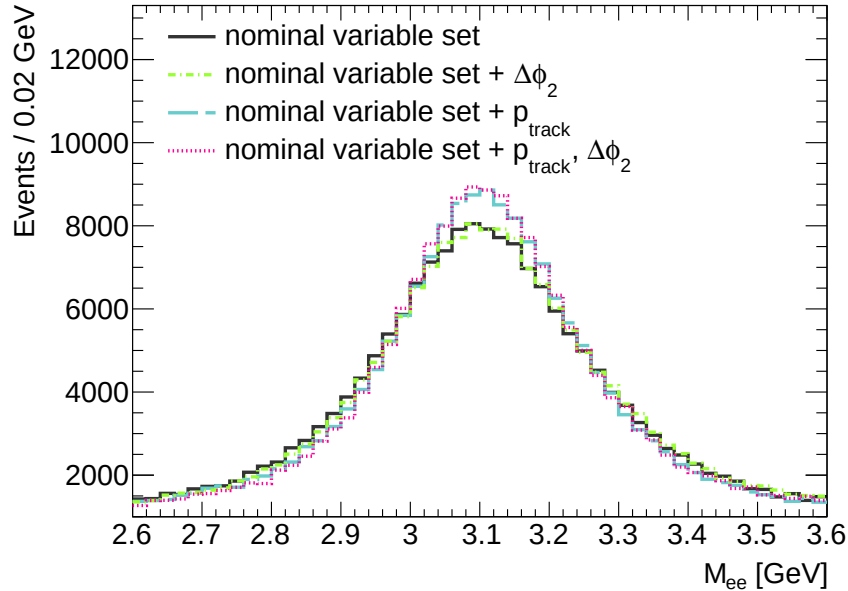


Figure 4.4.12: Invariant di-electron mass measured in events from a $J/\psi \rightarrow e^+e^-$ selection in 2015 and 2016 data. The distribution is shown in black for electron energies which are calibrated with the nominal variable set. The calibration with variable sets which are extended by $\Delta\phi_2$, p_{track} and both are depicted in green, blue and pink, respectively

Chapter 5

Search for Stopped Long-Lived Particles

Exotic *long-lived particles* (LLPs) are predicted by various BSM theories, as introduced in Section 2.2. The persistent absence of evidence of new physics in prompt searches [111, 112], motivates dedicated searches for more exotic scenarios like long-lived particles. Although the ATLAS experiment is primarily designed for direct searches, the proclaimed LLPs can evoke interesting detector signatures which are worth studying. However, non-standard data sources and reconstruction settings are often required. The analysis presented in this chapter is such a search, targeting lifetimes of a few nanoseconds up to several years. Motivated by SUSY models including R-parity conserving scenarios, like split-SUSY [40, 41], gluinos can be long-lived. Given a significant lifetime, they can hadronise and bind with SM gluons and quarks forming an *R-hadron* (c.f. Section 2.2). If the gluino is produced near threshold, the R-hadron is slow-moving, such that a significant amount of its kinetic energy is lost while traversing the detector. In some fraction of cases the R-hadron may stop within the detector volume. This allows the detection of the decay event which may occur significantly later than the bunch crossing in which it was produced. If the gluino came to rest in the boundaries of the calorimeter, its decay leaves high energy deposits inside the calorimeters reconstructed as jets. Hence, events with at least one high- p_T jet and a non-negligible missing transverse energy, E_T^{miss} , are potential signal candidates. In order to identify these decays, data taken in empty bunch crossings provide a unique chance as they offer a cleaner environment compared to filled bunch crossings. The remaining backgrounds originate from jets induced by cosmic rays, stray muons as a consequence of beam losses and detector noise in the calorimeters.

The targeted signal models as well as the generation and simulation of such events is outlined in Section 5.1. Section 5.2 summarises the probed data samples. The definition and reconstruction of the relevant physics objects is discussed in Section 5.3. Section 5.4 is dedicated to the event selection. The relevant backgrounds and their treatments are the focus of Section 5.5. The description is concluded with Section 5.6 and 5.7 exploring the background estimation and signal sensitivity, respectively.

5.1 Signal Models

The targets of this search are gluinos which are promptly produced in proton-proton collisions and are long-lived due to a weak coupling to the gravitino [113–115] or suppression from very heavy intermediate particles [40, 41], as introduced in Section 2.2. This allows them to hadronise with SM quarks and gluons and form new composite states: R-hadrons.

5.1.1 Mass Spectra

Predictions about the R-hadron mass spectra are based on a set of phenomenological equations accounting for constituent masses and hyperfine splitting, the MIT bag model and several lattice QCD calculations [116–120]. In particular the lightest states are of high interest for R-hadron searches at the LHC as heavier R-hadrons are expected to decay rapidly into lighter states.

The recently updated calculations of the R-hadron mass spectrum in [121] have been implemented in PYTHIA8 [122]. They are based on the equation [123, 124]:

$$m_{\text{hadron}} = \sum_i m_i - k \cdot \sum_{i \neq j} \frac{(\mathbf{F}_i \cdot \mathbf{F}_j)(\mathbf{S}_i \cdot \mathbf{S}_j)}{m_i m_j}, \quad (5.1.1)$$

with the constituent masses, m_i and m_j , and F_i and S_i as the colour SU(3) and spin SU(2) matrices. The constant k is derived from fits of this equation to SM baryons and mesons to 0.025 GeV³ and 0.043 GeV³, respectively, [125]. Depending on the spin of the quark-anti-quark system this equation can be used to calculate the R-meson spectrum as

$$m_{\tilde{g}q\bar{q}} = m_{\tilde{g}} + m_q + m_{\bar{q}} - k \cdot \frac{1/6 \times 3/4}{m_q \times m_{\bar{q}}} \quad \text{for } S_{q\bar{q}} = 0, \quad (5.1.2)$$

$$m_{\tilde{g}q\bar{q}} = m_{\tilde{g}} + m_q + m_{\bar{q}} - k \cdot \frac{1/6 \times 1/4}{m_q \times m_{\bar{q}}} \quad \text{for } S_{q\bar{q}} = 1. \quad (5.1.3)$$

For R-baryons the splitting term is less trivial due to the mixing of spin and/or colour configuration of the three-quark system. However, the splitting term is only included for the lightest states ($R_{\tilde{g}\Lambda}^0$, $R_{\tilde{g}\Delta}^{0,+,++}$), as the splitting between like-flavour states is expected to be less than 100 MeV [123] and the mass splitting of the lightest states is of particular interest as heavier R-hadrons are expected to quickly decay into lighter states. Thus, the formula for the mass spectra of the remaining R-baryons reduces to a simple sum over the gluino and constituent quark masses:

$$m_{\tilde{g}qq'q''} = m_{\tilde{g}} + m_q + m_{q'} + m_{q''}. \quad (5.1.4)$$

The mass of $R_{\tilde{g}g}^0$ is defined as $m_{\tilde{g}} + 700$ MeV under the assumption of a dynamical gluon mass of 700 MeV [126]. A more detailed discussion of the R-hadron mass spectra including variations on the constituent masses can be found elsewhere [121].

5.1.2 Event Generation & Simulation

The generation of R-hadrons in 13 TeV proton-proton collisions and simulation of their interaction with the ATLAS detector is realised with PYTHIA8 and GEANT4 (c.f. Section 3.2.8).

The interaction between R-hadrons and matter is not precisely defined and depends heavily on the chosen interaction model. For the presented analysis the so-called *Regge model* [127, 128] is chosen. It provides various assumptions about the mass spectra and the production rates.

While traversing the detector the R-hadron engages in hadronic and electromagnetic interactions (if they are electrically charged). The latter are the main contributor to the energy loss as shown in Figure 5.1.1(a) for two different mass points.

The fraction of neutral, singly and doubly charged generated R-hadrons is independent of the gluino mass but varies with the fraction of gluinoballs (bound states of a gluino and gluon). More than half are electrically neutral at a gluinoball fraction of 0 % and the fraction steadily increases with increasing gluinoball fraction. There are slightly more positively than negatively charged R-hadrons, both, singly and doubly charged, due to an abundance of positive charges in proton-proton collisions. The gluinoball fraction is fixed to 10 % motivated by [129], although the value can vary significantly as glueball formation is not well understood and neither has

been observed nor excluded, yet. The presented analysis provides a unique coverage of scenarios with predominantly neutral R-hadrons, as many other LLP searches rely on detector timing and dE/dx [50, 130], and lose sensitivity with an increasing rate of neutral R-hadrons.

By interacting hadronically the R-hadron can exchange its constituents with the detector material. Thus, its internal state is altered and its electrical charge can change multiple times between neutral, charged or doubly charged. The extent of the alternation of the electrical charge varies with the mass spectra of the R-hadron states. Any $2 \rightarrow 2$ and $2 \rightarrow 3$ hadronic interaction that ensures the conservation of charge, baryon number and strangeness, is permitted. Due to the lack of a dedicated interaction model, charm and bottom quarks are considered to contribute to the strangeness of the initial state and decay quickly to strange or light-flavour quarks. On average about 14 hadronic interactions occur for each R-hadron with an energy loss of less than 0.5 GeV per interaction (c.f. Figure 5.1.1(b)). The number of re-hadronisations and charge changes peak around five and are independent of the gluino mass.

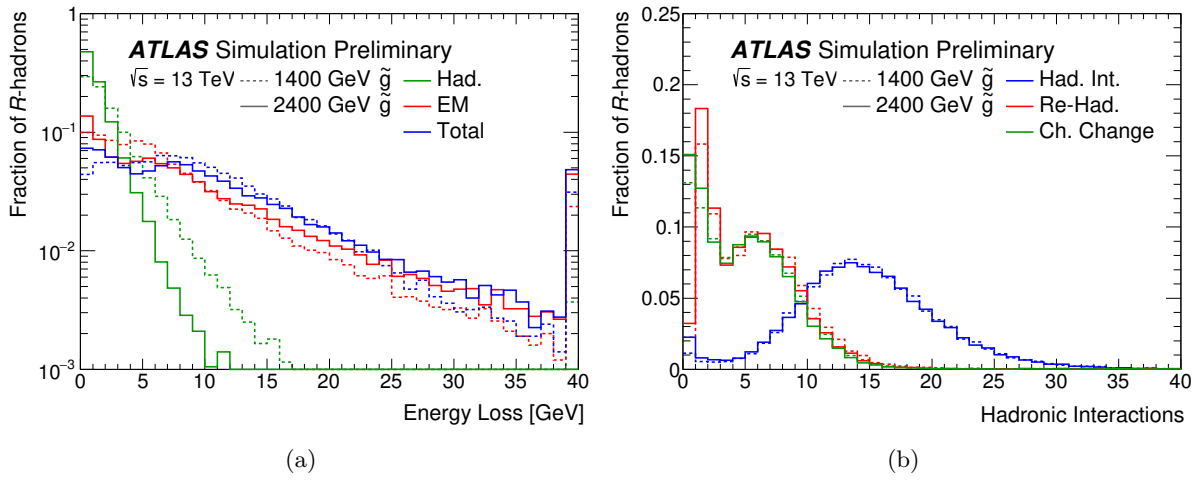


Figure 5.1.1: The total energy loss (a) and the number of hadronic interactions (b) for gluino R-hadrons as they travel through the ATLAS detector. Energy loss is divided into electromagnetic (“EM”) and hadronic (“Had.”) components. The number of hadronic interactions that cause a change of electric charge (“Ch. Change”) and that cause a change of light-quark system (“Re-Had.”) are shown separately. The final bin includes the overflow. [121]

The fraction of mesonic to baryonic R-hadrons depends strongly on the traversed detector material as depicted in Figure 5.1.2. The change in the R-hadron state can be more rapid in the gaps than the active material or air due to the installed service material. A rise in R-baryons is observed with the increase of service material after the ID. The tendency to convert R-mesons into R-baryons is a consequence of the conservation of baryon number in each hadronic interaction and the abundance of baryons in the detector material. Most R-hadrons which leave the detector are neutral as the lightest gluino R-baryon is a neutral flavour singlet state.

5.1.3 Stopping & Decay

To facilitate the detection of a signal, a high stopping fraction is essential. In the simulation it is assumed that all R-hadrons have the same lifetime as the constituent gluino or squark. The R-hadron mass spectrum only has a small impact on the relativistic velocity, β , but heavier R-hadrons tend to be generated with lower β . Assuming the R-hadron is sufficiently long-lived and sufficiently slow, it can lose all its kinetic energy traversing the detector and eventually come to rest inside it. The stopping condition on the R-hadron velocity, v , is given by

$$v \leq \frac{v_F}{A^{2/3}} , \quad (5.1.5)$$

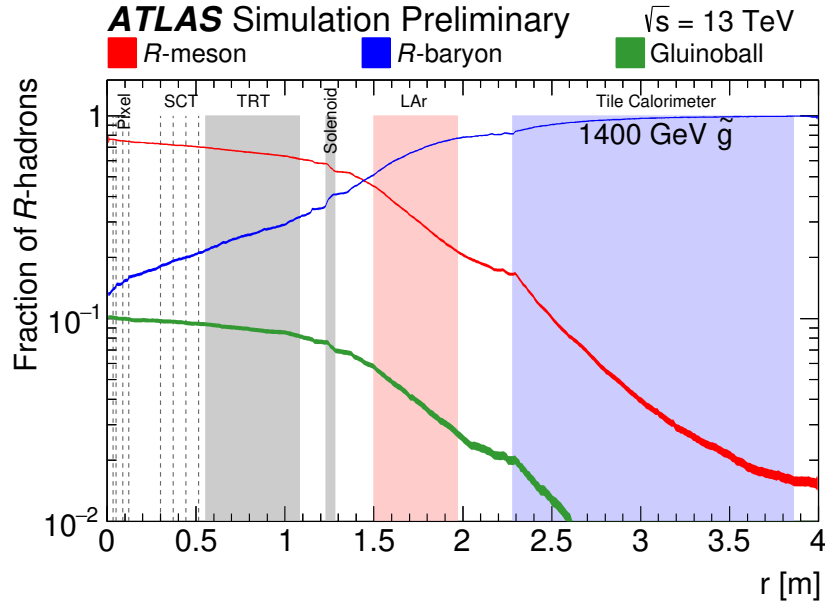


Figure 5.1.2: The states of the R-hadron while moving through the ATLAS detector. The fraction of R-mesons, R-baryons, and gluinoballs for a 1400 GeV gluino depicted in red, blue and green, respectively. The shaded lines and boxes indicate the active regions of the detector. [121]

where v_F is the Fermi velocity of the nucleons within the nucleus, and A is the atomic mass number of the material.

The stopping fraction per gluino, shown in Figure 5.1.3(a), doubles over a gluino mass range from about 0.4 at 1000 GeV to 0.8 at 2800 GeV due to a lower β at production. The gluinoball fraction has no impact on the R-hadron stopping fraction. For stopping R-hadrons, the fraction of doubly charged gluino R-hadrons is disproportionally higher compared to other charge states which can be explained by a higher energy loss in electromagnetic interactions (Figure 5.1.3(b)). Less than 10 % of the stopped R-hadrons are neutral at low gluino masses but the fraction rapidly increases to more than 20 % at higher masses on the cost of doubly positively charged states. Doubly charged states are only possible for gluino R-hadrons resulting in a higher stopping fraction compared to squark R-hadrons owing to the hadronic interaction cross section and higher average ionisation as can be seen in Figure 5.1.3(a). The fraction of singly negatively and positively charged stopped R-hadrons is similar, ranging between 20 % and 25 %, with a slight favour towards negatively charged states at low energies. The contribution of doubly negatively charged gluino R-hadrons is negligible.

Figure 5.1.4 shows the stopping position within the r - z -plane of the ATLAS detector for a 2.4 TeV gluino. The majority of stopping R-hadrons do so in the cryostat in front of the calorimeters. This is because the cryostat wall is the first dense material that they encounter beyond the thin material of the beam pipe and inner tracking detector. Apart from the cryostat, R-hadrons predominantly come to rest in the central calorimeters. Particularly, heavy R-hadrons tend to have lower kinetic energy such that they are more likely to stop immediately after reaching the calorimeter. The specific stopping conditions are discussed elsewhere [121].

The eventual decay of the gluino may happen much later after its production, with a delay from a few nanoseconds to several years. Again PYTHIA8 is used with the same configuration as in the event generation step. The decay products are subsequently re-inserted in GEANT4, whereby all R-hadron decay products are placed at the point of the decay, ignoring any propagation.

More details including variations of various parameters in the generation and simulation of R-hadrons can be found elsewhere [121].

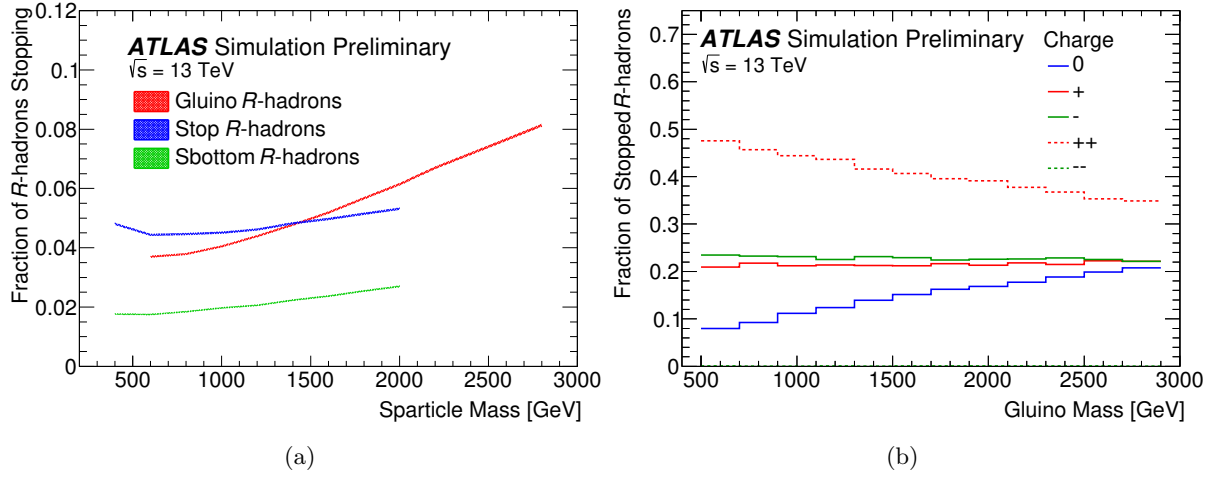


Figure 5.1.3: (a) The expected fraction of stopping R-hadrons as a function of the heavy sparticle mass. Gluino hadrons are shown in red. The band indicates the statistical uncertainty. (b) The variation of the charge of the stopped gluino R-hadrons. [121]

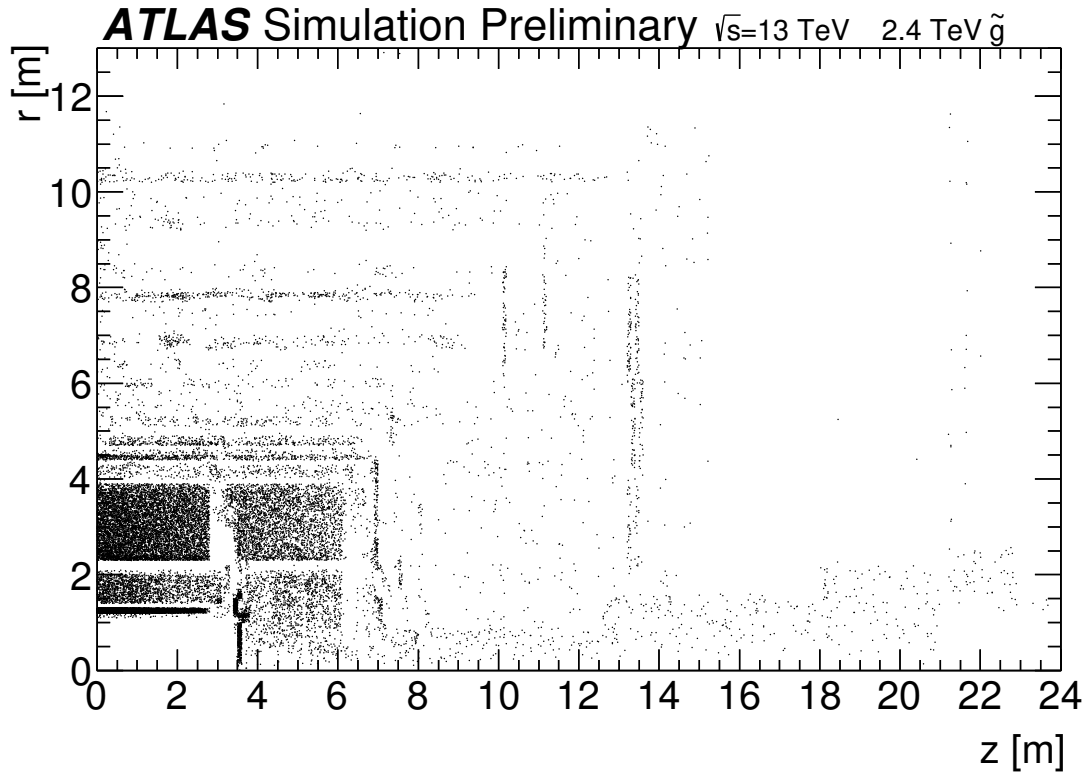


Figure 5.1.4: The stopping locations within the ATLAS detector for 2.4 TeV gluino R-hadrons depicted in the r - z -plane [121]

5.1.4 Signal Samples

Various signal samples with different gluino masses and mass splittings to the LSP have been generated. The gluino mass ranges from 400 GeV to 1800 GeV, and mass splittings of 100 GeV and 500 GeV have been used. In addition, a scenario with a 100 GeV neutralino is added for each gluino mass point; thus mass splittings of up to 1700 GeV have been realised. A total of 100000 events per mass point have been simulated for gluino masses up to 1400 GeV. This number is reduced to 70000 for gluino masses of 1600 GeV and 1800 GeV owing to the lower production cross sections. All available mass points are summarised in Table 5.1.1.

Gluino mass $m(\tilde{g})$ [GeV]	Neutralino mass $m(\tilde{\chi}_1^0)$ [GeV]	Mass splitting Δm [GeV]	Number of re- constructed events	Production cross section [pb]
400	100	300	7193	98.0459
400	300	100	7237	98.0459
600	100	500	6897	11.3
600	500	100	6912	11.3
800	100	700	7027	1.81
800	300	500	7015	1.81
800	700	100	7024	1.81
1000	100	900	7300	0.385
1000	500	500	7347	0.385
1000	900	100	7313	0.385
1200	100	1100	7895	0.0985
1200	700	500	8035	0.0985
1200	1100	100	8050	0.0985
1400	100	1300	8705	0.0284
1400	900	500	8571	0.0284
1400	1300	100	8648	0.0284
1600	100	1500	6428	0.00887
1600	1100	500	6630	0.00887
1600	1500	100	6536	0.00887
1800	100	1700	7000	0.00293
1800	1300	500	7000	0.00293
1800	1700	100	7000	0.00293

Table 5.1.1: Overview of the gluino and neutralino masses, as well as the mass splittings of the R-hadron signal samples used in this analysis. The number of reconstructed events and the production cross sections are listed in columns on the right.

5.1.5 Signal Characteristics

The decay of the R-hadron is locally isotropic, as it has come to rest inside the detector. This analysis features models for the $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$ gluino decay. Depending on the orientations of the decay, the deposited energy in the calorimeter can be clustered to multiple jets. However, most signal events have one or two jets as shown in Figure 5.1.5(a). The jet multiplicity increases with gluino mass but single jet events are still most likely. Owing to the higher likelihood for the R-hadron to stop in the central part of the calorimeter, the decay products are located close to the decay point, resulting in a central high- p_T leading jet (c.f. Figure 5.1.5(b)). Figure 5.1.5(c) shows that its p_T heavily depends on the mass splitting, and is low for small mass splittings ($\Delta m = 100$ GeV) and increases significantly for medium ($\Delta m = 500$ GeV) and high mass splittings ($\Delta m = 1300$ GeV). The same relation is reflected in E_T^{miss} as depicted in Figure 5.1.5(d). The decay kinematics are not affected by the spectator partons in the R-hadron. A typical event display of a decay event is presented in Figure 5.1.6.

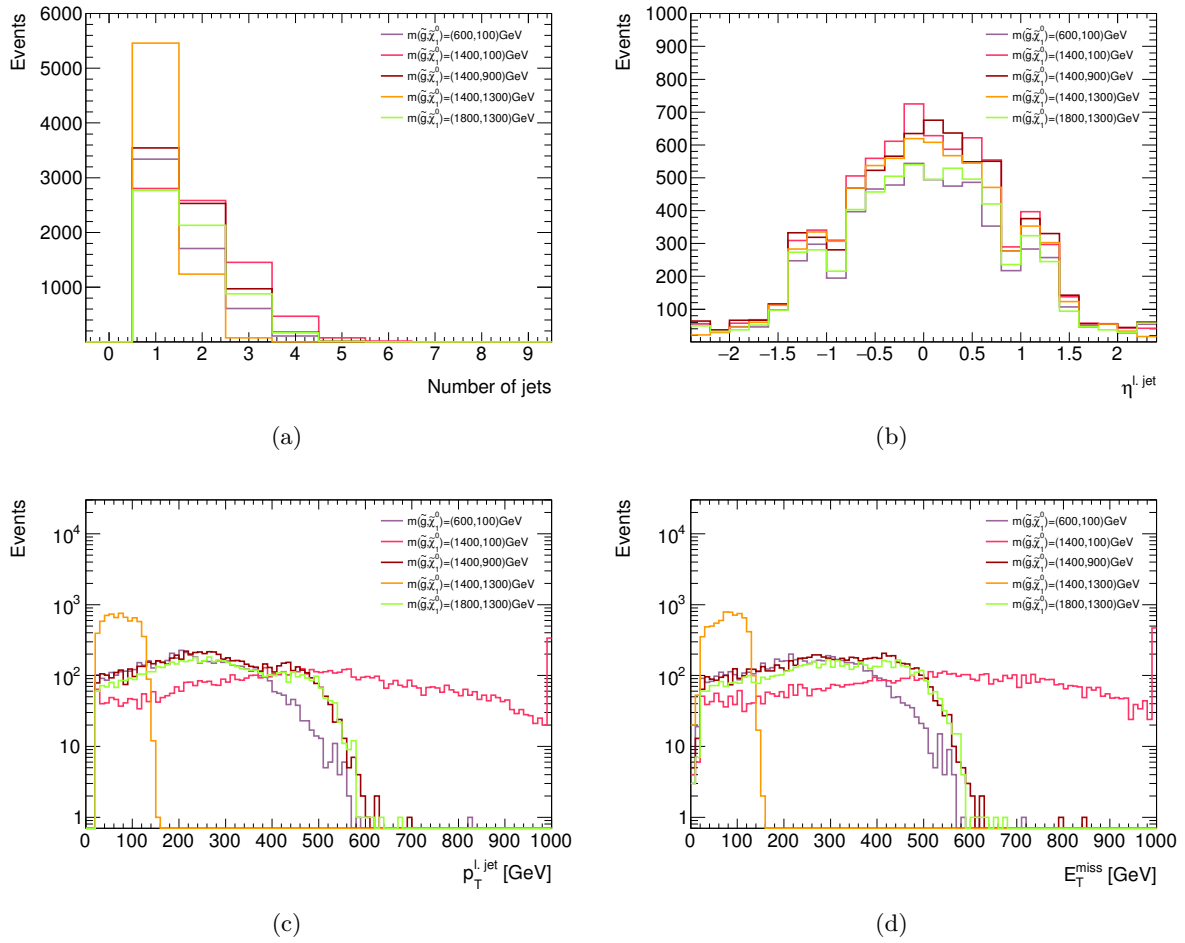


Figure 5.1.5: Number of jets (a), leading jet η (b), p_T (c) and E_T^{miss} (d) extracted from simulated signal events for different mass points: $m(\tilde{g}, \tilde{\chi}_1^0) = (600, 100)$ GeV (violet), $(1400, 100)$ GeV (pink), $(1400, 900)$ GeV (red), $(1400, 1300)$ GeV (orange) and $(1800, 1300)$ GeV (green).

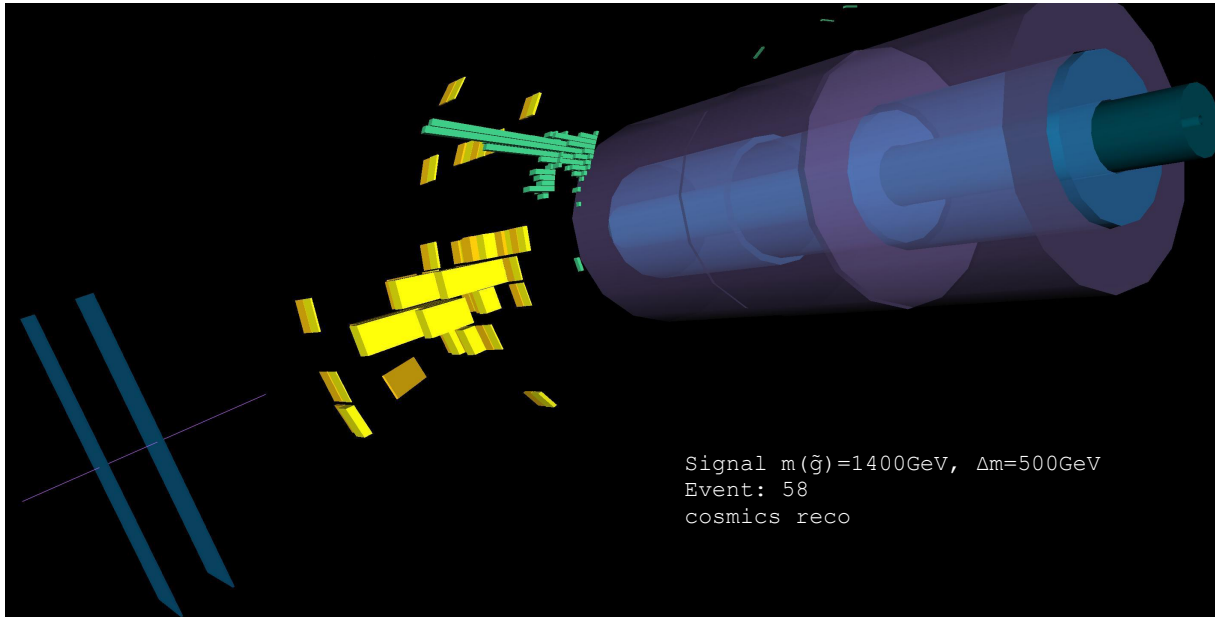


Figure 5.1.6: An event display of a typical signal event with a 1400 GeV gluino and a 500 GeV mass splitting. Clusters in the LAr and Tile calorimeter are shown as green and yellow boxes, respectively. The pink line illustrates a reconstructed muon track, the MDTs with the corresponding hits are depicted as blue planes. For visibility reasons only these MDT chambers are shown. The inner detector (purple cylinder) is included as orientation.

5.1.6 Random Event Overlay

Even in empty bunch crossings, spurious detector activity as a result of non-collision backgrounds or residual radiation (e.g. as a result of the β -decay of activated nuclei) in the ATLAS cavern can occur. Such activity is not modelled in the signal MC simulation. To ensure this is taken into account a *random event overlay* procedure is applied to all simulated signal events.

The `HLT_noalg_cosmiccalo_L1RD1_EMPTY` trigger randomly accepts events occurring in empty bunch crossings during a given collision run and records them in the `physics_CosmicCalo` stream. These events represent an unbiased sample from which spurious detector activity can be studied. A total of 17062070¹ random events are obtained from events recorded in 2016–2018 data-taking, which exceeds the required number for the event overlay by far as only 161763 simulated signal events are available. Hence, a subset of these events is randomly picked independently of the data-taking period whereby it is ensured that each event is only used once. Each simulated signal event is then merged with one of these random events.

The overlay procedure involves a simple sum of physics and detector-based objects, such as muon segments and jets. Quantities which are constructed based on different objects, like angular distances between objects, are recalculated.

Less than 0.03% of the random events contain a jet, with only three events having a jet with $p_T > 80$ GeV. For 20 random events a primary vertex has been reconstructed. The majority of random events contain solely muon segment activity. The number of reconstructed muon segments in simulated events with a 1400 GeV gluino and a 500 GeV mass splitting is shown in Figure 5.1.7. More than half of the pure signal events have no reconstructed muon segment, which is reduced to less than 10% if random events are added, emphasising the importance of the random event overlay to include spurious muon segment activity.

If not stated otherwise, the signal with random event overlay is used throughout this chapter and is labelled as “+ random”.

¹The GRL is applied.

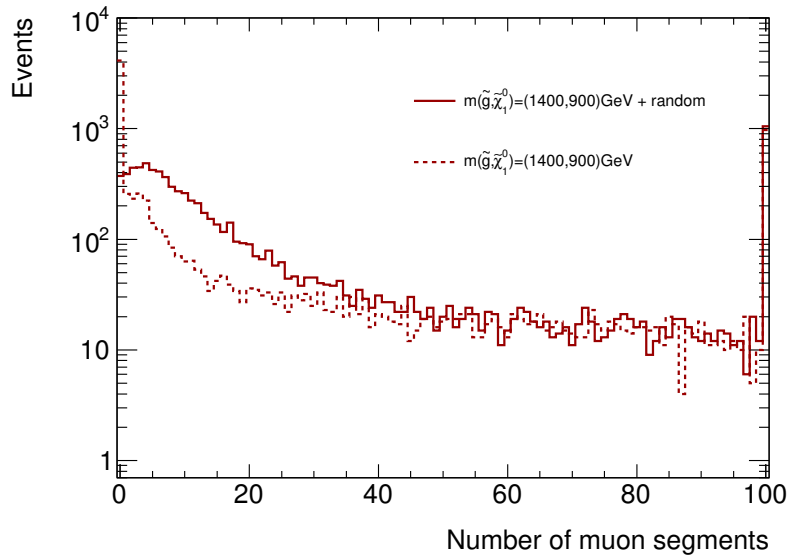


Figure 5.1.7: Number of reconstructed muon segments in simulated events for a 1400 GeV gluino with a mass splittings of 500 GeV. The pure signal is shown as dashed line and the signal with an overlay of random events is depicted as solid line.

5.2 Data Samples

The presented studies were conducted by analysing data taken with the ATLAS detector in 2016–2018. A total integrated luminosity of 149.1 fb^{-1} was delivered for proton-proton collisions at 13 TeV, of which 135.8 fb^{-1} [89] are data of good quality. The GRLs used and respective luminosities per year can be found in Appendix B.1.

The bunch groups in a bunch group scheme are categorised in different types:

- PAIRED ... colliding filled bunches, with each bunch of the two beams being populated with protons;
- UNPAIRED ... only one of the two beams holds a filled bunch, while the bunch from the other beam is empty,
- ISO ... at least seven bunch crossings away from a BCID with the other beam filled,
- NONISO ... the seven bunch crossings closest to a BCID with the other beam filled;
- EMPTY ... neither beam holds a filled bunch and at least five BCIDs away from a paired BCID;
- FIRSTEMPTY ... neither beam holds a filled bunch and less than six BCIDs away from a paired BCID.

A schematic overview of a typical arrangement of bunch groups in a bunch group scheme is depicted in Figure 5.2.1. The number and distribution of each BCID type is dictated by the LHC filling scheme and may vary from run to run. Data recorded in `empty` and `firstempty` bunch crossings are used as for this analysis as the contamination from collisions occurring in `paired` bunch crossings is minimise. In addition, data recorded in `unpaired` bunch crossings are used for background studies.

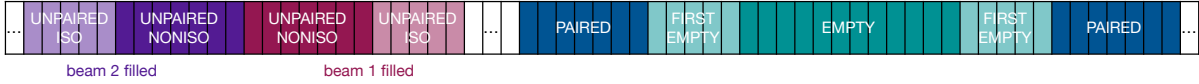


Figure 5.2.1: Schematic of a typical arrangement of bunch groups in a bunch group scheme which repeats several times throughout a run. **Unpaired** bunch groups typically commence with beam 2 filled (purple) first followed by beam 1 filled (magenta). The **paired** bunch groups (blue) are shown severely shortened for illustrative purposes and are separated by a sequence of **firstempty** and **empty** bunches (teal).

Dedicated triggers are defined for these BCIDs and the accepted events are recorded in different streams. All triggers, streams and their purpose are summarised in Table 5.2.1. The search sample is collected with the signal trigger targeting signal-like events in **empty** BCIDs by requiring at least one jet with $p_T > 55$ GeV and $|\eta| < 2.4$, and 50 GeV of missing transverse momentum at the HLT level. Candidate events were recorded by the `HLT_j55_0eta240_xe50_L1J30_EMPTY` trigger in the `physics_Late` stream (abbreviated `Late`). In 2018 the same trigger requirements were applied to data in `firstempty` BCIDs to allow a possible expansion towards lower lifetimes as less time has elapsed since the previous collision.

The main sample to study background induced by cosmic muons is provided by a dedicated cosmic run recorded in 2016. Data streamed in the `physics_Background` stream (abbreviated `Background`), requiring one L1-jet with $p_T > 12(50)$ GeV in isolated (`ISO`) and non-isolated (`NONISO`) **unpaired** BCIDs, are used to study beam-induced background. To take cavern background and out-of-time pile-up into account, randomly recorded events in **empty** bunch crossings are used for the event overlay described in Section 5.1.6.

The triggers used in this analysis are generally not primary analysis triggers and hence might be prescaled. To verify this a luminosity-weighted prescale is calculated for each trigger and year by taking the trigger prescale for each LB in which at least one event was accepted by the given trigger, and scale it by the integrated luminosity recorded in the given LB. Details on the procedure are given in Appendix B.2.

The data recorded in the `Late`, `CosmicCalo` and `Background` stream have been reconstructed with `cosmics` and `collisions` settings. The differences of the two reconstruction modes are discussed in detail in Section 5.3. All datasets used are listed in Table B.3.1 in Appendix B.3.

Purpose	Data-taking mode	Stream	Trigger
Search sample	Collisions	<code>physics_Late</code>	<code>HLT_j55_0eta240_xe50_L1J30_EMPTY</code> <code>HLT_j55_0eta240_xe50_L1J30_FIRSTEMPTY</code>
Cosmic-induced background	Cosmics	<code>physics_Main</code>	<code>HLT_j0_L1J12_EMPTY</code>
Beam-induced background	Collisions	<code>physics_Background</code>	<code>L1_J12_UNPAIRED_ISO</code> <code>L1_J50_UNPAIRED_ISO</code> <code>L1_J12_UNPAIRED_NONISO</code> <code>L1_J50_UNPAIRED_NONISO</code>
Cavern background & pile-up	Collisions	<code>physics_CosmicCalo</code>	<code>HLT_noalg_cosmiccalo_L1RD1_EMPTY</code>

Table 5.2.1: Data streams and triggers used in this analysis for background studies and the selection of the search region.

5.3 Object Definition & Reconstruction

Standard *collisions* reconstruction settings are optimised to efficiently reconstruct in-time signal originating from the IP. The targeted out-of-time signal cannot be traced back to the IP, which is also the case for one of the main backgrounds. Cosmic muons traverse the detector from top to bottom, moving in the opposite direction as expected in the upper detector hemisphere and are thus less likely to be reconstructed. In order to elude these drawbacks and increase the reconstruction efficiency, *cosmics* reconstruction settings² have been used. *Cosmics* reconstruction offers looser requirements, e.g. on hit order and timing constraints; thus it is more suited to reconstruct out-of-time and non-projective signatures.

This section introduces the objects which are used in this analysis and discusses the impact of the reconstruction settings on them. The differences between *cosmics* and *collisions* reconstruction modes have been studied in a cosmic and a collision run (c.f. Table 5.3.1 for details) which were reconstructed with both configurations.

The following event selection, unless stated otherwise, is applied on the investigated data samples:

- pass GRL (collision run only),
- no primary vertex,
- HLT_j55_0eta240_xe50_L1J30_EMPTY (collision run only),
HLT_j0_xe50_L1J12_EMPTY (cosmic run only),
- at least one jet,
- leading jet $p_T > 80$ GeV, $|\eta| < 2.4$, and
- HLT $E_T^{\text{miss}} > 50$ GeV.

The impact of the reconstruction settings on signal is expected to be minimal as depicted in the event displays in Figure 5.3.1 for a simulated signal event.

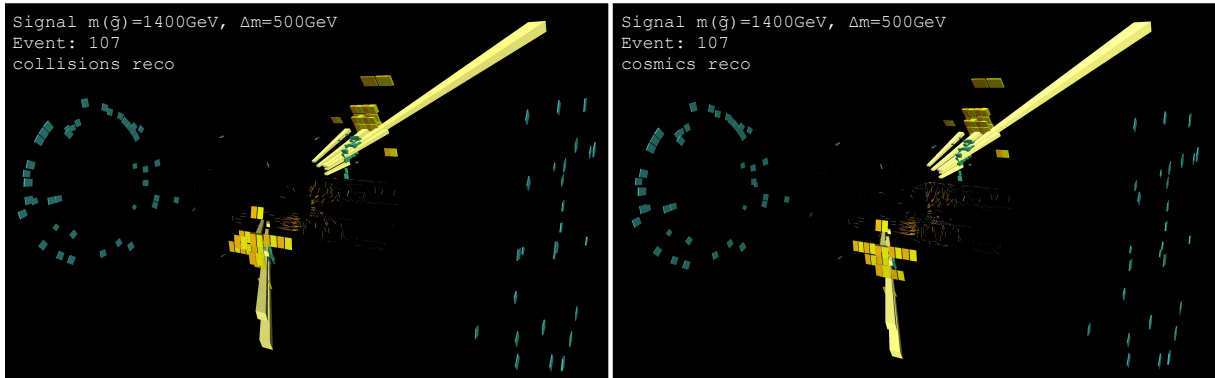


Figure 5.3.1: Event displays of a signal event of a 1400 GeV gluino and a 500 GeV mass splitting reconstructed with *collisions* (left) and *cosmics* (right) settings. Hits in the Pixel detector and SCT are illustrated by dots, hits in the TRT as orange stripes. Clusters in the LAr and Tile calorimeter are shown as green/blue and yellow/orange boxes, respectively. The pale yellow trapezoids are combined calorimeter clusters indicating the presence of jets.

²beamType=cosmics has been used in the reconstruction job configuration.

Data-taking mode	Year	Run number	Run duration	Time in stable beams	Stream	Total number of events	Trigger	Number of events recorded by trigger
Cosmics	2016	306147	10 hrs, 53 min	—	Main	924187	HLT_j0_L1J12_EMPTY	10245
Collisions	2018	357409	23 hrs, 12 min	12 hrs, 5 min	Late	32889	HLT_j55_Oeta240_xe50_L1J30_EMPTY	7064
						HLT_j55_Oeta240_xe50_L1J30_FIRSTEMPTY		11155
					CosmicCalo	1549198	HLT_noalg_cosmiccalo_L1J30_EMPTY	10035

Table 5.3.1: Details on the two runs selected to perform studies on the differences between using *cosmics* or *collisions* mode to reconstruct data recorded in a dedicated cosmic run in 2016 and an exemplary collision run in 2018.

5.3.1 Jets

Jet candidates are taken from the `AntiKt4EMTopoJet` collection. These jets are reconstructed using the anti-kt algorithm [131] with a distance parameter $R = \sqrt{y^2 + \phi^2} = 0.4$. The input to the jet reconstruction algorithm are three-dimensional topological clusters made of calorimeter cell energies measured at the EM scale. These topological clusters are then clustered by the anti-kt algorithm.

All baseline jets are required to have $p_T > 20$ GeV and $|\eta| < 4.5$. Driven by the signal trigger, `HLT_j55_Oeta240_xe50_L1J30_[FIRST]EMPTY`, these cuts are further tightened to $p_T > 80$ GeV and $|\eta| < 2.4$ for the highest- p_T jet in the event. The leading jet must meet the cleaning requirements outlined in Section 5.4.1; however, this is not enforced for the reconstruction studies discussed here.

As data recorded in `empty`, `firstempty` and `unpaired` bunch crossings and reconstructed in `cosmics` configuration are used in this analysis, the standard jet calibration algorithm [132] is not applicable. Due to the absence of any dedicated jet calibration, the JES MC calibration configuration for low-pile-up data-taking without pile-up subtraction [133] has been employed.

In standard reconstruction settings the OFCs used to interpret the sampled pulse shape measured in the calorimeters (c.f. Section 3.2.2) are fixed, assuming the detector signal originated from a collision in-time with the LHC clock. In case of out-of-time detector signals, a different fraction of the pulse is sampled depending on the phase shift between the initiation of the signal and the LHC clock. This can lead to inefficiencies in the determination of the energy deposits and time distribution. To account for this, a set of multi-phase or “iterative” OFCs exists allowing to chose the set of OFCs for which the time shift of the maximum sample with respect to the expected value is minimised. Hence, a more reliable energy reconstruction of out-of-time signals can potentially be achieved. Given the asymmetric pulse shape (c.f. Figure 3.2.5) the reconstructed energy is likely higher when employing iterative OFCs. When running in `cosmics` reconstruction configuration these iterative OFCs are automatically deployed for the Tile calorimeter. For the LAr calorimeter this is not done by default but can be activated in the reconstruction step. The cosmic and collision run have both been reconstructed in `cosmics` mode with standard and iterative OFCs for LAr. Reconstruction with `collisions` configuration is always with standard OFC settings. In the following only the collision run is addressed as a similar behaviour can be observed in the cosmic run, summarised in Appendix B.4.

Figure 5.3.2 shows distributions of the main kinematic variables for leading jets reconstructed with the two `cosmics` configurations in comparison to `collisions` configuration. A good agreement can be observed between `collisions` and `cosmics` reconstruction with standard OFCs. The event-by-event comparison of the leading jet p_T in Figure 5.3.3 reveals an overall slight shift towards higher values if `cosmics` settings are chosen, which is expected. In case of `cosmics` reconstruction with iterative OFCs a few non-negligible deviations are present. In particular an abundance of leading jets at $(\eta, \phi) \approx (0.8, 3.1)$ is evident compared to the other two configurations. By using `cosmics` reconstruction with iterative OFCs it can happen that sporadic noise in the calorimeter is not rejected, since the data quality assessment is based on data reconstructed with standard OFCs; hence quantities such as the LAr Quality can differ resulting in hot spots in confined η - ϕ regions. An example for this is the aforementioned abundance of jets at $(\eta, \phi) \approx (0.8, 3.1)$, shown in Figure 5.3.4 for `cosmics` reconstruction with standard and iterative OFCs. An investigation of the jets in the affected region revealed that these are mostly single jet events, whereby the jet p_T and E_T^{miss} are two orders of magnitude lower when reconstructed with standard OFCs and fail the selection criteria listed above. These jets, when reconstructed with iterative OFCs are, albeit without a physical signal, characterised by a good LAr quality factor and typically more than 90 % of the energy is within a single cluster, `n90` (c.f. Figure 5.3.5).

Although the latter feature allows an easy way to reject such events it was decided not to use iterative OFCs and rely on standard OFCs. On the one hand, the observation of this single-run studies cannot simply be extended to the entire 2016–2018 dataset but would require a rigorous

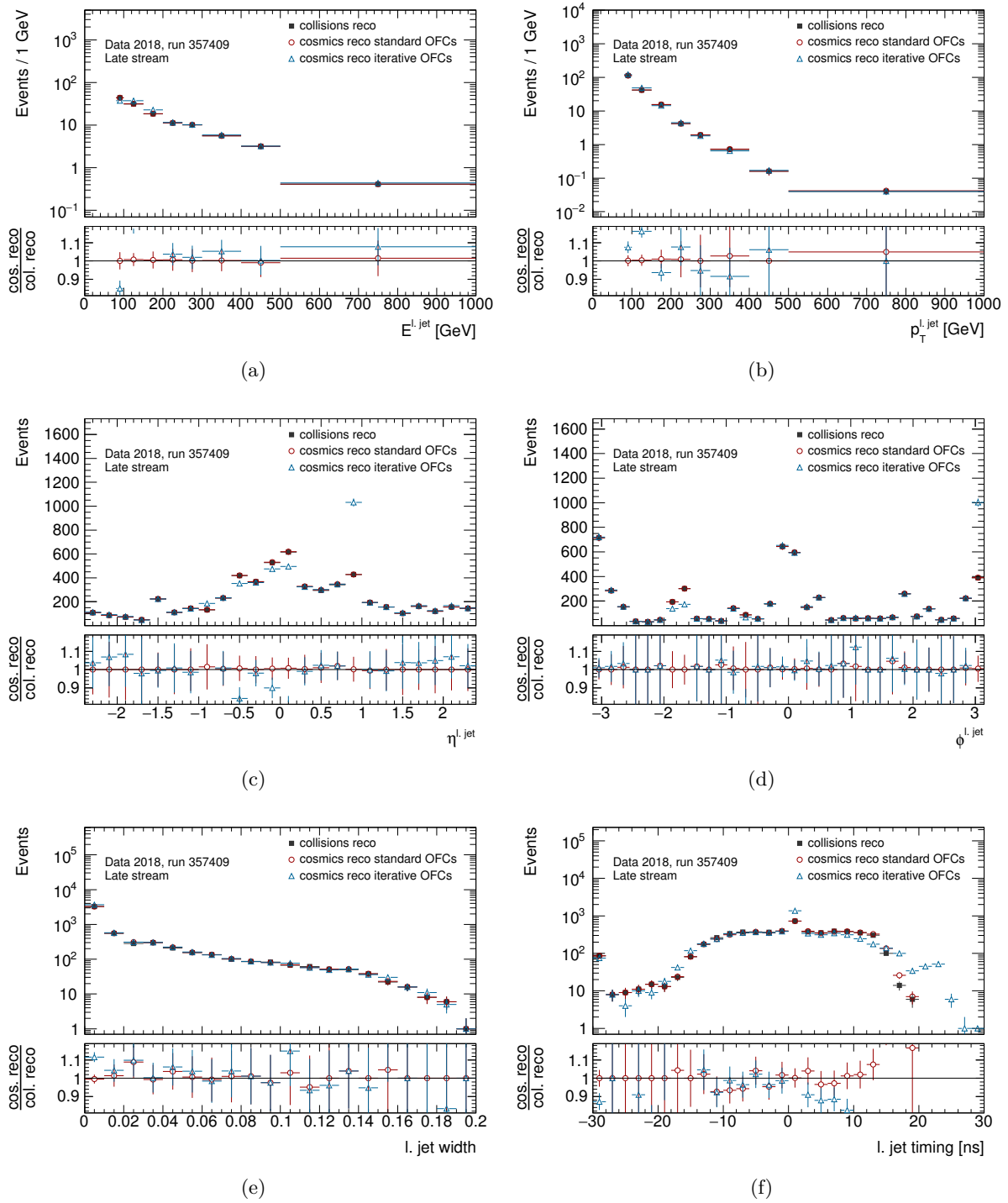


Figure 5.3.2: Leading jet energy (a), p_T (b), η (c), ϕ (d), width (e) and timing (f) in events reconstructed with *collisions* (black), *cosmics* mode with standard (red) and iterative OFCs (blue) in a collision run.

revision of the DQ assessment for the LAr calorimeter. On the other hand and even more severe, no implementation equivalent to iterative LAr OFCs exists in the simulation framework at the present moment. Moreover, the rather small deviations in leading jet quantities between standard and iterative OFCs suggest that the gain would be minimal for this analysis. However, the good agreement of *collisions* and *cosmics* reconstruction with standard OFCs support that the jet calibration above mentioned, which is optimised for the first, is applicable to the latter.

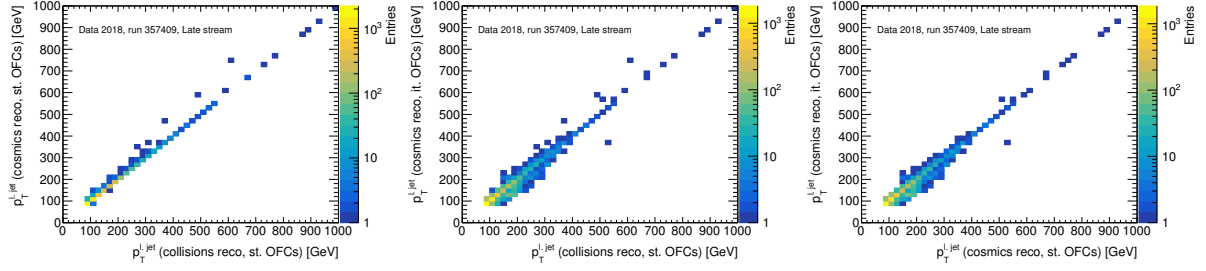


Figure 5.3.3: Event-by-event comparison of $p_T^{l.j et}$ reconstructed with *collisions* and *cosmics* mode with standard OFCs (a), *collisions* and *cosmics* mode with iterative OFCs (b), *cosmics* mode with standard and iterative OFCs (c) in a collision run.

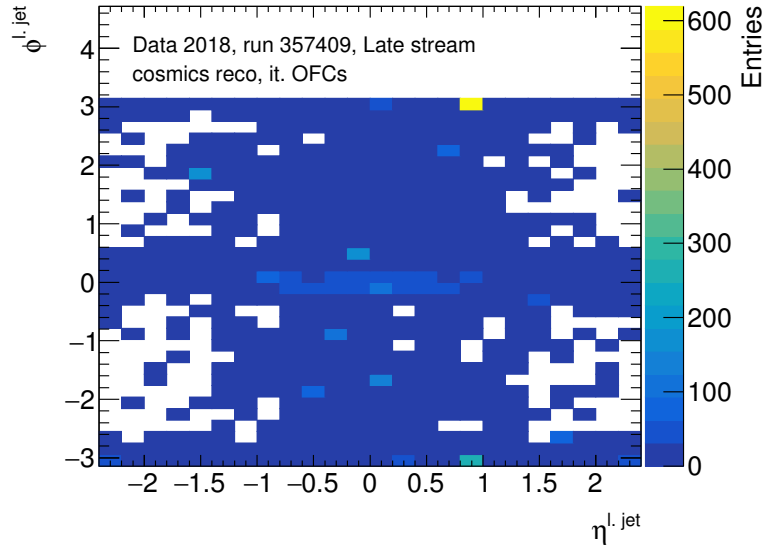
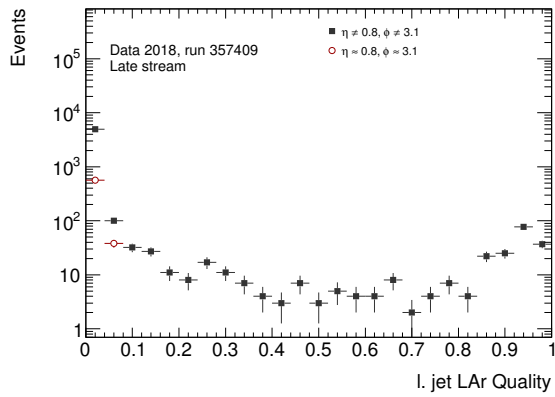
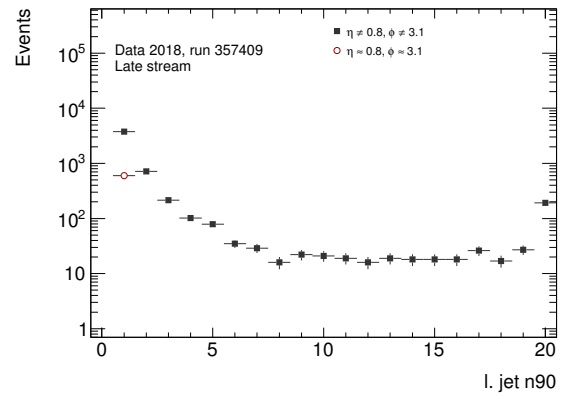


Figure 5.3.4: Leading jet occupancy in the η - ϕ -plane for a collision run reconstructed with *cosmics* configuration with iterative OFCs.



(a)



(b)

Figure 5.3.5: LAr quality (a) and n90 (b) for leading jets reconstructed with *cosmics* settings and iterative OFCs. Leading jets inside the region affected by noise, $(\eta, \phi) \approx (0.8, 3.1)$, are highlighted in red.

5.3.2 Muon Segments

Muon segments are reconstructed from at least three hits in the MDTs or three hits in both, η and ϕ , layers of the CSCs [134]. In the latter case an exception is made if two of four layers are inactive, by lowering the minimum number of hits to two per layer [135]. The muon segments for this analysis are taken from the `MuonSegments` collection.

Figure 5.3.6 shows the number of muon segments reconstructed with *collisions* and *cosmics* settings in a collision and cosmic run. By applying *cosmics* reconstruction settings, the pointing and impact parameter requirements applied to the muon segments formed from MDT hits, are removed³ and hence the muon tracks do not necessarily point to the centre of the detector as they do if *collisions* settings are applied. This is compared for the cosmic run in Figure 5.3.7 by looking at the pointing direction of the muon segments in the x - y -plane. The pointing towards the centre of the detector can be seen if *collisions* reconstruction is used, while in case of *cosmics* reconstruction, a tendency of downward pointing can be observed as these segments predominantly originate from cosmic muons traversing the detector from top to bottom. Due to the latter no hit order is required and the constraints on the number of missing hits is loosened. Similar distributions for a collision run can be found in Appendix B.4.

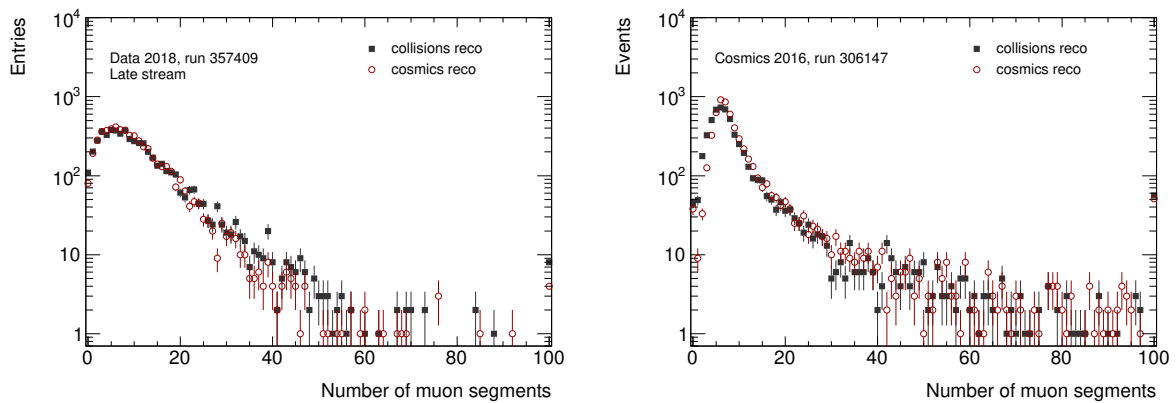


Figure 5.3.6: Number of muon segments as reconstructed with *collisions* (black) and *cosmics* (red) settings for a collision (left) and cosmic (right) run.

One of the free parameters of the muon segment fit is the drift time of the ionisation electrons in the MDTs. While the end-of-drift time can be measured, the starting time, T_0 , is unknown. If *collisions* reconstruction settings are adapted, T_0 is fixed for each chamber relative to the bunch crossing time. As this assumption is not applicable for *cosmics* reconstruction configuration, different values for T_0 are scanned and the one providing the best reconstruction is selected [136]. In case the fit fails entirely, T_0 cannot be determined and a default value of 0 is assigned. The T_0 distribution for muon segments reconstructed with the two configurations in a collision and cosmic run are shown in Figure 5.3.8. The segments with a failed fit can clearly be identified in the peak at 0. These segments are removed from consideration in this analysis as their information is not reliable. The loosened constraints on the T_0 determination in *cosmics* mode are reflected in the broader spread of the distribution. The maximum extent of T_0 is within ± 750 ns marking the maximum drift time of the MDTs. In some cases in the collision run, segments have a $T_0 \approx \pm 1000$ ns regardless of the reconstruction mode. This is a consequence of the detector latency, i.e. muon segments that overlap with the previous or next consecutive event can be reconstructed resulting in longer drift times. For segments with T_0 beyond that,

³The constraints on pointing and impact parameter are still in place for segments built from hits in the CSCs even if *cosmics* reconstruction is used. However, due to the almost perpendicular positioning with respect to the surface and the comparatively small cross section area of the CSC modules, only very few CSC hits can be expected compared to a majority of MDT hits.

the track fit is unsuccessful. Thus, any segments with $|T0| > 750$ ns are discarded in the analysis.

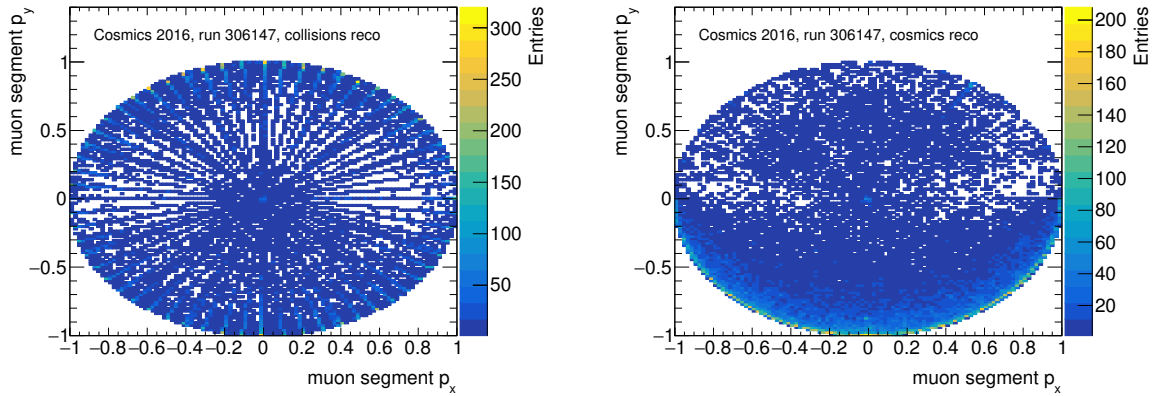


Figure 5.3.7: Direction of the momentum vector of muon segments in the x - y -plane for the cosmic run. The results obtained with *collisions* and *cosmics* reconstruction are shown on the left and right, respectively.

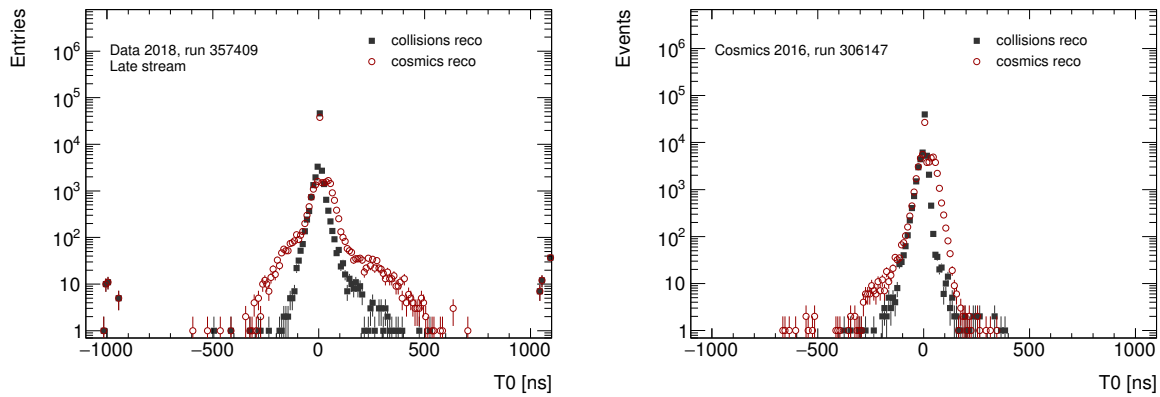


Figure 5.3.8: Muon segment $T0$ reconstructed with *collisions* (black) and *cosmics* (red) settings for a collision (left) and cosmic (right) run.

5.3.3 Muons

The muon reconstruction algorithm can combine information from all sub-detectors to build muon candidates. Given the non-standard character of the expected signal and background signatures and the usage of *cosmics* reconstruction configuration, only *standalone muons* are considered. Standalone muons [137] are solely defined by a track in the MS and are not required to match any ID tracks or calorimeter clusters. A track in the MS is formed by applying a Hough transformation to all MDT hits of clustered muons segments [137]. Subsequently, hits are added and outliers are removed by a repeated χ^2 -fit. In *collisions* reconstruction configuration an inside-outside hit order and pointing of the fitted track to the IP is demanded. Both requirements are neglected in *cosmics* reconstruction configuration. Thanks to the loosened constraints on the muon and muon segment reconstruction procedures (c.f. Section 5.3.2) the reconstruction efficiency for out-of-time muons and cosmic muons is increased, especially for the upper detector hemisphere, providing essential information to efficiently reject cosmic-induced jets.

The impact of the reconstruction type on cosmic muons is illustrated in Figure 5.3.9. Only one muon traversing from the inside to the outside of the detector in the lower hemisphere is reconstructed if *collisions* settings are deployed as it induced a detector signal compatible to

the expectations from collision events. Contrarily, for *cosmics* setting an additional muon is reconstructed in the upper hemisphere. Both reconstructed muons align as they are legs from the same cosmic muon.

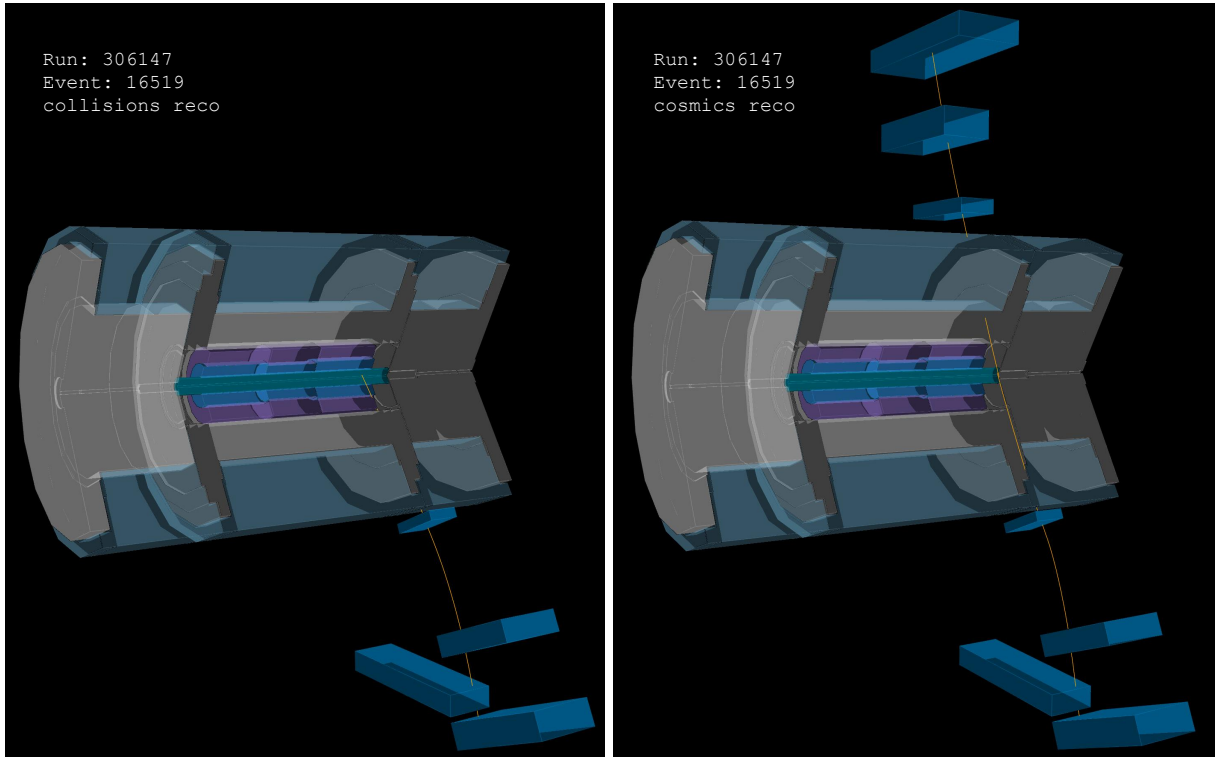


Figure 5.3.9: Event displays showing the same event from cosmic run 306147 reconstructed in *collisions* (left) and *cosmics* (right) configuration. The orange lines illustrate reconstructed muons, the MDTs in which the muon induced a detector response are depicted as blue boxes. For visibility reasons only these MDT chambers are shown. A cut-away view of the LAr and Tile calorimeters is included as orientation.

One important point for cosmic data-taking is that only muon trigger chambers in the lower half of the detector are enabled, as shown in Figure 5.3.10. This only has implications for the muon objects at trigger level, since the upper half of the muon system is still considered in the reconstruction step. This is independent of the chosen reconstruction type and applies solely for runs for which the detector was configured in cosmic data-taking mode. The slight discrepancies between the two distributions can be explained by the difference in the reconstructed events, i.e. not every event reconstructed with *cosmics* settings is reconstructed with *collisions* settings and vice versa.

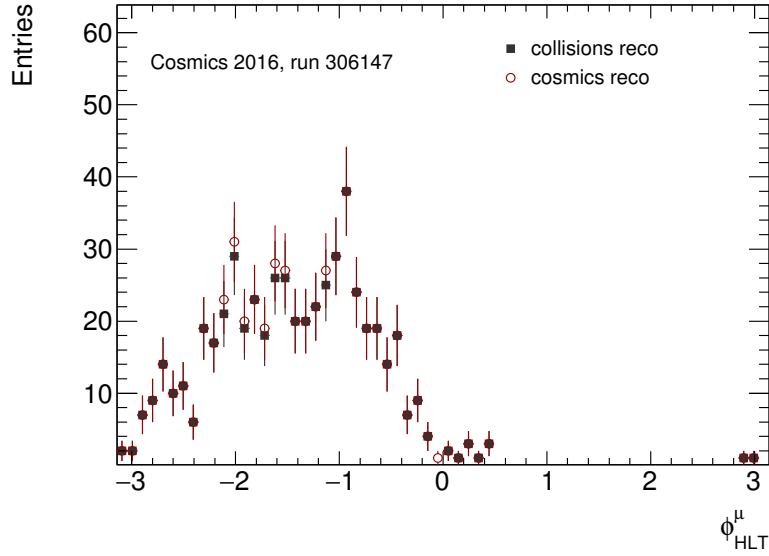


Figure 5.3.10: ϕ of HLT muons reconstructed with *collisions* (black) and *cosmics* (red) settings for the cosmic run. No selection cuts specific to physics objects applied.

5.3.4 Primary Vertex

A primary vertex is reconstructed by fitting all tracks to seed vertices along the beam axis and selecting the one with the highest p_{T}^2 sum. The procedure of vertex building relies on the assumption that all tracks belong to particles originating from a proton-proton collision, and thus is only performed if *collisions* reconstruction settings are applied but not in case of *cosmics* configuration. Although the presented analysis exploits data recorded in **empty**, **firstempty** and **unpaired** bunch crossings where proton-proton collisions are unlikely thanks to the absence of a proton bunch in one or both beams, collisions might still occur due to debunching of previous filled bunches and trailing ghost bunches. Long tails with a non-negligible number of protons can cause collisions especially in non-isolated **unpaired** bunches. These collision events must be removed to allow an unbiased estimate of the relevant non-collision backgrounds in the search region.

Since the analysis samples are reconstructed with *cosmics* settings, no vertex information is available. Fortunately, all samples have been reconstructed in *collisions* configuration as well, allowing the extraction of all events which have a reconstructed PV. Hence, events without a reconstructed PV can be filtered from the data samples reconstructed with *cosmics* settings by vetoing all events with a reconstructed PV in *collisions* reconstruction mode. The impact of this selection is discussed further in Section 5.4 and in Sub-section 5.5.2.

5.3.5 Inner Detector Tracks

Tracks of charged particles traversing the ID are reconstructed based on the hits in different sub-detector layers. A seed cluster of hits must contain at least three space points and more can be added by a combinatorial Kalman filter [101]. The final track is determined by a fit, parametrised by the transverse impact parameter, d_0 (distance of closest approach between track candidate and vertex in transverse plane), longitudinal impact parameter, z_0 (z coordinate where d_0 is measured), azimuthal angle, ϕ_0 , polar angle, θ and ratio of the assigned charge and momentum, q/p . A reconstructed track must meet several quality criteria, like a minimum number of hits and maximum number of missing hits in the Pixel, SCT and TRT layers, if *collisions* reconstruction settings are used. In the *cosmics* reconstruction configuration these restrictions are loosened and partially disregarded, allowing for more combinations of hits to form tracks. Observations

between tracks of the same events reconstructed with both configurations are shown in this section in light of the usefulness of ID track particles for the performed search for stopped long-lived particles. Tracks from the `InDetTrackParticles` collection are taken for these studies, i.e. all reconstructed inner detector tracks. In the following the focus is on the collision run as similar observations are made for the cosmic run which can be found in Appendix B.4.

By using *cosmics* reconstruction settings the number of ID tracks is significantly increased, mainly by tracks with hits only in the TRT as shown in Figure 5.3.11(a). This is reflected in the distribution of the number of TRT hits as it can be separated in hits from TRT-only tracks and tracks with Pixel and SCT hits (Figure 5.3.11(b)). The latter populate the distribution up to ten hits while the vast majority of hits is associated to TRT-only tracks.

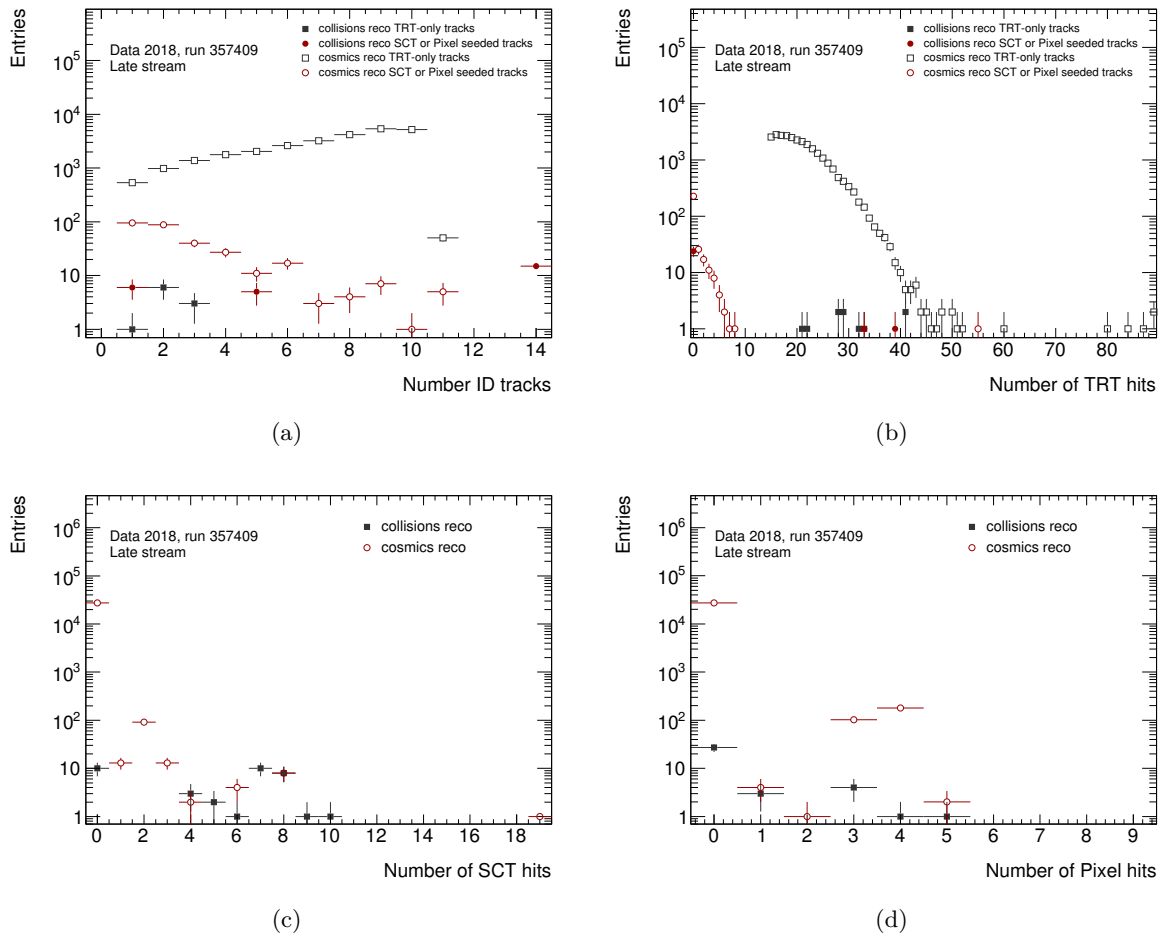


Figure 5.3.11: Number of ID tracks (a), number of TRT (b), SCT (c) and Pixel hits (d) in a collision run reconstructed with *cosmics* and *collisions* configuration depicted by empty and filled markers, respectively. The number of ID tracks and TRT hits distributions are further split in TRT-only and SCT or Pixel seeded tracks in black squares and red circles, respectively.

Cosmics reconstruction settings are based on the assumption that cosmic muons traverse the detector from top to bottom leaving a track in the ID which only gets one ϕ value in the lower half assigned as shown in Figure 5.3.12(a). As most of the tracks are built from TRT hits, information of the z position is not available and a fixed value is used to stabilise the track fit. Hence, d_0 is spread over a wide range and z_0 is shifted to high negative values for tracks reconstructed with *cosmics* setting as opposed to *collisions* settings for which d_0 is centred around 0 and z_0 is spread over the expansion of the ID. These contrary features of the reconstruction types of TRT-only tracks is depicted in Figure 5.3.12(b–d). Consequently, θ of

TRT-only tracks cannot be determined and peaks at $\pi/2$.

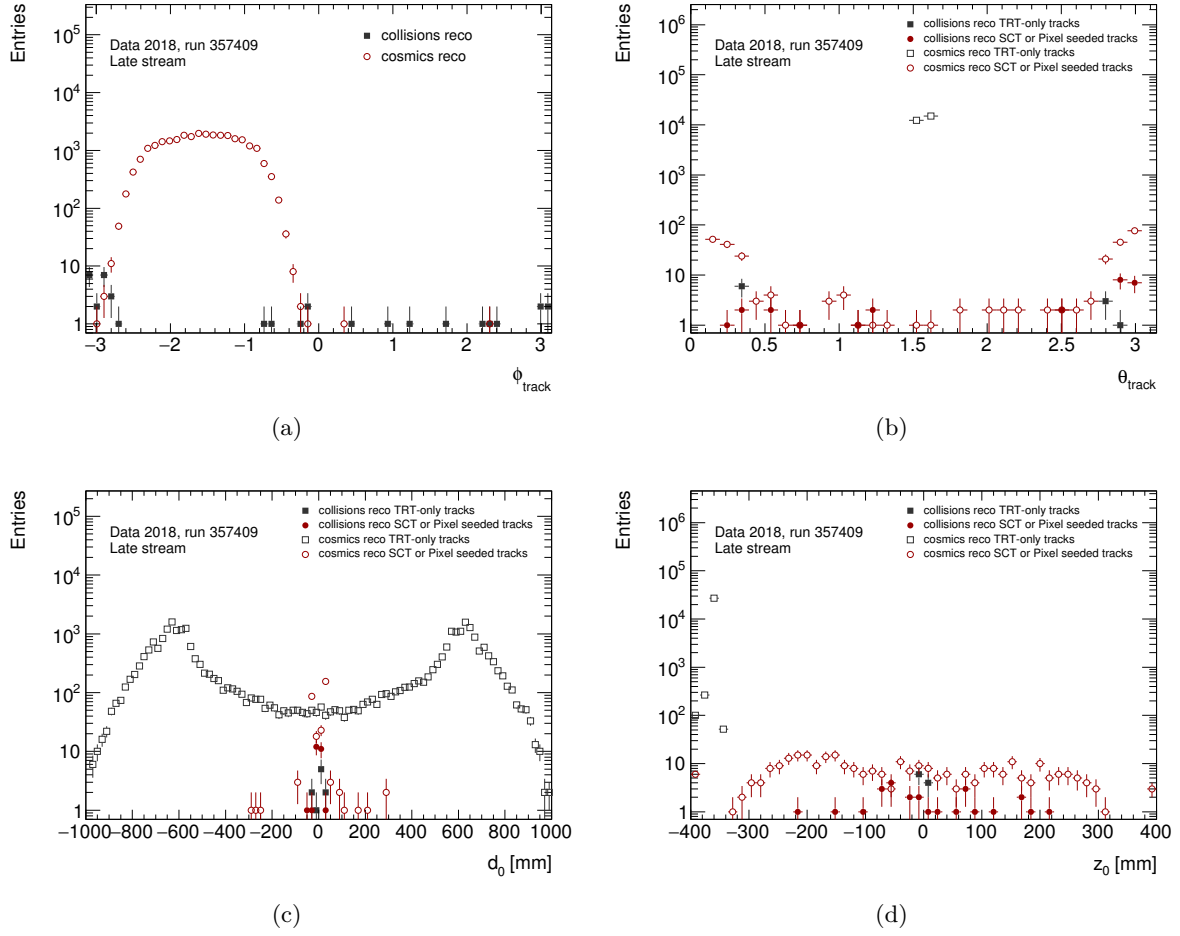


Figure 5.3.12: Distribution of track ϕ (a), θ (b), d_0 (c) and z_0 (d) in a collision run reconstructed with *cosmics* and *collisions* configuration depicted by empty and filled markers, respectively. The distributions of track θ , d_0 and z_0 are further split in TRT-only and SCT or Pixel seeded tracks in black squares and red circles, respectively.

It was observed that the track multiplicity rises with the instantaneous luminosity as depicted in Figure 5.3.13 for four runs with different peak instantaneous luminosities. The increase in the instantaneous luminosity causes a higher occupancy in the TRT and thus more tracks are reconstructed. The occupancy is not reduced significantly before several microseconds have passed; hence the gaps in between paired bunch crossings in a regular filling scheme, $\approx 0.5 \mu\text{s}$, are not long enough.

In regard of the vast number of, especially TRT-only, tracks which are an artefact of the looser reconstruction requirements or originating from pile-up, ID tracks are not further used in this analysis.

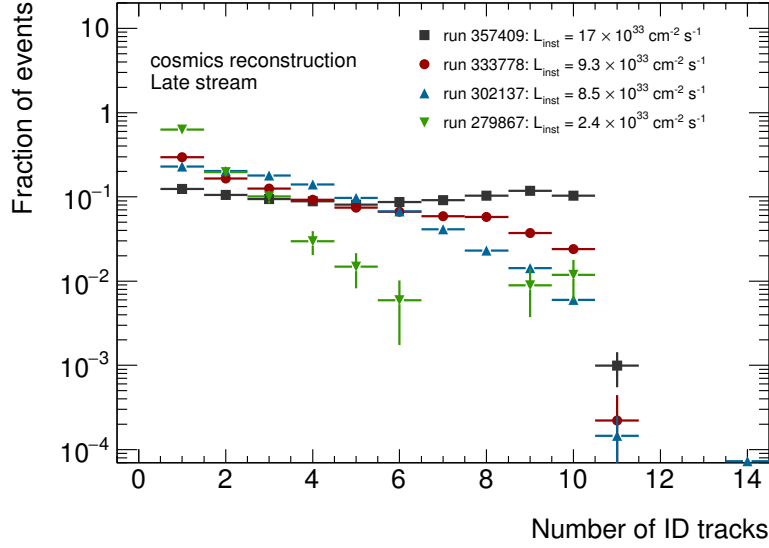


Figure 5.3.13: Number of ID tracks reconstructed with *cospics* reconstruction settings for four collision runs with different peak instantaneous luminosities, L_{inst} .

5.4 Event Selection & Jet Cleaning

The events selected for the search region were recorded in **empty** and **firstempty** bunch crossings, passing the requirements of the HLT_j55_0eta240_xe50_L1J30_[FIRST]EMPTY trigger. Only events that pass the GRL are considered to ensure that the selected events are of good quality. Events where one or more sub-detectors encountered problems are discarded. Motivated by the HLT thresholds of the signal trigger, only events with at least one jet with $p_T > 60$ GeV and $|\eta| < 2.4$ are taken into consideration. As introduced in 5.3.4, events with a PV reconstructed in *collisions* configuration are removed from the sample to suppress collision background. The impact of the PV veto on data recorded in **unpaired** bunch crossings is more dramatic than on **empty** and **firstempty** bunch crossings owing to the abundance of proton-proton collisions of the filled beam and trailing ghost bunches in the other beam. This is discussed in detail in Section 5.5.2. The PV cut has a negligible effect on simulated signal events overlaid with randomly triggered events. The aforementioned selection cuts are referred as “preselection” in the following. Table 5.4.1 summarises the event counts for data recorded in the **Late** stream in 2016–2018, a 2016 cosmic run and simulated signal samples with the same gluino mass but three different mass splittings. The selection efficiencies of each cut is calculated with respect to the preselection in data and with respect to the raw count of reconstructed simulated signal events. The **firstempty** dataset is not included in the event selection and jet cleaning studies. Appendix B.8 summarises investigations of the usability of data recorded for **firstempty** bunch crossings in the stopped particle analysis.

Motivated by the signal trigger a cut on HLT $E_T^{miss} > 50$ GeV is applied. By definition the efficiency of this cut is 100 % for data collected with the signal trigger (c.f. Figure 5.4.1(left)), while it ranges from ≈ 35 % up to ≈ 82 % for the small and large mass splittings, respectively. In order for the trigger to be fully efficient relative to the leading jet p_T , it is enforced that $p_T^{l, jet} > 100$ GeV. Figure 5.4.1(right) shows the trigger efficiency from which this threshold is derived from. Further, leading jets have to pass the cleaning criteria tailored for this analysis which are described in Section 5.4.1. These cleaning standards are met by 70 % of the signal events with a medium or high mass splitting but only by less than 20 % for small mass splitting or data events. The event yields for the combination of all cuts is given in the bottom row of Table 5.4.1. The presented event and leading jet selection cuts reduce the number of data

Selection	Number of events		Number of simulated signal events		
	Data 2016–2018	Cosmics 2016	$m(\tilde{g}) = 1400 \text{ GeV}$	$m(\tilde{g}) = 1400 \text{ GeV}$	$m(\tilde{g}) = 1400 \text{ GeV}$
	Late stream	run 306147	$m(\tilde{\chi}_1^0) = 100 \text{ GeV}$	$m(\tilde{\chi}_1^0) = 900 \text{ GeV}$	$m(\tilde{\chi}_1^0) = 1300 \text{ GeV}$
			+ random	+ random	+ random
Raw			8705 (100 %)	8571 (100 %)	8648 (100 %)
Preselection	5081560 (100 %)	11879 (100 %)	7192 (82.62 %)	6844 (79.85 %)	4350 (50.30 %)
HLT $E_T^{\text{miss}} > 50 \text{ GeV}$	5081560 (100 %)	6522 (54.90 %)	7112 (81.70 %)	6665 (77.76 %)	2997 (34.66 %)
$p_T^{\text{jet}} > 100 \text{ GeV}$, $ \eta < 2.4$	2544567 (50.07 %)	4182 (35.20 %)	7023 (80.68 %)	6421 (74.92 %)	1690 (19.54 %)
Jet cleaning	1575718 (31.01 %)	11041 (93.69 %)	6985 (92.95 %)	6755 (78.81 %)	6325 (73.14 %)
Total	616881 (12.14 %)	3853 (32.44 %)	6552 (75.27 %)	6016 (70.19 %)	1677 (19.39 %)

Table 5.4.1: Number of events that fulfil the event selection criteria, summarised for collision data recorded in 2016–2018, the 2016 cosmic run and three simulated signal samples with the same gluino mass but different mass splittings. The cuts are applied distinctively in addition to the preselection for data. The total event yields, reached after all cuts are combined, are given in the last row. The cut efficiencies, given in the brackets, are with respect to the preselection in data and with respect to the raw count of reconstructed simulated signal events.

events to only 12 % with respect to the preselection, mainly due to the p_T^{jet} restriction and jet cleaning. More than 70 % of the generated signal events for high and medium mass splittings remain. However, for the low mass splitting this is the case for only about 20 % of the events. This low efficiency is driven by the restriction on the leading jet p_T which also explains the low individual efficiency of the HLT E_T^{miss} cut as there is a strong correlation. However, both selection criteria are inevitable as they are dictated by the signal trigger.

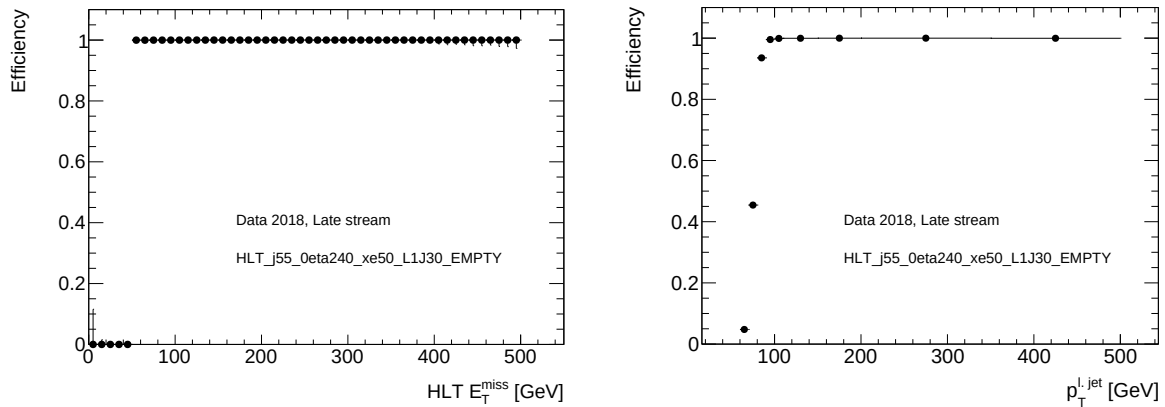


Figure 5.4.1: Efficiency of the HLT_j55_0eta240_xe50_L1J30_EMPTY trigger relative to the L1_J30_EMPTY trigger in the Late stream in 2018 as a function of HLT E_T^{miss} (left) and p_T^{jet} (right).

5.4.1 Jet Cleaning

Jet cleaning is essential to reduce the number of jets induced by detector noise and non-collision background, and to select good quality jets which could originate from a potential signal. Four different jet cleaning working points are predefined based on various calorimeter quantities [138]. However, they are optimised for jets originating from proton-proton collisions at the IP and hence not applicable to the presented analysis as signal jets are expected to be out-of-time, non-projective, odd-looking and might not fulfil all requirements and even mimic detector noise. To avoid vetoing such jets, a customised cleaning was developed which is partially based on the LooseBadLLP working point. Table 5.4.2 summarises the variables used.

Name	Description
EMFrac	Fraction of the jet energy deposited in the EM calorimeter
HECFrac	Fraction of the jet energy deposited in the HEC
fracSamplingMax	Index of the layer where the highest fraction of the jet energy is deposited
fracSamplingMaxIndex	Maximum fraction of the jet energy deposited in a single calorimeter layer
n90	Minimum number of clusters holding 90 % of the jet energy
LArQuality	Fraction of jet energy corresponding to clusters with a Q -factor greater than 4000
averageLArQF/65535	Relative LAr quality factor computed as the energy squared cluster mean quality ⁴
HECQuality	Same as LArQuality except calculated only for HEC clusters
negativeE	Sum of negative energy measured in the clusters associated to the jet

Table 5.4.2: Names and descriptions of the variables used in the jet cleaning.

The jet cleaning is only applied on leading jets, as sub-leading jets are not considered in this search. The variables sensitive to the jet quality, listed in Table 5.4.2 are combined to cuts targeting different types of jets induced by noise or non-collisions background. In the following, they are referred to as “standard” if they are adopted from the LooseBadLLP working point, the notation “custom” is used if they were modified or added. Each cut and its purpose is summarised in this list:

- PS noise (custom):

`!(fracSamplingMaxIndex==0 || fracSamplingMaxIndex==4)`

- Isolated activity in LAr (modified standard):

`!((fracSamplingMax>0.9 && fracSamplingMaxIndex<12))`

⁴The LAr quality factor is defined in Equation 3.2.5 in Section 3.2.2. It is computed by a DSP chip in a 16-bit word, and thus limited to $2^{16}-1=65535$. Hence, the relative average LAr quality factor is the LAr quality factor averaged over all cells divided by this saturation value.

- Isolated activity in LAr (custom):

`!((n90==1 && fracSamplingMaxIndex<12))`

- EM calorimeter noise (standard):

`!(EMFrac>0.95 && abs(LArQuality)>0.8
&& abs(eta)<2.8 && AverageLArQF/65535.>0.8)`

- Noise bursts (custom):

`!(fracSamplingMaxIndex>4 && fracSamplingMaxIndex<7)`

- HEC noise and beam-induced background (custom):

`!(HECFrac>0.9)`

- HEC spikes (standard):

`!(HECFrac>0.5 && abs(HECQuality)>0.5 && averageLArQF/65535>0.8)`

- Beam halo (standard):

`!(abs(negativeE)/1000.>4. && fracSamplingMax>0.85)`

The impact of each jet cleaning step was studied individually in a collision run (c.f. Table 5.3.1 for details) and three simulated signal samples with the same gluino mass but different mass splittings. Data from the cosmic run are included in these studies as well, as they are crucial for the design of a veto of cosmic-induced background (c.f. Section 5.5.1). The event yields and individual cut efficiencies are listed in Table 5.4.3. The applied preselection extends the aforementioned definition: The cut on HLT $E_T^{\text{miss}} > 50$ GeV and leading jet $|\eta| < 2.4$ are both applied but p_T^{jet} is lowered to be larger than 80 GeV as opposed to Table 5.4.1.

The jet cleaning results in the rejection of almost $3/4$ of events recorded with the signal trigger, but less than 7 % of the investigated simulated signal events. The high rejection efficiency for data is acceptable as the low rejection efficiency for simulated signal events suggests that only few potential signal events are removed. Hence, the jet cleaning predominantly rejects background events. Only about 7 % of jets induced by cosmic muons are considered not clean based on the outlined cleaning cuts which underlines the significance of a dedicated effective cosmic background veto. In the following each jet cleaning cut is discussed in detail.

Presampler Noise (custom)

The PS layers (`fracSamplingMaxIndex = {0, 4}`⁵) of the LAr calorimeter are comparatively narrow and prone to noise. Signal jets are not expected to have the maximum fraction of their energy deposited in these layers; hence such jets are rejected to reduce the contamination by noise. A notable fraction of leading jets in a collision run have their maximum energy fraction in the PS as depicted in Figure 5.4.2. Less than 1 % of signal, but 10 % of all leading jets in collision data are affected.

⁵The indices assigned to the individual calorimeter sampling layers can be found elsewhere [139].

Selection	Number of events		Number of simulated signal events		
	Data 2016–2018	Cosmics 2016	$m(\tilde{g}) = 1400 \text{ GeV}$	$m(\tilde{g}) = 1400 \text{ GeV}$	$m(\tilde{g}) = 1400 \text{ GeV}$
	Late stream	run 306147	$m(\tilde{\chi}_1^0) = 100 \text{ GeV}$	$m(\tilde{\chi}_1^0) = 900 \text{ GeV}$	$m(\tilde{\chi}_1^0) = 1300 \text{ GeV}$
			+ random	+ random	+ random
Preselection	4459669 (100 %)	5731 (100 %)	7062 (100 %)	6542 (100 %)	2679 (100 %)
PS noise	3981372 (89.28 %)	5721 (99.83 %)	7015 (99.33 %)	6488 (99.17 %)	2671 (99.70 %)
Isolated activity in LAr (mod. st.)	1798495 (40.33 %)	5430 74 (94.75 %)	6905 (97.78 %)	6398 (97.80 %)	2651 (98.95 %)
Isolated activity in LAr (custom)	2332758 (52.31 %)	5413 (94.45 %)	6989 (98.97 %)	6434 (98.35 %)	2663 (99.40 %)
EM noise	3945426 (88.47 %)	5711 (99.65 %)	7062 (100 %)	6542 (100 %)	2679 (100 %)
Noise bursts	4117200 (92.32 %)	5704 (99.53 %)	6940 (98.27 %)	6448 (98.56 %)	2679 (100 %)
HEC noise	3868360 (86.74 %)	5640 (98.41 %)	6872 (97.31 %)	6383 (97.57 %)	2678 (99.96 %)
HEC spikes	4340735 (97.33 %)	5728 (99.95 %)	7062 (100 %)	6542 (100 %)	2679 (100 %)
Beam halo	4240895 (95.09 %)	5705 (99.55 %)	6988 (98.95 %)	6465 (98.82 %)	2678 (99.96 %)
Total	1138793 (25.54 %)	5316 (92.76 %)	6598 (93.43 %)	6129 (93.69 %)	2631 (98.21 %)

Table 5.4.3: Event yields following various jet cleaning cuts. The preselection is applied on data events. Each jet cleaning cut is applied one at a time so that the yields reflect the number of events resulting from the preselection plus the specified cleaning cut only. The cut efficiency with respect to the preselection are given in parentheses. The event yields and efficiencies of all cuts combined are given in the bottom row.

Isolated Activity in LAr (modified standard)

For the LooseBadLLP working point jets within $|\eta| < 2$ and more than 99 % of their energy in a single sampling layer are rejected. This requirement was found to be too strict as a substantial number of simulated signal jets deposit most of their energy in a single layer of the Tile barrel calorimeter as depicted in Figure 5.4.2. However, in collision data about 90 % of leading jets deposit more than 90 % of their energy in one of the LAr calorimeter layers while this ratio is inverted for simulated signal jets, as shown in Figure 5.4.3(left) and Figure 5.4.4. Hence, the condition on the maximum energy fraction per sampling layer was increased to 90 % but only for leading jets which deposit most of their energy in the LAr EM barrel, end-cap calorimeters and HEC (`fracSamplingMaxIndex` < 12). The rejection efficiency of this cleaning cut is almost 60 % for collision data and only about 2 % for simulated signal events.

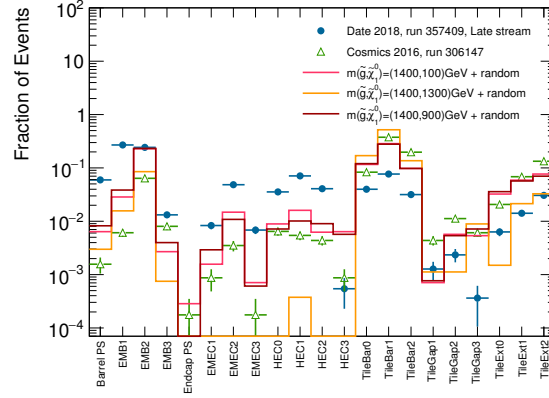


Figure 5.4.2: The sampling layer index with the maximum fraction of energy, `fracSamplingMaxIndex`, of leading jets recorded in the `Late` stream of a collision run (blue), the cosmic run (green) and leading jets originating from simulated signal events for a 1400 GeV gluino and 100 GeV (orange), 500 GeV (red) and 1300 GeV (pink) mass splittings.

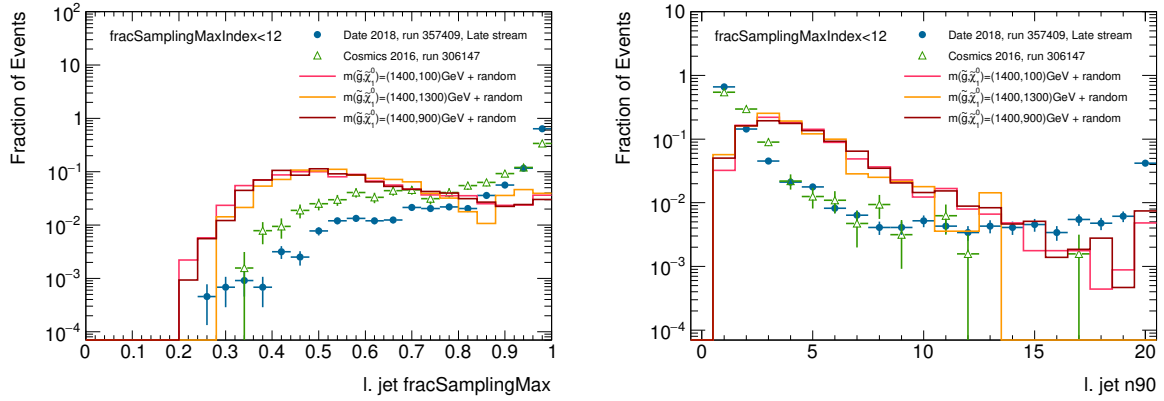


Figure 5.4.3: Maximum energy fraction in one sampling layer, `fracSamplingMax`, (left) and number of clusters holding 90 % of the energy, `n90`, (right) of leading jets recorded in the `Late` stream of a collision run (blue), the cosmic run (green) and leading jets originating from simulated signal events for a 1400 GeV gluino and 100 GeV (orange), 500 GeV (red) and 1300 GeV (pink) mass splittings.

Isolated Activity in LAr (custom)

Signal jets are expected to have more than 90 % of their energy spread over at least two clusters if they are located in the EM calorimeter or HEC (Figure 5.4.5). While the energy of most of such jets recorded in collision data is localised in a single cluster as shown in Figure 5.4.3(right). To further reduce the number of jets induced by noise in the LAr calorimeter, it is required that 90 % of the leading jet energy is spread over at least two clusters. This requirement is not enforced for jets which deposit most of their energy in the Tile calorimeter as a significant number of signal jets would be removed due to the larger cell and hence cluster size in this sub-detector. The rejection efficiency of this cleaning cut is almost 50 % for collision data and less than 2 % for simulated signal events.

EM Calorimeter Noise (standard)

The impact of noise in the EM calorimeter is further minimised by only considering leading jets with a LAr quality and relative average LAr quality factor below 80 %. As these quantities are

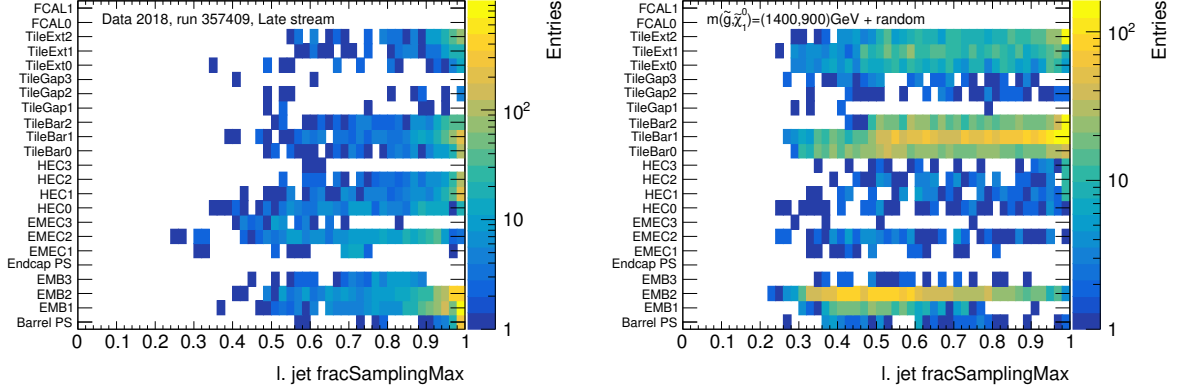


Figure 5.4.4: The sampling layer index, `fracSamplingMaxIndex`, versus maximal energy fraction in one sampling layer, `fracSamplingMax`, of leading jets recorded in the `Late` stream of a collision run (left) and simulated signal events with a 1400 GeV gluino and 500 GeV mass splitting (right).

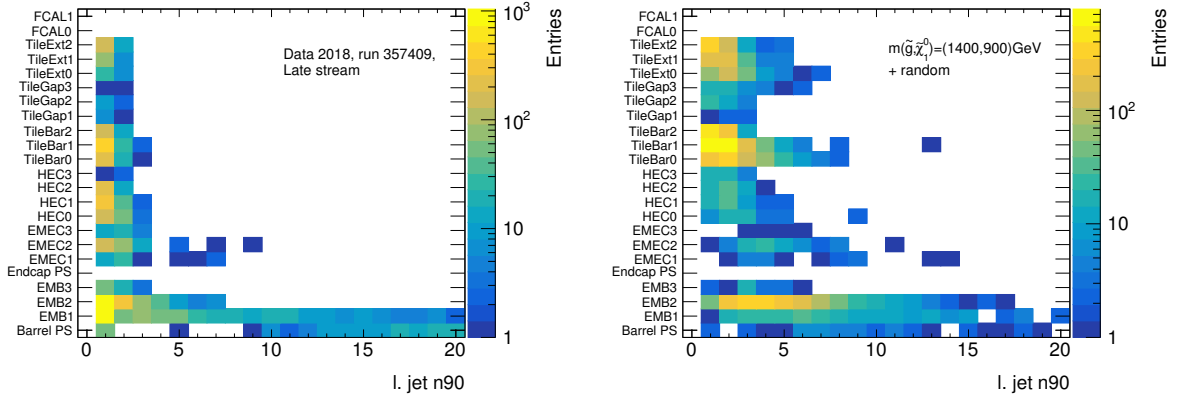


Figure 5.4.5: The sampling layer index with the maximum fraction of energy, `fracSamplingMaxIndex`, versus number of clusters holding 90 % of the energy, `n90`, for leading jets recorded in the `Late` stream of a collision run (left) and leading jets in simulated signal events with a 1400 GeV gluino and 500 GeV mass splitting (right).

specific for the LAr calorimeter, the selection is only applied on leading jets with $|\eta| < 2.8$ and an EM fraction above 95 %. Figure 5.4.6 shows the LAr quality and relative average LAr quality factor for such jets recorded in a collision and the cosmic run, and simulated signal events for three different mass splittings. This cleaning cut has no impact on simulated signal events but affects almost 12 % of jets from collision data.

Noise Bursts (custom)

Events with a leading jet with its maximum energy fraction in the EM calorimeter end-caps (`fracSamplingMax` = {4, 7}) are excluded to remove any potential noise due to noise bursts by definition (c.f. Section 3.2.7). For this analysis it is especially crucial to avoid any contamination from noise bursts as they mimic signal. Almost 8 % and less than 2 % of events in collision data and simulated signal events, respectively, are affected.

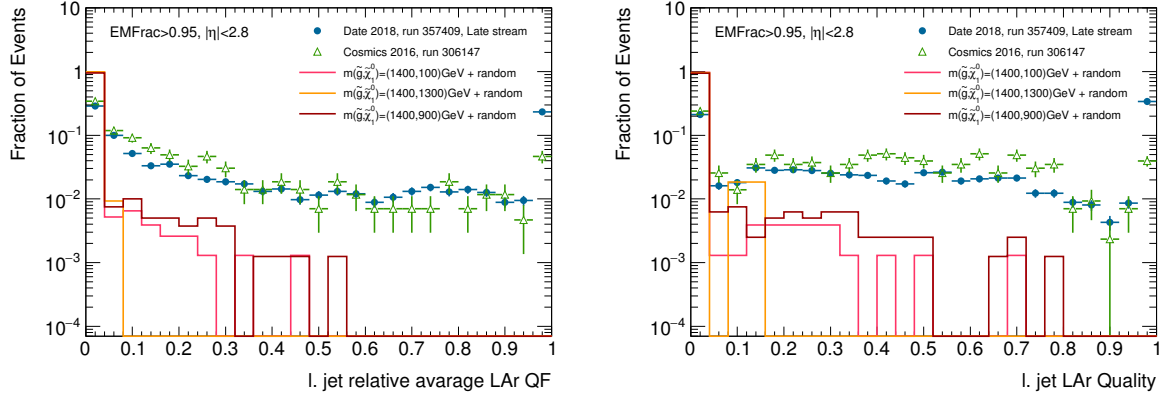


Figure 5.4.6: The relative average LAr quality factor (left) and LAr quality (right) of leading jets recorded in the **Late** stream of a collision run (blue), the cosmic run (green) and leading jets in simulated signal event with a 1400 GeV gluino and 100 GeV (orange), 500 GeV (red) and 1300 GeV (pink) mass splitting. Only jets with an EM fraction larger than 95 % are included.

HEC Noise & Beam-Induced Background (custom)

To reduce the number of jets induced by noise, it is exploited that such jets tend to be localised to one detector part. Thus, leading jets with a HEC fraction of 90 % and above are likely to be induced by noise rather than stem from signal and thus removed from the selection. Figure 5.4.7(left) compares the HEC fraction of leading jets in events from a collision run and simulated signal events. About 13 % of leading jets in collision data are characterised by a high HEC fraction, while this is only the case for less than 3 % of jets in simulated signal events.

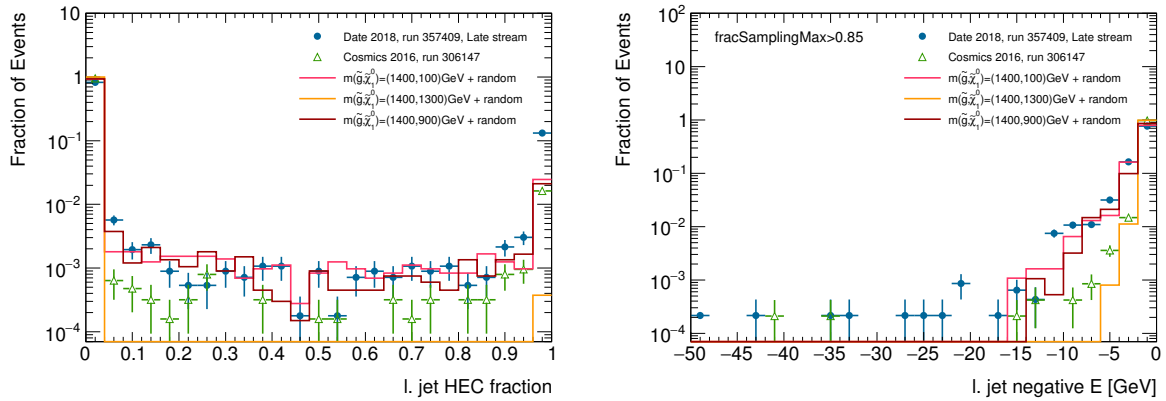


Figure 5.4.7: Left: The HEC fraction of leading jets recorded in the **Late** stream of a collision run (blue), the cosmic run (green) and leading jets in simulated signal events with a 1400 GeV gluino and 100 GeV (orange), 500 GeV (red) and 1300 GeV (pink) mass splitting. Right: The negative reconstructed energy for leading jets with a maximum energy fraction above 85 %.

HEC Spikes (standard)

In order to further suppress jets originating from spikes of noise in the HEC, leading jets with a HEC fraction above 50 % are only considered if their HEC quality and relative average LAr quality are below 50 % and 80 %, respectively. Both quality factors for leading jets with more than half of their energy deposited in the HEC are shown in Figure 5.4.8. This cleaning cut has no impact on simulated signal events but affects almost 3 % of jets from collision data.

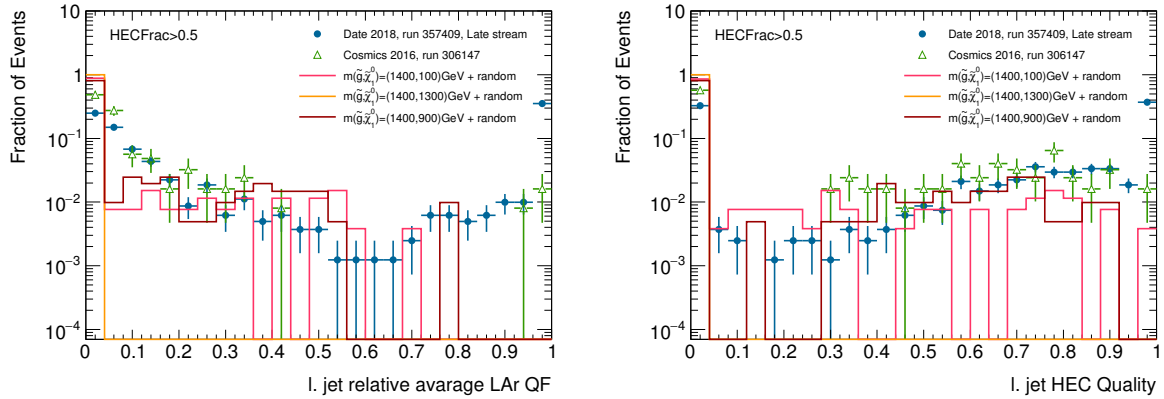


Figure 5.4.8: The relative average LAr quality factor (left) and HEC quality (right) of leading jets recorded in the **Late** stream of a collision run (blue), the cosmic run (green) and leading jets in simulated signal events with a 1400 GeV gluino and 100 GeV (orange), 500 GeV (red) and 1300 GeV (pink) mass splitting. Only jets with a HEC fraction larger than 50 % are included.

Beam Halo (standard)

In previous dedicated studies [140] on jet cleaning it was observed that fake jets induced by beam halo can be suppressed by removing jets with a negative reconstructed energy below -4 GeV given an energy fraction per sampling layer of above 85 %. Figure 5.4.9 shows the maximum energy fraction per sampling layer versus the negative reconstructed energy for jets recorded in a collision run and simulated signal events. For the latter it can be seen that on the one hand the spread of `fracSamplingMax` is large, especially to lower energy fractions per sampling layer; and on the other hand that in case of a large `fracSamplingMax` a very small negative reconstructed energy is likely. On the contrary, jets originating from beam halo tend to deposit almost all of their energy in only one sampling layer and have a longer tail towards high negative reconstructed energies which is confirmed in Figure 5.4.7(right). 5 % of leading jets from collision data, but less than 2 % from simulated signal events, are characterised by these features.

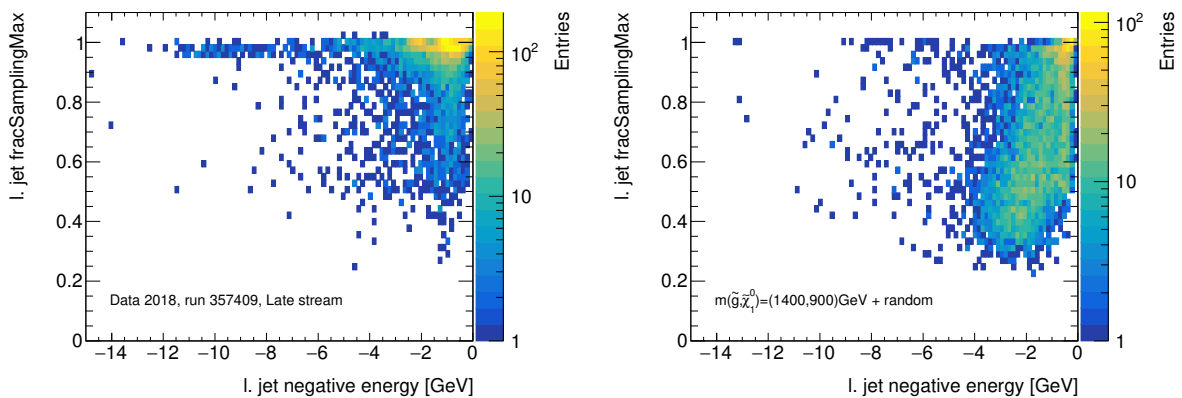


Figure 5.4.9: Maximum energy fraction in one sampling layer, `fracSamplingMax`, versus negative reconstructed energy of leading jets recorded in the **Late** stream of a collision run (left) and leading jets in simulated signal events with a 1400 GeV gluino and 500 GeV mass splitting (right).

5.5 Background Considerations

The presented search for stopped particles is conducted in **empty** and **firstempty** bunch crossings where the usual backgrounds expected in standard searches have a negligible impact. The relevant backgrounds for this analysis are:

- **Cosmic-induced background (CIB):** Muons from cosmic rays traversing the detector can induce energetic jets in the calorimeters;
- **Beam-induced background (BIB):** Stray protons interacting with the upstream collimators, the beam pipe or residual beam gas, producing energetic muons which traverse the detector in the horizontal plane and can induce energetic jets in the calorimeters;
- **Detector noise:** Spurious noise in the detector can induce signal-like features;
- **Cavern background:** Residual radiation in the detector cavern can cause spurious muon segment activity; and
- **Out-of-time pile-up:** Remnants from proton-proton collisions in filled BCIDs can provoke collision-like detector signatures.

Section 5.5.1 and 5.5.2 are dedicated to cosmic- and beam-induced background, respectively. Detector noise is briefly addressed in Section 5.5.3. The impact of cavern background and pile-up is mimicked by an overlay of signal and randomly triggered events, described in Section 5.1.6.

5.5.1 Cosmic-Induced Background

Energetic jets induced by muons from cosmic rays are the dominant background for this search as they have a longer high- p_T tail than other backgrounds, like BIB. Hence, this background must be suppressed as much as possible. Cosmic reconstruction settings provide an improved reconstruction efficiency for cosmic muons and are an asset in tagging cosmic muon events (c.f. Section 5.3). In order to study cosmic events in data, a dedicated cosmic run, with all sub-detectors active, as well as DQ sign-off was recorded in 2016 offering almost 11 hours of cosmic data-taking and over 900000 events recorded in the **physics_Main** stream (abbreviated **Main**) entirely free from BIB (c.f. Table 5.3.1). These events are used to study the detector-level geometry of cosmic events resulting in a geometrical cosmic veto exploiting calorimeter and muon system information. The construction of this geometrical cosmic veto is described in the following.

Geometrical Cosmic Veto

When a cosmic muon traverses the detector from top to bottom, it passes through the MS and is likely to induce detector signals which can be reconstructed as muon segments in both detector hemispheres which allows the identification of cosmic muon event candidates. Given the detector design it is likely that such a cosmic muon penetrates the calorimeters as well, and may cause a highly energetic jet as a consequence of bremsstrahlung. Unfortunately, a similar detector signature is expected from potential signal events, especially if the mass splitting is rather large. The highly energetic jets, which are produced in gluino decays, can punch through the calorimeter resulting in the reconstruction of several muon segments in one detector hemisphere. If signal punch through were to occur in conjunction with muon segments from spurious activity in the MS, a similar constellation of muon segments and jets as from cosmic muons is created. Hence, it is not sufficient to rely on the occurrence of muon segments in both detector hemispheres alone and rather use a more sophisticated approach exploiting the geometrical relation between muon segments and the leading jet. A discriminating quantity,

labelled $\alpha_{\cos}$, is defined as the smallest angle between the jet and the assumed path of the muon. Thus, $\alpha_{\cos}$ characterises the likelihood that the jet was produced by the muon. The construction of $\alpha_{\cos}$ follows these four steps:

- ① find top-bottom muon segment pairs,
- ② account for detector inefficiencies at $\eta=0$ ($\eta=0$ check),
- ③ calculate points of closest approach between the muon segment pair and leading jet, and
- ④ extract the smallest angular distance between these points, called $\alpha_{\cos}$.

The presented studies are conducted on data recorded in the 2016 cosmic run and simulated signal samples for different mass points, whereby the following preselection was applied:

- no PV,
- HLT_j0_L1J12_EMPTY (cosmic run only),
- at least one jet,
- leading jet $p_T > 80$ GeV, $|\eta| < 2.4$,
- HLT $E_T^{\text{miss}} > 50$ GeV, and
- jet cleaning (c.f. Section 5.4.1).

Further, only muon segments which meet the requirements outlined in Section 5.3.2 are taken into consideration.

First, the reconstructed muon segments are categorised in top and bottom segments based on their position in Cartesian coordinates. Subsequently, top and bottom segments are paired, whereby each possible pairing is considered valid as long as the pointing direction vector of at least one of them points towards the direction of the other one.

This condition is deemed satisfied providing that the angle between the pointing direction vector of one of the segments and a straight line connecting the segment pair is less than 0.8. This threshold was chosen based on a study conducted in a di-muon selection in the 2016 cosmic run, and attempts to account for the distortion of the cosmic muon path due to the magnetic field.

For this study only the muon segments associated to the two muons are considered, whereby the set of associated segments must lie in opposite sides in ϕ . Hence, it can be assumed that the two reconstructed muons are two legs of the same cosmic muon. The jet and HLT E_T^{miss} related selection criteria are ignored in this study as the only relevant physics objects are muons and muon segments. Figure 5.5.1(left) shows the angle between the position of a reconstructed muon segment associated with one of the two muons and the position of the “ghost segment” that would exist if a dummy segment is inserted at the space point where the extrapolated pointing direction vector of the reconstructed segment intersects with the plane at the z -coordinate of the reconstructed segment associated to the other muon. The distribution is steeply falling and peaks at very low angles close or equal to zero as most segments in a pair point to one another as they originate from the same cosmic muon. Slightly larger values can be explained by the influence of the magnetic field on the muon trajectory. The long tail towards higher values likely originates from spurious muon segment activity. This check is conducted for the pointing direction vectors of both segments but has to be fulfilled only for one of them. This study also confirms the validity of the straight-line approach.

Step ② addresses the inefficiencies related to the lack of coverage in the service gap in the MS at $\eta=0$ which may result in no segment being reconstructed due to missing detector

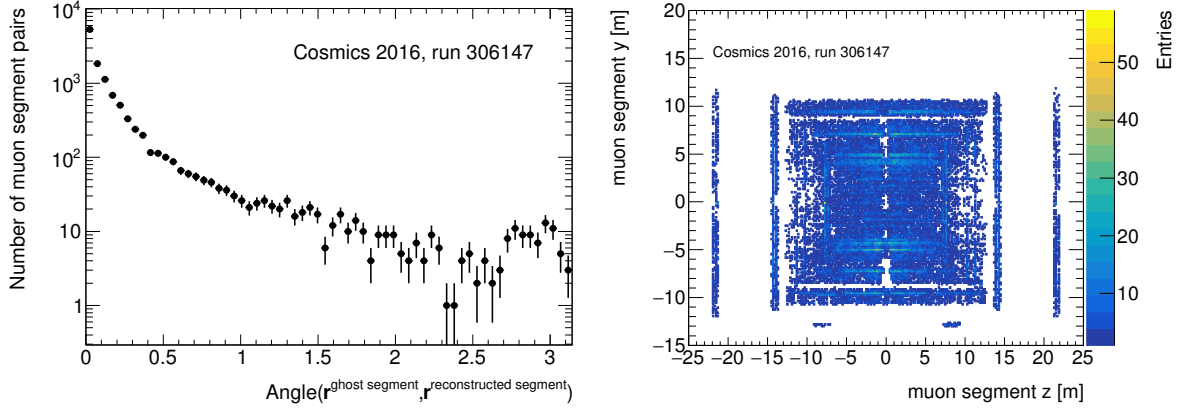


Figure 5.5.1: Left: Relative angle between the position vector of the “ghost segment” and the reconstructed segment with the same z -component and in the same detector hemisphere. The position of the “ghost segments” is defined as the intersection of the to the opposite detector hemisphere extended pointing direction vector of one reconstructed segment associated to a muon and the plane at the z -position of a reconstructed segment of the other muon. Right: Position of reconstructed muon segments in the η - ϕ -plane, revealing the lack of coverage in at $\eta=0$

information (c.f. Figure 5.5.1(right)). Therefore, the pointing direction vector of each muon segment is extrapolated to the opposite detector side in ϕ until it crosses the plane at $\eta=0$. If this intersection lies within the radius otherwise instrumented with the MS, a “ghost segment” is inserted at this position and further dealt with as with reconstructed segments described in step ①. The validity of this approach is studied in the aforementioned di-muon selection in the 2016 cosmic run. Given the di-muon selection, the extrapolated pointing direction vector of a segment associated to one of the muons should reach a position on the opposite detector side in ϕ close to the position of one of the segments associated to the other muon. The stopping criteria for the extrapolation is defined by fixing the z -component of the extrapolated pointing vector to the z -coordinate of the reconstructed segment associated to the other muon. A “ghost segment” is inserted at the intersection point of the extrapolated pointing vector of a muon segment of one of the muons and the plane at the z -coordinate of the segment of the other muon. If the described extrapolation approach is reliable the position of the “ghost segment” and the segment which was the target have to be close to each other. Figure 5.5.2(left) shows the radius versus ϕ of the reconstructed muon segments displaying the structure of the MS stations clearly. The same distribution for the “ghost segments” is shown in Figure 5.5.2(right) revealing a similar structure with very few outliers. This confirms that the proposed extrapolation approach is successful and hence validates the $\eta=0$ check.

Now that all valid muon segment pairs are defined, their location relative to the leading jet in the events can be examined. The points of closest approach between the line connecting the muon segment positions and the line defined by the η and ϕ of the jet are calculated. Hence, a set of two space points per muon segment pair is defined. This array of pairs of points is further reduced by requiring that both points of closest approach must be located within the boundaries of the calorimeter volume. This removes many events with a valid muon segment pair and a jet which was not induced by the cosmic muon from the list of potential background events. This is a likely scenario for signal events with the overlay of random events taken into account.

The final step, is the determination of α_{cos} which is defined as the minimum ΔR between the points of closest approach for each of the remaining sets. A visualisation of α_{cos} is given in Figure 5.5.3. Figure 5.5.4 shows the α_{cos} distribution for events recorded in the cosmic run and simulated signal events for three different mass points. Three default bins below 0 are

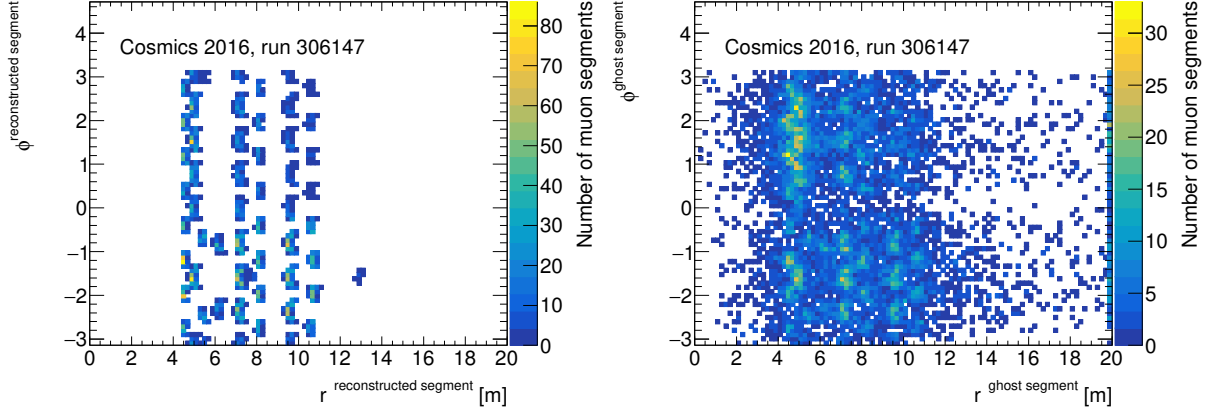


Figure 5.5.2: Muon segment position in the r - ϕ -space for reconstructed segments associated to muons in a di-muon selection using events recorded in the cosmic run (left). The same distribution is shown on the right for “ghost segments”, whereby their position is defined as the intersection of the to the opposite detector hemisphere extended pointing direction vector of one reconstructed segment associated to a muon and the plane at the z -position of a reconstructed segment of the other muon.

included in the distribution accounting for different reasons for which the calculation of α_{cos} is not possible. A value of -1 is assigned in case no segments that pass the selection criteria from Section 5.3.2 are in the event, which is rarely the case for cosmic data events but affects about 20 % of simulated signal events. In case no valid segment pairing can be established, whether it be due to the restriction on the position of the segments with respect to the pointing of their pointing direction vectors or the absence of segments in one detector hemisphere, a default value of -0.7 is allocated. Again this applies more often for simulated signal than cosmic data events. A default value of -0.3 is given if the two points of closest approach can be calculated but are rejected as one or both reside outside of the calorimeter volume. Given the characteristics of cosmic data and simulated signal events this is more likely to be true for the latter. Cosmic events tend to have small α_{cos} values since a jet induced by a cosmic muon is in close proximity of the muon itself and hence the line connecting the segments associated to the muon. While for signal events α_{cos} peaks less dramatically and a large fraction of events reside in the long tail or are assigned to one of the default values. It is worth noting that α_{cos} is very different for signal depending on whether the simulated signal events are combined with randomly collected events or not, which is shown in Appendix B.6. Based on the α_{cos} distribution in Figure 5.5.4, events with $|\alpha_{\text{cos}}| < 0.2$ are rejected.

The cosmic background rejection efficiency versus the signal efficiency of this geometrical cosmic veto ($|\alpha_{\text{cos}}| > 0.2$) with respect to the above mentioned preselection is shown in Figure 5.5.5. A cosmic background rejection efficiency of 90 % and a signal efficiency ranging from 81 % to 96 % for high and low mass splittings for simulated 1400 GeV gluinos can be achieved. The lower efficiency for high mass splittings can be explained by the increased likelihood of jets from the gluino decay punching through into the MS resulting in more reconstructed muon segments. The performance of different versions of the α_{cos} veto are included in the efficiency curve. In case of omitting step ② of the procedure, a higher signal efficiency can be achieved at the cost of lowering the background rejection rate. As the signal efficiency is still satisfactory the gain in background rejection is prioritised and hence the $\eta = 0$ check is not discarded from the α_{cos} calculation. Although the full α_{cos} veto is very powerful in rejecting cosmic background, it is possible to further reduce the remaining contamination from background events by removing all events with a reconstructed muon. The signal efficiency for the low and medium mass splitting point drops to 63 % and 74 %, respectively, but remains above 90 % for a smaller mass splitting.

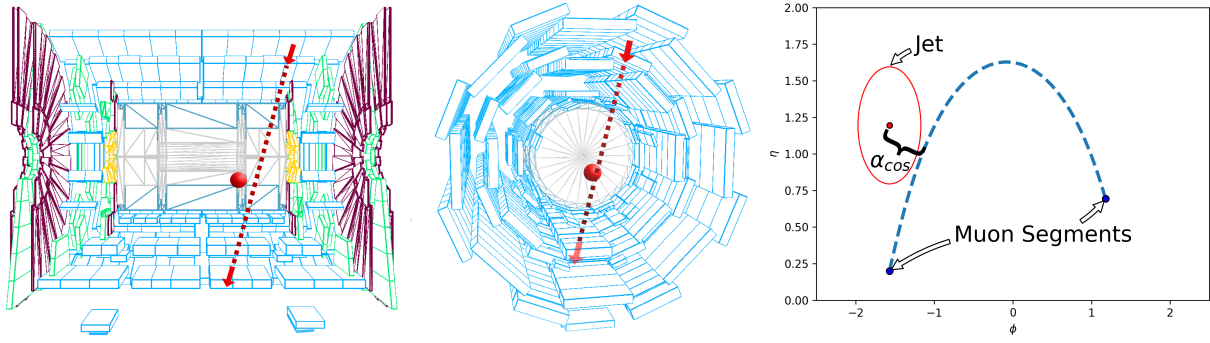


Figure 5.5.3: Illustration of the procedure to determine $\alpha_{\cos}$. A sideways and frontal view of the MS are shown on the left and in the centre. A jet is depicted as red sphere and the muon segments as red arrows, their direction is indicated by the pointing of the arrow. The red dashed line connects the position of the muon segments in Cartesian space. The representation in η - ϕ -space is shown on the right. $\alpha_{\cos}$ is indicated as the smallest angular distance between the jet and the muon segment connection (dashed blue line). Courtesy of Lawrence Lee, Jr.

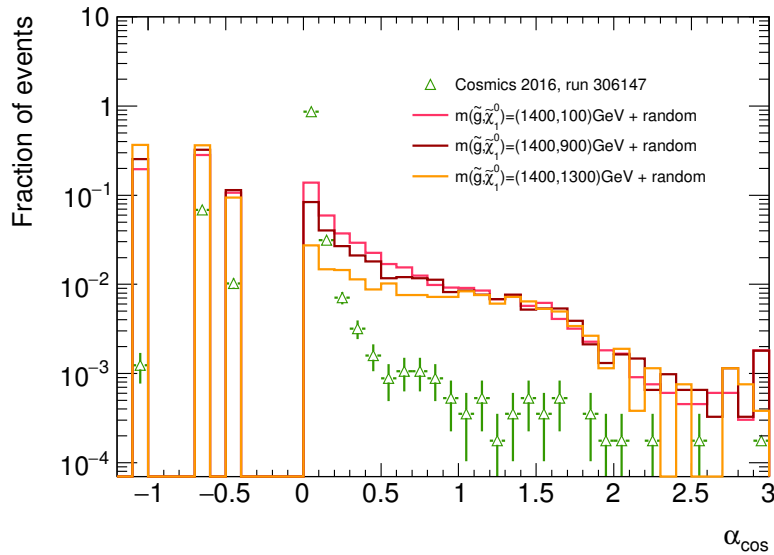


Figure 5.5.4: $\alpha_{\cos}$ for events recorded in the cosmic run (green) and simulated signal events with a 1400 GeV gluino and three different mass splittings of 1300 GeV (pink), 500 GeV (red) and 100 GeV (orange).

This loss in signal efficiency is justified in light of the gain in background rejection efficiency to almost 97%. Increasing the threshold on the angle between the line connecting the segment pair and the pointing direction vector of one of them to 1.5, has a negligible effect on the background rejection efficiency but decreases the signal efficiency notably. Lowering the threshold to 0.4 on the other hand, increases the signal efficiency but at the expense of reducing the background rejection power. However, the impact of this threshold is less relevant if the additional muon veto is considered. Hence, 0.8 is kept as upper threshold. Based on these studies the veto of cosmic-induced background used throughout the rest of this chapter is defined such that only events with a $|\alpha_{\cos}| > 0.2$ and no reconstructed muon are accepted.

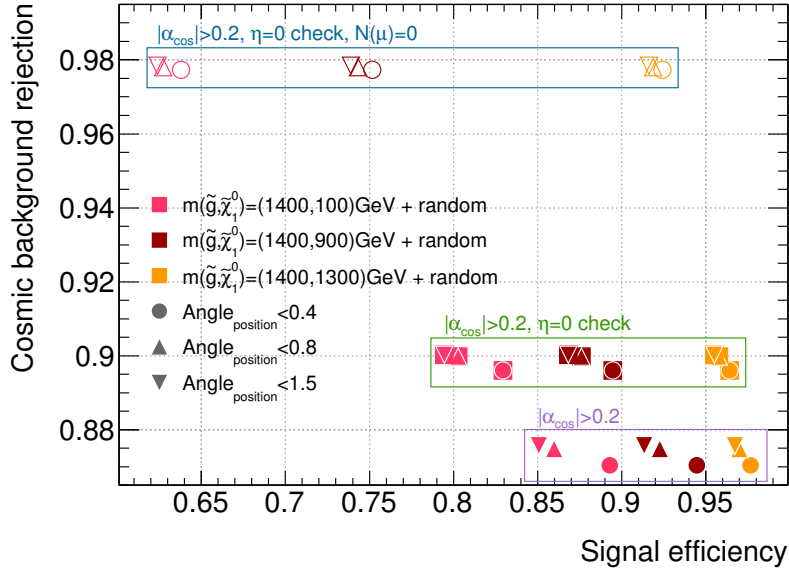


Figure 5.5.5: The cosmic background rejection efficiency and signal efficiency achievable for different configurations of α_{cos} and a fixed restriction of $|\alpha_{\text{cos}}| > 0.2$. The cosmic background rejection efficiency is extracted from data recorded in the cosmic run and calculated with respect to the preselection. The signal efficiency is shown for a 1400 GeV gluino and three different mass splittings of 1300 GeV (pink), 500 GeV (red) and 100 GeV (orange). Three different thresholds, of 0.4 (circle), 0.8 (upwards-pointing triangle) and 1.5 (downwards-pointing triangle) on the constraint of the positioning of muon segments in one pair are shown. The performance of an α_{cos} determination without the $\eta=0$ check is enclosed in the violet box. The results for including this step in the determination of α_{cos} is marked by the green box. The impact of an additional muon veto is represented by the blue box.

5.5.2 Beam-Induced Background

Beam-induced background is the second most dominant background for this analysis behind CIB. The geometrical cosmic veto described in Section 5.5.1 partially suppresses BIB, but further dedicated measures are essential to reduce it to an acceptable level. BIB originates from stray protons that collide with residual beam gas, the beam pipe or upstream collimators.⁶ The latter causes the dominant form of BIB for this analysis: beam halo. Due to the positioning of the collimators with respect to the detector and the bending of the LHC dipoles, beam halo tends to occur in the horizontal plane, provoking characteristic bands at $\phi=0$ and $\pm\pi$ stretching over the entire η range in the jet population in the η - ϕ -plane. BIB can be observed in isolated and non-isolated **unpaired**, as well as **empty** and **firstempty** BCIDs, while the relative contribution of BIB with respect to other backgrounds changes. The characteristics of BIB discussed in the following have been studied in **unpaired** and **empty** bunch crossings recorded in the **Background** and **Late** stream, respectively. Different approaches were explored to suppress BIB based on jet quantities, the most efficient one exploits the width of the leading jet in the x - y -plane and is introduced in Section 5.5.2. An alternative approach is touched in Appendix B.7.

The presence of a filled bunch in only one beam makes **unpaired** bunches an ideal environment for BIB studies. Further, it is a data selection orthogonal to the signal region (which is confined solely to **empty** and **firstempty** bunch crossings). However, the number of isolated and non-isolated **unpaired** BCIDs in the bunch group schemes used during 2016–2018 data-taking was on average only 10 and 14, respectively, and thus the available dataset is limited. In the

⁶A more detailed discussion of beam-induced background can be found elsewhere [141, 142].

following the focus is on events that pass these selection criteria:

- L1_J[{12,50}]_UNPAIRED_[NON] ISO,
- at least one jet,
- leading jet $p_T > 80$ GeV, $|\eta| < 2.4$,
- jet cleaning,
- $|\alpha_{\cos}| > 0.2$ and no muon.

Events recorded with L1_J12_UNPAIRED and L1_J50_UNPAIRED triggers are combined to avoid the turn-on effect from the latter close to the leading jet p_T cut but profit from the higher statistics thanks to the lower prescales. Therefore, the events are weighted by the prescale of the trigger they have passed; the procedure is explained in Section B.2. Although jet cleaning is applied and some of its cuts already target beam halo, as discussed in Section 5.4.1, they might not be sufficient as they are motivated by studies relying on **paired** bunch crossings. Thus, a significant fraction of beam halo remains in **unpaired** as well as **empty** and **firstempty** bunch crossings, including the signal region. The veto of CIB (c.f. Section 5.5.1) is applied to select a sample enriched in beam halo and undiluted by cosmic-induced background.

Unpaired bunch crossings are contaminated by collisions of protons of the filled beam with protons from ghost bunches trailing the other beam. Both lead to jets uniformly distributed in the η - ϕ -plane. In order to suppress these events a veto on reconstructed PVs is applied. The PV veto and HLT $E_T^{\text{miss}} > 50$ GeV are strongly correlated. As the PV cut was introduced before the HLT E_T^{miss} selection, the latter is omitted here in order to demonstrate the impact of the PV veto. Only the data collected in 2018 were used in these dedicated studies.

Figure 5.5.6 shows the leading jet occupancy in the η - ϕ -plane separately for isolated and non-isolated **unpaired** bunches. The aforementioned bands at $\phi = 0$ and $\pm\pi$ are not visible in the distribution of events recorded in non-isolated bunches and only recognisable faintly for isolated bunches. This is explained by the pollution from proton-proton collisions which is especially severe for non-isolated bunch crossings due to the closeness to bunches with the other beam filled from which long tails of debunched protons and trailing ghost bunches originate; thus the likelihood of such collisions is increased. To cope with these, all events with a reconstructed PV are removed. This particularly affects events taken in non-isolated **unpaired** bunch crossings as only 5 % of the events remain with respect to the preselection, while about 33 % of isolated **unpaired** events pass this selection. Thanks to the PV veto the leading jet occupancy in the η - ϕ -plane changes dramatically revealing the beam halo characteristic bands at $\phi = 0$ and $\pm\pi$, as can be seen in Figure 5.5.7. A comparison of the leading jet ϕ and p_T of the events recorded in isolated and non-isolated bunches, see Figure 5.5.8, further confirms that a good agreement between both bunch groups is achieved if the PV veto is applied, which allows combining them to increase the number of events for BIB studies.

As beam halo depends on the equipment installed far away from the detector, a distinct difference in the contribution from one or the other beam is visible. The leading jet occupancy in the η - ϕ -plane is shown in Figure 5.5.9 for beam 1 (clockwise circulating) filled and beam 2 (anticlockwise circulating) empty and vice versa. As events from isolated and non-isolated bunches are combined and no PV veto is applied, the distributions are polluted by proton-proton collisions. Only for bunch crossings in which beam 2 is filled, a faint presence of beam halo features can be spotted. In case of beam 1 being filled the number of recorded events is significantly higher, predominantly due to pollution by collision events. This is a consequence of the bunch group scheme, in which the order of which beam is filled first is always fixed to beam 2, and the extraction from the PS. The kicker magnet for the beam extraction is timed to the beginning of the train but also extracts any trailing ghost bunches resulting in the **unpaired** trains to have

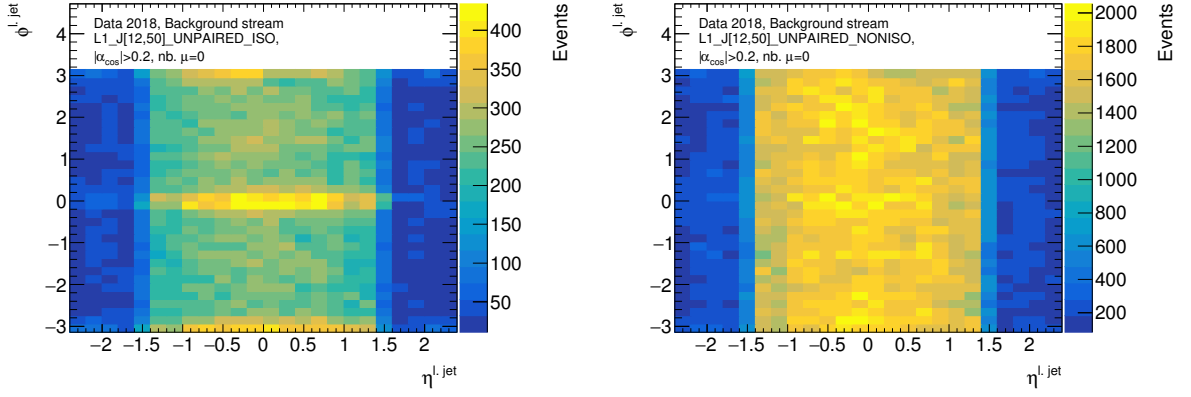


Figure 5.5.6: Leading jet occupancy in the η - ϕ -plane of events recorded in isolated (left) and non-isolated (right) **unpaired** bunch crossings in 2018 collision data.

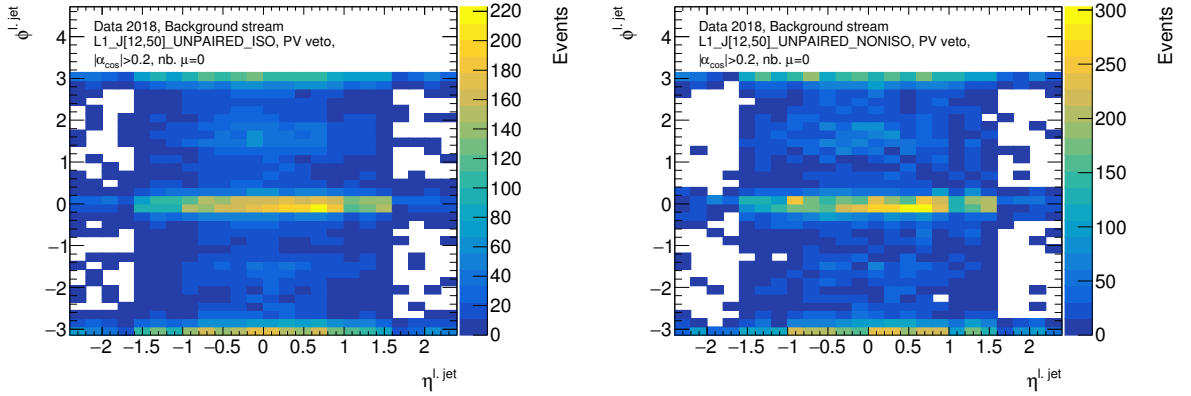


Figure 5.5.7: Leading jet occupancy in the η - ϕ -plane of events recorded in isolated (left) and non-isolated (right) **unpaired** bunch crossings in 2018 collision data. Only events without a PV are shown.

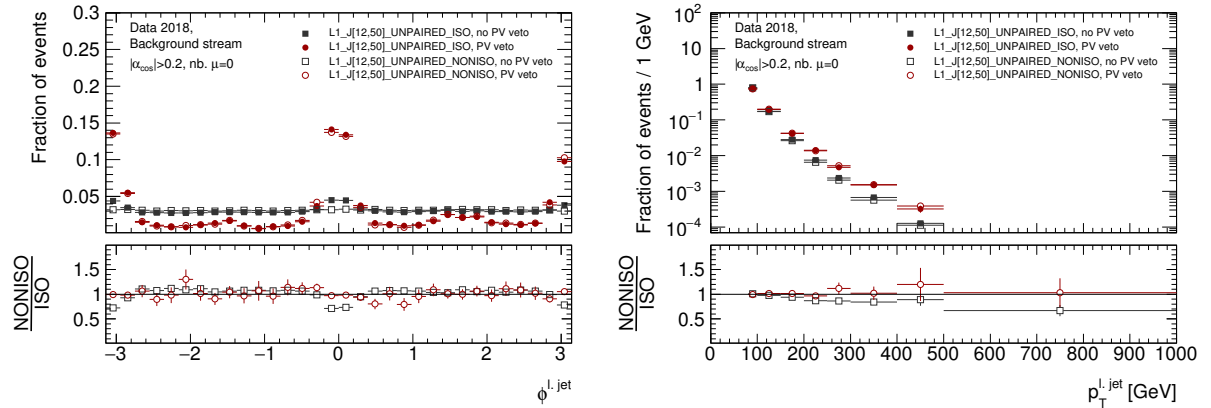


Figure 5.5.8: Leading jet ϕ (left) and p_T (right) distribution of events recorded in isolated (filled markers) and non-isolated **unpaired** (empty markers) bunch crossings in 2018 collision data. The distributions are shown before (black squares) and after (red circles) the application of the PV veto. The distributions and the ratios between events recorded in non-isolated and isolated bunch crossings, are shown before (black squares) and after (red circles) the application of the PV veto.

a systematically higher intensity in trailing than heading injected ghost bunches (c.f. [142]). Hence, it is more likely to have beam remnants in bunch crossings with beam 1 filled than beam 2 filled. However, by rejecting events that have a PV when reconstructed with *collisions* settings, the differences vanish and clear beam halo features are visible regardless which of the two beams is filled as proven in Figure 5.5.10. The PV veto predominantly affects events taken when beam 1 was filled as less than 6% of the events remain with respect to the preselection, while about 20% of events recorded when beam 2 was filled fulfil this criterion. Now the number of leading jets and hence events is higher if beam 2 is filled. This difference originates in the beam cleaning equipment situated in the interaction regions (IRs) in the middle of the long straight sections in octant 3 and 7 of the LHC (c.f. Figure 5.5.11). Particles with deviant momenta and large betatron amplitudes are deflected by the collimators in IR3 and IR7, respectively. The collimators in IR3 are more open and less efficient than those in IR7 resulting in a higher leakage of cleaning debris. Before reaching the ATLAS detector beam 2 passes through the momentum cleaning in IR3 and thus beam halo is more likely to originate from beam 2 than beam 1. A comparison of the leading jet ϕ and p_T of the events recorded in bunch crossings with beam 1 or 2 filled, see Figure 5.5.12, confirms a good agreement between events from the two types of **unpaired** bunches after the application of the PV veto which allows combining them to increase the number of events for BIB studies.

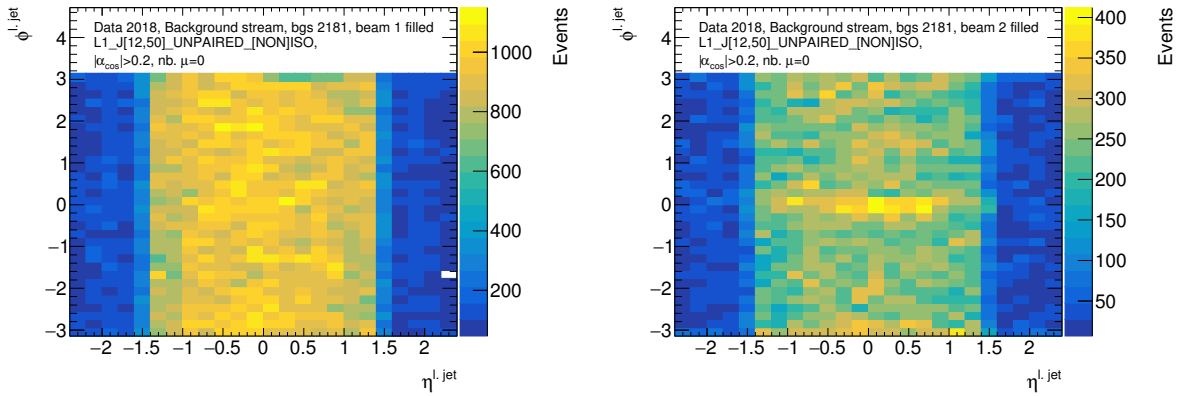


Figure 5.5.9: Leading jet occupancy in the η - ϕ -plane of events recorded in **unpaired** bunch crossings with beam 1 (left) and 2 (right) filled in 2018 collision data.

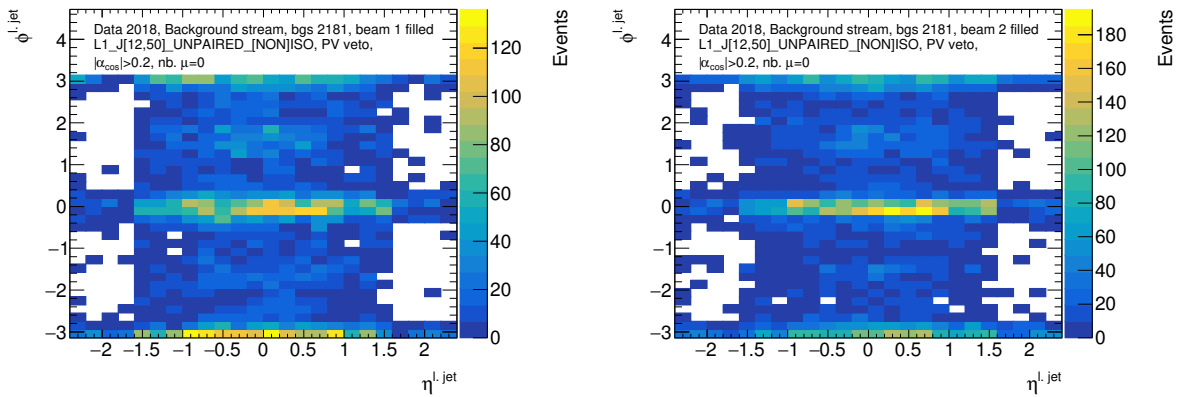


Figure 5.5.10: Leading jet occupancy in the η - ϕ -plane of events recorded in **unpaired** bunch crossings with beam 1 (left) and 2 (right) filled in 2018 collision data. Only events without a PV are shown.

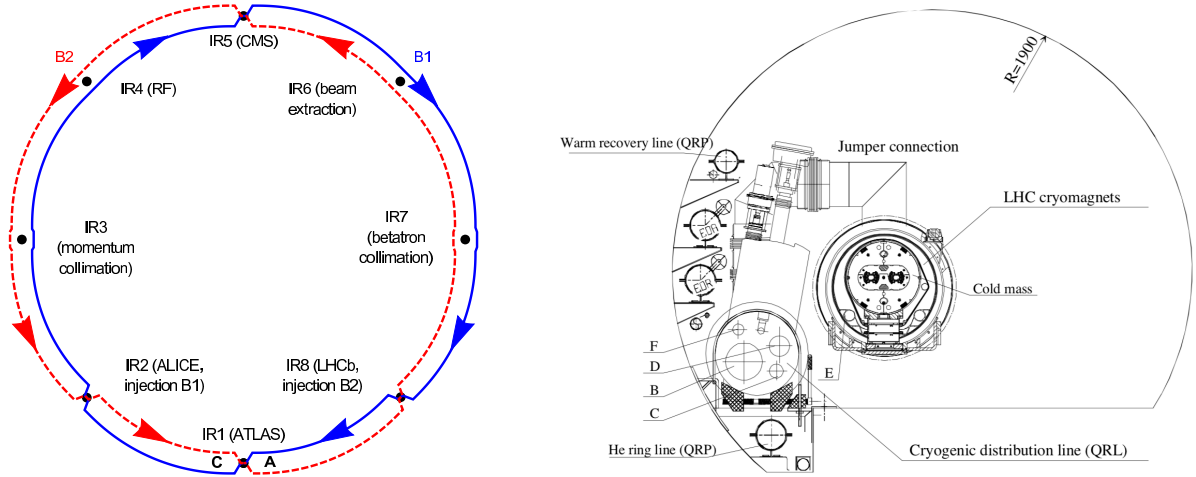


Figure 5.5.11: Layout of the LHC ring [143] and tunnel [144] on the left and right, respectively. Beam 1 is shown as blue solid line, labelled with “B1”, and beam 2 as red dashed line, labelled “B2”.

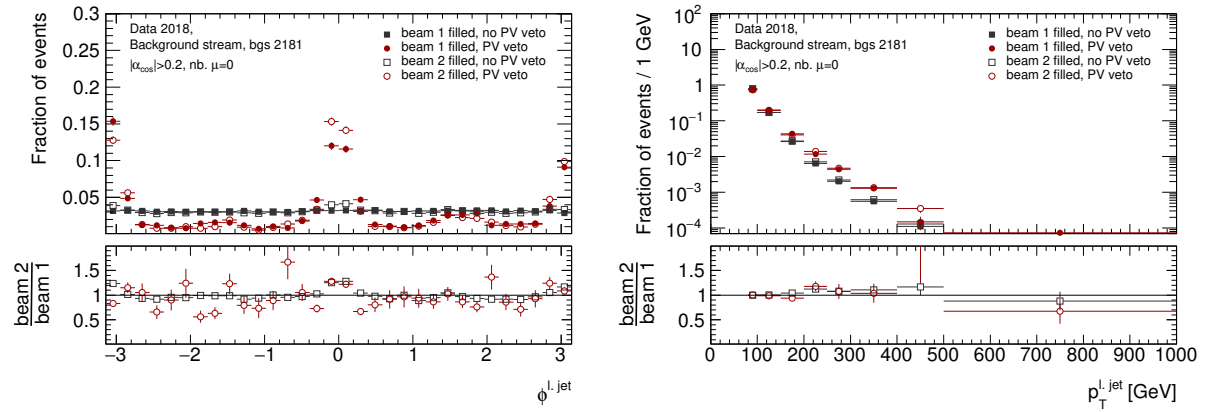


Figure 5.5.12: Leading jet ϕ (left) and p_T (right) distribution of events recorded in bunch crossings with beam 1 (filled markers) and beam 2 (empty markers) filled in 2018 collision data. The distributions are shown before (black squares) and after (red circles) the application of the PV veto. The distributions and the ratios between events recorded in bunch crossings with beam 2 and beam 1 filled, are shown before (black squares) and after (red circles) the application of the PV veto.

Figure 5.5.13 shows the leading jet occupancy on the η - ϕ -plane for all events recorded in **unpaired** bunches in 2018 collision runs without any discrimination between isolated and non-isolated bunch crossings or the filling status of beam 1 and beam 2. The observations in the 2018 subset of events from **unpaired** bunches are confirmed, as beam halo features are only faintly visible if events with reconstructed PVs are not rejected but are clearly recognisable after these events are removed. This is also reflected in the ϕ distribution in Figure 5.5.14. Two bumps at $\phi = \pm\pi/2$ are visible in between the predominant peaks after the PV veto, though less pronounced. These can be categorised as beam halo contributions as well, being mainly produced closer to the detector. An asymmetry of the main peaks between the detector half facing the inside ($\phi=0$) and the outside ($\phi=\pm\pi$) of the LHC ring and the intermediate bumps between the upper ($\phi>0$) and lower ($\phi<0$) detector half is observable due to the layout of the LHC tunnel. The LHC is not in the centre of the tunnel but closer to the tunnel wall on the outside of the ring and the tunnel floor (c.f. Figure 5.5.11). Consequently, a fraction of beam halo muons are absorbed by the tunnel wall and floor resulting in a slightly lower contribution

of beam halo in these regions. The p_T spectra after the rejection of events with a reconstructed PV is harder than without the veto.

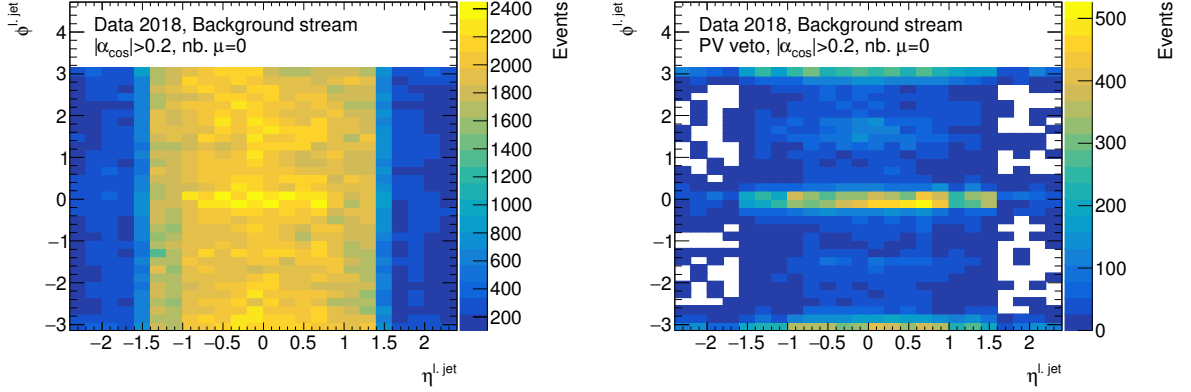


Figure 5.5.13: Leading jet occupancy in the η - ϕ -plane of events recorded in unpaired bunch crossings in 2018 collision data. Events with a reconstructed PV are removed from the righthand plot.

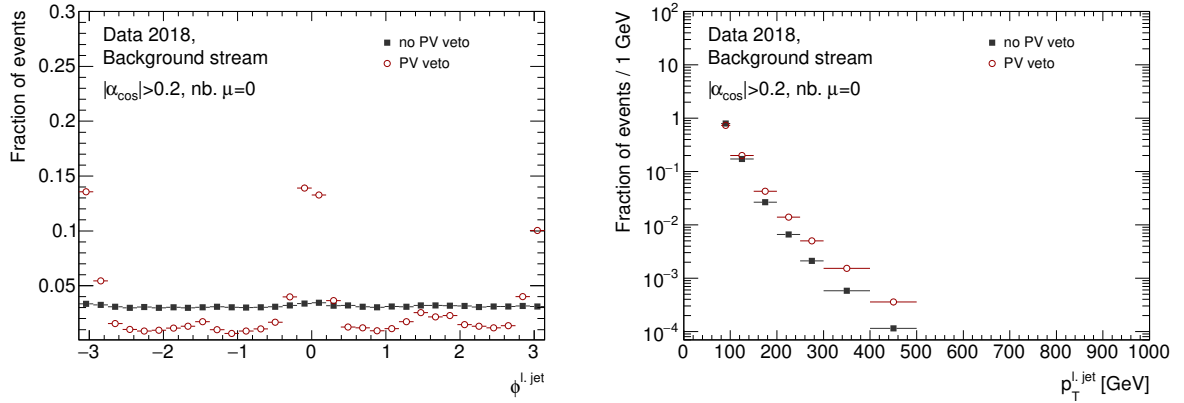


Figure 5.5.14: Leading jet ϕ (left) and p_T (right) distribution of events recorded in unpaired bunch crossings in 2018 collision data. The distributions are shown before (black filled square) and after (red empty circle) the application of the PV veto.

The so far described BIB features were solely examined in a subset of the collected collision events. An expansion to the entire dataset taken in 2016–2018 reveals the same structures for events recorded in **unpaired** and **empty** bunch crossings in the **Background** and **Late** stream, respectively, as shown in Figure 5.5.15(a) and (b). While leading jets in events recorded in the cosmic run and simulated signal events demonstrate no preference in the η - ϕ -plane (c.f. Figure 5.5.15(c) and (d)). This confirms that the observed bands at $\phi=0$ and $\pm\pi$ are exclusively beam-induced. Throughout the rest of this chapter, events with a reconstructed PV are removed from all datasets, although the largest impact is on events taken in **unpaired** bunch crossings.

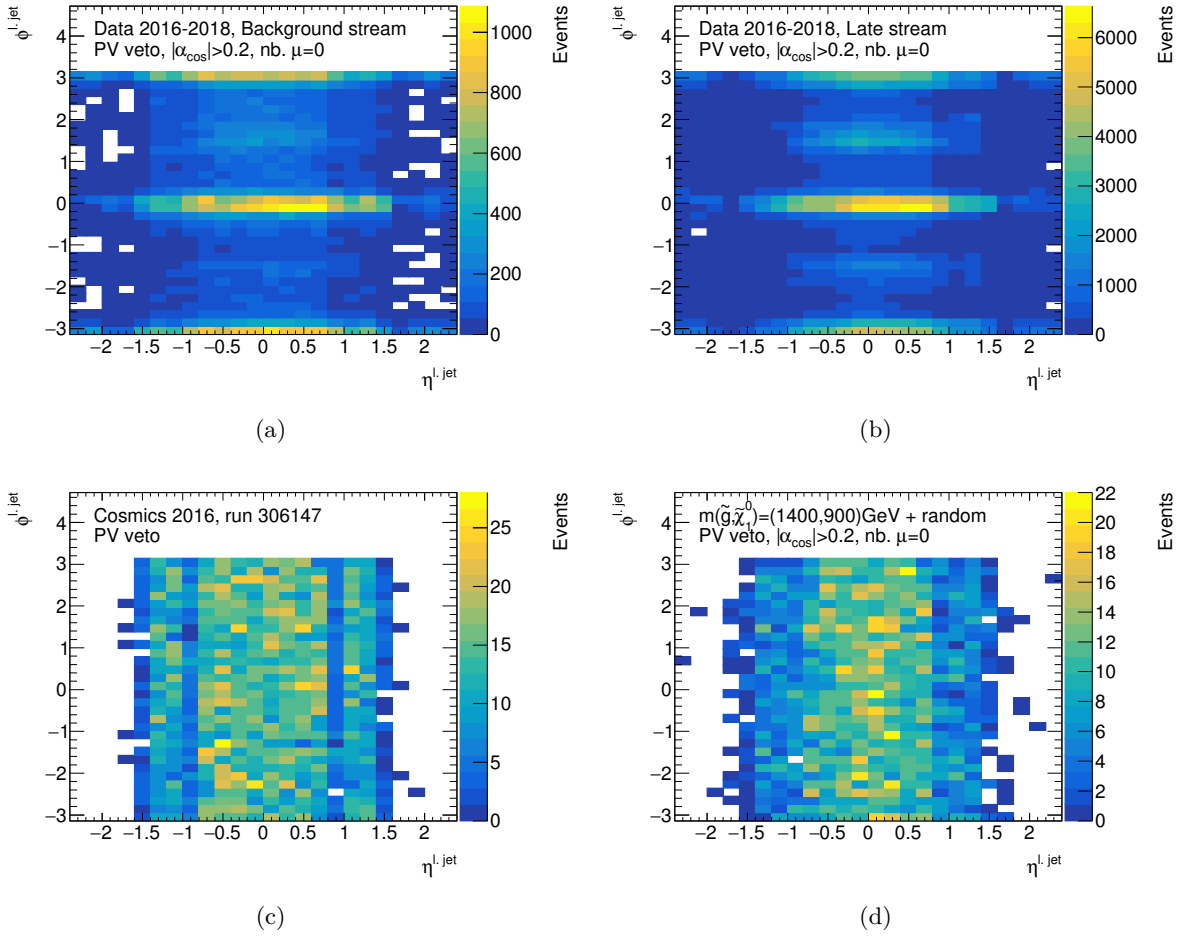


Figure 5.5.15: Leading jet occupancy in the η - ϕ -plane of events recorded in **unpaired** (a) and **empty** (b) bunch crossings in 2016–2018 collision data, the 2016 cosmic run (c) and simulated signal events for a 1400 GeV gluino and a mass splitting of 500 GeV (d). Only events without a PV and HLT $E_T^{\text{miss}} > 50$ GeV are shown. In order to have a sufficient amount of statistics for the distribution obtained from the cosmic run, no cosmic veto is applied solely on these events.

Beam-Induced Background Veto with the Leading Jet ϕ -Width

Since BIB traverses the detector parallel to the beam-pipe, the induced jets tend to have a large width in η but are confined in ϕ as energy deposits are predominantly electromagnetic resulting in comparably narrow showers. This characteristic of BIB allows separating it from potential signal. The jet width in ϕ is defined by the p_T -weighted sum of the $\Delta\phi$ between the jet and each of its constituents:

$$\phi_{\text{width}} = \frac{\sum |\Delta\phi^{\text{jet-constituent}}| \times p_T^{\text{constituent}}}{\sum p_T^{\text{constituent}}} . \quad (5.5.1)$$

Hence, single-constituent jets have a ϕ_{width} of exactly 0. The ϕ_{width} versus ϕ is shown in Figure 5.5.16(left) for leading jets recorded in **unpaired** bunch crossings revealing a correlation between both quantities for beam halo induced jets. Figure 5.5.17(left) shows the ϕ_{width} for leading jets obtained from events recorded in **unpaired** bunch crossings in collision data and the cosmic run, as well as simulated signal events. Although a notable fraction of signal events contain single-constituent jets it is more than a factor of 2 smaller compared to collision and cosmic data. Further, simulated signal jets have a longer tail in ϕ_{width} than jets from recorded data. Based on this a cut of $\phi_{\text{width}} > 0.02$ is applied on the search sample to efficiently reduce

BIB to 0.5 % with respect to the preselection while preserving a sufficiently high signal efficiency, especially for medium ($>67\%$) and large mass splittings ($>72\%$). The impact on the leading jets recorded in **unpaired** bunch crossings can clearly be seen in Figure 5.5.16(right). Simultaneously the remaining contamination of CIB is further minimised to less than 10 % with respect to the preselection which already included the cosmic veto. The cosmic veto (α_{cos} part) and BIB veto are correlated as can be seen in Figure 5.5.17(right). Events with $|\alpha_{\text{cos}}| < 0.2$ tend to have a leading jet with $\phi_{\text{width}} < 0.02$. The additional reduction of CIB by the BIB veto targets events for which no valid muon segment pair can be found ($\alpha_{\text{cos}} = -0.7$).

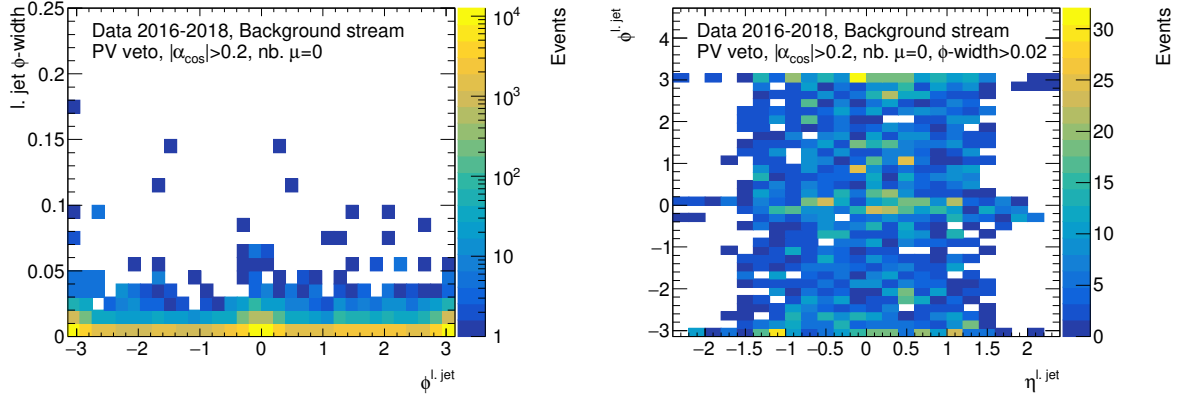


Figure 5.5.16: ϕ_{width} versus ϕ and ϕ versus η of leading jets recorded in events occurring in **unpaired** bunch crossings in 2016–2018 collision data. Only events without a PV and $\text{HLT } E_{\text{T}}^{\text{miss}} > 50 \text{ GeV}$ are shown.

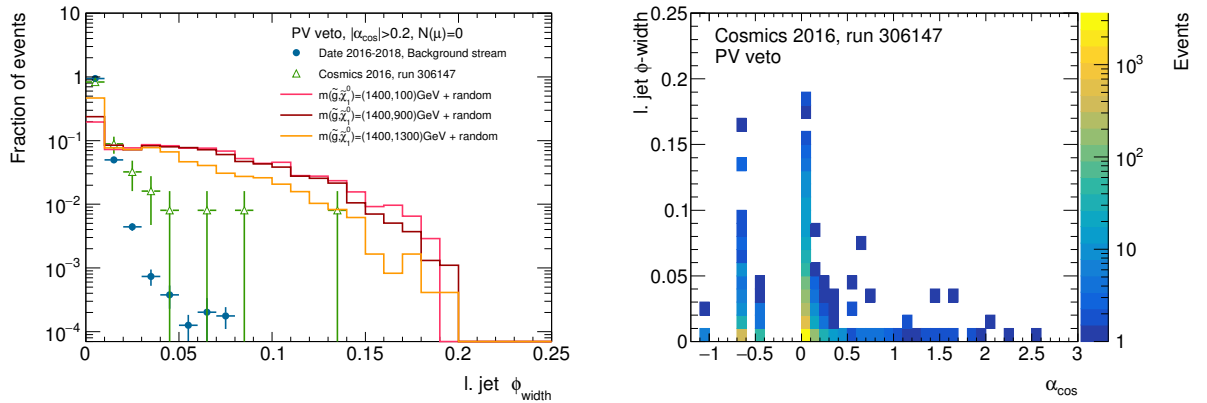


Figure 5.5.17: Left: Leading jet ϕ_{width} for events recorded in collision data taken in 2016–2018 (blue), the cosmic run (green) and simulated signal events for a 1400 GeV gluino and three different mass splittings of 1300 GeV (pink), 500 GeV (red) and 100 GeV (orange). Only events without a PV and $\text{HLT } E_{\text{T}}^{\text{miss}} > 50 \text{ GeV}$ are shown. Right: Leading jet ϕ_{width} versus α_{cos} for events recorded in the cosmic run. The PV veto and $\text{HLT } E_{\text{T}}^{\text{miss}} > 50 \text{ GeV}$ cut are applied; the cosmic veto is not applied.

5.5.3 Detector Noise & Cavern Background

The presented analysis targets out-of-time jets which are often odd looking and can show features similar to detector noise. By considering only events recorded in LBs that are included in the GRL the majority of events with fake jets originating from spurious noise in the calorimeters are already removed. The application of jet cleaning further reduces the number of jets caused by noise. Some of the jet cleaning cuts had to be loosened given the odd nature of the expected signal jets (c.f. Section 5.4.1). However, additional requirements are introduced which specifically target detectors noise, especially in the LAr calorimeters. One of these is the noise bursts cut which rejects all jets originating from noise bursts by definition. Thanks to the GRL and these stricter cleaning cuts, it can be assumed that the impact of detector noise is limited to a negligible level. In case any remaining strange features are observed a thorough investigation will be conducted.

Further, residual radiation, e.g. as a result of the β -decay of activated nuclei, in the ATLAS cavern can occur. This is a priori not included in the signal simulation but accounted for by overlaying events randomly triggered in **empty** bunch crossings, described in Section 5.1.6.

5.6 Background Estimate

The background estimate for this analysis is divided in the estimate of the cosmic- and beam-induced background. As the first is always present it needs to be dealt with prior to the latter. Fortunately, a pure sample can be extracted from the 2016 cosmic run. The procedure to obtain a full background estimate is outlined in this section, including the definition of control (CR), validation (VR) and signal (SR) regions.

Cosmic-Induced Background

The control sample for the estimate of CIB is provided by the 2016 cosmic run (c.f. Table 5.3.1). Additional CRs are defined in data collected in **empty**, **firstempty** and **unpaired** bunch crossings in the **Late** and **Background** stream by inverting the selection on α_{cos} and requiring a central muon. These regions are referred to as “cos-tag”. Figure 5.6.1 shows the leading jet p_T for the cos-tag selection in the cosmic run and **Late** and **Background** stream in collision data.

The shapes agree very well verifying the effectiveness to extract a pure cosmic sample from collision data (additional material on this can be found in Appendix B.6). The leading jet p_T template describing CIB, for the SR and VRs is derived from the cos-tag CR in data. To determine the expected cosmic background contribution in the SR or any other region, the template from a cos-tag CR is extrapolated by applying a transfer factor, TF , defined by

$$TF = \frac{N(\text{cosmic run, target region})}{N(\text{cosmic run, cos-tag CR})} , \quad (5.6.1)$$

where $N(\text{cosmic run, target region})$ and $N(\text{cosmic run, cos-tag CR})$ are the number of events in the target and cos-tag CR in the cosmic run, respectively. This transfer factor is derived from the cosmic run as the ratio between the event yields in the cos-tag region and a SR-like region where the cosmic veto is applied, “cos-veto”. The p_T distribution in these two regions and an additional “cos-enhanced” region which is the cos-veto region but without the requirement on a central muon, in the cosmic run are shown in Figure 5.6.2(left). For reference the definition of all cosmic CRs are given in Table 5.6.1. The p_T shapes in the cos-tag and the cos-enhanced region agree very well, while the shape differs in the cos-veto region. In order to mitigate these discrepancies, a bin-wise reweighting is included when extrapolating the p_T template from the cos-tag to the cos-veto region. The weights, presented in Figure 5.6.2(right), are taken from the cosmic run and are applied on collision data. An uncertainty of 100 % of the impact of the reweighting is attributed.

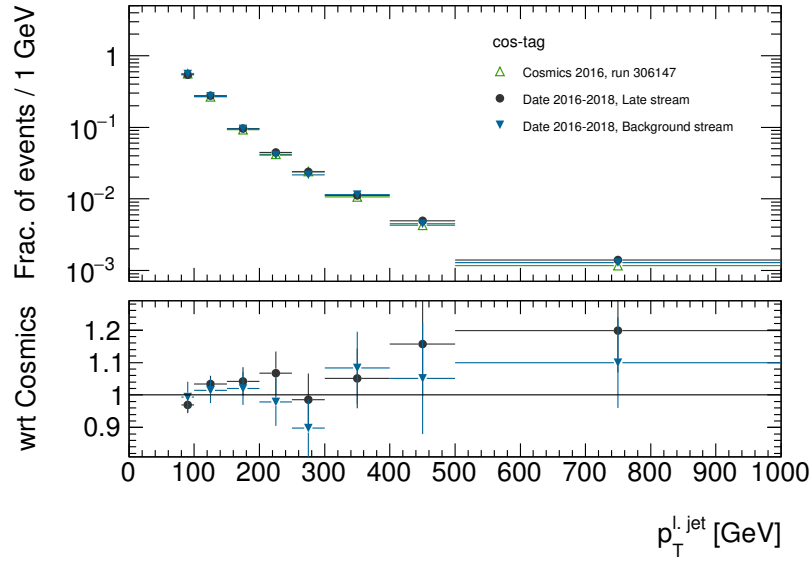


Figure 5.6.1: Leading jet p_T spectrum for a cos-tag selection in events collected in the 2016 cosmic run (green), in the **Late** (black) and the **Background** (blue) stream. The ratio is shown with respect to the cosmic run.

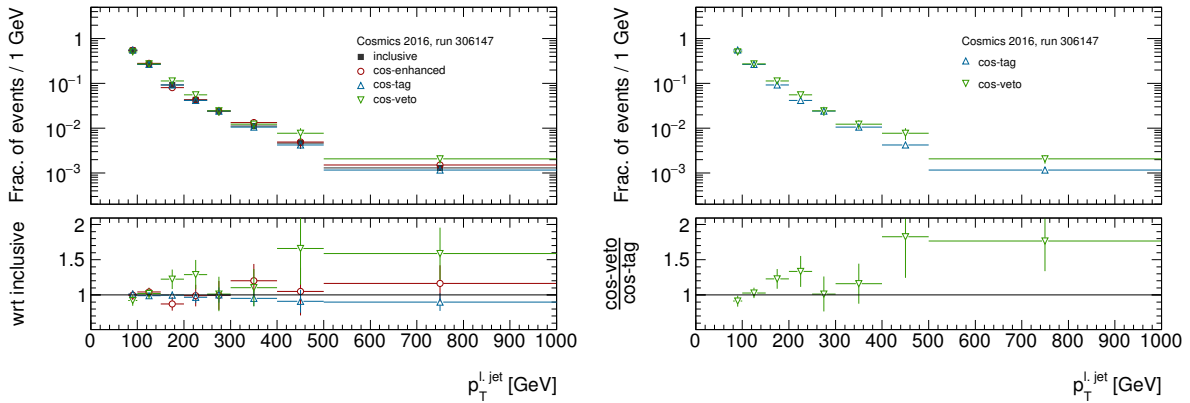


Figure 5.6.2: Leading jet p_T in an inclusive (black), cos-enhanced (red), cos-tag (blue) and cos-veto (green) selection in data collected in the 2016 cosmic run. The ratio is shown with respect to the inclusive distribution. The cos-veto and cos-tag selection are shown separately in the right plot including the binned ratio between them which serves as weights for the reweighting of the p_T spectra when extrapolating from a cos-tag to a cos-veto region.

	cos-tag	cos-enhanced	cos-veto
Number of muons ($ \eta < 1.4$)	≥ 1	0	—
Leading jet p_T [GeV]	> 80	> 80	> 80
α_{cos}	< 0.2	< 0.2	> 0.2

Table 5.6.1: Overview of the cosmic-tag, cosmic-enhanced and cosmic-veto selections used in the cosmic background study.

The selection for the SR includes a cut on $\phi_{\text{width}} > 0.02$ to reject BIB contribution. Cutting on ϕ_{width} affects the shape of the p_T template as shown for the cos-tag region in the cosmic run in Figure 5.6.3. Hence, the cos-tag CR in data is split into a “BIB-veto”, “BIB-incl[usive]” and “BIB-int[ermediate]” sub-region. The same sub-regions are used in the cos-tag CR corresponding to the SR and the VRs (c.f. Table 5.6.2).

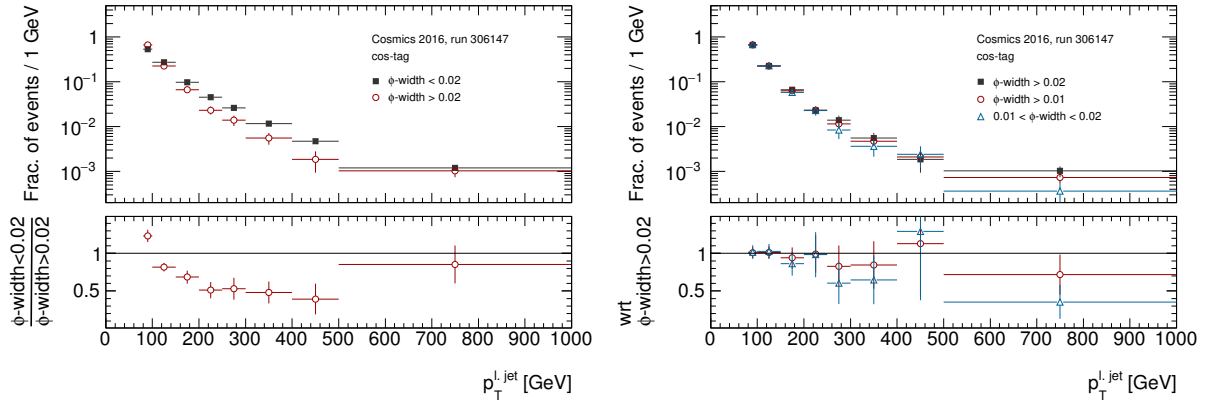


Figure 5.6.3: Leading jet p_T in a cos-tag selection in data collected in the 2016 cosmic run. The split by a ϕ_{width} above and below the threshold of 0.02 defined for the BIB veto is shown on the left. The split into the “BIB-veto”, “BIB-int” and “BIB-incl” sub-regions is shown on the right.

Beam-Induced Background

The BIB contribution in the SR or VRs in the **Late** stream is determined based on the leading jet p_T template from the corresponding BIB CR in the **Background** stream defined in Table 5.6.2.

First, the cosmic background fraction needs to be subtracted by taking the p_T template from the cos-tag CR with the appropriate ϕ_{width} selection. This cos-tag template is the sum of the p_T distributions from the **Late** and **Background** streams normalised to the number of events in the cos-tag CR in the **Background** stream. The combination of the **Late** and the **Background** stream increases the exploited number of events and hence reduces the statistical uncertainties. Following that, the template is extrapolated to the SR or VRs by applying the transfer factor obtained from the cosmic run. As mentioned above, a bin-wise reweighting is necessary when going from a cos-tag to a cos-veto region.

After the subtraction of the cosmic template a BIB-only template remains which is then normalised in the lowest p_T bin (80–100 GeV) in the **Late** stream. From the latter the cosmic contribution needs to be subtracted prior to the normalisation as well. Table 5.6.4 summarises for the SR and all VRs from which CRs the cosmic and BIB templates are retrieved, and where the latter are normalised. The **Background** stream data in each of the BIB CRs, with the cosmic template used for cosmic subtraction, can be seen in Figure 5.6.4.

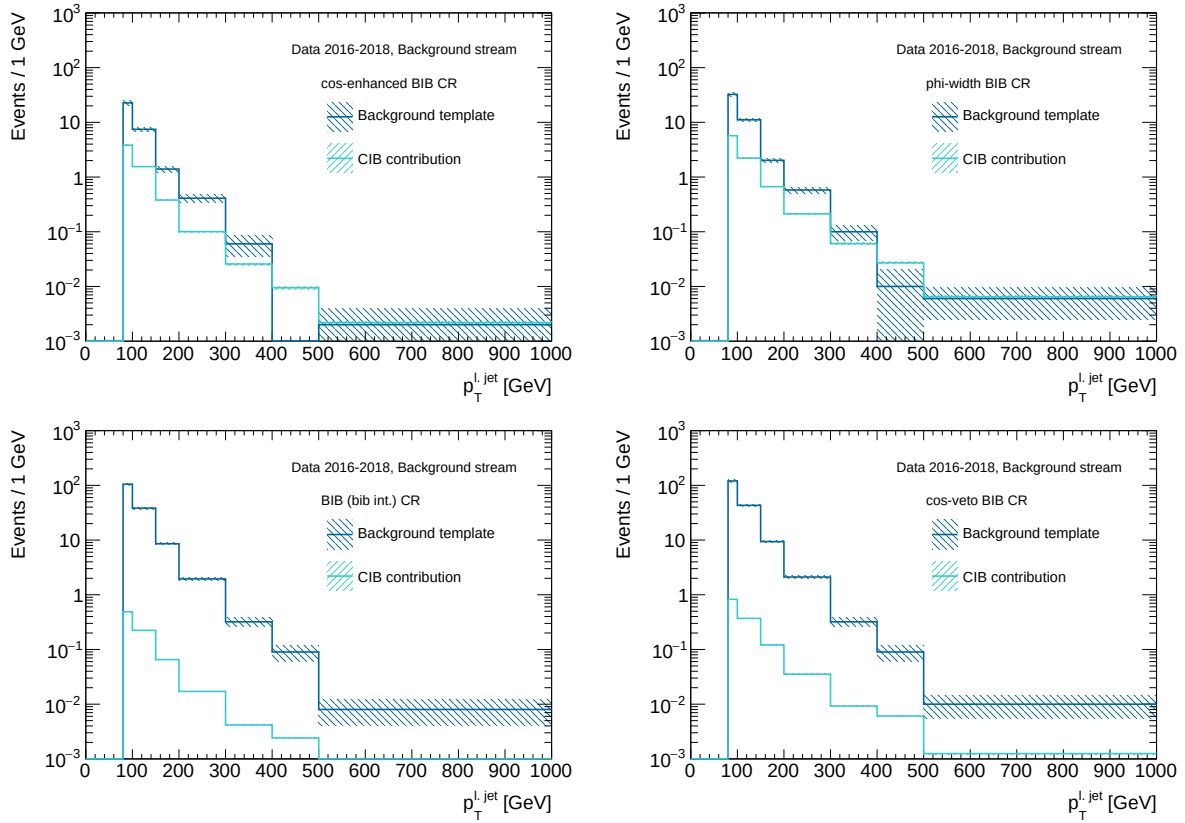


Figure 5.6.4: Leading jet p_T template in each of the BIB CRs extracted from data collected in 2016–2018 in the **Background** stream (dark blue), with the cosmic template used for subtracting the cosmic contribution overlaid (light blue). The hatched band includes the statistical uncertainty from the templates only. The last bin includes the overflow.

Finally, the full background estimation procedure can be summarised by this recipe:

- Extract the leading jet p_T template from the BIB CR corresponding to the targeted SR or VR;
- Subtract the cosmic contribution from the BIB CR template,
 - ↪ Calculate the cosmic contribution:
 - Retrieve the leading jet p_T template from the cos-tag region corresponding to the target region,
 - Normalise the template to the total number of events in the cos-tag region in the **Late** stream,
 - Extrapolate the p_T template to the target region by applying the appropriate transfer factor from Table 5.6.3,
 - Reweight the p_T template with the weights extracted from the cosmic run shown in Figure 5.6.2(right), when transferring from a cos-tag to a cos-veto region;
- Normalise the BIB template in the 80–100 GeV leading jet p_T bin to the SR or the VR in the **Late** stream,
 - ↪ Subtract the cosmic contribution the SR or VR as described above.

Region	Stream	Number of muons	Leading jet p_{T} [GeV]	α_{cos}	Leading jet ϕ_{width}
Cosmic control regions					
cos-tag (BIB-veto) CR	Late & Background	≥ 1 ($ \eta < 1.4$)	> 80	< 0.2	> 0.02
cos-tag (BIB-int) CR					$0.01 - 0.02$
cos-tag (BIB-incl) CR					> 0.01
BIB control regions					
cos-enhanced BIB CR	Background	0	> 80	< 0.2	$0.01 - 0.02$
ϕ_{width} BIB CR				< 0.2	> 0.01
BIB (BIB-int) CR				> 0.2	$0.01 - 0.02$
cos-veto BIB CR				> 0.2	> 0.01
Validation regions					
cos-enhanced VR	Late	0	> 100	< 0.2	$0.01 - 0.02$
ϕ_{width} VR		0		< 0.2	> 0.02
BIB VR		0		> 0.2	$0.01 - 0.02$
α_{cos} VR		≥ 1 ($ \eta < 1.4$)		> 0.2	> 0.01
Signal region					
SR	Late	0	> 100	> 0.2	> 0.02
BIB normalisation regions					
cos-enhanced Norm	Late	0	$80 - 100$	< 0.2	$0.01 - 0.02$
ϕ_{width} Norm		0		< 0.2	> 0.02
BIB Norm		0		> 0.2	$0.01 - 0.02$
α_{cos} Norm		≥ 1 ($ \eta < 1.4$)		> 0.2	> 0.01
SR Norm		0		> 0.2	> 0.02

Table 5.6.2: Overview of the cosmic- and BIB-induced background control and validation regions, including the normalisation regions for the normalisation of the VR and the SR.

Region	Number of events (VR)	Number of events (CR)	Transfer factor
cos-enhanced VR	77	502	0.1534 ± 0.0188
ϕ_{width} VR	64	665	0.0962 ± 0.0126
BIB VR	11	502	0.0219 ± 0.0067
α_{cos} VR	81	1167	0.0694 ± 0.0080
Signal Region	10	665	0.0150 ± 0.0048

Table 5.6.3: Summary of the transfer factors (c.f. Equation 5.6.1) and statistical uncertainties, derived from the 2016 cosmic run, applied to the cosmic template in the validation and signal regions. The event yields used to calculate the transfer factor are shown as well.

Region	Cosmic template	BIB template	BIB normalisation region (normalisation factor)
cos-enhanced VR	cos-tag (BIB int) CR	cos-enhanced BIB CR	cos-enhanced Norm (6.33 ± 1.21)
ϕ_{width} VR	cos-tag (BIB veto) CR	ϕ_{width} BIB CR	ϕ_{width} Norm (3.98 ± 0.64)
BIB VR	cos-tag (BIB int) CR	BIB (BIB int) CR	BIB Norm (5.42 ± 0.27)
α_{cos} VR	cos-tag (BIB incl) CR	cos-veto BIB CR	α_{cos} Norm (1.04 ± 0.14)
Signal Region	cos-tag (BIB veto) CR	cos-veto BIB CR	SR Norm (0.94 ± 0.06)

Table 5.6.4: Overview of the control regions used to derive the cosmic and BIB background templates for each of the validation and signal regions. The normalisation regions and factors as well as statistical uncertainties for the latter are shown in the rightmost column.

Validation

As the cosmic run is pure in cosmics but the **Late** stream is contaminated with BIB, it is vital to verify the procedure of calculating the contribution of CIB. Therefore, three validation regions, defined in Table 5.6.2, are investigated. The α_{cos} VR allows testing the p_{T} reweighting. The modelling of the backgrounds for a high ϕ_{width} (>0.02) and an intermediate ϕ_{width} (0.01 – 0.02) is verified in the ϕ_{width} VR and the cos-enhanced VR, respectively. These three VRs are also suitable to validate the procedure to estimate BIB and are extended by a fourth region, a BIB VR. The corresponding distributions of data from the **Late** stream and the estimated backgrounds are shown in Figure 5.6.5. The BIB VR reveals that the predicted $p_{\text{T}}^{\text{L, jet}}$ spectrum is harder in data which is covered by systematics (see below).

Systematic Uncertainties

The following uncertainties are considered based on the procedure used to calculate the cosmic and BIB contribution in the various regions and the validation of these:

- Cosmic-induced background uncertainties:
 - statistical uncertainty on the cosmic transfer factor (c.f. Table 5.6.3), and
 - uncertainty due to the reweighting of the $p_{\text{T}}^{\text{L, jet}}$ template fixed to 100 % of the impact of the reweighting (only applied when extrapolating from a cos-tag to a cos-veto region);
- Beam-induced background uncertainties:
 - statistical uncertainty on the BIB normalisation factor (c.f. Table 5.6.4),
 - uncertainty applied to the cosmic contribution due to the reweighting of the $p_{\text{T}}^{\text{L, jet}}$ template (see above) is propagated, and
 - additional uncertainty is defined based on the shape differences of the $p_{\text{T}}^{\text{L, jet}}$ distribution in the BIB VR in the **Late** and **Background** stream (c.f. Figure B.9.1(c) in Appendix B.9).

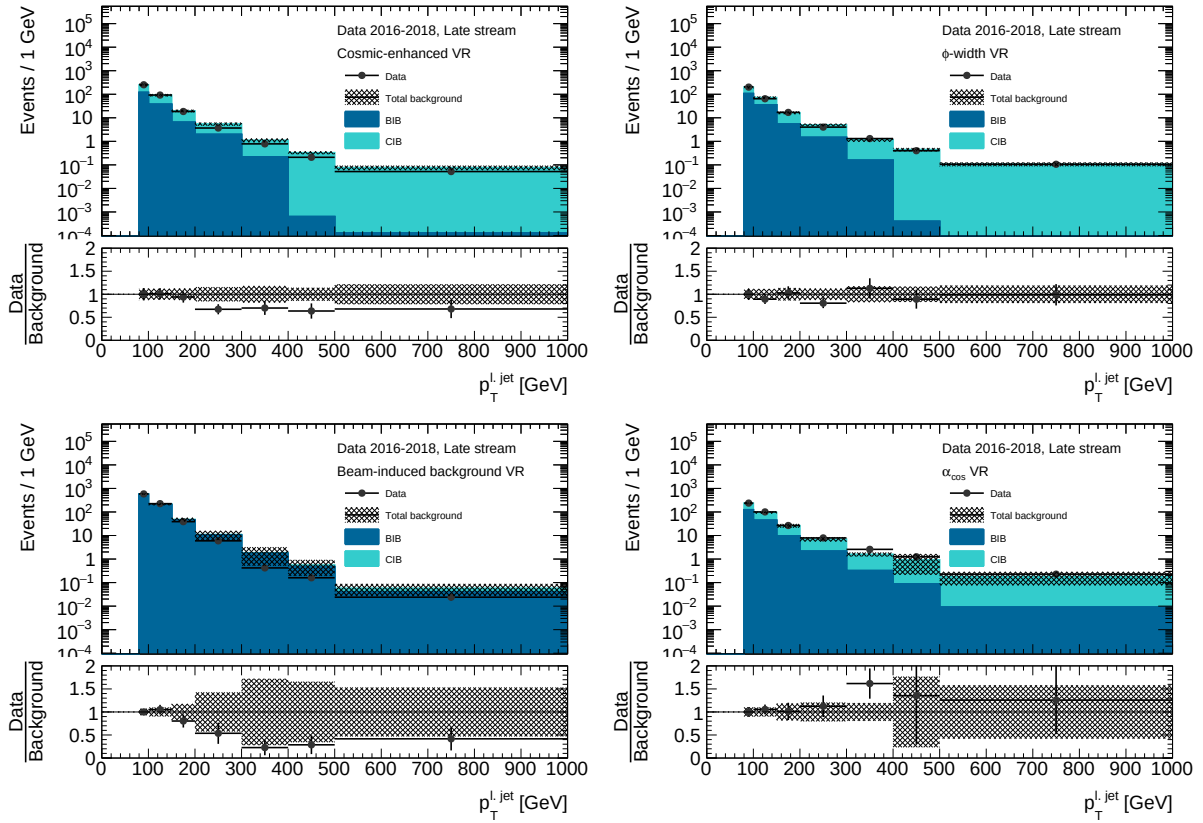


Figure 5.6.5: Leading jet p_T template in each of the VRs. The ratio shows the **Late stream** data over the total background. The hatched band represents the statistical and systematic uncertainties. The last bin includes the overflow.

Results

The predicted and observed event yields, split in cosmic and BIB contribution, in the VRs are shown in Table 5.6.5 and Figure 5.6.5. The background estimates for the SR are included, the yields in data are blinded. Overall a good agreement is observed between the background model and data. The VRs dominated by CIB reveal only small deviations which are covered by systematic uncertainties. In the BIB VR a stronger deviation is observed due to the shape differences between the **Background** and the **Late stream**. However, the discrepancy is covered by uncertainties. Future studies will be conducted to improve the modelling performance.

Region	Leading jet p_T bins		
	100 – 300 GeV	300 – 500 GeV	> 500 GeV
Cosmic-enhanced VR			
CIB	3713.6 ± 344.0	122.6 ± 12.4	38.2 ± 5.2
BIB	2390.6 ± 449.5	21.8 ± 16.4	0.1 ± 6.4
Total background	6104.3 ± 566.0	144.3 ± 20.6	38.2 ± 8.3
Data	5916	99	26
ϕ_{width} VR			
CIB	2743.7 ± 256.0	145.2 ± 14.9	53.6 ± 7.4
BIB	2189.4 ± 350.1	15.7 ± 15.4	0.0 ± 7.0
Total background	4933.1 ± 433.7	160.9 ± 21.4	53.6 ± 10.2
Data	4472	171	53
Beam-induced background VR			
CIB	562.6 ± 129.4	23.0 ± 9.1	8.5 ± 5.7
BIB	13684.6 ± 1222.3	218.5 ± 138.4	20.3 ± 14.2
Total background	14247.1 ± 1299.1	241.4 ± 138.7	28.8 ± 15.3
Data	13806	58	12
α_{cos} VR			
CIB	3870.1 ± 398.1	211.0 ± 75.5	86.1 ± 52.4
BIB	2908.6 ± 379.6	40.9 ± 17.0	4.5 ± 4.0
Total background	6778.8 ± 550.1	251.9 ± 77.3	90.7 ± 52.5
Data	7144	383	114
Signal Region			
CIB	452.4 ± 103.3	29.9 ± 12.7	12.8 ± 8.7
BIB	2643.7 ± 228.8	37.0 ± 14.9	4.0 ± 3.5
Total background	3096.1 ± 251.1	66.9 ± 19.6	16.8 ± 9.4
Data	–	–	–

Table 5.6.5: Overview of predicted and observed event yields in the validation and signal regions. The observed yields are blinded for the latter. The expected yields are split in the contribution from cosmic background and BIB. Both systematic and statistical uncertainties are shown.

5.7 Signal Sensitivity

The signal sensitivity of this search to various lifetimes depends on the gluino production cross section, $\sigma_{\tilde{g}\tilde{g}}$, given in Table 5.1.1, and the stopping fraction, f_{stopping} , which varies between 4 % and 8 % depending on the mass (c.f. Figure 5.1.3). Additionally, the reconstruction efficiency, ϵ_{reco} , is included. It is taken from Table 5.1.1, whereby the stopping fraction is already factored in. The selection efficiency, $\epsilon_{\text{selection}}$, needs to be considered on top of that. Table 5.4.1 provides the selection efficiency with respect to the number of reconstructed events, i.e. the event yields represent the combined application of stopping fraction, reconstruction and selection efficiency. Further, the signal sensitivity depends on the integrated luminosity, L_{int} . For short gluino lifetimes, i.e. much smaller than the duration of an LB, the gluino decays in the same LB as it was produced in; hence the integrated GRL luminosity is relevant. With an increase in lifetime, the decay is gradually more likely to occur in a different LB than the production of the gluino and therefore the integrated delivered luminosity becomes more important. Moreover, the fraction of **empty** and **firstempty** BCIDs on the total run time of collision data-taking, i.e. the live fraction f_{empty} , must be accounted for. It is dictated by the bunch group scheme which often differs between runs. Over the course of Run2 the fraction of **paired** BCIDs increased at the cost of **empty** BCIDs. The average number of **empty**(**firstempty**) BCIDs was 962 in 2016, 686 in 2017 and 583(414) in 2018, leading to an overall live fraction of 25 %. For very short lifetimes (up to a few 100 ns) the live fraction varies with the lifetime of the gluino. Owing to the arrangement of **empty** and **firstempty** BCIDs in the bunch group scheme, the decay of the gluino is likely to happen before the next empty bunches. With an increase in lifetime the live fraction increases and eventually saturates once the lifetime becomes longer than about a quarter of an LHC turn. Finally, the trigger live fraction, f_{trigger} , of 95 % must be factored in.⁷ In conclusion, the number of expected signal events can be calculated by

$$N_{\text{events}} = L_{\text{int}} \times \sigma_{\tilde{g}\tilde{g}} \times 2 \times \epsilon_{\text{reco}} \times \epsilon_{\text{selection}} \times f_{\text{stopping}} \times f_{\text{empty}} \times f_{\text{trigger}} . \quad (5.7.1)$$

The additional factor of 2 accounts for the fact that gluinos are pair-produced and do not necessarily decay at the same time; hence the chance to detect the decay per produced gluino pair doubles.

The final background expectation and three representative signal distributions in the signal region are shown in Figure 5.7.1. Based on this, the signal sensitivity is estimated by means of a hypothesis test comparing the compatibility between the background-only hypothesis and the signal-plus-background hypothesis. The expected background events and its uncertainty, $b \pm \sigma_b$, is given in Table 5.6.5, while the expected signal yields, s , are calculated according to Equation 5.7.1. Assuming no uncertainties, the total event count, N , follows a Poisson distribution, $P(N|s+b)$ with central value $s+b$. The background uncertainty is accounted for by a Gaussian constraint, $G(B|b, \sigma_b)$. The probability density function for the signal-plus-background hypothesis, $f(N|s+b, \sigma_b)$, can then be constructed by convoluting the Poisson and Gaussian terms:

$$f(N|s+b, \sigma_b) = \frac{\int_0^\infty P(N|s+b)G(B|b, \sigma_b)dB}{\int_0^\infty G(B|b, \sigma_b)dB} . \quad (5.7.2)$$

The figure of merit used in this analysis is the p -value which defines the probability to observe b events or less in data. It is obtained by the sum of the probability density function from zero to b observed events:

$$p\text{-value} = \frac{\int_0^\infty \sum_{N=0}^b P(N|s+b)G(B|b, \sigma_b)dB}{\int_0^\infty G(B|b, \sigma_b)dB} . \quad (5.7.3)$$

⁷This value is extracted from the trigger database provided by the ATLAS trigger group.

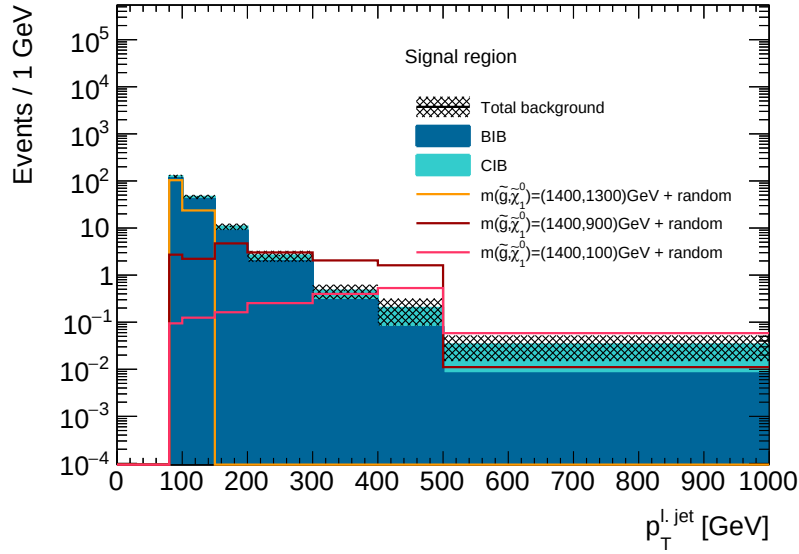


Figure 5.7.1: Predicted number of CIB (light blue) and BIB (dark blue) events contributing to the signal region. The expected yields from simulated signal samples with a 1400 GeV gluino and mass splittings of 100 GeV (orange), 500 GeV (red) and 1300 GeV (pink) are overlaid; note that the signals are scaled by a factor of 1000 for visibility. The hatched band represented statistical and systematical uncertainties.

Lower p -values correspond to a higher probability of the signal hypothesis and vice versa. In case of an absence of an excess over the background model, though, a p -value less than 5 % excludes the signal-plus-background hypothesis with 95 % confidence level. The p -value can also be related to the Z -score which describes the significance in one-sided Gaussian deviations.

Taking the values summarised above, the p -values and significance are numerically calculated in each $p_T^{l, jet}$ bin for each simulated gluino mass and mass splitting using RooFit [145]. The obtained results are summarised in Figure 5.7.2 assuming a gluino lifetime of $100 \mu\text{s}$. The assumed lifetime is long enough to be on the plateau of f_{empty} , but short enough to use the integrated GRL luminosity of 135.8 fb^{-1} (c.f. Table B.1.1). It can be observed that the lower the considered gluino mass the larger is the expected significance due to the larger cross section. For small mass splittings the expected signal yields drop and so does the significance. The same is observed for larger gluino masses. For low masses the sensitivity is larger in the low- $p_T^{l, jet}$ bins, as expected. A similar dependency is evident for variations of the mass splitting. Thus, it is important to consider the $p_T^{l, jet}$ shape rather than performing an inclusive analysis. Given the obtained results a sensitivity of more than 3σ is observed for gluino masses up to 1.2 TeV and large mass splittings.

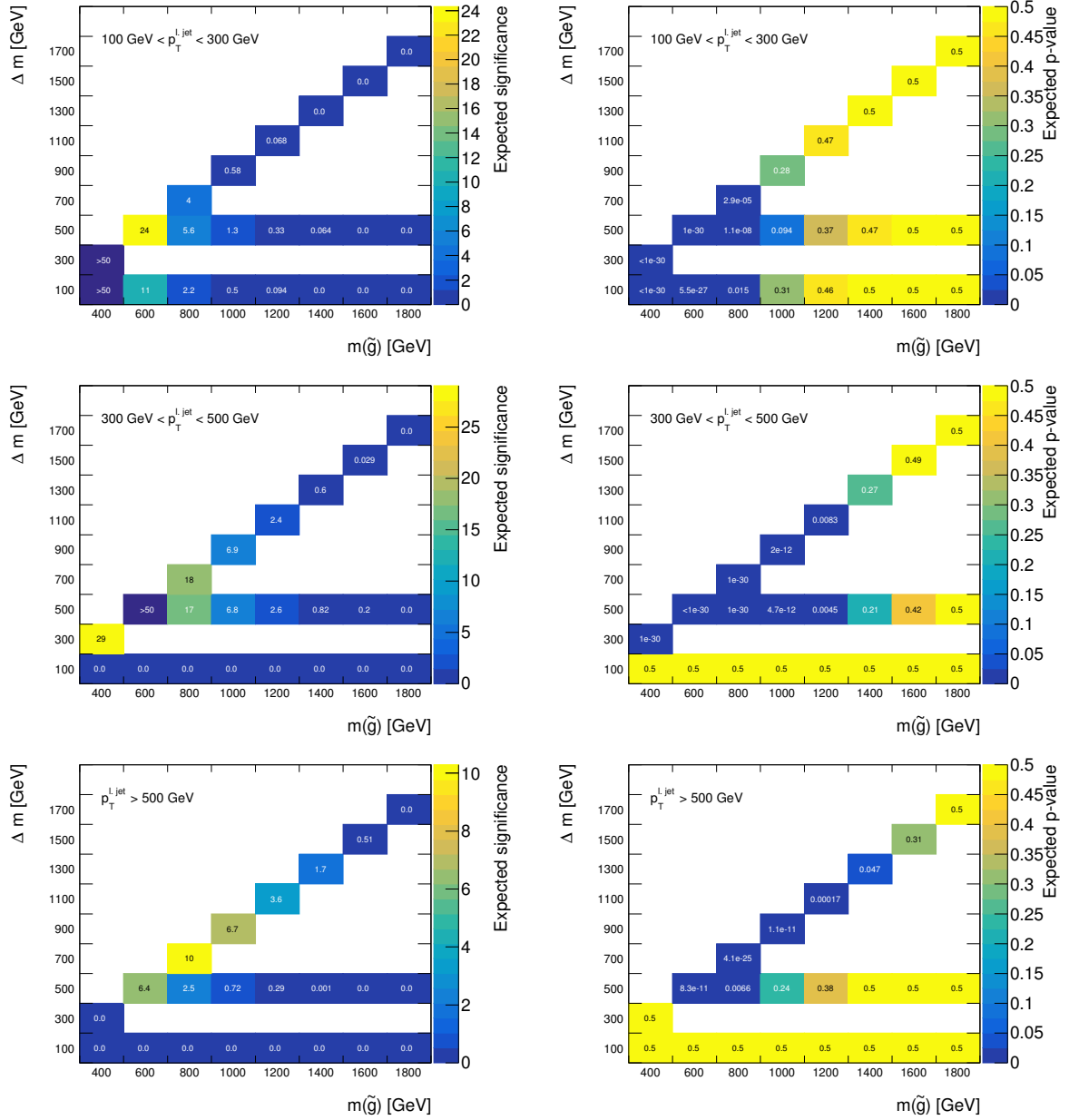


Figure 5.7.2: Expected significance (left) and p -values (right) for each simulated gluino mass and mass splitting (c.f. Table 5.1.1) in the three analysed $p_T^{l,jet}$ bins. Both statistical and systematic uncertainties are considered in the calculation.

Chapter 6

Summary & Outlook

In this thesis studies of the three key aspects of experimental particle physics were presented demonstrating the importance of exploiting the symbiosis between detector hardware and software to the ATLAS experiment: data integrity, object reconstruction and identification, and data analysis.

An exceptional detector setup and operation are the foundation for successful physics analysis. A key ingredient is the reliability of the collected data which is ensured by the data quality assessment. As different as the sub-detectors are, so different are the challenges involved, but all have to confront detector noise. For the LAr calorimeter noisy channels are a constant struggle which can be dealt with by masking the affected cells and averaging their energy from the neighbouring cells. However, in Run 2 an increase of close-by noisy channels was observed creating holes in the detector coverage if all were to be masked. To avoid this a new tool was developed which spots such excessive masking and warns the shifters to take action. Given the large number of over 180000 read-out channels, with many of them being noisy for a short or extended period of time throughout each data-taking run, this tool is a valuable support for the shifters and provides the capability to address or prevent over-masking at an early stage. Another tool which was designed within the scope of this thesis allows monitoring of the Front-End Boards (FEBs) and helps to identify those which are prone to Mini Noise Bursts (MNBs). This form of coherent noise was first spotted in Run 2 and observed to be often confined to single FEBs. The possibility to frequently monitor the FEBs is important to follow the development of MNBs over time and helps to improve the treatment of them. Although both tools worked successfully during Run 2, a more automatised implementation would be preferable to reduce the need for manual intervention to avoid errors and reduce the time required for the data quality assessment. This can be realised for the upcoming Run 3 including adjustments to the change in data-taking conditions.

The importance of a good understanding of the detector and its configuration is especially crucial for precision measurements. Non-uniformities in the LAr calorimeter can compromise the energy measurement of electrons, positrons and/or photons, resulting in an impairment of the results of analyses with these particles in their final state. Two of the dominant non-uniformities are dealt with in the energy calibration: the intermodule-widening (IMW) effect and non-nominal high voltage (HV) settings. Both effects are not accounted for in the Monte Carlo simulation and must be addressed by data-driven correction factors relying on advanced fit methods applied to events from a $Z \rightarrow e^+e^-$ selection in data. The IMW effect stems from the slightly larger gaps in between the LAr modules than inside each module, which are further altered by gravitational sagging. Owing to the increased amount of data collected in Run 2 a correction factor for each individual intermodule-gap was derived, contrary to Run 1 where four modules had to be overlaid. The derived correction factors successfully restore the uniformity in ϕ , have an $\approx 1\%$ effect on the energy resolution and shift the invariant di-electron mass in $Z \rightarrow e^+e^-$ events about 0.1% closer to the expected value. The increase in data further allowed

the investigation of the end-cap calorimeters. However, no similar effect was observed, which can be explained by the different construction compared to the EM barrel calorimeter. Including electrons from a $J/\psi \rightarrow e^+e^-$ selection further extended the study of the IMW effect to lower energies revealing an energy dependence. Accessing the IMW effect for several energy slices of a combined $J/\psi \rightarrow e^+e^-$ and $Z \rightarrow e^+e^-$ dataset showed that the effect is largest for medium energies of 20–40 GeV but decreases in strength towards lower and higher energies. The latter can be explained by the reduced overlap of the electromagnetic shower and the gap as the shower expands, thus mitigating its impact. An investigation of events with energies below 20 GeV revealed that the stronger curvature of the electron path under the influence of the magnetic field results in a notable inclination of the EM shower with respect to the intermodule-gap. Hence, the overlap of the two is decreased as is the impact of the IMW effect. The non-nominal HV settings have been studied in close cooperation with the LAr hardware experts and 17 modules, which are partially different from Run 1, have been identified as require dedicated correction factors. The derived correction factors allow a successful recovery of the deteriorations in the energy measurement in the affected HV sectors, improve the energy resolution by $\approx 1\%$ and shift the invariant di-electron mass in $Z \rightarrow e^+e^-$ events about 0.1% closer to the expected value. Both, the IMW and HV corrections, need to be revisited in the upcoming Run 3 as the first still changes under the gravitational deforming of the detector and the second changes with the configuration of the LAr calorimeter. In the course of these studies another, so far unaddressed, detector non-uniformity was discovered affecting the energy measurement at $\phi \approx 0$ and $\pm\pi/2$ which was traced back to additional material from the supporting wedges of the inner detector. Fortunately, they are included in the detector description used for the Monte Carlo simulation providing the opportunity to account for them by adding the cluster ϕ of the electron or photon in the MVA-based calibration step. Additionally, this approach mitigates other non-uniformities in ϕ . Eventually, an improvement in the linearity of the energy response versus p_T and η_{calo} is observed in particular for electrons with $p_T < 30$ GeV. The energy resolution is reduced by 2% for electrons with $p_T > 10$ GeV and up to 5% in the end-cap calorimeters.

Another improvement of the MVA-based calibration presented in this thesis, is the exploitation of tracking information. Motivated by the better resolution of the ID for low energies compared to the EM calorimeter, several tracking-based variables have been examined for their potential benefit on the historically purely calorimeter-based MVA energy calibration for electrons. The most promising candidates are the track momentum, p_{track} , and the difference in ϕ between the calorimeter cluster and the impact point in the second calorimeter layer of the extrapolated track, $\Delta\phi_2$. Including one or both of these variables enhances the linearity in the MVA response versus p_T and improves the energy resolution by 7% to 30% for electrons with a p_T of 20 GeV and 5 GeV, respectively. A reduction of the resolution of about 2.5% equally distributed over the entire η range is observed. The study of di-electron events from a $J/\psi \rightarrow e^+e^-$ and $Z \rightarrow e^+e^-$ selection in data showed that the resolution as a function of pile-up is about $4\text{--}5\%$ better if p_{track} is considered in the MVA calibration. As the positive impact of both variables, p_{track} and $\Delta\phi_2$, as well as their combination, is largest for low- p_T electrons, a next step is to validate the performance of the modified MVA calibration on sensitive physics analyses, such as $R_{K^{(*)}}$. The impact on the invariant di-electron mass peak in a $J/\psi \rightarrow e^+e^-$ selection in data already confirmed that the resolution is improved up to 15% by exploiting p_{track} . As these studies have been conducted based on electrons reconstructed with the sliding-window approach, which was the default at the time, but is now replaced in favour of the super-cluster reconstruction, a reassessment of the MVA calibration featuring tracking information is necessary.

The improvements of the energy calibration of electrons and photons are most beneficial for precision measurements which are one way to test and challenge the Standard Model. The other path is to search for new particles. One such search for stopped long-lived particles was conducted in this thesis. This search is designed to generically target any LLP that could stop in the detector motivated e.g. by split-SUSY. Assuming that the gluino is produced near threshold

and is sufficiently long-lived, it binds with SM quarks and gluons forming a quasi-stable R-hadron which slowly traverses the detector, losing its kinetic energy until the R-hadron comes to rest likely in the calorimeters owing to the high material density. The eventual decay results in large energy deposits in the calorimeters which are reconstructed as jets. As the targeted long lifetimes result in a significant time span between the production and the decay of the gluino, they likely occur in different bunch crossings. Hence, **empty** and **firstempty** bunch crossings are the ideal search environment as they are free from collision background. The dominant backgrounds are jets induced by cosmic muons and beam background. Several data streams and triggers have been investigated as to their usefulness to define a search sample and to serve for background studies. As the signal is expected to emerge from somewhere within the detector and is not timed with the LHC clock and the electronics read-out window, the standard reconstruction algorithms optimised for signal originating from proton-proton collisions in the centre of the detector are not ideal. Hence, extensive studies on the reconstruction with *collisions* and the less stringent *cosmics* settings have been conducted. The latter provides a favourable configuration as neither a pointing nor an IP requirement is enforced and the restrictions on hit order and track fits are relaxed among others. This is especially beneficial for the reconstruction of cosmic muons, which allows studying and vetoing these background sources more efficiently. Further, a customised jet cleaning was designed as the standard working points are not applicable. It features loosened constraints on jets with a high fraction of their energy in the Tile calorimeter but tightened restrictions on those jets which are mainly located in the LAr calorimeter to reduce the contamination of fake jets due to detector noise. This dedicated cleaning allows the removal of about 75 % of the background jets in **empty** bunch crossings but less than 10 % of cosmic-induced jets; hence an efficient rejection of these cosmic-induced jets is essential. Therefore, a novel cosmic veto exploiting the geometrical relation between the jet and muon segments was designed. The discriminating variable, α_{cos} , is defined as the angular distance between the jet direction and the line connecting one muon segment in the top and one in the bottom half of the detector which must point towards each other. Variations of the construction of α_{cos} have been explored resulting in a rejection power of more than 90 % of cosmic-induced jets with the favoured configuration. As activity in the muon system does not only originate from cosmic muons or punch-through from signal jets, but also cavern background, it is crucial to account for this by overlaying events from an unbiased dataset selected from randomly triggered events in **empty** bunch crossings with the simulated signal events. This allows a realistic evaluation of the veto efficiency.

Comprehensive studies on the beam-induced background (BIB) have been performed including analysing the differences between isolated and non-isolated **unpaired** bunch crossings and which of the two beams is filled. A good agreement is reached after introducing the veto of any events with a reconstructed primary vertex. This primary vertex veto further removes any residual contamination from proton-proton collisions in the search and control regions in **empty** bunch crossing data.

A purely data-driven background estimate has been performed showing good agreement in most validation and control regions. Based on this an expected signal sensitivity of more than 3σ for gluino masses up to 1.2 TeV has been calculated for large mass splittings. The at 95 % CL upper limit has been evaluated to 1.4 TeV at large mass splittings, increasing the Run 1 limit by 600 GeV. The anticipated final results are expected to have a higher reach as further optimisations are planned, e.g. the shape differences in the BIB-dominated control region might be addressed by a p_T reweighing. Further, the sensitivity mentioned in this thesis assumes a lifetime larger than $100 \mu\text{s}$ which will be expanded to different lifetime interpretations. As the analysis is not published no final results are available, yet.

For a future iteration of this search it would be beneficial to have more cosmic runs available in order to reduce the uncertainties on the cosmic background estimate. Unfortunately, only one cosmic run was recorded with nominal detector configuration during Run 2 and went through

data quality assessment, i.e. is suitable for analyses. Thus, this could easily be improved in Run3. Lowering the HLT p_T thresholds of the signal trigger would allow an expansion of the BIB normalisation region improving the reliability of the estimate. Further, it might be worth exploring the possibility of utilising cell information to construct an even more effective BIB veto. Studies concerning the usability of **firstempty** revealed that even more than the currently included BCIDs could be considered for the search sample if a random trigger had been enabled during data-taking to allow the evaluation of the influence from BIB, pile-up and after glow for these bunches. This could be changed in Run3. These possibilities offer further potential for this search for stopped long-lived particles.

Regardless of whether we observe an absence or presence of a new physics signal, this search will provide valuable information in the pursuit to understand the underlying principles of nature.

Appendix A

Auxiliary Information on Physics with Electrons

This appendix summarises auxiliary information on physics with electrons presented in Chapter 4.

A.1 Intermodule-Widening Correction

In additions to the studies of the intermodule-widening presented in Section 4.3.1, the calorimeter end-caps on the A and C side have been investigated separately as shown in Figure A.1.1.

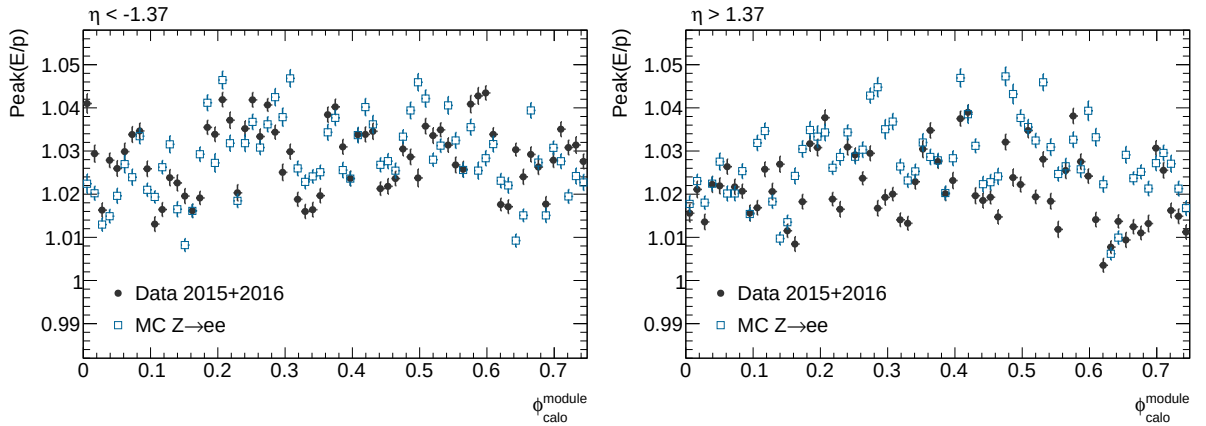


Figure A.1.1: Folded E/p profile with respect to $\phi_{\text{calo}}^{\text{module}}$ of all calorimeter modules in the end-caps, shown separately for the C (left) and A (right) side. $Z \rightarrow e^+e^-$ events selected in data collected in 2015 and 2016 and simulated $Z \rightarrow e^+e^-$ events are depicted as black dots and blue squares, respectively.

A.2 Cluster ϕ

In Section 4.4.1 the recovery of the energy loss due to the ID support structure was confirmed in the distribution of the invariant di-electron mass ratio in $Z \rightarrow e^+e^-$ events selected in data taken in 2015 and 2016 as a function of the $\phi_{\text{calo}}^{\text{module}}$. Figure A.2.1 shows the E/p profiles for the same electrons revealing the same features with respect to $\phi_{\text{calo}}^{\text{module}}$.

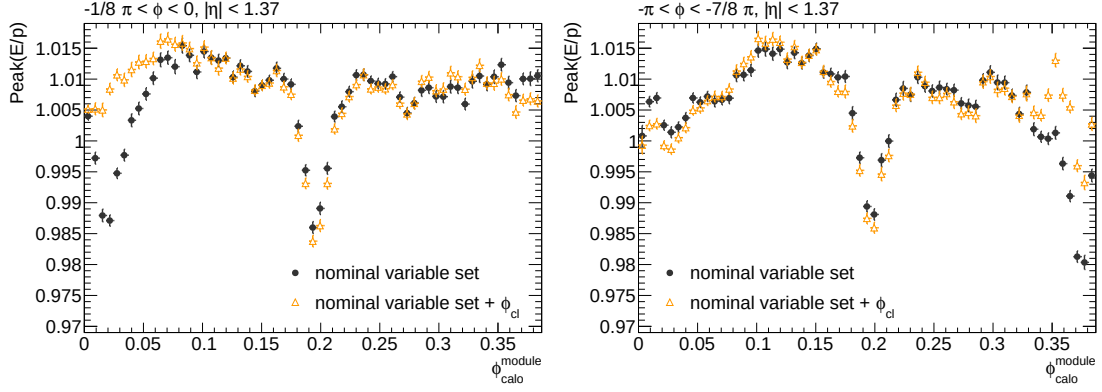


Figure A.2.1: E/p profiles with respect to $\phi_{\text{calo}}^{\text{module}}$ for electrons from $Z \rightarrow e^+e^-$ events selected in data calibrated with the nominal variable set (black dots) and calibrated with the variable set extended by ϕ_{cl} (orange triangles). The profile is extracted from the peak position of a double-sided Crystal Ball fit of the E/p distribution in each $\phi_{\text{calo}}^{\text{module}}$ bin. Only the regions where the ID support wedges are located are shown.

The linearity and resolution based on the invariant di-electron mass ratio as a function of η , presented in Figure A.2.2, supports the results discussed in detail in Section 4.4.1.

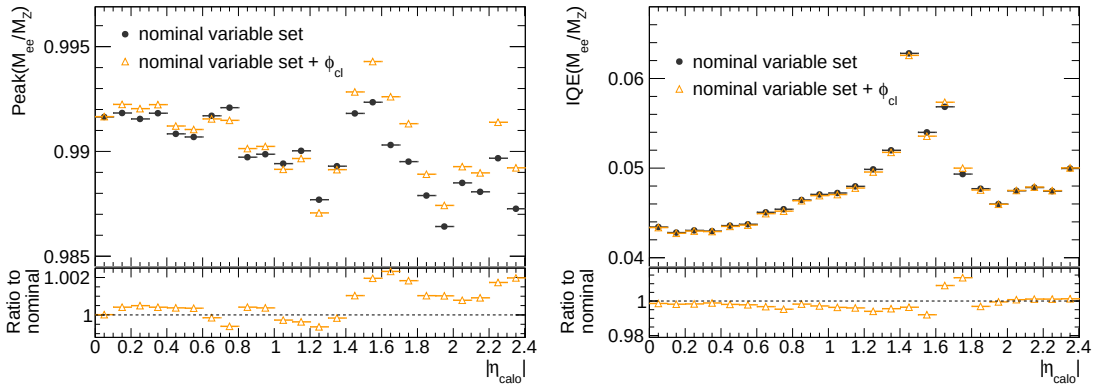


Figure A.2.2: M_{ee}/M_Z profile with respect to η for electrons from $Z \rightarrow e^+e^-$ events selected in data calibrated with the nominal variable set (black dots) and calibrated with the variable set extended by ϕ_{cl} (orange triangles). The profile of the peak position of the M_{ee}/M_Z in each η bin is extracted from a truncated Gaussian fit and shown on the left. The profile of the IQE of the M_{ee}/M_Z in each η bin is shown on the right.

A.3 Tracking Information

The linearity and resolution of an MVA calibration including tracking variables is measured in E/p profiles of electrons in $J/\psi \rightarrow e^+e^-$ and $Z \rightarrow e^+e^-$ events selected in data recorded in 2015 and 2016 and depicted as a function of η in Figure A.3.1. It supports the results discussed in detail in Section 4.4.2.

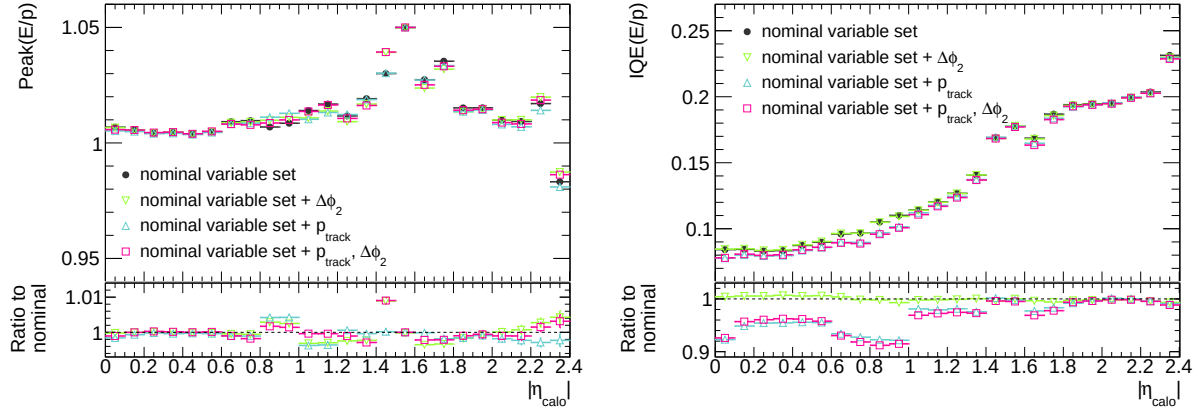


Figure A.3.1: E/p profiles with respect to η for electrons from $J/\psi \rightarrow e^+e^-$ and $Z \rightarrow e^+e^-$ events selected in data, calibrated with a variable set extended by $\Delta\phi_2$, p_{track} and both is depicted in green, blue and pink, respectively. As reference the profile for the nominal calibration is included as black dots. The profile of the peak position of the E/p distribution in each η bin is extracted from a double-sided Crystal Ball fit and shown on the left. The profile of the IQE of the E/p distribution in each η bin is shown on the right.

Appendix B

Auxiliary Information on Search for Stopped Long-Lived Particles

This appendix summarises auxiliary information on the search for stopped long-lived particles presented in Chapter 5.

B.1 Data Samples

Table B.1.1 summarises the GRLs which were used to extract good quality data from collision data recorded in 2016–2018. The total integrated luminosity collected per year as well as after applying the GRL listed, too. Table B.1.2 lists the luminosity-weighted prescales for each trigger and year.

Year	GRL	GRL int. lumi. [fb^{-1}]	Tot. int. lumi. (Delivered) [fb^{-1}]
2016	data16_13TeV.periodAllYear_DetStatus-v89-pro21-01_ DQDefects-00-02-04_PHYS_StandardGRL_All_Good_25ns.xml	33.0	38.0
2017	data17_13TeV.periodAllYear_DetStatus-v99-pro22-01_ Unknown_PHYS_StandardGRL_All_Good_25ns_TriggerNo17e33prim.xml	44.3	49.0
2018	data18_13TeV.periodAllYear_DetStatus-v102-pro22-04_ Unknown_PHYS_StandardGRL_All_Good_25ns_TriggerNo17e33prim.xml	58.5	62.1

Table B.1.1: Summary of 2016–2018 GRLs and collected integrated luminosity at 13 TeV. Delivered luminosity numbers are quoted using the luminosity calibration tag `Of1Lumi-13TeV-010`, as in [89].

B.2 Trigger Prescales

The integrated luminosity recorded in a given LB is extracted from the lumicalc files that correspond to the respective GRL (c.f. Table B.1.1). The combined results of this procedure for 2016–2018 are summarised in Table B.2.1; the values separated for each year can be found in Table B.1.2 in Appendix B.1.

The main analysis triggers are rarely prescaled, usually only for a short period of time to cope with spikes of noise in the calorimeter which can cause temporarily high trigger rates. The `HLT_noalg_cosmiccalo_L1RD1_EMPTY` trigger is heavily prescaled as otherwise each event in empty bunch crossings would be accepted which is technically not feasible. However, the collected number of events is plenty for the random event overlay as discussed in Section 5.1.6.

Year	Stream	Trigger	Luminosity-weighted prescale	Integrated luminosity [fb ⁻¹]
2016	physics_Late	HLT_j55_0eta240_xe50_L1J30_EMPTY	1.02	33.0
		HLT_j55_0eta240_xe50_L1J30_FIRSTEMPTY	N/A	N/A
	physics_CosmicCalo	HLT_noalg_cosmiccalo_L1J30_EMPTY	7.0	32.69
		HLT_noalg_cosmiccalo_L1RD1_EMPTY	9880716	32.94
	physics_Background	L1_J12_UNPAIRED_ISO	1.30	32.95
		L1_J12_UNPAIRED_NONISO	10.98	32.04
		L1_J50_UNPAIRED_ISO	1.0	24.74
		L1_J50_UNPAIRED_NONISO	1.0	30.73
2017	physics_Late	HLT_j55_0eta240_xe50_L1J30_EMPTY	1.01	44.12
		HLT_j55_0eta240_xe50_L1J30_FIRSTEMPTY	N/A	N/A
	physics_CosmicCalo	HLT_noalg_cosmiccalo_L1J30_EMPTY	2.31	44.26
		HLT_noalg_cosmiccalo_L1RD1_EMPTY	6935945	44.30
	physics_Background	L1_J12_UNPAIRED_ISO	1.02	20.09
		L1_J12_UNPAIRED_NONISO	6.77	43.56
		L1_J50_UNPAIRED_ISO	1.0	16.10
		L1_J50_UNPAIRED_NONISO	1.0	42.98
2018	physics_Late	HLT_j55_0eta240_xe50_L1J30_EMPTY	1.00	58.34
	physics_Late	HLT_j55_0eta240_xe50_L1J30_FIRSTEMPTY	1.13	58.34
	physics_CosmicCalo	HLT_noalg_cosmiccalo_L1J30_EMPTY	1.24	58.43
		HLT_noalg_cosmiccalo_L1RD1_EMPTY	5800898	58.44
	physics_Background	L1_J12_UNPAIRED_ISO	1.07	58.37
		L1_J12_UNPAIRED_NONISO	5.10	58.25
		L1_J50_UNPAIRED_ISO	1.0	36.27
		L1_J50_UNPAIRED_NONISO	1.0	57.86

Table B.1.2: List of luminosity-weighted prescales for the triggers used in this analysis for 2016–2018 data-taking. The integrated luminosity over which the luminosity-weighting is calculated is given in the right-most column. This number is lower than the GRL integrated luminosity per year, since some LBs are completely removed from the denominator in cases where the prescale is so large that no event is ever recorded in the given LB. The **FIRSTEMPTY** trigger item was only active during 2018; hence no prescale and luminosity information is available for 2016 and 2017 for this trigger.

The **L1_J12_UNPAIRED** trigger items which are used to select events for beam-induced background studies, is especially prescaled during non-isolated **unpaired** bunch crossings. Albeit rarely prescaled, the **L1_J50_UNPAIRED** trigger items are no ideal choice either as they are not fully efficient down to the minimum leading jet p_T requirement of 80 GeV. A combination of the **L1_J12_UNPAIRED** and **L1_J50_UNPAIRED** triggers is performed to ensure that as many events as possible are selected for BIB related studies. This allows profiting from the negligible prescaling of the **L1_J50_UNPAIRED** triggers, while including low- p_T events collected by **L1_J12_UNPAIRED**. Figure B.2.1 shows the efficiency of the **L1_J50_UNPAIRED** [NON] ISO triggers with respect to **L1_J12_UNPAIRED** [NON] ISO for 2018 data. The efficiency plateau of **L1_J50_UNPAIRED** [NON] ISO is reached at a leading jet p_T of 120 GeV. Hence, events accepted by **L1_J12_UNPAIRED** [NON] ISO are chosen if they contain a leading jet with $p_T < 120$ GeV and events recorded by **L1_J50_UNPAIRED** [NON] ISO are included if they have a leading jet with $p_T > 120$ GeV. Event specific prescales are applied to obtain smooth distributions.

Stream	Trigger	Luminosity-weighted prescale	Integrated luminosity [fb^{-1}]
Late	HLT_j55_0eta240_xe50_L1J30_EMPTY	1.01	135.4
	HLT_j55_0eta240_xe50_L1J30_FIRSTEMPTY	1.13	58.34
CosmicCalo	HLT_noalg_cosmiccalo_L1J30_EMPTY	2.97	135.38
	HLT_noalg_cosmiccalo_L1RD1_EMPTY	7162097.33	135.7
Background	L1_J12_UNPAIRED_ISO	1.13	111.41
	L1_J12_UNPAIRED_NONISO	7.05	133.85
	L1_J50_UNPAIRED_ISO	1.0	77.12
	L1_J50_UNPAIRED_NONISO	1.0	131.56

Table B.2.1: List of luminosity-weighted prescales for the triggers used in this analysis for 2016–2018 data-taking. The integrated luminosity over which the luminosity-weighting is calculated is given in the right-most column. This number is lower than the GRL integrated luminosity per year, since some LBs are completely removed from the denominator in cases where the prescale is so large that no event is ever recorded in the given LB. The `firstempty` trigger item was only active during 2018; hence the significantly lower integrated luminosity as no prescale and luminosity information is available for 2016 and 2017 for this trigger.

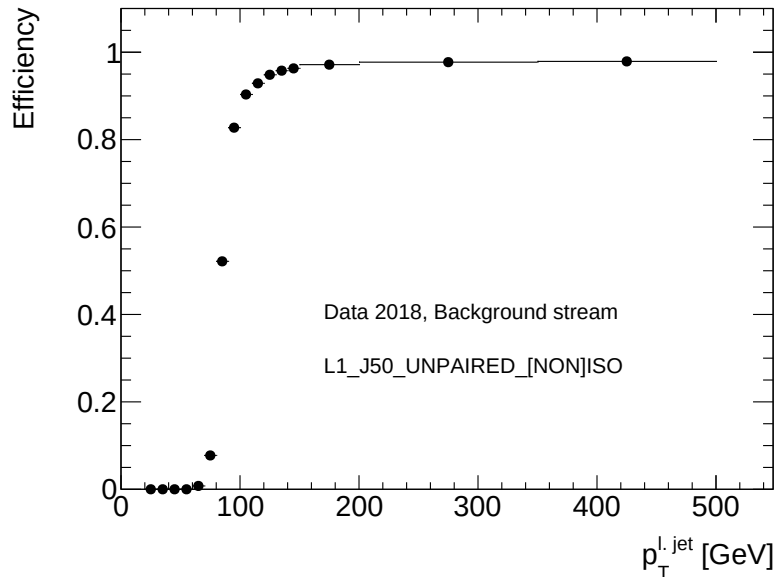


Figure B.2.1: Efficiency of the L1_J50_UNPAIRED triggers relative to the L1_J12_UNPAIRED triggers in the Background stream in 2018 as a function of the leading jet p_T .

B.3 AOD Samples

Table B.3.1 summarises the collision AOD (Analysis Object Data) datasets used in this analysis.

Reconstruction mode	Stream	AODs
<i>cosmics</i>	Late	data16_13TeV.periodAllYear.physics_Late.PhysCont.AOD.pro24_v01
		data17_13TeV.periodAllYear.physics_Late.PhysCont.AOD.pro24_v01
		data18_13TeV.periodAllYear.physics_Late.PhysCont.AOD.pro24_v01
	CosmicCalo	data16_13TeV.periodAllYear.physics_CosmicCalo.PhysCont.AOD.pro24_v01
		data17_13TeV.periodAllYear.physics_CosmicCalo.PhysCont.AOD.pro24_v01
		data18_13TeV.periodAllYear.physics_CosmicCalo.PhysCont.AOD.pro24_v01
	Background	data16_13TeV.periodAllYear.physics_Background.PhysCont.AOD.pro24_v01
		data17_13TeV.periodAllYear.physics_Background.PhysCont.AOD.pro24_v01
		data18_13TeV.periodAllYear.physics_Background.PhysCont.AOD.pro24_v01
<i>collisions</i>	Late	data16_13TeV.periodAllYear.physics_Late.PhysCont.AOD.repro21_v03
		data17_13TeV.periodAllYear.physics_Late.PhysCont.AOD.pro22_v03
		data18_13TeV.periodAllYear.physics_Late.PhysCont.AOD.t0pro22_v01
	CosmicCalo	data16_13TeV.00*.physics_CosmicCalo.merge.AOD.f*_m*
		data17_13TeV.00*.physics_CosmicCalo.merge.AOD.f*_m*
		data18_13TeV.00*.physics_CosmicCalo.merge.AOD.f*_m*
	Background	data16_13TeV.periodAllYear.physics_Background.PhysCont.AOD.repro21_v03
		data17_13TeV.periodAllYear.physics_Background.PhysCont.AOD.pro22_v03
		data18_13TeV.periodAllYear.physics_Background.PhysCont.AOD.pro22_v03

Table B.3.1: Overview of the AOD datasets reconstructed with *cosmics* and *collisions* settings used in this analysis.

B.4 Object Definition & Reconstruction

A collision and cosmic run have been reconstructed with three different configurations: *collisions* with standard OFCs, *cosmics* with standard OFCs and *cosmics* with iterative OFCs. In case only the term “*cosmics* reconstruction” is used, it refers to *cosmics* reconstruction with standard OFCs. The impact of the reconstruction mode on the relevant physics objects is discussed in Section 5.3. In the following distributions which were not shown in Section 5.3, are presented.

Jets

Key kinematic distributions of leading jets in a cosmic run are shown in Figure B.4.1. An event-by-event comparison of the leading jet p_T for the three reconstruction modes is shown in Figure B.4.2.

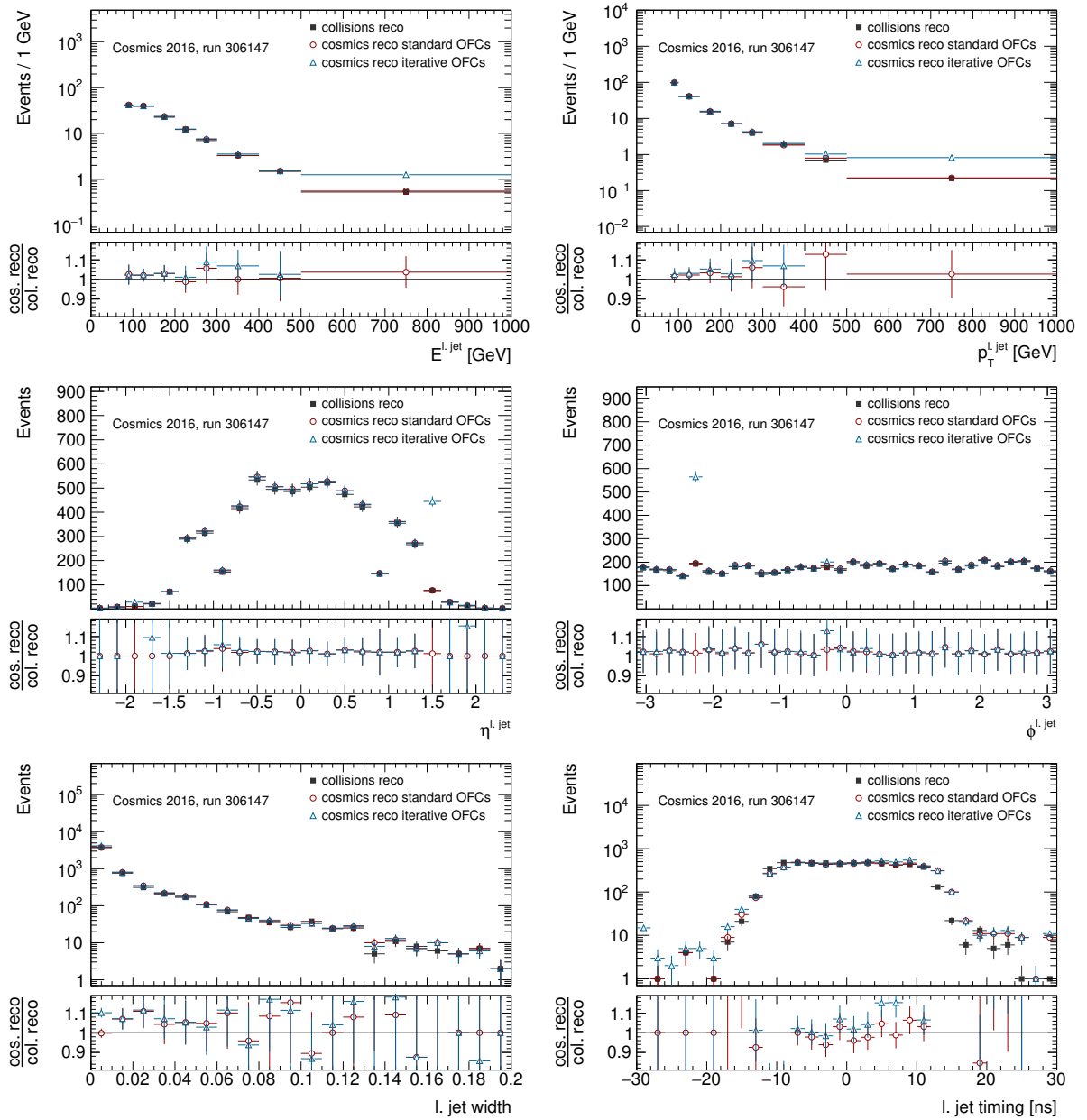


Figure B.4.1: Leading jet energy (top left), p_T (top right), η (middle left), ϕ (middle right), width (bottom left) and timing (bottom right) reconstructed in *collisions* (black), *cosmics* mode with standard (red) and iterative OFCs (blue) in a cosmic run.

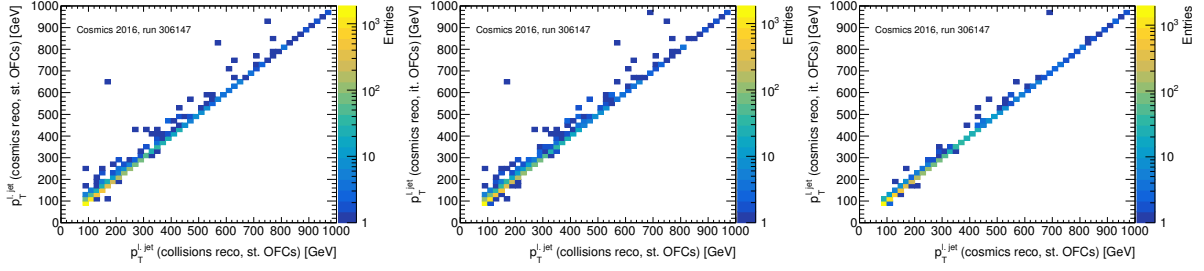


Figure B.4.2: Event-by-event comparison of the leading jet p_T reconstructed in *collisions* and *cosmics* mode with standard OFCs (left), *collisions* and *cosmics* mode with iterative OFCs (centre), *cosmics* mode with standard and iterative OFCs (right) in cosmic run events.

Muon Segments

Figure B.4.3 shows the orientation of the muon segment direction vector in the x - y -plane for segments recorded in a collision run and reconstructed with *cosmics* and *collisions* settings.

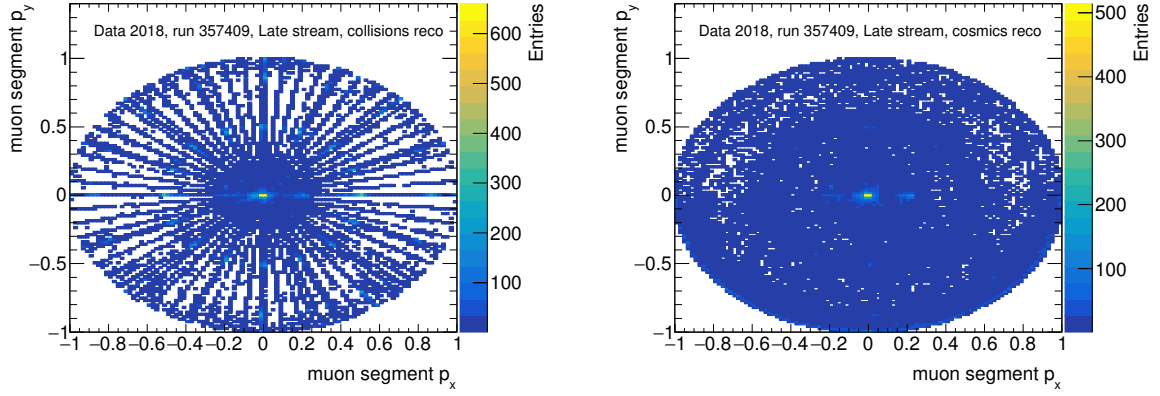


Figure B.4.3: Orientation of the direction vector of muon segments in the x - y -plane for a collision run. The results obtained with *collisions* and *cosmics* reconstruction are shown on the left and right, respectively.

Inner Detector Tracks

The number of reconstructed tracks and the underlying number of hits in the ID sub-detectors in a cosmic run is shown in Figure B.4.4. The track parameters ϕ , θ , d_0 and z_0 are depicted in Figure B.4.5.

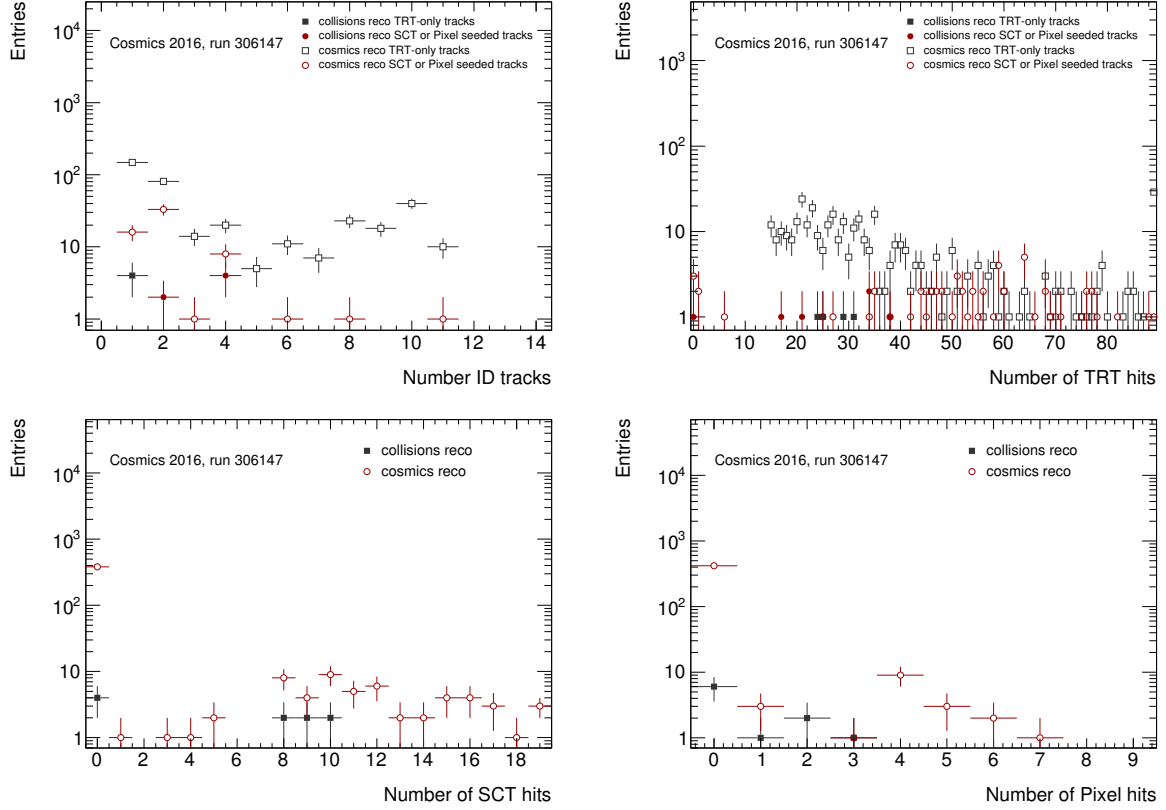


Figure B.4.4: Number of ID tracks (top left) and number of TRT (top right), SCT (bottom left) and Pixel hits (bottom right) in a cosmic run reconstructed with *cosmics* and *collisions* configuration depicted by filled and empty markers, respectively. The number of ID tracks and TRT hits distributions are further split in TRT-only and SCT or Pixel seeded tracks in black squares and red circles, respectively.

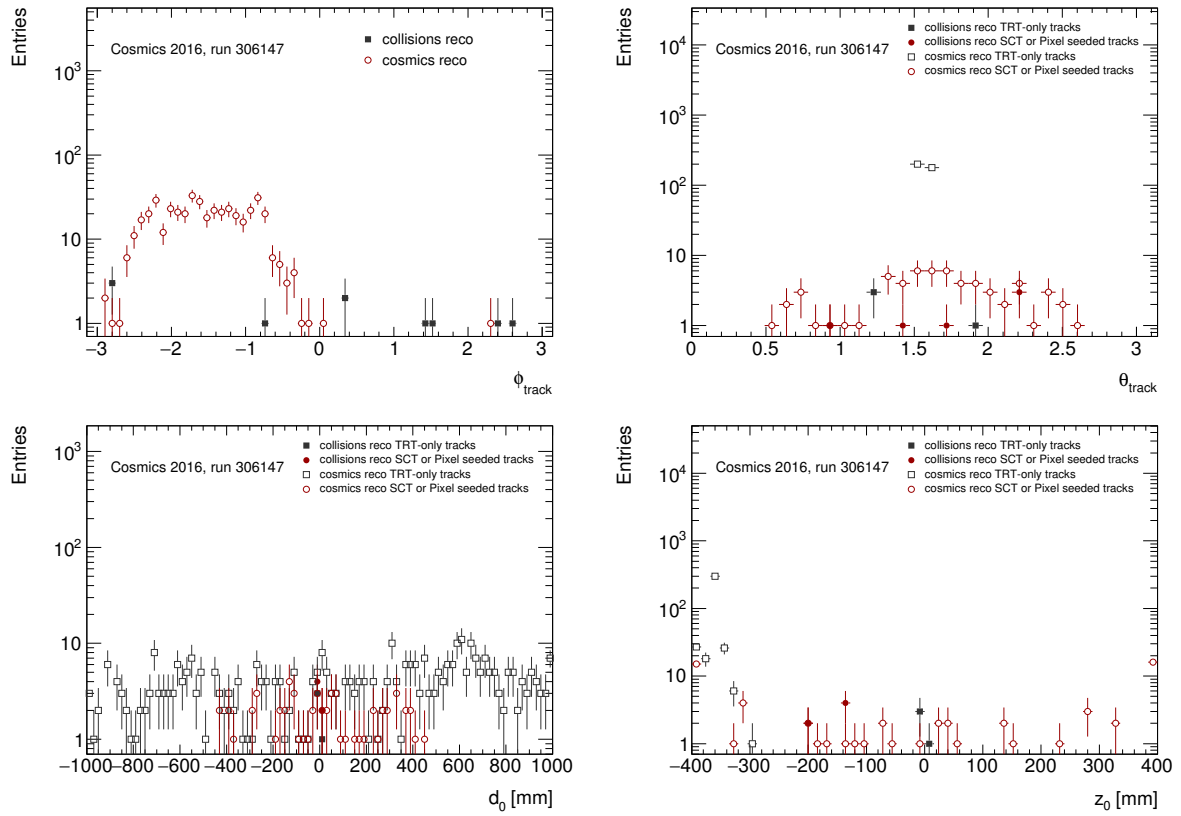


Figure B.4.5: Distribution of track ϕ (top left), θ (top right), d_0 (bottom left) and z_0 (bottom right) in a cosmic run reconstructed with *collisions* and *cosmics* configuration depicted by filled and empty markers, respectively. The distributions of track θ , d_0 and z_0 are further split in TRT-only and SCT or Pixel seeded tracks in black squares and red circles, respectively.

B.5 Event Selection & Jet Cleaning

Table B.5.1 summarises the event yields after the application of the individual and combined selection cut for collision and cosmic data. These are compiled for simulated signal samples in Table B.5.2 to B.5.4.

Selection	Data 2016–2018 Late stream	Data 2016–2018 Background stream	Cosmics 2016 run 306147
Preselection	5081560 (100 %)	840403 (100 %)	11879 (100 %)
HLT $E_{\text{T}}^{\text{miss}} > 50 \text{ GeV}$	5081560 (100 %)	477413 (56.81 %)	6522 (54.90 %)
$p_{\text{T}}^{\text{l. jet}} > 100 \text{ GeV}, \eta < 2.4$	2544567 (50.07 %)	291494 (34.69 %)	4182 (35.20 %)
Jet cleaning	1429177 (28.12 %)	259683 (30.90 %)	11041 (92.95 %)
Total	616881 (12.14 %)	75886 (9.03 %)	3853 (32.44 %)

Table B.5.1: Number of events that fulfil the event selection criteria, summarised for collisions data collected in **empty** and **unpaired** bunch crossings in the **Late** and **Background** stream in 2016–2018 and the 2016 cosmic run. The cuts are applied separately in addition to the preselection. The total event yields reached after all cuts are combined are given in the last row. The cut efficiencies, given in the brackets, are with respect to the preselection.

Selection	$m(\tilde{g}) = 400 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 300 \text{ GeV}$		$m(\tilde{g}) = 600 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 500 \text{ GeV}$		$m(\tilde{g}) = 800 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 700 \text{ GeV}$		$m(\tilde{g}) = 1000 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 900 \text{ GeV}$		$m(\tilde{g}) = 1200 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 1100 \text{ GeV}$		$m(\tilde{g}) = 1400 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 1300 \text{ GeV}$		$m(\tilde{g}) = 1600 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 1500 \text{ GeV}$		$m(\tilde{g}) = 1800 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 1700 \text{ GeV}$	
	+ random	(100 %)	+ random	(100 %)	+ random	(100 %)	+ random	(100 %)	+ random	(100 %)	+ random	(100 %)	+ random	(100 %)	+ random	(100 %)
Raw	7237	(100 %)	6912	(100 %)	7024	(100 %)	7313	(100 %)	8050	(100 %)	8648	(100 %)	6536	(100 %)	7000	(100 %)
HLT $E_T^{\text{miss}} > 50 \text{ GeV}$	2450	(33.85 %)	2413	(34.91 %)	2477	(35.26 %)	2622	(35.85 %)	2819	(35.02 %)	2997	(34.66 %)	2295	(35.11 %)	2398	(34.26 %)
$p_T^{\text{jet}} > 100 \text{ GeV}, \eta < 2.4$	1287	(17.78 %)	1334	(19.30 %)	1436	(20.44 %)	1535	(20.99 %)	1605	(19.94 %)	1690	(19.54 %)	1244	(19.03 %)	1352	(19.31 %)
Jet cleaning	5073	(70.10 %)	4874	(70.52 %)	4903	(70.66 %)	5267	(72.02 %)	5779	(71.79 %)	6258	(72.36 %)	4779	(73.12 %)	5112	(73.03 %)
Total	1283	(17.73 %)	1328	(19.21 %)	1423	(20.26 %)	1529	(20.91 %)	1587	(19.71 %)	1677	(19.39 %)	1235	(18.90 %)	1336	(19.09 %)

Table B.5.2: Number of events that fulfil the event selection criteria, summarised are simulated signal samples with different gluino masses but the same mass splitting of 100 GeV. The cuts are applied separately. The total event yields reached after all cuts are combined are given in the last row. The cut efficiencies, given in the brackets, are with respect to raw number of reconstructed events.

Selection	$m(\tilde{g}) = 600 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 100 \text{ GeV}$		$m(\tilde{g}) = 800 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 300 \text{ GeV}$		$m(\tilde{g}) = 1000 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 500 \text{ GeV}$		$m(\tilde{g}) = 1200 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 700 \text{ GeV}$		$m(\tilde{g}) = 1400 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 900 \text{ GeV}$		$m(\tilde{g}) = 1600 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 1100 \text{ GeV}$		$m(\tilde{g}) = 1800 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 1300 \text{ GeV}$	
	+ random	(100 %)	+ random	(100 %)	+ random	(100 %)	+ random	(100 %)	+ random	(100 %)	+ random	(100 %)	+ random	(100 %)
Raw	6897	(100 %)	7015	(100 %)	7347	(100 %)	8035	(100 %)	8571	(100 %)	6630	(100 %)	7000	(100 %)
HLT $E_T^{\text{miss}} > 50 \text{ GeV}$	5160	(74.82 %)	5404	(77.03 %)	5725	(77.92 %)	6301	(78.42 %)	6665	(77.76 %)	5213	(78.63 %)	5525	(78.93 %)
$p_T^{\text{jet}} > 100 \text{ GeV}, \eta < 2.4$	4931	(71.49 %)	5189	(73.97 %)	5510	(75.00 %)	6076	(75.62 %)	6421	(74.92 %)	5052	(76.20 %)	5341	(76.30 %)
Jet Cleaning	5289	(76.69 %)	5429	(77.39 %)	5690	(77.45 %)	6264	(77.96 %)	6619	(77.23 %)	5108	(77.04 %)	5475	(78.21 %)
Total	4647	(67.38 %)	4894	(69.76 %)	5155	(70.16 %)	5712	(71.09 %)	6016	(70.19 %)	4712	(71.07 %)	5015	(71.64 %)

Table B.5.3: Number of events that fulfil the event selection criteria, summarised are simulated signal samples with different gluino masses but the same mass splitting of 500 GeV. The cuts are applied separately. The total event yields reached after all cuts are combined are given in the last row. The cut efficiencies, given in the brackets, are with respect to the raw number of reconstructed events.

Selection	$m(\tilde{g}) = 400 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 100 \text{ GeV}$		$m(\tilde{g}) = 800 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 100 \text{ GeV}$		$m(\tilde{g}) = 1000 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 100 \text{ GeV}$		$m(\tilde{g}) = 1200 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 100 \text{ GeV}$		$m(\tilde{g}) = 1400 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 100 \text{ GeV}$		$m(\tilde{g}) = 1600 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 100 \text{ GeV}$		$m(\tilde{g}) = 1800 \text{ GeV}$ $m(\tilde{\chi}_1^0) = 100 \text{ GeV}$	
	+ random	(100 %)	+ random	(100 %)	+ random	(100 %)	+ random	(100 %)	+ random	(100 %)	+ random	(100 %)	+ random	(100 %)
Raw	7193	(100 %)	7027	(100 %)	7300	(100 %)	7895	(100 %)	8705	(100 %)	6428	(100 %)	7000	(100 %)
HLT $E_T^{\text{miss}} > 50 \text{ GeV}$	4879	(67.83 %)	5463	(77.74 %)	5794	(79.37 %)	6581	(83.36 %)	7112	(81.70 %)	5359	(83.37 %)	5860	(83.71 %)
$p_T^{\text{jet}} > 100 \text{ GeV}, \eta < 2.4$	4387	(60.99 %)	5306	(75.51 %)	5681	(77.82 %)	6449	(81.68 %)	7023	(80.68 %)	5265	(81.91 %)	5796	(82.80 %)
Jet Cleaning	5403	(75.11 %)	5455	(77.63 %)	5684	(77.86 %)	6315	(79.99 %)	6860	(78.81 %)	5085	(79.11 %)	5617	(80.24 %)
Total	4237	(58.90 %)	4983	(70.91 %)	5319	(72.86 %)	6022	(76.28 %)	6552	(75.27 %)	4878	(75.89 %)	5392	(77.03 %)

Table B.5.4: Number of events that fulfil the event selection criteria, summarised are simulated signal samples with different gluino masses and a neutralino mass of 100 GeV. The cuts are applied separately. The total event yields reached after all cuts are combined are given in the last row. The cut efficiencies, given in the brackets, are with respect to raw number of reconstructed events.

B.6 Cosmic-Induced Background

Signal without Random Event Overlay

The the number of muon segments in simulated signal events is increased by the event overlay of randomly triggered events (c.f. Section 5.1.6). Consequently, the chance of a valid muon segment pair for the α_{cos} calculation is increased and thus the determination of an α_{cos} value is more likely. Figure B.6.1 shows α_{cos} for simulated signal events for a 1400 GeV gluino with a 500 GeV mass splitting with and without the random event overlay. More than twice as many pure signal events have no valid muon segment compared to signal events with random event overlay. These events are spread equally over the rest of the default bins and α_{cos} main distribution for the events with the random event overlay. Hence, the number of signal events rejected by the $|\alpha_{\text{cos}}| > 0.2$ requirement would be more than 30 % lower given the absence of any random detector activity.

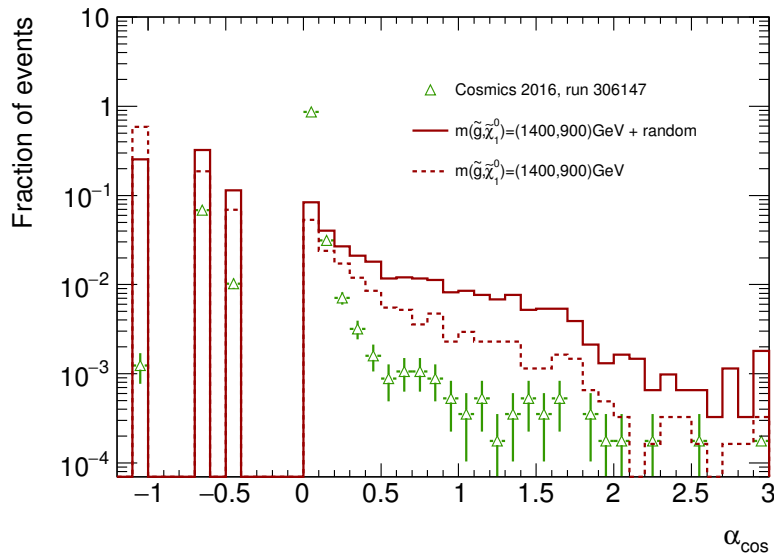


Figure B.6.1: α_{cos} for events recorded in a cosmic run (green) and simulated signal events for a 1400 GeV gluino with a mass splitting of 500 GeV (red). The latter is shown for the pure signal (dashed line) and the signal with an overlay of random events (solid line).

Cosmic-tagged Selection

Figure B.6.2 shows the leading jet occupancy in the η - ϕ -plane for a cos-tag selection, $\alpha_{\text{cos}} < 0.2$ and at least one central muon, in the cosmic run and **Late** and **Background** stream in collision data. All distributions look very similar which is supported by Figure B.6.3 showing a good agreement of the ϕ projections. This further underlines the effectiveness to extract a pure cosmic sample from collision data.

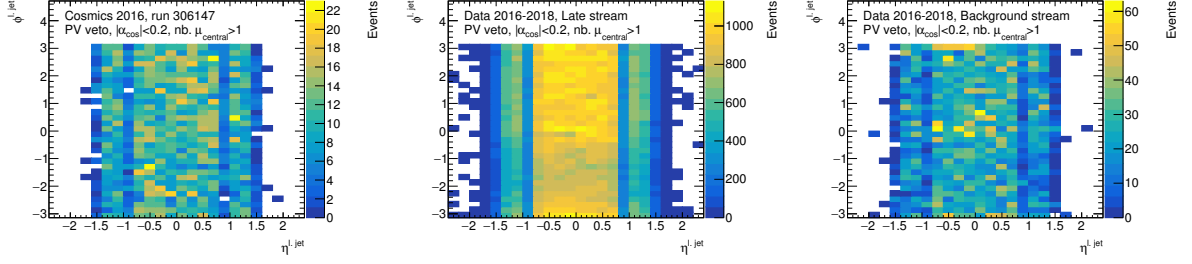


Figure B.6.2: Leading jet occupancy in the η - ϕ -plane of events recorded in the cosmic run (left), **empty** (middle) and **unpaired** (right) bunch crossings in 2016–2018 collision data. A cos-tag selection and the PV veto are applied.

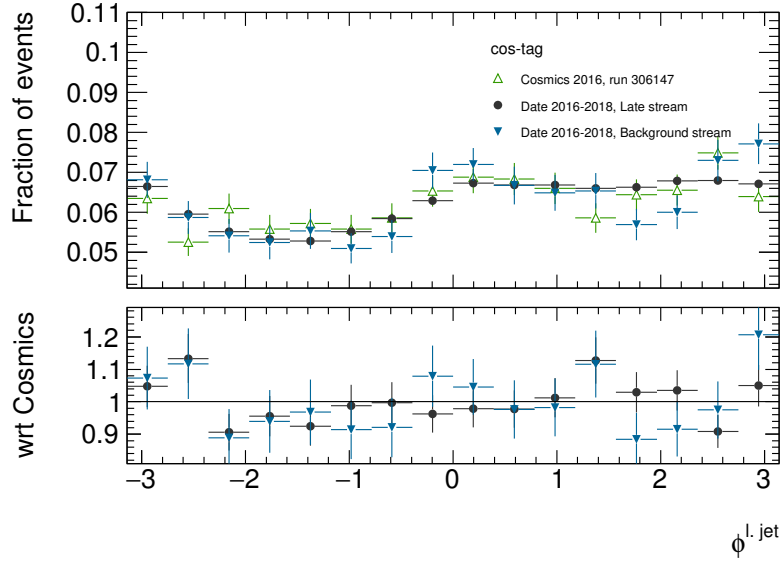


Figure B.6.3: Leading jet ϕ distribution for a cos-tag selection in events collected in the 2016 cosmic run (green), in the **Late** (black) and **Background** (blue) stream. The PV veto is applied. The ratio is shown with respect to the cosmic run.

B.7 Beam-Induced Background

Leading Jet Pull Angle

Within the scope of the BIB studies other possibilities to reduce the contribution of this background source have been investigated. One featured the application of a rectangular cut in η - ϕ -space selecting the peaks at $\phi=0$ and $\pm\pi$ and intermediate bumps at $\phi=\pm\pi/2$, which was found to be too strict leading to an unacceptable reduction of simulated signal events. Another approach exploited the pull of the leading jet. The pull of a jet is defined by

$$\vec{p} = \frac{1}{\sum_{i \in \text{jet}} p_T^i} \times \sum_{i \in \text{jet}} \left(p_T^i \times \Delta R_i \times \vec{r}_i \right), \quad (\text{B.7.1})$$

where $\vec{r}_i$ is a two-dimensional vector in the y - ϕ -plane in the direction of the constituent from the jet axis and ΔR_i is the opening angle between the jet and the i -th constituent. A correlation between the ϕ component of the jet pull, the pull angle, and the jet ϕ was observed as depicted in Figure B.7.1(top left). As reference the distribution is also shown for events recorded in **empty** bunch crossings (top right), a cosmic run (bottom left) and simulated signal events for a 1400 GeV gluino and a mass splitting of 500 GeV (bottom right). Hence, a selection on the peaks in pull angle- ϕ -space was considered. However, the discriminating power of the pull angle

diminishes for large η and thus was abandoned in favour of the cut on the ϕ_{width} , discussed in Section 5.5.2.

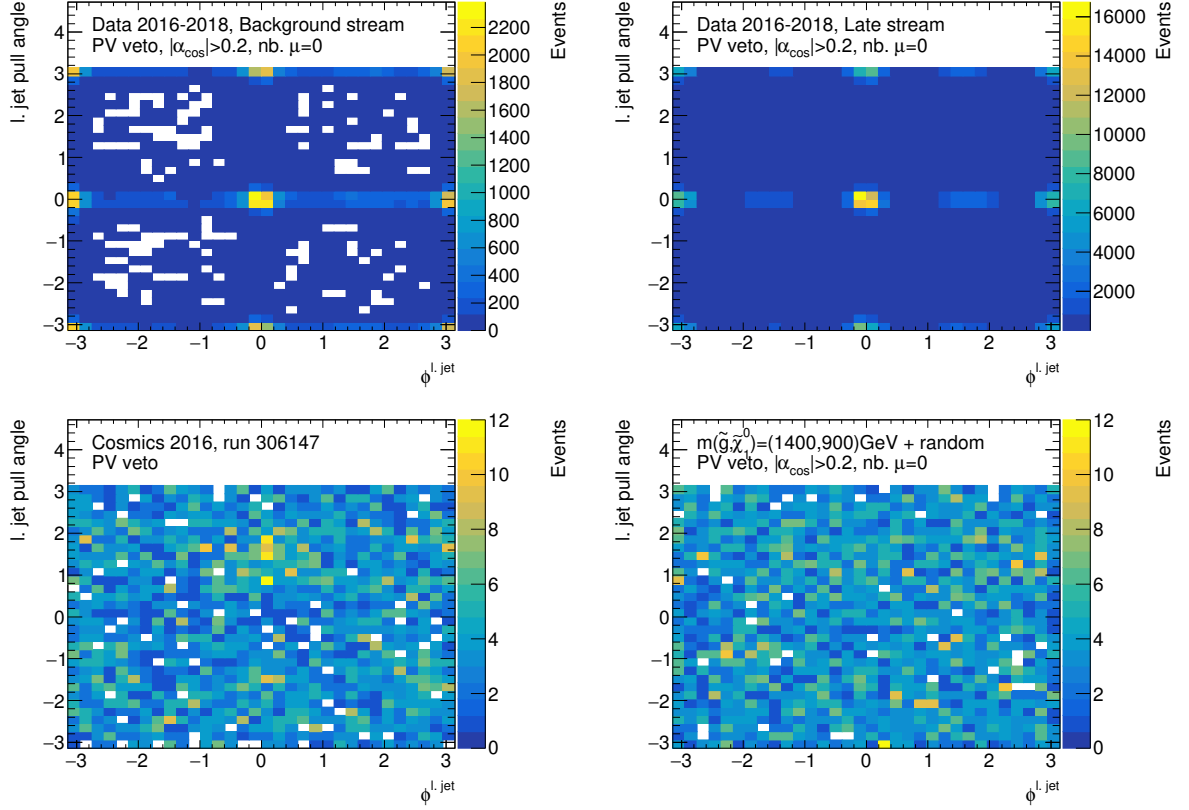


Figure B.7.1: The pull angle of the leading jet versus ϕ reconstructed in events recorded in **unpaired** (top left) and **empty** (top right) bunch crossings in 2016–2018 collision data, the 2016 cosmic run and simulated signal events for a 1400 GeV gluino and a mass splitting of 500 GeV. Only events without a PV reconstructed with *collisions* reconstruction settings and HLT $E_{\text{T}}^{\text{miss}} > 50$ GeV are shown. In order to have a sufficient amount of statistics for the distribution obtained from the cosmic run and signal sample, no cosmic veto is applied solely on these events.

B.8 FIRSTEMPTY BCIDs

During 2018 data-taking, the signal trigger, `HLT_j55_0eta240_xe50_L1J30_EMPTY`, was also enabled during `firstempty` bunch crossings, allowing the possible expansion of the search to `firstempty` BCIDs. In order to decide whether the data collected during these BCIDs can be treated together with the data from `empty` BCIDs, the impact of the *cosmics* reconstruction settings and contamination of out-of-time pile-up, afterglow and BIB must be carefully evaluated. This is crucial to ensure that the same background estimation method is valid when applied to `firstempty` BCIDs, and to examine whether the gain in live fraction is not outweighed by a large increase in background rates. Cosmic-induced background is not explicitly studied in `firstempty` bunch crossings as it is independent of the bunch group type.

Reconstruction

Within the scope of the studies of different reconstruction modes, discussed in Section 5.3, data recorded in `firstempty` bunch crossings has been investigated as well. Similar observations as for data from `empty` bunch crossings were made. A few differences arise as by considering events from `firstempty` bunch crossings, namely the level of pile-up noise is increased. This manifests in a higher number of sub-leading jets as shown in Figure B.8.1(left). These jets are mainly localised to the Tile gap layer 3 and the innermost three cells of the extended Tile barrel layer 0, marked as E1–E4 and A12–A14, respectively, in the scheme of the Tile calorimeter in Figure B.8.2. This leads to an increase of sub-leading jets in $1 < |\eta| < 1.5$ compared to events collected in `empty` bunch crossings, as can be seen in Figure B.8.1(right). Removing the two Tile layers prone to noise, Tile gap layer 3 and extended Tile barrel layer 0, reduces the excess. A residual increased sub-leading jet population, especially in the end-caps, is still present.

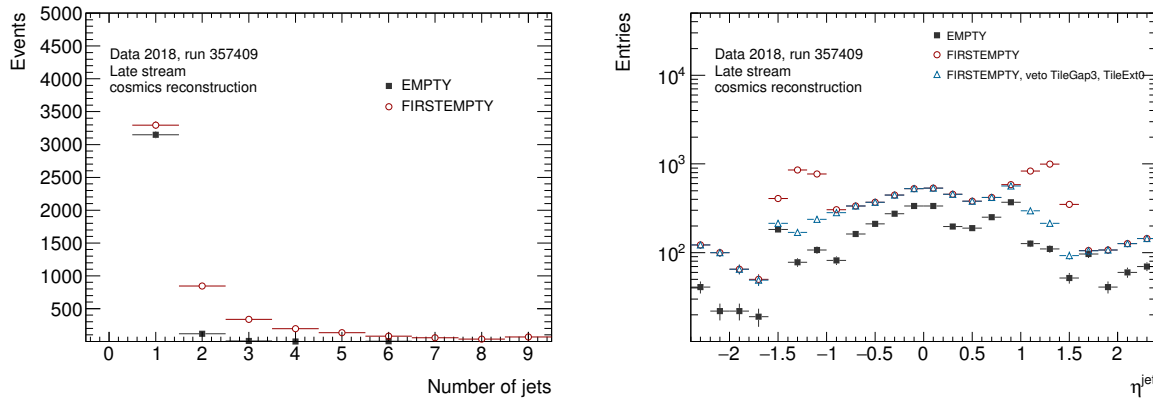


Figure B.8.1: The number of jets reconstructed with *cosmics* settings in events collected in `empty` (black squares) and `firstempty` (red circles) bunch crossings is shown on the left. The η of these jets is shown on the right. The distribution for `firstempty` with a veto on jets that reside in the Tile gap layer 3 or extended Tile barrel layer 0 is included (blue triangles).

Background Contamination

The full 2018 data sample is used to compare the background contribution in events recorded in `empty` and `firstempty` bunch crossings. In these studies the `firstempty` data are split based on their distance from the previous (in the case of `firstempty` after `paired`) and following (in the case of `firstempty` before `paired`) filled bunches by cutting on the `gapBeforeBunch` (abbreviated “gBB”) and `gapAfterBunch` (abbreviated “gAB”) variables, respectively. The gBB and gAB variables give the distance between the bunch in question and the closest previous or

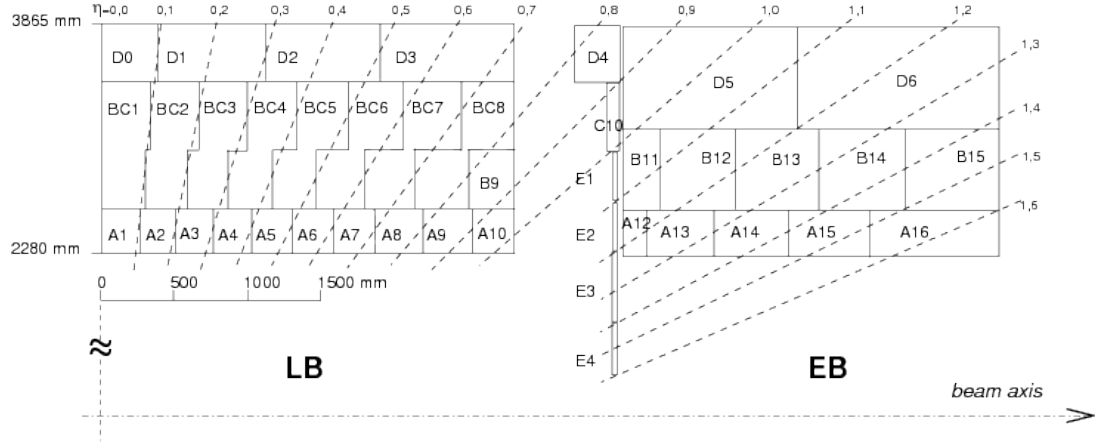


Figure B.8.2: Schematic of the cell layout in a plane parallel to the beam axis, shown only for positive η (the detector being symmetric with respect to $\eta=0$). The three radial layers (A, BC and D) are visible. Special scintillators, called “gap cells” (E1 and E2) and “crack cells” (E3 and E4), are located between the barrel and the end-cap. [146]

consecutive filled bunch in ns, respectively. The selection and cleaning described in Section 5.4 are applied.

Firstempty bunch crossings come in two different arrangements in the bunch group schemes: Either the gap separating **paired** trains is long enough to fit ten **firstempty**, five after and five before **paired**, and a certain number of **empty** bunch crossings in between them; or it is too short and only a sequence of **firstempty** BCIDs finds enough space. In the latter case, there might be an overlap of the five **firstempty** after and five before **paired**, e.g. the fourth and fifth bunches after can be the fifth and fourth bunches before **paired**, respectively. These **firstempty** are not considered here as they are highly contaminated by in-time BIB, out-of-time pile-up and afterglow owing to their proximity to **paired** BCIDs. Figure B.8.3 shows the two configurations.

	PAIRED	FEa 1	FEa 2	FEa 3	FEa 4	FEa 5	EMPTY	...	EMPTY	FEb 5	FEb 4	FEb 3	FEb 2	FEb 1	PAIRED
gapBeforeBunch [ns]		25	50	75	100	125	150			>150	>175	>200	>225	>250	
gapAfterBunch [ns]		>250	>225	>200	>175	>150			150	125	100	75	50	25	

	PAIRED	FEa 1 FEb 7	FEa 2 FEb 6	FEa 3 FEb 5	FEa 4 FEb 4	FEa 5 FEb 3	FEa 6 FEb 2	FEa 7 FEb 1	PAIRED
gapBeforeBunch [ns]		25	50	75	100	125	150	175	
gapAfterBunch [ns]		175	150	125	100	75	50	25	

Figure B.8.3: Schematic of the two configurations of **firstempty** bunch crossings. The top scheme represents the case when the gap in between **paired** bunch crossings is long enough to fit five **firstempty** after (abbreviated “FEa”) and before (abbreviated “FEb”) **paired** and a certain number of **empty**. The case when the gap is too short such that only **firstempty** but no **empty** find enough space is shown in the bottom scheme. Each **firstempty** can be assigned a number from 1 to 5 or 5 to 1 depending on their increasing or decreasing distance to the previous or following filled bunch, respectively. In case of the bottom configuration an overlap of FEa and FEb can occur. The distance toward the previous and following filled bunch is given by the **gapAfterBunch** and **gapBeforeBunch** quantities in ns.

The contamination by BIB in **firstempty** bunch crossings is evaluated by studying the leading jet timing versus its η whereby the same distributions in **empty** and **unpaired** BCIDs are used as references, see Figure B.8.4. The **firstempty** distribution is dominated by an abundance of jets at 5 to 10 ns and central η which is not present in **empty** BCIDs. However,

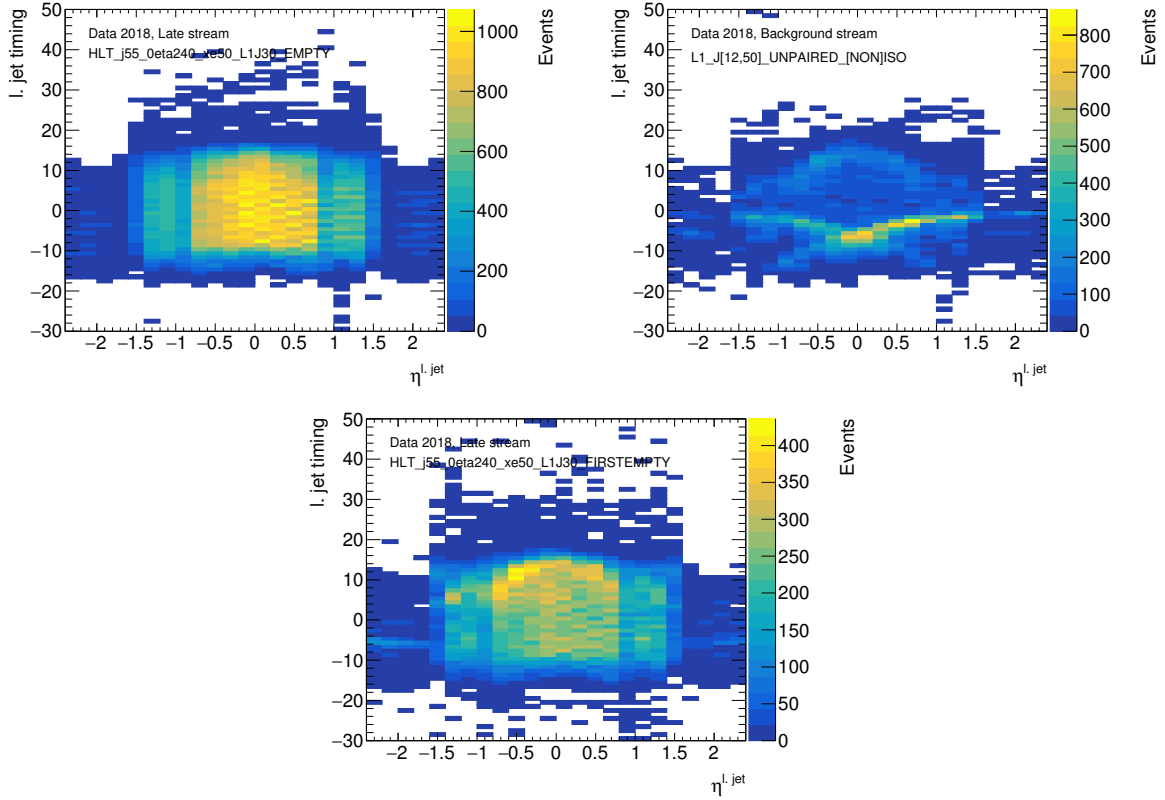


Figure B.8.4: Leading jet timing versus η in **empty** (top left), **unpaired** (top right) **firstempty** (bottom) bunch crossings recorded in 2018. For the **firstempty** bunch crossings, only those **firstempty** BCIDs that border a train of **empty** BCIDs are included.

in **unpaired** bunch crossings this feature is clearly visible, suggesting that these are upstream BIB-induced jets from the following bunch manifesting as late-arriving jets in the previous bunch crossing. This assumption is confirmed when looking at the time- η distribution for each **firstempty** BCID separately (c.f. Figure B.8.5 and B.8.6). Figure B.8.5(a) shows that only the **firstempty** directly followed by a **paired** bunch is affected by these BIB features. Further, the two slight excesses at ≈ 12.5 ns and $|\eta| = 1.5$ are, given their position, assumed to be BIB-induced jets originating from the filled bunches arriving 50 ns later. In the **firstempty** second-closest to the following **paired** this feature is predominant (c.f. Figure B.8.5(b)), verifying this statement. Two hotspots at -5 ns in each end-cap are apparent in the **firstempty** preceding **paired**, as well as **unpaired** bunch crossings. They can be linked to BIB-induced noise in the Tile Gap layer 3 and the innermost three cells of layer 0 of the Tile extended barrel. This was already mentioned in the above section on the reconstruction of events recorded in **firstempty** BCIDs. The distributions in the **firstempty** after **paired** bunches and the three farthest away from the following **paired** bunch crossings are similar to the one in **empty** BCIDs. This concludes that the two **firstempty** closest to the following **paired** bunches are too much contaminated by BIB to be used in this analysis.

To access the impact of out-of-time collisions the average number of PVs per **firstempty** BCID is consulted. The respective distribution is shown in Figure B.8.7, the corresponding values are summarised in Table B.8.1. No preselection has been applied in order to preserve sufficient statistics and allow an unbiased assessment. The two **firstempty** to both sides of an **empty** train have no PVs indicating that the contamination from out-of-time pile-up is negligible. The average number of PVs increases when moving closer to **paired** bunches.

The muon segments are especially important as they are a key element in the reconstruction of $\alpha_{\cos}$, used to reject CIB, but also to reflect the cavern background. As the latter is modelled

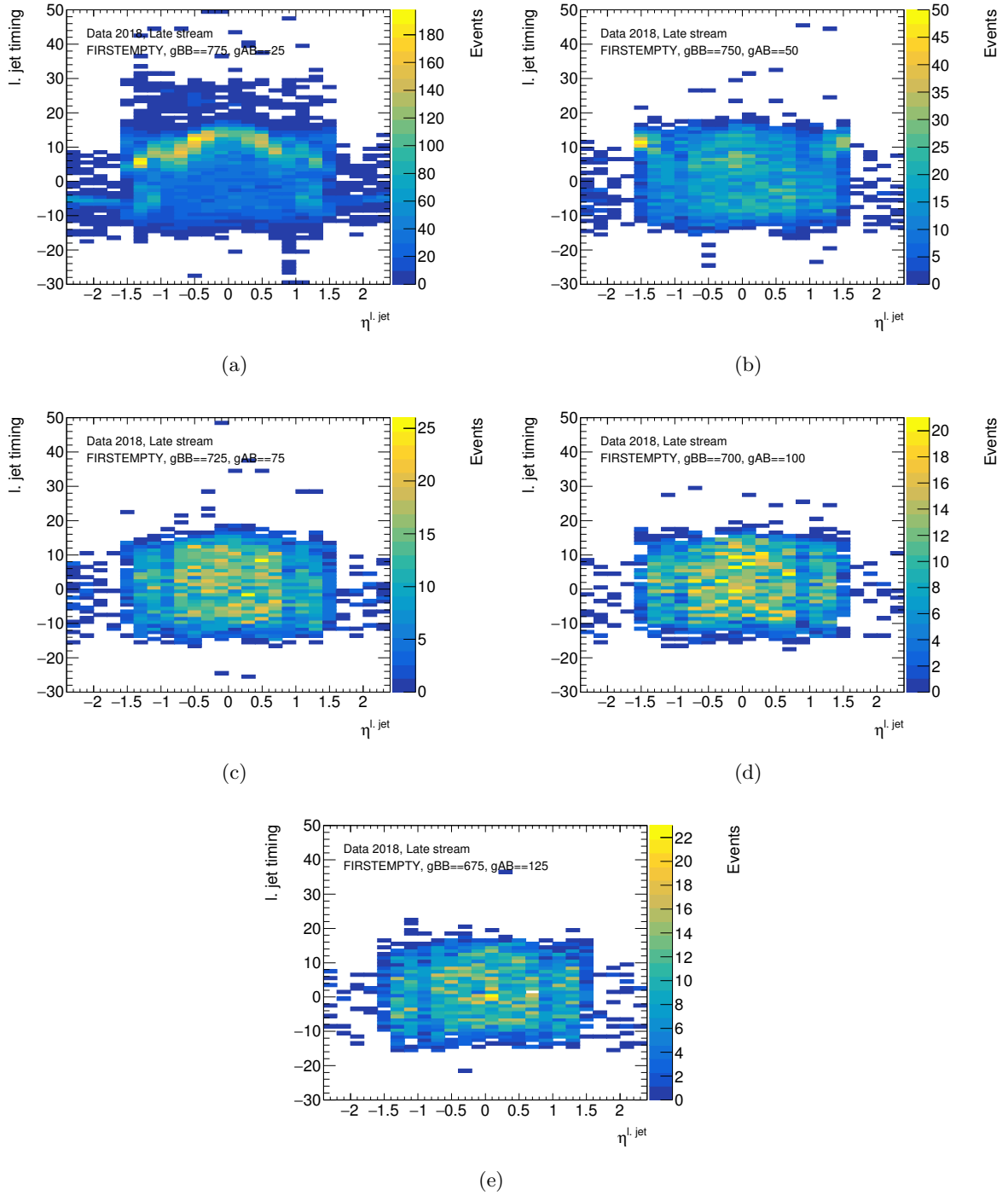


Figure B.8.5: Leading jet timing versus η in the last 5 firstempty bunch crossings before paired recorded in 2018. Only those firstempty BCIDs that border a train of empty BCIDs are included. The distributions are shown separately for each of the five BCIDs starting with the one closest to the following filled bunch in the top left.

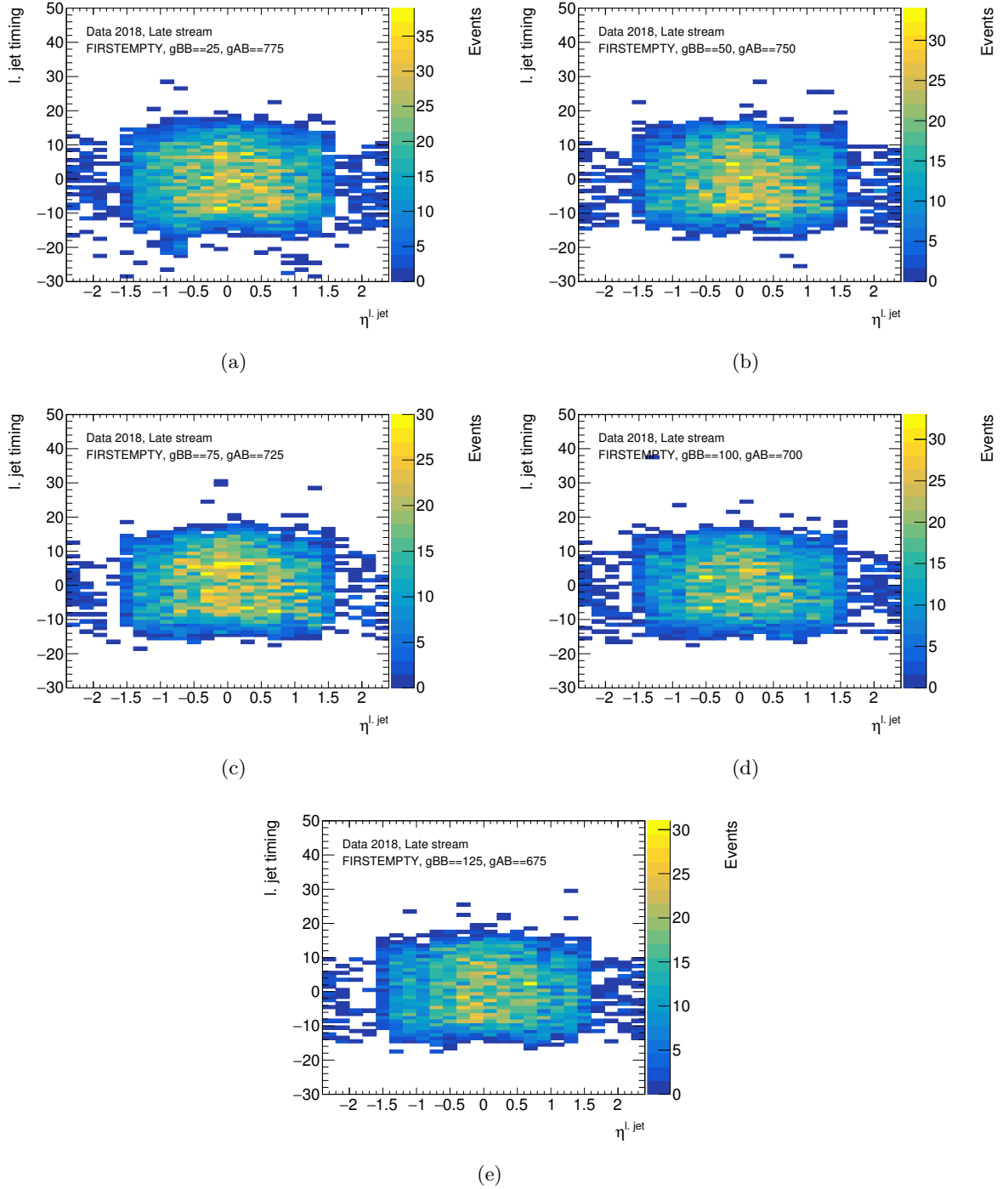


Figure B.8.6: Leading jet timing versus η in the first 5 firstempty bunch crossings after paired recorded in 2018. Only those firstempty BCIDs that border a train of empty BCIDs are included. The distributions are shown separately for each of the five BCIDs starting with the one closest to the previous filled bunch in the top left.

BCID	Number of events with PV	Total number of events	Fraction of events with PV
firstempty, gBB==25 && gAB==775 (FEa1)	25	78208	0.000319660392799
firstempty, gBB==50 && gAB==750 (FEa2)	2	74401	0.0000134406795608
firstempty, gBB==75 && gAB==725 (FEa3)	2	71554	0.0000139754590938
firstempty, gBB==100 && gAB==700 (FEa4)	0	69681	0.
firstempty, gBB==125 && gAB==675 (FEa5)	0	68234	0.
empty, gBB>=150 && gAB<=150	4	1823393	0.00000219371249094
firstempty, gBB==675 && gAB==125 (FEb5)	0	52040	0.
firstempty, gBB==700 && gAB==100 (FEb4)	0	53757	0.
firstempty, gBB==725 && gAB==75 (FEb3)	3	58205	0.0000515419637488
firstempty, gBB==750 && gAB==50 (FEb2)	20	64461	0.000310265121546
firstempty, gBB==775 && gAB==25 (FEb1)	100	130915	0.00076385440935

Table B.8.1: Total and relative number of events with a PV in each **firstempty** bunch crossings after and before **paired**. The values for **empty** bunch crossings are inclusive.

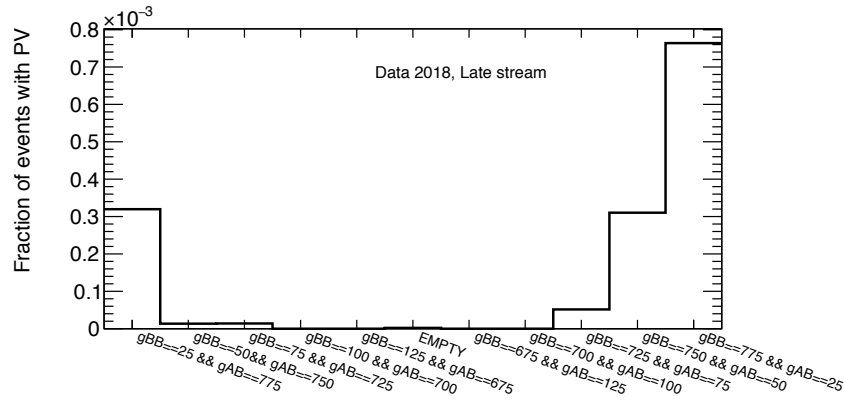


Figure B.8.7: Fraction of events with a PV for each **firstempty** BCID after and before **paired** and **empty** bunch crossings. The latter are shown inclusively.

by the random event overlay described in Section 5.1.6, the rate of muon segments in **empty** bunch crossings must be applicable for the considered **firstempty** BCIDs in order to adequately account for this background source. The number of muon segments is shown in Figure B.8.8 for each **firstempty** BCID separately. The two bunches before and after the **empty** train are similar to each other, while the spectra moves at higher values when approaching **paired** bunches. Figure B.8.9 compares the 4th and 5th **firstempty** following a **paired** bunch crossing to the first and last **empty** BCID in a train. A shift of the spectra towards higher values can be observed from the beginning to end of the **empty** train. The two consider **firstempty** lie in between these two extremes, ensuring that the random event overlay is reasonable and the $\alpha_{\cos}$ calculation are unaffected for these **firstempty** BCIDs. However, the 4th and 5th **firstempty** bunch crossings on the other side of the **empty** train display a notable higher muon segment multiplicity, jeopardising the effectiveness of the random event overlay and the $\alpha_{\cos}$ determination. Thus, the set of considered **firstempty** BCIDs shrinks to those two directly proceeding the **empty** train.

Finally, the jet multiplicity and leading jet p_T spectra in the 4th and 5th **firstempty** bunches after **paired** exhibit an acceptable agreement with the first **empty** bunch succeeding them (c.f. Figure B.8.11).

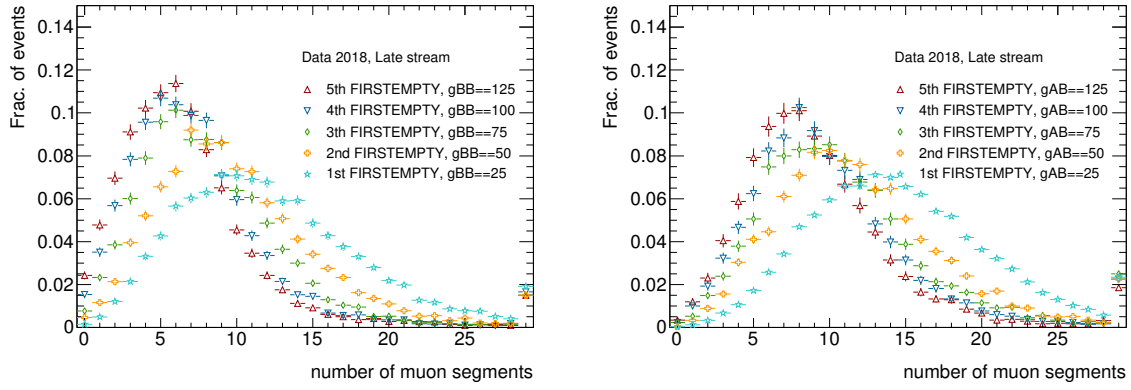


Figure B.8.8: Number of muon segments in **firstempty** bunch crossings after (left) and before (right) **paired** recorded in 2018. For the **firstempty** bunch crossings, only those **firstempty** BCIDs that border a train of **empty** BCIDs are included. The distributions are shown separately for each of the five BCIDs.

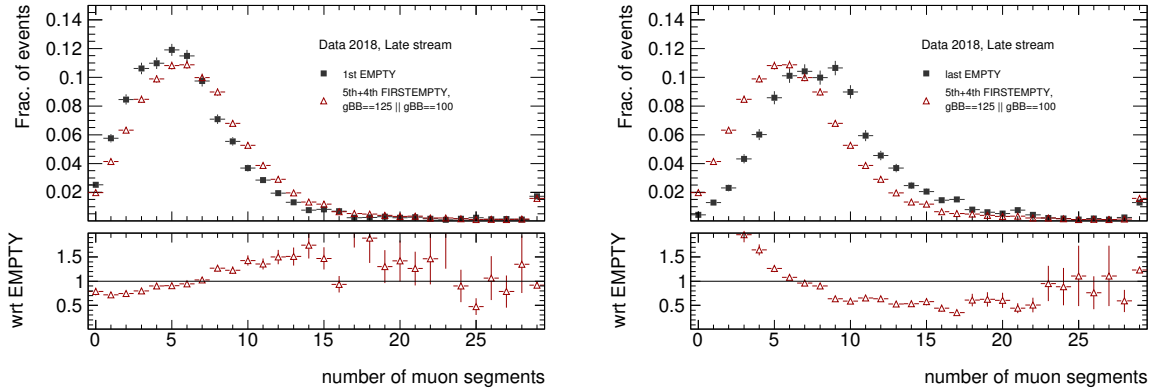


Figure B.8.9: Number of muon segments in the 4th and 5th **firstempty** bunch crossings after **paired** compared to the first (left) and last (right) **empty** bunch crossings shown in red and black, respectively. For the **firstempty** bunch crossings, only those **firstempty** BCIDs that border a train of **empty** BCIDs are included. The ratio below is shown versus the respective **empty** bunch crossing.

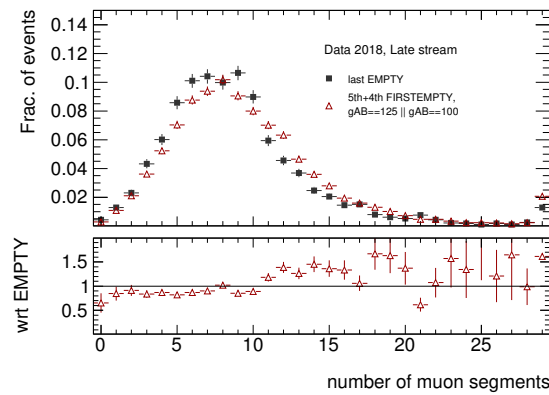


Figure B.8.10: Number of muon segments in the 4th and 5th **firstempty** bunch crossings before **paired** compared to the last **empty** bunch crossings shown in red and black, respectively. For the **firstempty** bunch crossings, only those **firstempty** BCIDs that border a train of **empty** BCIDs are included. The ratio below is shown versus the last **empty** bunch crossing.

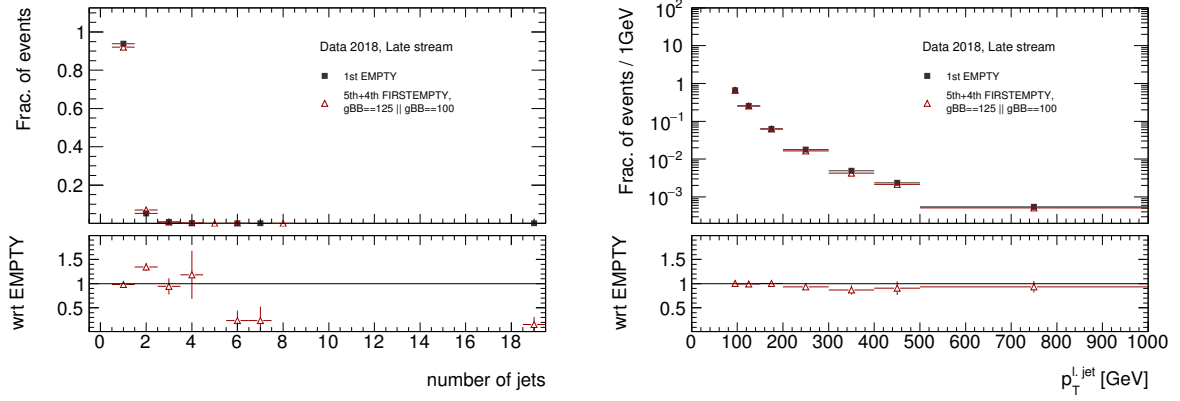


Figure B.8.11: Number of jets (left) and leading jet p_T (right) in the 4th and 5th **firstempty** bunch crossings after **paired** compared to the first **empty** bunch crossings shown in red and black, respectively. For the **firstempty** bunch crossings, only those **firstempty** BCIDs that border a train of **empty** BCIDs are included. The ratio below is shown versus the first **empty** bunch crossing.

As conclusion of these investigations, the 4th and 5th **firstempty** after **paired** bunches, immediately before a **empty** train commences, display a satisfactory similarity with **empty** BCIDs and thus are included in the background estimate and signal sensitivity of the stopped long-lived particle analysis presented in Section 5.6 and 5.7, respectively.

B.9 Background Estimate

Figure B.9.1 shows the difference in the p_T shape extracted from the Late and Background stream dataset for the four VRs.

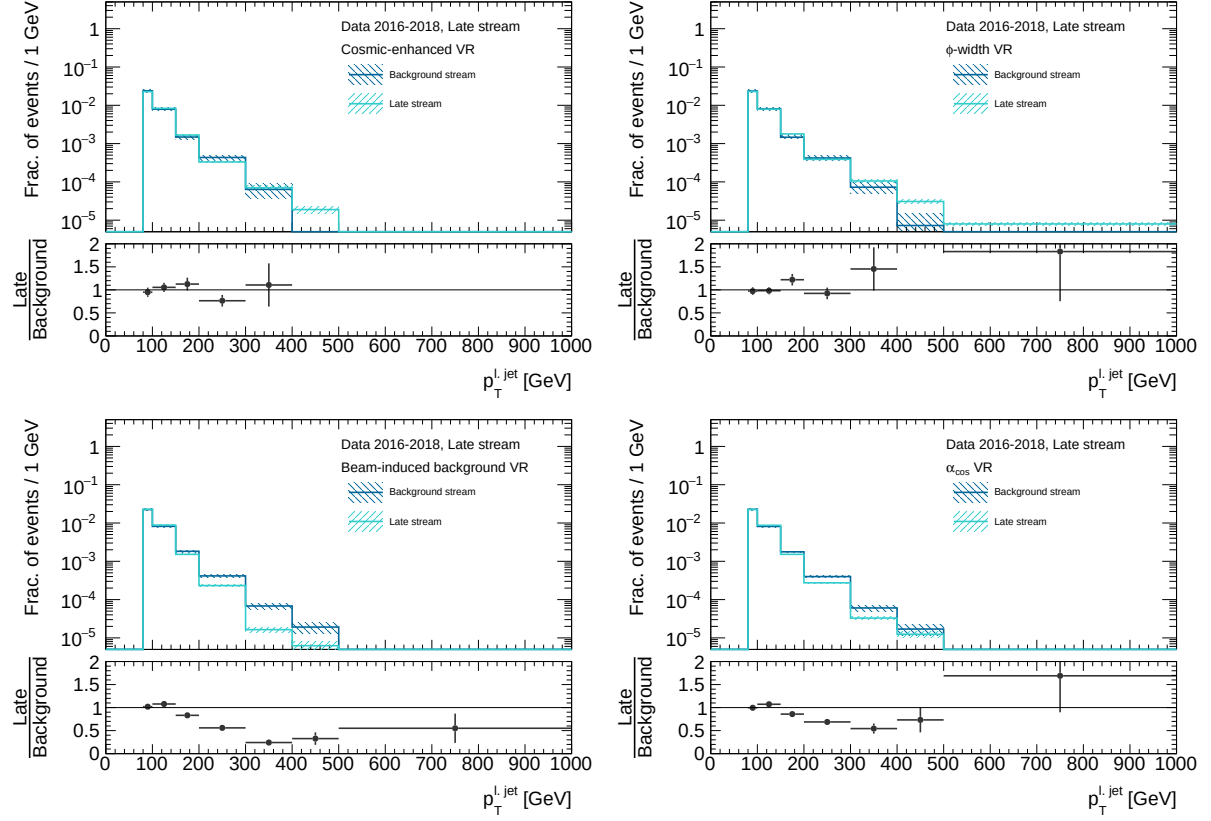


Figure B.9.1: Comparison of p_T shapes taken in the BIB CRs from data recorded 2016–2018 in the Late (light blue) and the Background (dark blue) stream. The hatched band shows the statistical uncertainties. The last bin includes the overflow.

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List of Abbreviations

ALFA	Absolute Luminosity for ATLAS
ALICE	A Large Ion Collider Experiment
ATLAS	A Toroidal LHC ApparatuS
BCID	Bunch-Crossing Identification
BCM	Beam Condition Monitor
BIB	Beam-Induced Background
BSM	Beyond Standard Model
Bulk	Bulk Processing
CIB	Cosmic-Induced Background
CMS	Compact Muon Solenoid
CR	Control Region
CSC	Cathode Strip Chamber
CTP	Central Trigger Processor
DM	Dark Matter
DQ	Data Quality
ECAL	Electromagnetic Calorimeter
EM	Electromagnetic
EMB[{A,C}]	Electromagnetic Barrel (Calorimeter) [{A,C} side]
EMEC[{A,C}]	Electromagnetic End-cap(Calorimeter) [{A,C} side]
ES1	1 st Express Processing
FCAL[{A,C}]	Forward Calorimeters [{A,C} side]
FEB	Front-End Board
GRL	Good Runs List
GSF	Gaussian Sum Filter
GUT	Grand Unified Theory
HCAL	Hadronic Calorimeter
HEC[{A,C}]	Hadronic End-cap[{A,C} side]

HLT	High Level Trigger
hnHG	highNoiseHighGain
HV	High Voltage
IBL	Insertable b-Layer
ID	Inner Detector
IoV	Intervals of Validity
IMW	Intermodule-Widening
IP	Interaction Point
ITC	Intermediate Tile Calorimeter
L1	Level 1 (trigger)
LAr	Liquid Argon
LArCalo	Liquid Argon Calorimeter
LB	Luminosity Block
LINAC	Linear Accelerator
LH	Likelihood
LHC	Large Hadron Collider
LHCb	Large Hadron Collider beauty
LLP	Long-Lived Particle
LS2	Long Shutdown 2
LSP	lightest SUSY particle
LUCID	LUminosity measurement using Cherenkov Integrating Detector
MC	Monte Carlo
MDT	Monitoring Drift Tube
MNB	Mini Noise Burst
MPV	Most Probable Value
MS	Muon Spectrometer
MSSM	Minimal Supersymmetric Standard Model
NB	Noise Burst
OFC	Optimal Filtering Coefficient
PDF	Parton Density Function / Probability Density Function
PS	Presampler / Proton Synchrotron
PSB	Proton Synchrotron Booster
PV	Primary Vertex
RMS	Root Mean Square
RoI	Region of Interest
RPC	Resistive Plate Chamber

SCT	Semi-Conductor Tracker
SM	Standard Model
spBN	sporadicBurstNoise
SPS	Super Proton Synchrotron
SSB	Spontaneous Symmetry Breaking
SUSY	Supersymmetry
SR	Signal Region
TGC	Thin Gap Chamber
VR	Validation Region
ZDC	Zero Degree Calorimeter

Own Contributions

The ATLAS collaboration has more than 3000 members working closely together to reach their ambitious goals which only can be achieved through teamwork. Hence, the contribution of a single member has to be regarded in the context of the collaborative effort, building upon the work of and providing input for others. Thus, in the following my own contributions to the studies presented in this thesis are outlined.

Within the scope of the **data quality assessment of the Liquid Argon calorimeter** (c.f. Section 3.2.7), I developed the tool to detect excessive over-masking of noisy channels and warn the shifter. Further, I designed a tool to monitor the development of the by mini noise bursts affected front-end boards over extended data-taking periods. These additions are based on own experience as a shifter and benefit the overall LAr and general DQ assessments documented in [89].

I conducted several studies to maintain and optimise the performance of the **energy calibration of electrons and photons**. I extracted the correction factors for non-uniformities in the energy response due to non-nominal high voltage settings and the intermodule-widening effect, and improved the procedures used to determine these corrections to achieve a more precise result as discussed in Section 4.3. With these studies I contributed to [104] summarising the status of the electron and photon energy calibration in Run 2. Further, I investigated the potential of exploiting tracking information in the MVA calibration and defined an extended variable set which enhances the energy response significantly at low transverse momentum. Additionally, I suggested the consideration of the azimuthal position of the electromagnetic cluster in the MVA calibration and conducted the relevant performance and sanity checks. These improvements of the MVA calibration step are covered in Section 4.4.

As one of the main analysers of the **search for stopped long-lived particles** presented in Chapter 5, I significantly contributed to the analysis design including the validation of the utilised data streams, comparison of the reconstruction methods and signal validation. I developed the analysis framework including the method for the random event overlay, and performed studies on the object selection and jet cleaning. Further, I conducted the investigations of beam- and cosmic-induced backgrounds. I especially promoted the design and tuning of the geometrical veto of jets originating from cosmic muons. The studies on these non-collisions backgrounds found general interest and allowed me to expand them to a broader scope which will be published soon in a dedicated paper summarising non-collision background observations with the ATLAS detector in Run 2. Finally, I worked on the background estimate and implemented the presented preliminary sensitivity estimate. Since the official analysis is not public, yet, I could not unblind the final results, however, together with the analysis team I am finalising the documentation at the moment such that the publication is expected in the near future.

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Versicherung

Hiermit versichere ich, dass ich die vorliegende Arbeit ohne unzulässige Hilfe Dritter und ohne Benutzung anderer als der angegebenen Hilfsmittel angefertigt habe. Die aus fremden Quellen direkt oder indirekt übernommenen Gedanken sind als solche kenntlich gemacht. Die Arbeit wurde bisher weder im Inland noch im Ausland in gleicher oder ähnlicher Form einer anderen Prüfungsbehörde vorgelegt.

Die vorliegende Dissertation wurde am Institut für Kern- und Teilchenphysik der Technischen Universität Dresden unter der wissenschaftlichen Betreuung von Prof. Dr. Arno Straessner angefertigt.

Es haben keine früheren erfolglosen Promotionsverfahren stattgefunden.

Hiermit erkenne ich die Promotionsordnung des Bereichs Mathematik und Naturwissenschaften der Universität Dresden vom 23.02.2011 an.

Meyrin, 26.08.2020

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