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Measurement of lepton efficiency in lead-lead collisions
in the ATLAS experiment at the LHC

Pomiar wydajności leptonów w zderzeniach ołów-ołów
w eksperymencie ATLAS na LHC

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1 Introduction

The European Organization for Nuclear Research (CERN), established across divisions in 1954, was initially intended to provide European scientists with a local research facility. Today, the laboratory is known for exploring phenomena that reach deeper than the atom nuclei and discovering physics beyond the Standard Model [1]. A key component of CERN is the Large Hadron Collider (LHC). This advanced accelerator allows heavy-ions, such as lead, to collide at extremely high energies, temporarily recreating a state similar to the one that occurred immediately after the Big Bang. It facilitates the study of quark-gluon plasma (QGP), where quarks and gluons exist in a free, unbound state [2, 3].

The ATLAS experiment is one of CERN’s major general-purpose detectors. It plays a crucial role in detecting particles produced from proton-proton (pp) and heavy-ion (HI) collisions [4]. Data collected by ATLAS in 2015 and 2018 during Run 2, with center-of-mass energy of 5.02 TeV per nucleon pair and a total integrated luminosity of 1.9 nb^{-1} , allowed for the first study of top-quark pair ($t\bar{t}$) production in lead-lead (Pb+Pb) collisions by ATLAS. These heaviest elementary particles almost immediately decay into b -quarks and W bosons. The W boson decays into a neutrino and a lepton (electron or muon) in 21% of cases, with the detection of these leptons being crucial for identifying and reconstructing $t\bar{t}$ events and studying the QGP.

In 2020, the CMS experiment at the LHC reported the first evidence of $t\bar{t}$ pair production in Pb+Pb collisions [5]. Building on this progress, the ATLAS Collaboration is conducting a similar analysis. Accurate analysis of $t\bar{t}$ events in ATLAS requires precise measurement of lepton efficiencies, including identification, isolation, and triggering. Due to potential differences between the simulation and real data in detector response, it is crucial to derive scale factors to correct these discrepancies and ensure that simulated results align with actual detector performance [6].

The first part of this thesis focuses on measuring lepton efficiencies in Pb+Pb collisions using the tag-and-probe method focusing on Z boson dileptonic decay. By comparing reconstructed, identified, isolated and triggered lepton performance in experimental data with simulation, we derive scale factors to adjust simulated results. These corrections are essential for refining $t\bar{t}$ measurements and enhancing our understanding of the QGP. They play a key role in a recent observation of $t\bar{t}$ production in Pb+Pb collisions by ATLAS [2].

In the second part of this thesis, the analysis focuses on the data collected during the 2024 LHC HI run, specifically investigating electron performance in Z boson dileptonic decays at a center-of-mass energy of 5.36 TeV per nucleon pair. The primary goal of this analysis is to validate and assess the response of the ATLAS detector to high-density environments in Pb+Pb collisions. The tag-and-probe method is applied to select a sample of isolated electrons and investigate their identification performance across different working points, starting with reference pp data, the analysis extends to Pb+Pb collisions, revealing the significant challenges posed by the high particle multiplicity and background contamination typical of HI collisions.

2 Overview of the ATLAS Experiment

2.1 The Large Hadron Collider and Heavy-Ion Program

The HI collisions at the LHC at CERN have been planned since the very beginning of the LHC project. There was a need to further expand the knowledge gained from HI collisions in the CERN Super Proton Synchrotron (SPS) and Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory. Between 1998 and 2008, in place of the Large Electron-Positron (LEP) collider, a 27-kilometer long accelerator was built [7]. The LHC machine enables ions to collide with the nominal energy of 2.56 TeV per nucleon [8], creating states impossible to observe in nature, even with advanced cosmological instruments [3].

Before the ions collide, they undergo several acceleration stages, starting at the Electron Cyclotron Resonance source, where lead isotopes are produced. After strict selection of appropriately ionized lead ions, bunches from the Linear Accelerator 3 (LINAC 3) are formed into short, high-intensity bunches by the Low Energy Ion Ring (LEIR). Following this, the ions are further accelerated through the Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS) before being injected into the LHC, where they are collided in four interaction points [7]. Figure 2.1 shows the intricate and vast CERN accelerator complex.

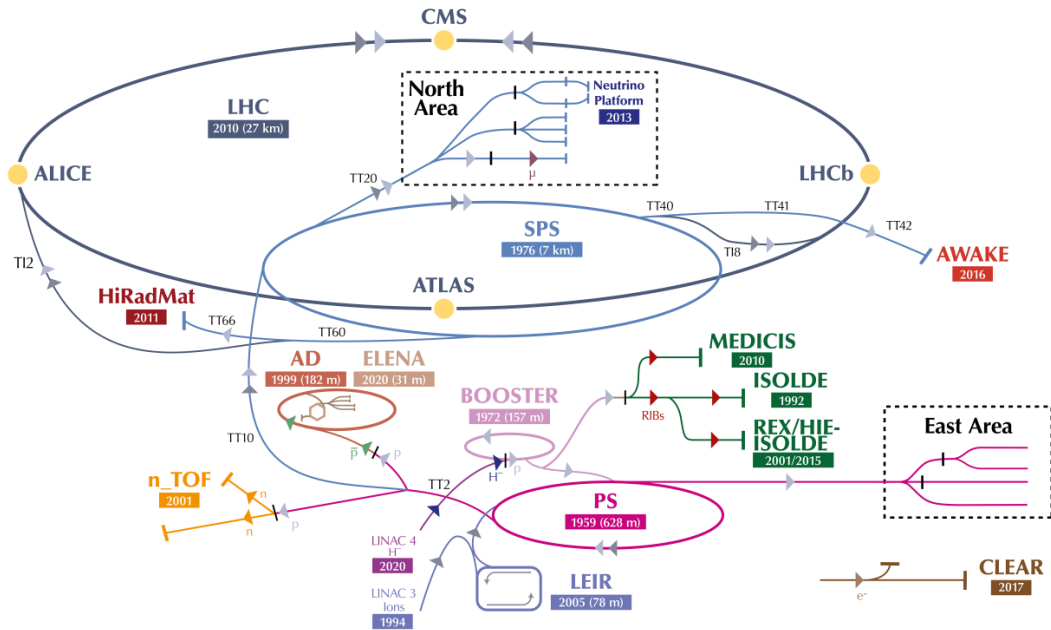


Figure 2.1: The CERN accelerator complex [8].

There are four main detectors at the LHC. ALICE specializes in HI collisions, and its central cylinder is equipped with a time projection chamber and an internal tracking system. ATLAS, a general-purpose detector, is described in detail later in the thesis. CMS is equipped with a high-field superconducting solenoid and integrates a silicon tracker, an electromagnetic calorimeter, a hadronic calorimeter, and an advanced muon detection system [7]. Focusing on b physics, LHCb features a forward-looking detector optimized for precise particle tracking and identification [9].

2.2 The ATLAS Detector

The ATLAS detector, one of two general-purpose detectors at the LHC, is designed to probe the highest energy pp and HI collisions ever achieved in laboratory settings [4]. The detection system enables the observation of collision products generated in the interaction point at nearly full solid angle, providing coverage for pseudorapidity values within $|\eta| < 4.9$ [10].

Over 15 years of work done by an international collaboration of thousands of physicists, engineers and technicians is represented by the 25 meters tall, 46 meters long, weighing around 7000 tons device. The ATLAS detector consists of several subdetectors arranged in concentric layers, with each one designed for a specific task [4], the key ones are marked in the scheme on the left in Figure 2.2. Together, these layers work to identify particles, register their trajectories, and measure their momenta and energies, all while handling the tough conditions of high particle flow, radiation, and collision rates up to 40 MHz.

The ATLAS coordinate system is crucial to accurately describe particle behaviour, a visual representation of it is shown in the diagram on the right in Figure 2.2. The interaction point is defined in the origin of the coordinate system. The z -axis follows the direction of the particle beams, the positive x -axis points towards the center of the LHC ring, and the positive y -axis points upward. Key angular variables used in ATLAS include the azimuthal angle ϕ , measured around the z -axis, and the polar angle θ , which measures the angle relative to the beam axis.

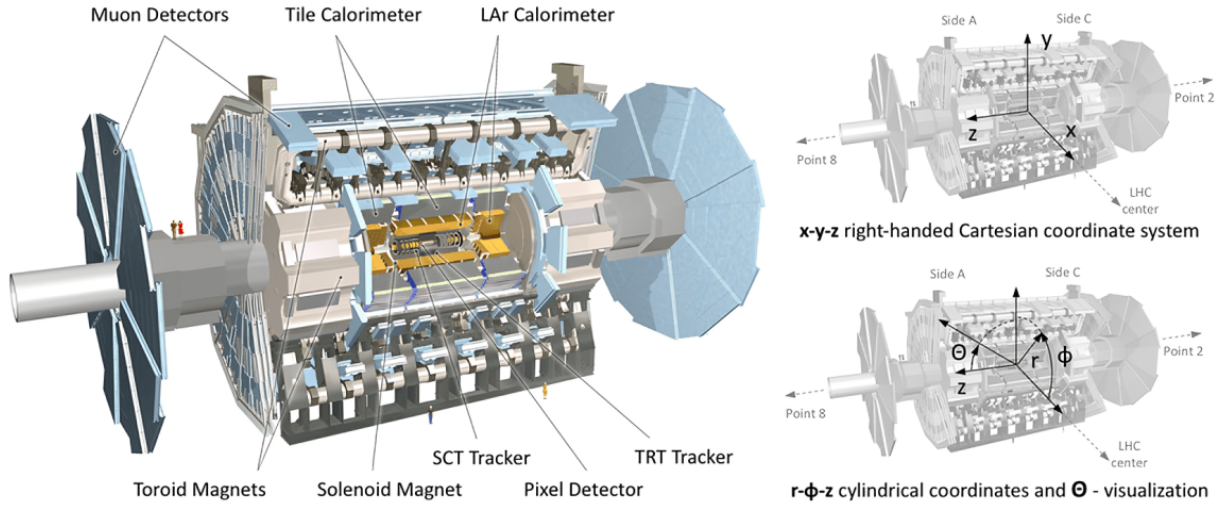


Figure 2.2: The ATLAS detector and its components. The two diagrams on the right depict the ATLAS coordinate system [11].

The relation between pseudorapidity η and θ is defined as $\eta = -\ln \tan(\theta/2)$ and is used for describing particle coordinates. Other important quantities such as transverse momentum (p_T), transverse energy (E_T), and missing transverse energy (E_T^{miss}) are measured within the x - y plane.

2.2.1 Precision Tracking and the Inner Detector System

The central component of the ATLAS detector is its Inner Detector (ID), which plays a crucial role in the precise tracking of charged particles. The ID allows for the measurement of particle momentum for $|\eta| < 2.5$ by following the curvature of the tracks caused by the 2 T axial magnetic field generated by a surrounding superconducting solenoid. The ID, visualized in Figure 2.3, is composed of three main subsystems: the pixel detector, the semiconductor tracker (SCT), and the transition radiation tracker (TRT), each contributing to the precise reconstruction of particle trajectories [4].

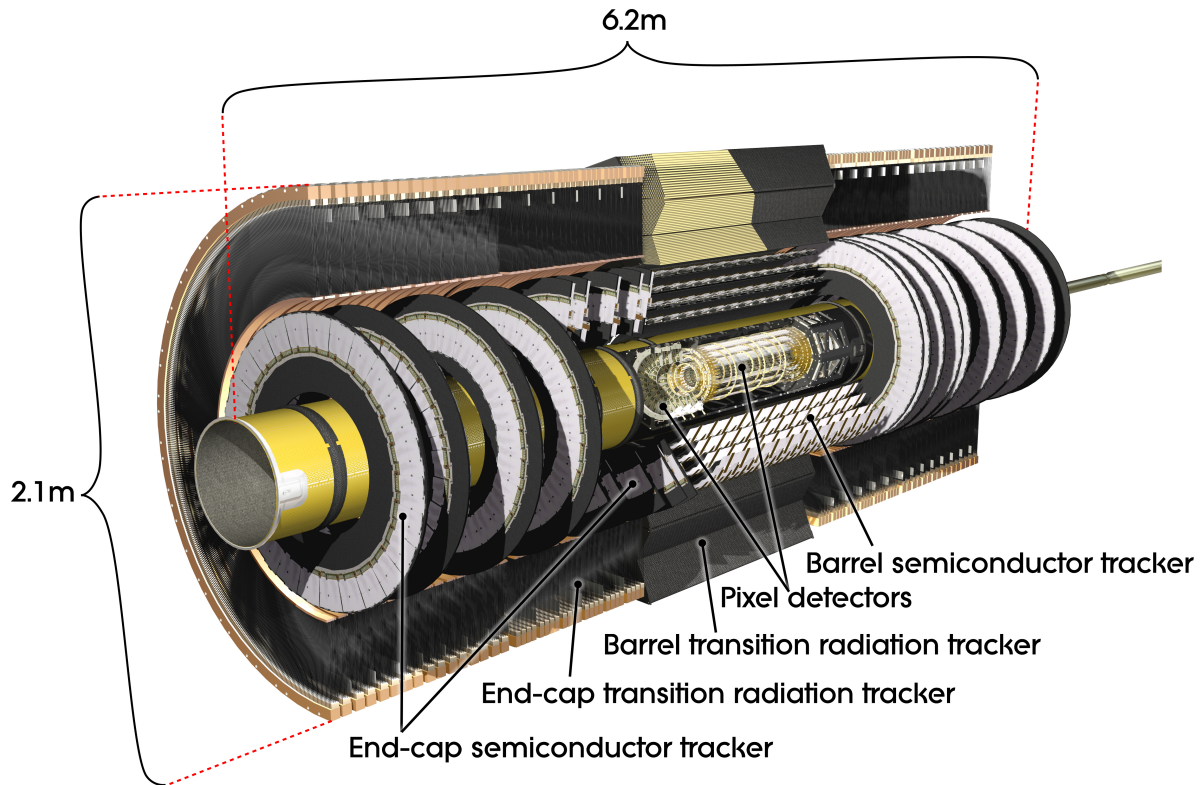


Figure 2.3: Computer generated image of the ATLAS inner detector subsystem [12].

The ID begins with a B-layer that significantly improves the impact parameter resolution before particles reach the high-granularity silicon pixel detector. This is where the first position measurement (i.e., the first hit) can be made. In the pixel sensors, usually four hits per track are recorded. Two layers of silicon microstrips constituting SCT surround the pixel detector, providing information about an additional four hits allowing for better 3D reconstruction of the track in high-density track environment. The outermost part of the ID is the TRT, which consists of straw drift tubes and improves identification capabilities with an additional 35 hits on average [4, 6, 10].

2.2.2 High-Resolution Electromagnetic and Hadronic Calorimeters

As particles traverse through the ID, they subsequently encounter the ATLAS calorimeter system presented in Figure 2.4, which is crucial for measuring energy deposits. The electromagnetic (ECAL) component handles electrons and photons, while the hadronic component measures hadrons and jets. The whole calorimeter system covers pseudorapidity range of $|\eta| < 4.9$, extending beyond the ID reach and ensuring measurements across a broad angular range.

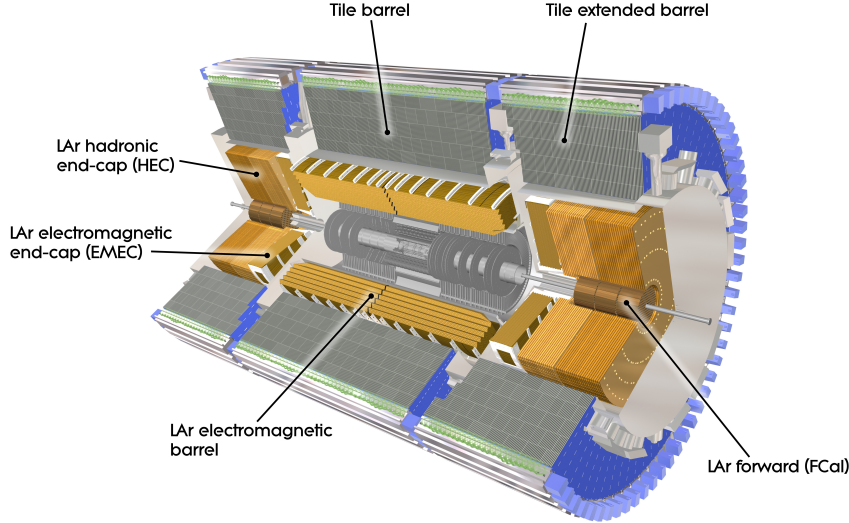


Figure 2.4: Computer generated image of the ATLAS calorimeter subsystem [12].

The ECAL detectors use lead/liquid-argon technology arranged in an accordion geometry and are segmented into two half-barrels and two endcaps components, covering the pseudorapidity range $|\eta| < 1.475$ and $1.375 < |\eta| < 3.2$ respectively, with a transition region between them. The hadronic calorimeter, made of steel/scintillator-tile detectors, covers the barrel region up to $|\eta| < 1.7$, while copper/LAr calorimeters handle the endcaps ($1.5 < |\eta| < 3.2$). The Forward Calorimeter (FCal), covering the region of $3.1 < |\eta| < 4.9$, enables precise measurements in high-particle density environments. Combined hadronic and ECAL subsystems ensure precise measurements of jet energies and missing transverse energy, while minimizing the penetration into the muon system [4, 6, 10].

2.2.3 Advanced Muon Detection and Spectrometry System

The ATLAS Muon Spectrometer (MS), depicted in Figure 2.5, is designed for precise tracking and identification of muons. The superconducting air-core toroids generate a magnetic field ranging from 2 to 6 T·m, bending the muon tracks in the r - z plane. This system is comprised of precision tracking chambers, including monitored drift tubes (MDTs) and cathode-strip chambers (CSCs), which cover the pseudorapidity range of $|\eta| < 2.7$. A single MDT device

provides six to eight η measurements along the muon trajectory, whereas the CSC devices allow four measurements of η and ϕ simultaneously.

The muon trigger system utilizes resistive-plate chambers (RPCs) and thin-gap chambers (TGCs), operating in conjunction with the MDTs and CSCs. This ensures effective event selection and high rate capability and resolution. Together, these components enable muon identification and momentum determination [10].

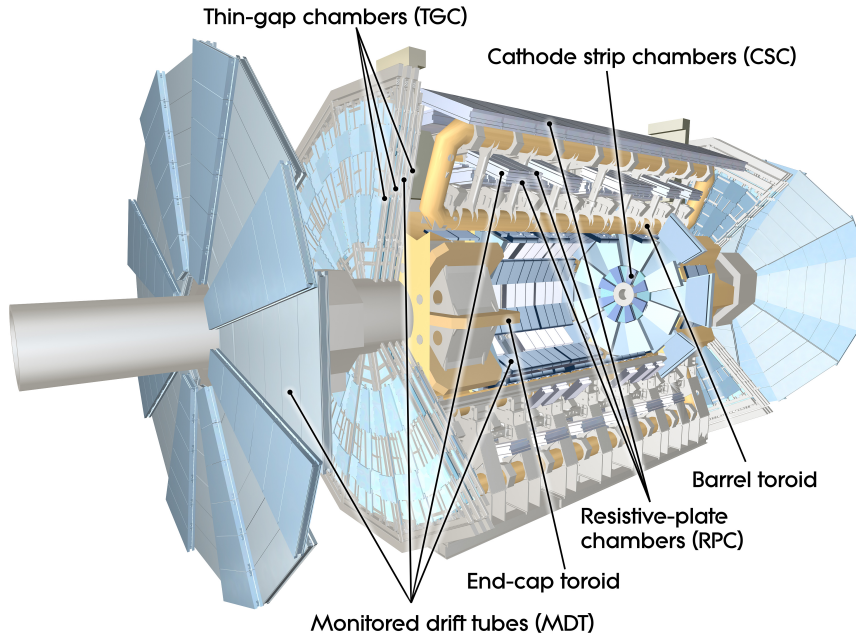


Figure 2.5: Computer generated image of the ATLAS Muons subsystem [12].

2.2.4 Real-Time Event Selection: The ATLAS Trigger System

The ATLAS experiment utilizes an advanced two-level trigger system to select events of interest from the large volume of data generated during collisions at the LHC.

The first, hardware-based level is called the Level-1 (L1) Trigger. It uses signals from the calorimeters and muon chambers, selects regions of interest, and reduces the event rate to at most 100 kHz [13]. Events accepted by the L1 trigger are then passed to the software-based High-Level Trigger (HLT). By using precision measurements from the ID, calorimeters, and MS, along with advanced reconstruction algorithms, the HLT further reduces the event rate to about 1 kHz. During LHC Run 2, the trigger coverage was improved through the use of new RPC detectors in regions previously uncovered due to support structures, thereby increasing trigger efficiency [14].

In addition to the primary L1 and HLT triggers, the ATLAS system includes rerun triggers, which are not used for event selection but for evaluating trigger efficiency offline. The flexibility of the trigger system is ensured by the *trigger menu*, which adjusts to LHC conditions by applying prescale factors to limit the number of events accepted by specific triggers under high-luminosity conditions [13].

2.3 Characteristics of Heavy-Ion Collisions

HI collisions are characterized by several parameters that describe the geometry and dynamics of the interaction, with centrality and impact parameters the most noteworthy.

Centrality is a critical metric used to categorize HI collision events based on the geometry of the interaction. This is primarily determined by the centrality impact parameter b , representing the distance between the centers of the two colliding nuclei in the x - y plane. Collisions at the smaller b are termed more central, corresponding to a greater degree of overlap between the nuclei, while larger b values indicate more peripheral interactions.

In the ATLAS experiment, centrality is determined experimentally using variables like the sum of transverse energy (ΣE_T) measured in the FCal. Peripheral events (e.g., 90–100% centrality) are particularly susceptible to background noise from electromagnetic interactions, including photon-photon processes, which necessitates careful calibration and corrections in simulations and data analysis [7].

The experimental observable, such as ΣE_T , is calibrated to centrality classes corresponding to different percentiles of the total nuclear cross-section. Figure 2.6 illustrates this relationship, showing the distribution of ΣE_T across various centrality classes (e.g., 0–10%, 10–20%, etc.), with the most central collisions characterized by the highest ΣE_T values. The steep decrease in the event fraction with increasing ΣE_T reflects the rarity of high-centrality (small b) events.

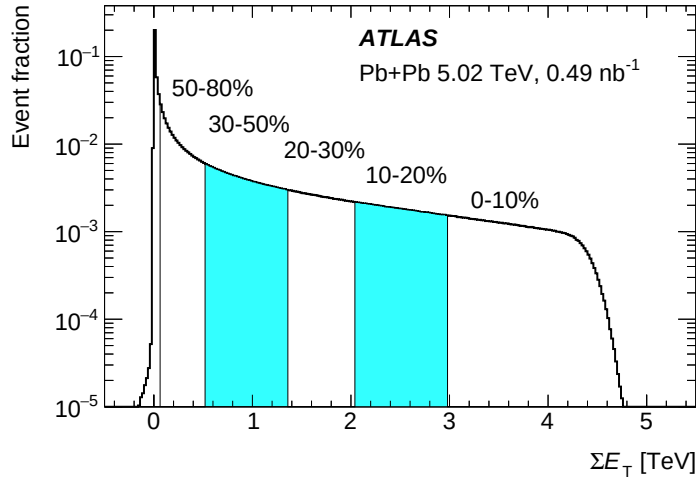


Figure 2.6: The distribution of ΣE_T in Pb+Pb collisions collected at $\sqrt{s_{NN}} = 5.02$ TeV with different centrality classes highlighted by shaded and unshaded regions [15].

Track impact parameters also play a role in interpreting the properties of particle tracks resulting from collisions. The longitudinal impact parameter, denoted as z_0 , corresponds to the beam axis, while the transverse distance, denoted as d_0 , is perpendicular to it. These parameters describe the reconstructed trajectories of individual products with the reference point situated at the primary vertex position of Pb+Pb collision interactions.

2.4 Electrons and Muons in ATLAS

Electrons and muons are important probes in the study of HI collisions, as they are produced in a variety of processes, including direct hard scatterings and decays of intermediate particles, such as vector bosons (e.g. W and Z bosons). Thanks to the intrinsic properties of these particles and the specialized design of the ATLAS detector, their clear signatures are obtained, even in the presence of complex backgrounds. Figure 2.7 highlights the intricate interactions within the ATLAS detector, showcasing the challenges posed by Pb+Pb collisions [7].

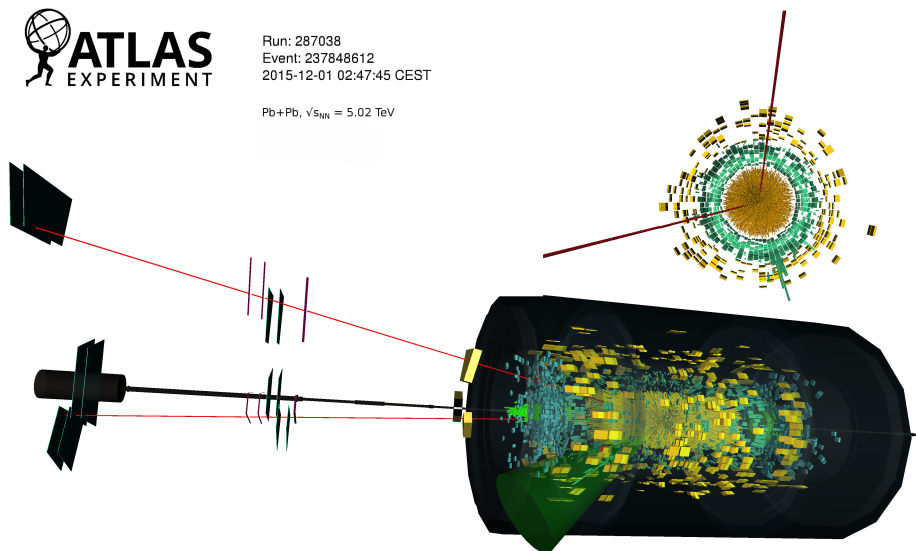


Figure 2.7: ATLAS event display featuring the decay of a Z boson candidate into two muons, which are marked in red, in the Pb+Pb collision. The graphics have been modified based on the original work presented in Ref. [16].

Since correctly identifying the type of particle is not a binary process, several stages of recognition are distinguished. The ATLAS experiment employs specialized algorithms for the detection of electrons and muons. Reconstruction refers to the process of combining signals from different detector components to recreate the trajectory, energy and charge of a particle. Signals from the ID are most often supplemented with the measurements from ECAL and MS, for electrons and muons, respectively.

Identification ensures that the reconstructed objects are truly electrons or muons, based on specific criteria, such as energy deposition patterns, curvature of the tracks, and consistency with the particle's expected properties. After identification, particles are subjected to isolation requirements, which reduce the contamination from nearby particles by introducing limitations for track activity in the given vicinity. Finally, a triggered lepton is one that is matched to an object recognized by the trigger system and satisfies the threshold for variables such as p_T , η , and ϕ [6, 10].

3 The Tag-and-Probe Method

To quantify differences in the overall detector’s ability to successfully detect reconstructed, identified, isolated and triggered leptons in data and simulation, scale factors (SFs) are introduced. Each SF represents the ratio of efficiency, ε , between data and Monte Carlo (MC) simulation

$$\text{SF}_X = \frac{\varepsilon_{\text{Data}}^X}{\varepsilon_{\text{MC}}^X}, \quad (3.1)$$

where SF compensates for potential discrepancies between data and MC predictions at stage X (reconstruction, identification, isolation or trigger).

For the identification stage, the scale factor SF_{id} compares the efficiency of identifying leptons in data and MC simulation, taking into account background-subtracted counts. It is calculated as:

$$\text{SF}_{\text{id}} = \frac{\varepsilon_{\text{Data}}^{\text{id}}}{\varepsilon_{\text{MC}}^{\text{id}}} = \sqrt{\frac{N_{\text{Data}}^{\text{id}} - N_{\text{Bkg}}^{\text{id}}}{N_{\text{Data}}^{\text{reco}} - N_{\text{Bkg}}^{\text{reco}}}} / \sqrt{\frac{N_{\text{MC}}^{\text{id}}}{N_{\text{MC}}^{\text{reco}}}}, \quad (3.2)$$

where N^{id} represents the number of identified leptons, and N^{reco} is the number of reconstructed leptons. Subscripts “Data” and “MC” denote whether the count is from real data or simulated events, while N_{Bkg} accounts for background contributions in data.

The scale factors for isolation (SF_{iso}) and trigger (SF_{trig}) are calculated using the same formula, applied to isolated or triggered lepton counts. The general expression is:

$$\text{SF}_{\text{iso/trig, (x)}} = \frac{\varepsilon_{\text{Data}}^{\text{iso/trig, (x)}}}{\varepsilon_{\text{MC}}^{\text{iso/trig, (x)}}} = \frac{N_{\text{Data}}^{\text{OS, (iso/trig)}} - N_{\text{Data}}^{\text{SS, (iso/trig)}}}{N_{\text{Data}}^{\text{OS, (x)}} - N_{\text{Data}}^{\text{SS, (x)}}} / \frac{N_{\text{MC}}^{\text{OS, (iso/trig)}} - N_{\text{MC}}^{\text{SS, (iso/trig)}}}{N_{\text{MC}}^{\text{OS, (x)}} - N_{\text{MC}}^{\text{SS, (x)}}}, \quad (3.3)$$

where N^{OS} and N^{SS} refer to the number of opposite-sign (OS) charge and same-sign (SS) charge lepton pairs, respectively. The subscript x corresponds to specific configurations based on whether the positively or negatively charged lepton satisfies the isolation or trigger criteria. The square root in equation (3.2) arises from the difference of two identified leptons in the numerator and denominator for ε^{id} . It is eliminated in equation (3.3) due to the difference of only one isolated or triggered lepton for ε^{iso} and $\varepsilon^{\text{trig}}$, respectively.

To ensure high-precision in efficiency measurements, a tag-and-probe method is employed. Relying solely on simulation to estimate efficiencies can lead to significant biases, as simulations may inaccurately model the detector’s response or the underlying physics processes. The data-driven tag-and-probe method addresses this challenge by selecting clean samples of particles from well-understood resonance decays, the method captures the true detector performance, including all its intricacies or potential imperfections.

The method is a powerful tool for measuring efficiencies in challenging environments like high pile-up or HI collisions, where substantial background, known as the Underlying Event (UE), occurs in the latter. By selecting clearly defined products of known decays, one can accurately evaluate efficiency [13].

3.1 Methodology

The tag-and-probe method utilizes a well-known resonance to select a sample of events with two decay products. One decay product, identified using strict criteria, serves as the *tag* for events of interest, while the other decay product, the *probe*, is used to evaluate the efficiency criteria being investigated. Decaying to electron or muon pairs, Z bosons, with a mass of about 91 GeV, are well-suited for measurements at higher E_T values (15–200 GeV). Meanwhile, the J/Ψ resonance, with a mass of approximately 3 GeV, is ideal for lower E_T values (4.5–20 GeV), where the Z boson becomes insufficient [6]. Although J/Ψ is not discussed in this thesis, it demonstrates the range of resonances applied in efficiency measurements across different E_T scales. As shown in Figure 3.1, this simplified scheme illustrates the decay processes of the Z boson into lepton pairs that is the primary focus of following sections.

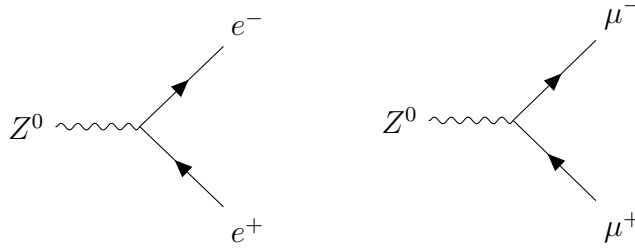


Figure 3.1: Scheme of a Z boson decaying into a lepton pair.

To discriminate the signal events from background processes, the invariant mass distribution of the tag-probe pair is used. The background estimation can be done by employing different methods, including sideband subtraction and template fitting.

For electrons, efficiency is calculated as the product of several components

$$\varepsilon_{\text{total}}^{ee} = \varepsilon_{\text{EMclus}} \times \varepsilon_{\text{reco}} \times \varepsilon_{\text{id}} \times \varepsilon_{\text{iso}} \times \varepsilon_{\text{trig}}. \quad (3.4)$$

Each component, such as cluster reconstruction (EMclus), electron reconstruction (reco), identification (id), isolation (iso), and trigger (trig) efficiency, corresponds to a step in the detection chain. For muons, a similar expression can be used

$$\varepsilon_{\text{total}}^{\mu\mu} = \varepsilon_{\text{TTVA}} \times \varepsilon_{\text{id}} \times \varepsilon_{\text{iso}} \times \varepsilon_{\text{trig}}, \quad (3.5)$$

where $\varepsilon_{\text{TTVA}}$ refers to track-to-vertex association, which accounts for the association of muon tracks with primary vertices. Muon efficiency calculations can be more intricate due to the complex detection process and the use of multiple reconstruction approaches, often requiring the incorporation of conditional probabilities to model the various steps.

3.2 Lepton Reconstruction

To apply the tag-and-probe method effectively, it is essential to accurately reconstruct the trajectories and characteristics of the particles involved. Due to differing ways electrons and muons interact with detector components, the reconstructions requires distinct approaches.

Electron reconstruction relies on data from the ID and the ECAL. The process begins with reconstruction of seed clusters in ECAL - cells with localized high energy deposits, signifying the presence of electromagnetic showers. Following seed identification, track reconstruction is performed within the ID. A dedicated pattern recognition algorithm is used to reconstruct electron trajectories, accounting for expected bremsstrahlung energy loss—which can reach up to 30% of an electron’s energy at each detector layer and may result in nonlinear tracks. Reconstructed tracks are then matched to clusters in the ECAL based on proximity in the $\eta \times \phi$ space to identify electron candidates [6].

Muon reconstruction, on the other hand, can be broken down into two main approaches. The first approach is MS based for high- p_T muons and focused on identification of track segments within MDTs or CSCs, further combined to create track and often using a pointing constraint that aligns with the collision interaction point. The second approach, full detector integration, takes different strategies. For low- p_T muons, the inside-out (IO) method extrapolates ID tracks to the MS, identifying hits for alignment. Combined (CB) muons match MS tracks to those in the ID for a full trajectory, while MS extrapolated (ME) muons rely solely on MS tracks when ID matches are unavailable. Segment-tagged (ST) muons involve extrapolating ID tracks to match MS segments, whereas calorimeter-tagged (CT) muons are identified using calorimeter energy deposits typical of minimum-ionizing particles [10].

3.3 Lepton Identification

The ATLAS experiment utilizes a likelihood-based (LH) identification method to select prompt electrons, within the central detector region ($|\eta| < 2.47$). The LH method combines measurements from the tracking and calorimeter systems to generate probability density functions (PDFs), which are used to construct the likelihood function for signal (L_S) and background (L_B). The likelihood discriminant is defined as the ratio

$$d_L = \frac{L_S}{L_S + L_B}, \quad (3.6)$$

where L_S and L_B are integrating multiple input variables for improved electron identification. The LH method operates with four working points (WP): VeryLoose, Loose, Medium, and Tight with increasing thresholds for the LH discriminant. A parameter that provides easier to interpret results is the transformed discriminant

$$d'_L = -\frac{1}{15} \ln(d_L^{-1} - 1).$$

The distribution of $Z \rightarrow ee$ signal events in proton-proton collisions at $\sqrt{s} = 13$ TeV for $d'_L = 1$ separated from the background extending to lower values is shown in Figure 3.2.

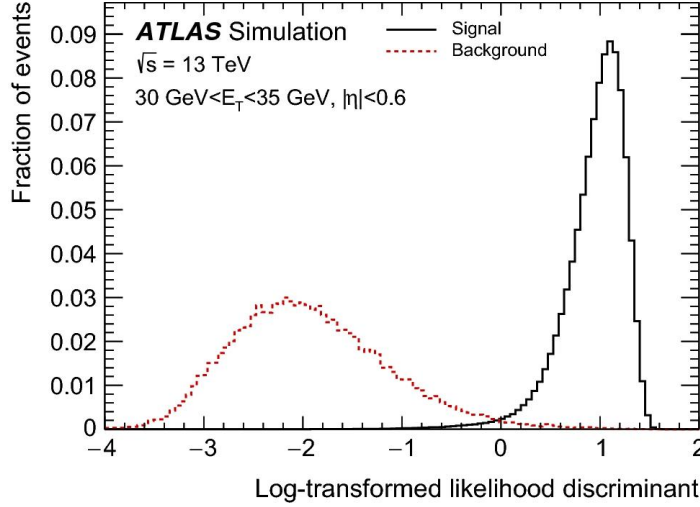


Figure 3.2: Distribution of the transformed LH discriminant d'_L for reconstructed electrons, representing prompt electrons from a $Z \rightarrow ee$ simulation, and the background [6].

Muon identification also uses predefined WP: Loose, Medium, and Tight. The Loose WP is optimized for maximum efficiency, achieving a prompt muon efficiency of approximately 99% for $p_T > 20$ GeV. It accepts muons reconstructed as CB or IO muons, along with additional muon types such as ST and CT candidates in specific pseudorapidity regions. The Medium WP, the default choice for most analyses, applies stricter quality requirements, including a minimum number of precision hits in the MS and tighter compatibility criteria for charge-over-momentum measurements in the ID and MS. This WP achieves a prompt muon efficiency of around 97%. Finally, the Tight WP imposes the most restrictive requirements, optimized to reject background from non-prompt muons, such as those arising from hadron decays in flight, while retaining high efficiency of about 93% for prompt muons. A similar approach as described above for pp collisions is applied to Pb+Pb collisions. Due to the differing characteristics of the pp and Pb+Pb systems, in the case of heavy ion collisions, different working points are used, defined as HIVeryLoose, HILoose, HIMedium, HITight.

3.4 Cut-Based Isolation

When leptons are identified, isolation is the next step in the selection chain. It can be implemented in two main forms: efficiency-targeted and cut-based isolation. Efficiency-targeted isolation applies varying criteria to achieve a specified isolation efficiency, which can be scaled to account for changes in leptons transverse momentum, while cut-based isolation uses fixed thresholds to maintain high background rejection.

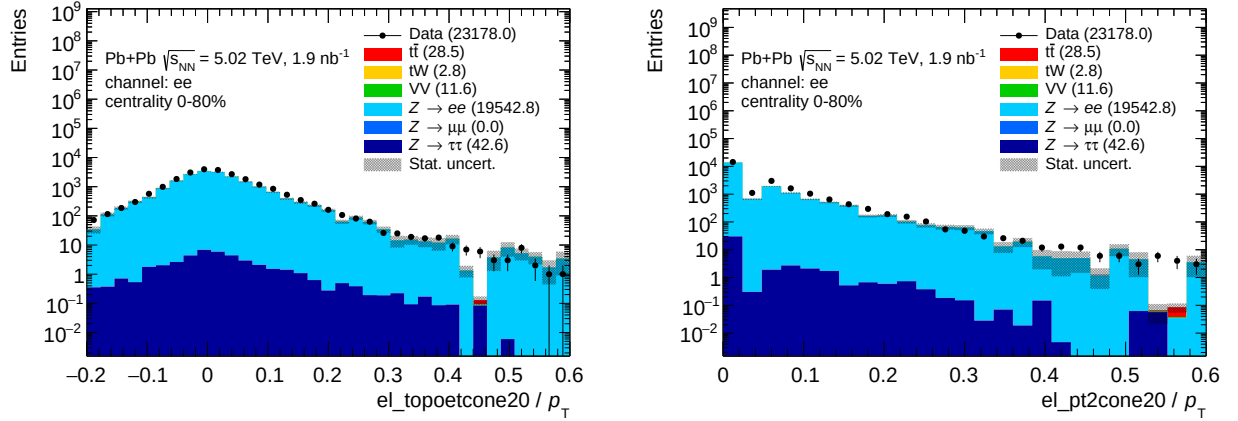


Figure 3.3: Distributions of isolation variables $el_topoetcone20/p_T$ (i.e. $E_{T,cone20}^{iso}/p_T$) and $el_pt2cone20/p_T$ (i.e. $p_{T,2cone20}^{iso}/p_T$) for electrons in the ee channel of Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with 0–80% centrality. The data is compared to simulated backgrounds from top-quark pair production ($t\bar{t}$), single top (tW), diboson (VV), and Z boson decays into electrons ($Z \rightarrow ee$), muons ($Z \rightarrow \mu\mu$), and tau pairs ($Z \rightarrow \tau\tau$) [2, 17].

In Figure 3.3, two key variables used in the cut-based isolation are displayed. The first variable, $E_{T,cone20}^{iso}/p_T$, measures the ratio of the calorimeter isolation energy in a cone with a radius of $R=0.2$ to the lepton p_T , while the second, $p_{T,2cone20}^{iso}/p_T$, represents the ratio of the sum of p_T tracks to the lepton p_T within the same cone. To account for higher track multiplicity in Pb+Pb collisions, the track isolation considers only tracks with $p_T > 2$ GeV, as opposed to $p_{T,varcone20}^{iso}/p_T$ in pp collisions accepting tracks with $p_T > 1$ GeV.

Cut-based isolation uses WPs to set thresholds for isolation variables. In pp collisions, the Loose WP for electrons requires $E_{T,cone20}^{iso}/p_T < 0.20$ and $p_{T,varcone20}^{iso}/p_T < 0.15$, while the Tight WP applies stricter cuts: $E_{T,cone20}^{iso}/p_T < 0.06$ and $p_{T,varcone20}^{iso}/p_T < 0.06$. A similar approach is used for muons, with minor adjustments to the cone size and thresholds.

In Pb+Pb collisions, for both electrons and muons, the calorimeter isolation criterion is set to $E_{T,cone20}^{iso}/p_T < 0.14$. This adjustment accommodates the increased energy deposits from the surrounding event environment, helping to maintain a reasonable lepton efficiency. The track isolation requirement remains at $p_{T,2cone20}^{iso}/p_T < 0.06$, as in the Tight WP for pp collisions and the higher track p_T threshold of 2 GeV is used, because track isolation continues to provide a robust measure of the immediate particle environment around the lepton candidate, serving as a reliable indicator of directly associated particles.

3.5 Triggers in HI Data-Taking

The trigger performance in HI data-taking is also evaluated using the tag-and-probe method with $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ events. In the ATLAS experiment, HI data-taking during Run 2 employed specialized triggers to capture key events amid the dense background conditions inherent to Pb+Pb collisions [13].

For electrons performance evaluation, two HI-optimized triggers were chosen: `HLT_e15_loose_ion` and `HLT_e15_lhloose_ion_L1EM12`. The triggers are set with a transverse energy (E_T) threshold on a single electron candidate of 15 GeV. The `loose_ion` trigger employs cut-based selection criteria, allowing for high signal efficiency, whereas the `lhloose_ion_L1EM12` trigger uses a LH identification for greater purity. These electron triggers apply a UE correction tailored to the HI background by adjusting the energy clusters and regions of interest (RoIs) at the trigger level, therefore reducing azimuthal asymmetries in the energy distribution. The criteria are satisfied across different collision centralities. Here, centrality refers to the degree of overlap between colliding ions, which corresponds to the collision geometry, with 0% corresponding to the most peripheral and 100% to the most central collisions [13].

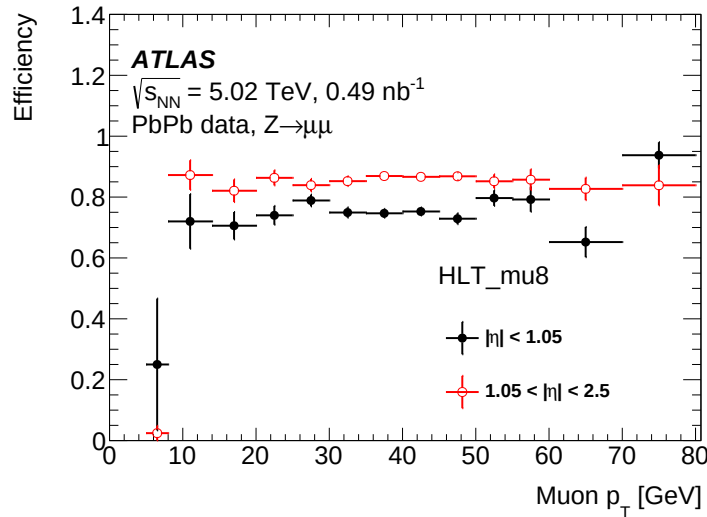


Figure 3.4: Trigger efficiency of `HLT_mu8` for single muons, shown as a function of transverse momentum (p_T) in both the barrel (black filled circles) and endcap (red open circles) regions for Pb+Pb collision data. Statistical uncertainties are indicated by the error bars [14].

For muons efficiency calculation, the selected trigger, `HLT_mu8`, is set at an 8 GeV transverse momentum (p_T) threshold on a single muon candidate and used to evaluate the trigger SFs. Figure 3.4 shows the trigger efficiency curve as a function of muon p_T in 2015 HI data-taking. The `HLT_mu8` trigger is optimized for the Pb+Pb environment, where high particle multiplicity increases the probability of random muon-like signals from background processes. The 8 GeV p_T threshold strikes a balance between capturing relevant muons and filtering out lower-momentum background muons [14].

4 Lepton Efficiency in 5.02 TeV Pb+Pb Collisions

4.1 Data Set

The data set consists of data collected by the ATLAS detector during Pb+Pb collisions at the LHC at a center-of-mass energy of $\sqrt{s_{\text{NN}}} = 5.02$ TeV per nucleon pair. The data were recorded during the 2015 and 2018 HI runs, with an integrated luminosity of 0.49 nb^{-1} and 1.4 nb^{-1} , respectively.

MC simulation is employed to model the signal processes, and is used to derive corrections to account for potential mismodeling. The $Z \rightarrow \ell\ell$ ($\ell = e, \mu$) signal was simulated using the **Powheg Box v2** [18] generator at next-to-leading order (NLO) in Quantum Chromodynamics (QCD), with the **CTEQ6L1** [19] parton distribution function set. Parton showering and hadronization are modeled with **Pythia8** [20], using the **AZNLO** set of tuned parameters. Only pp collision configurations for Z boson production are simulated. The number of generated events, prior to any selection or reconstruction, is 500,000 for the ee channel and 499,300 for the $\mu\mu$ channel. MC samples are overlaid with minimum-bias Pb+Pb events generated by **Hijing** [21] to replicate the complex underlying event in HI collisions. All simulated samples are generated using full ATLAS detector simulation based on the **Geant4** [22] framework to ensure consistency with the data-taking conditions. MC simulation is normalized to data using the corresponding process cross-section and data luminosity, weighted for the 0–80% centrality range.

4.2 Event Selection

The main area of interest is the set of events in which the Z boson decays into a pair of leptons, either electrons or muons. These are selected based on their clean and well-defined signature, enabling the study of lepton identification (id), isolation (iso), and trigger (trig) performance using the tag-and-probe method. For electrons, the selection criteria require $p_{\text{T}} > 18 \text{ GeV}$ and $|\eta| < 2.47$. For muons, the criteria are $p_{\text{T}} > 15 \text{ GeV}$ and $|\eta| < 2.5$. The data sample comprises events featuring same-flavor opposite-charge leptons, selected based on a reconstructed invariant mass within the Z boson mass window, $66 \leq m_{\ell\ell} \leq 116 \text{ GeV}$.

4.3 Fake Leptons

Non-prompt leptons from semileptonic heavy-flavour decays and misidentified leptons from hadrons and photons contribute to the fake-lepton background. The sideband subtraction technique is used, commonly applied in particle physics to estimate and remove the background contribution [6, 7]. The application of this method is shown in Figure 4.1.

In the first step, MC simulation, which is generated under the assumption of signal-only processes, is subtracted from data distributions of reconstructed or identified leptons.

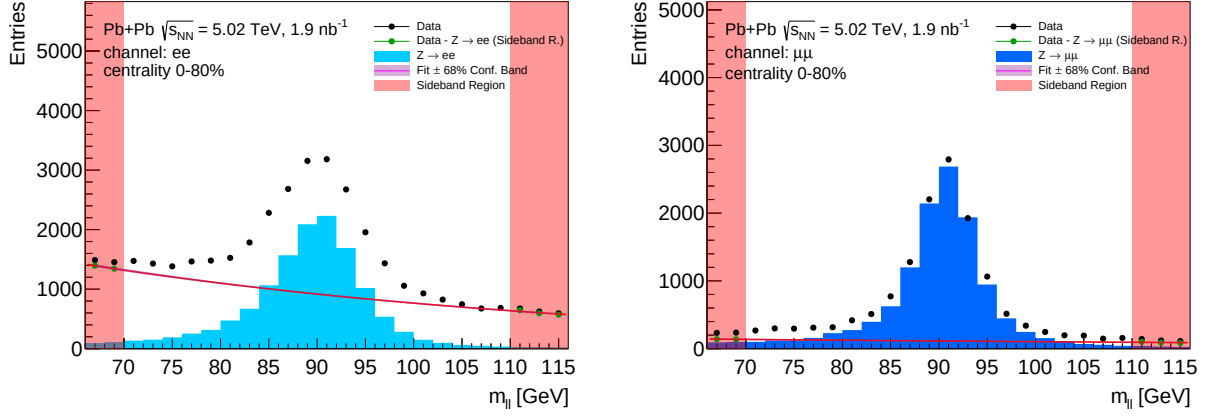


Figure 4.1: Invariant mass distribution ($m_{\ell\ell}$) of reconstructed electron (left) and muon (right) pairs in Pb+Pb data and MC simulation, denoted as $Z \rightarrow \ell\ell$ ($\ell = e, \mu$), for Z boson production. An exponential function is fitted to the sideband regions of the distributions obtained by subtracting MC simulation yields from the data, represented by green points (Data - $Z \rightarrow \ell\ell$), with a 68% confidence interval band. The sideband regions are highlighted with a red background. Results are presented for the 0–80% centrality class.

To estimate the fake-lepton background, sideband regions outside the Z -mass measurement window are utilized, spanning 66–70 GeV and 110–116 GeV, as denoted by the red areas in Figure 4.1. The background is modeled by fitting a smooth exponential function to the signal-subtracted data points in these sideband regions. This function is then interpolated into the signal region, a number of background events derived and subtracted from the data yields to isolate the signal and fake-lepton contributions.

The fake-lepton background constitutes about 62% and 19% of the reconstructed data in the electron and muon channels, respectively, and is subtracted in subsequent steps.

4.4 Identification Scale Factor

Reconstructed lepton pairs play a central role in the evaluation of identification scale factors (SF_{id}), as these pairs form the basis for calculating the denominator of the identification efficiency. The process begins with the determination of the invariant mass of the reconstructed lepton pairs, which provides a critical variable for isolating signal events from background contamination. This procedure is part of the calculation of SF_{id} , as shown in equation (3.2).

Electron reconstruction is performed by associating clusters of energy deposits in the electromagnetic calorimeter with tracks reconstructed in the ID. Muons are reconstructed by matching tracks in the ID with those in the MS. Muon and electron candidates are also required to originate from the primary vertex, with transverse and longitudinal impact parameters tightly constrained relatively to their uncertainties. Figure 4.2 presents an invariant mass distributions of lepton pairs, with a clearly visible peak at 91 GeV, corresponding to the Z boson mass. Data is represented by black markers, MC samples by the filled histogram, and the subtracted background is labeled as "Fake lepton". Only statistical uncertainties are considered. The distribution corresponds to the electron-electron (ee) and muon-muon ($\mu\mu$) channel in the 0–80% centrality range, chosen specifically to exclude any contributions from photon-induced processes. Bottom panels showing the ratio of the data to the expected yield, which consists of both the MC simulated and the fitted background.

A significant background contribution is observed in the electron channel due to processes such as photon conversions and misidentified hadrons, which are less prominent for the muon channel owing to the distinct muon signatures in the MS and their reduced interaction with the detector material. This results in 37,662 data yields for the ee channel, which is approximately twice as many as those for the $\mu\mu$ channel, with 15,095 yields. A leftward peak shift is observed in the electron channel, which results from residual miscalibration. This effect arises due to the challenges in electron calibration, especially in the presence of high detector activity. In contrast, such effects are less pronounced in the muon channel, where the cleaner signatures lead to a more accurate mass measurement.

Lepton identification uses LH criteria. For electrons, this identification combines calorimetric variables, tracking variables, and their correlations. Muon identification leverages the consistency of tracks between the ID and MS as well as energy loss in the calorimeters. Both electrons and muons are required to pass the HILoose working points for identification. Figure 4.3 shows the invariant mass distribution of lepton pairs, which forms the numerator in the calculation of identification efficiency. The identification stage effectively eliminates background contributions balancing the yields in both channels. However, a notable deviation is observed near 80 GeV, where imperfections in the simulation could contribute to mismatches.

As shown in Table 4.1, three mass windows were used to evaluate systematic uncertainties. The first window corresponds to an "up variation," where the mass range is extended upwards

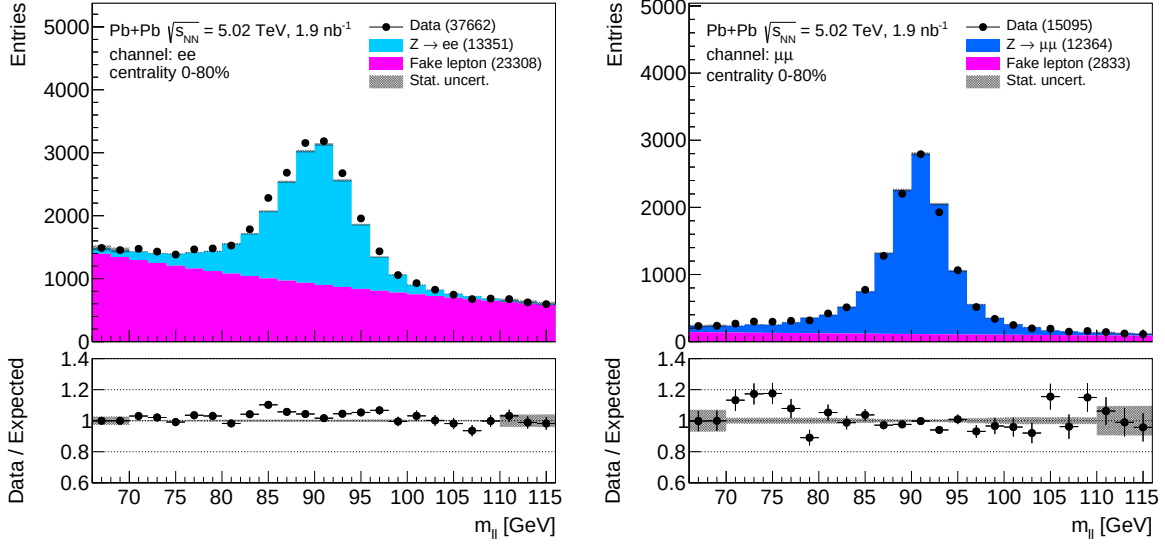


Figure 4.2: Invariant mass distribution ($m_{\ell\ell}$) of reconstructed electron (left) and muon (right) pairs in Pb+Pb data, MC simulation for Z boson production, and fitted background ("Fake lepton") presented in the 0–80% centrality class. Error bars and shaded boxes correspond to statistical uncertainties in data and MC, respectively.

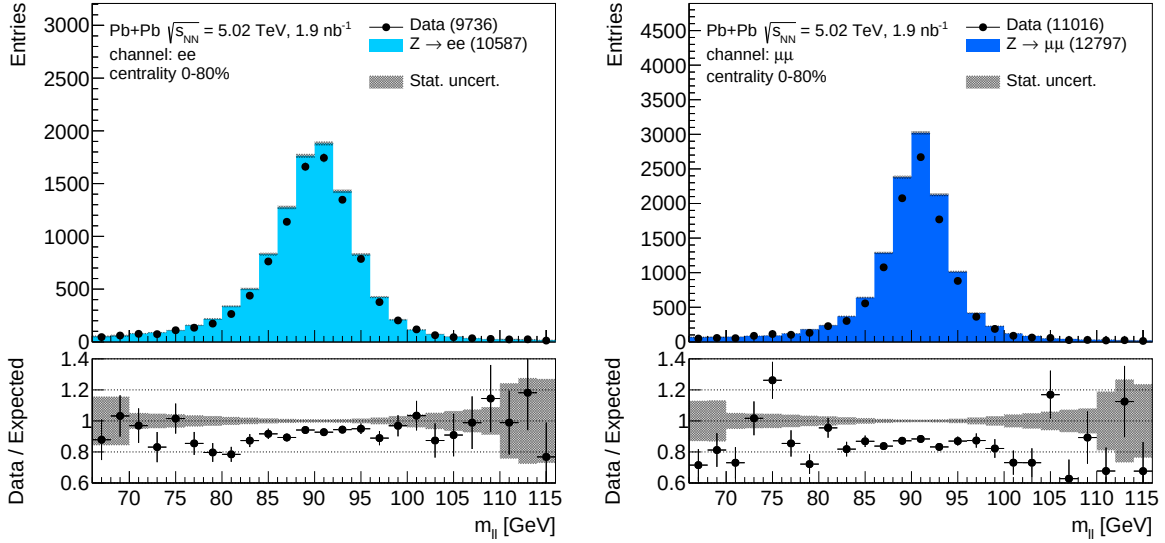


Figure 4.3: Invariant mass distribution ($m_{\ell\ell}$) of identified lepton pairs in the 0–80% centrality class of Pb+Pb data. Error bars and shaded boxes correspond to statistical uncertainties in data and MC, respectively.

from the nominal value. The second window is used for the nominal variation, with the default nominal mass range applied for the calculation of SFs. The third window represents a "down variation", where the mass range is narrowed downwards from the nominal value. Varying the mass range up and down from its nominal value helps assess the associated uncertainties.

The three distinct invariant mass windows shown in Figure 4.4 are used to estimate the systematic uncertainties for the SF_{id} . From the plots, we observe a reasonable agreement be-

Table 4.1: Mass windows used to evaluate systematic uncertainties on scale factors.

Window	Mass Range [GeV]	Usage
1	70–110	Up variation.
2	75–105	Nominal variation.
3	80–100	Down variation.

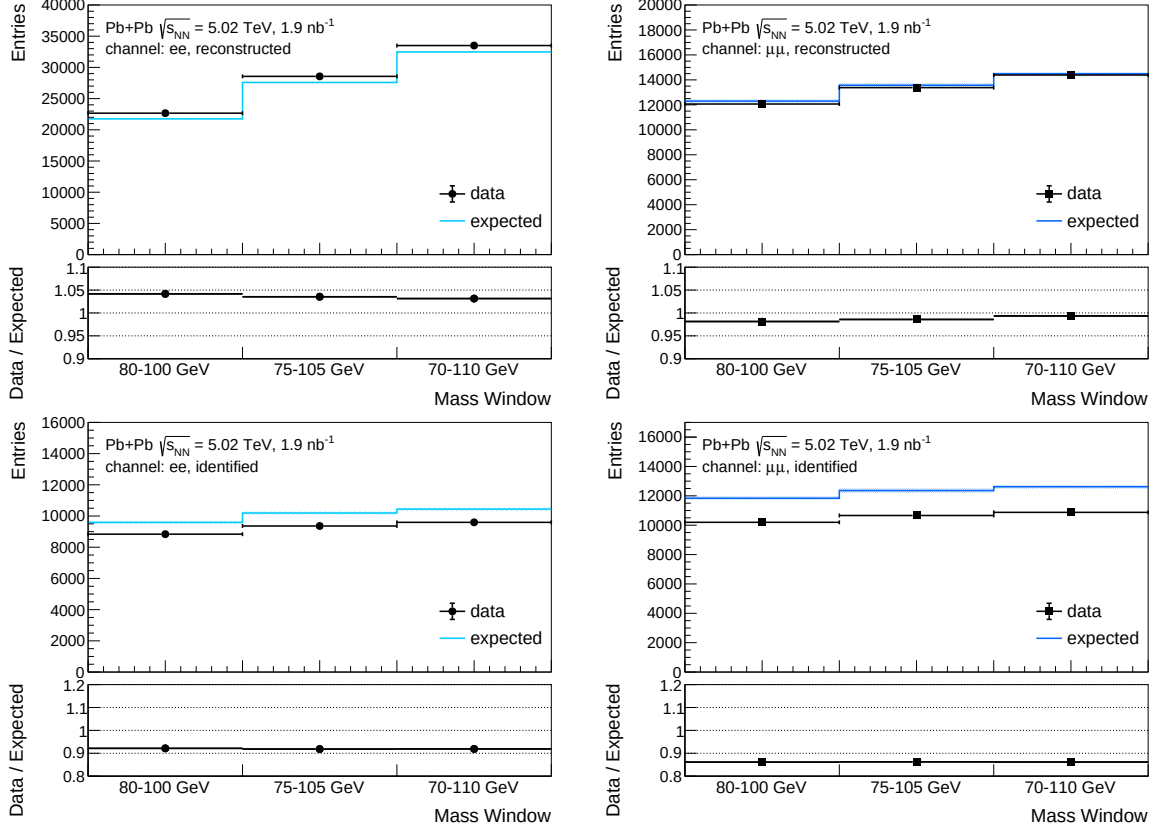


Figure 4.4: Comparison of the number of data and expected events in three distinct invariant mass windows for ee (left) and $\mu\mu$ (right) channels. The plots show the Z boson yields for reconstructed (top) and identified (bottom) leptons. Error bars correspond to statistical uncertainties in data.

tween the data and the expected results, which are derived as the sum of MC simulation and fake-lepton background. Notably, for the reconstructed electrons in data, we observe a higher number of events than expected, which can be attributed to the contribution of background effects, which are eliminated in the next stage of the detection chain (i.e. identification).

The final SF_{id} values derived for the combined data sets from 2015 and 2018, with an integrated luminosity of 1.9 nb^{-1} , are cross-checked against the results obtained separately for each data set. Figure 4.5 presents the calculated scale factors for the 2015 and 2018 data sets, as well as the combined result, including both statistical and systematic uncertainties. For both the ee and $\mu\mu$ channels, the SF_{id} values demonstrate good agreement across the data sets within the stated uncertainties.

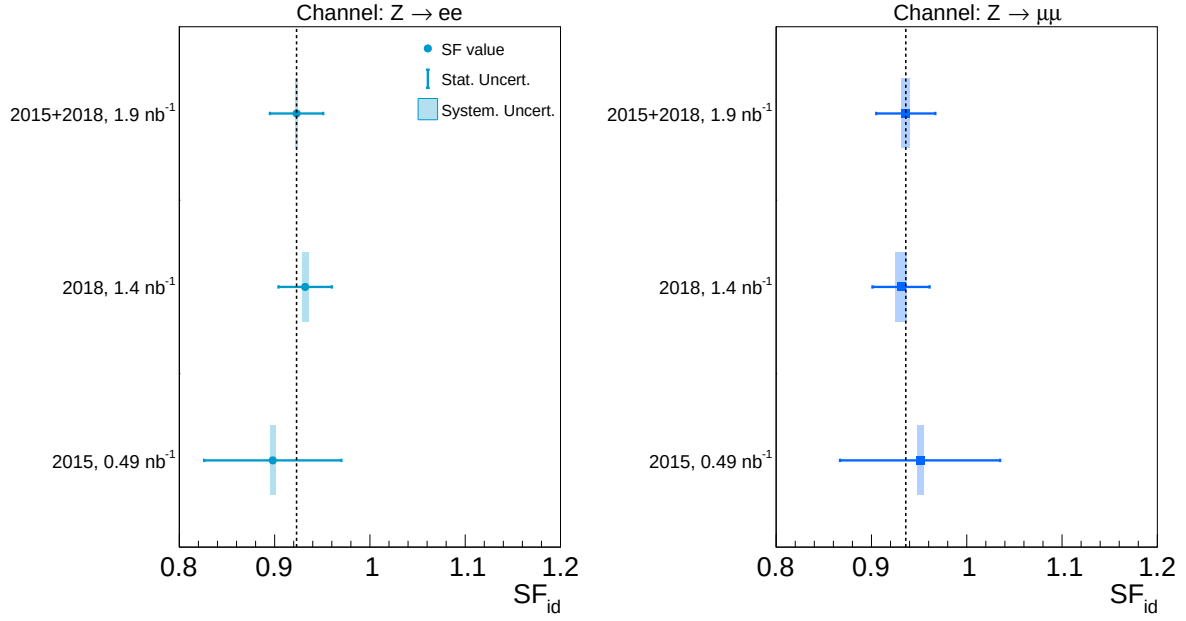


Figure 4.5: Identification scale factors, SF_{id} , for electrons (left) and muons (right). The vertical dashed line represents the central value of the combined data set for 2015+2018. Error bars and shaded boxes represent statistical and systematic uncertainties, respectively.

In the muon channel, the SF_{id} values are closer to unity, which is attributed to the better muon reconstruction and identification modeling in MC simulation compared to electrons, especially in the challenging HI collision environment, where distinct MS signatures could play a critical role.

The final identification scale factor for the 2015+2018 data set with an integrated luminosity of 1.9 nb^{-1} for electrons is

$$SF_{id}^{ee} = 0.923 \pm 0.028 \text{ (stat.) } {}^{+0.0015}_{-0.0002} \text{ (syst.)}$$

and for muons

$$SF_{id}^{\mu\mu} = 0.936 \pm 0.031 \text{ (stat.) } {}^{+0.0015}_{-0.0045} \text{ (syst.)}.$$

4.5 Isolation Efficiencies

To calculate the isolation efficiencies (ε_{iso}) and the scale factor for isolation (SF_{iso}), the appropriate isolation criteria are applied for identified leptons, as described in Equation (3.3). The study utilizes cut-based isolation with thresholds specifically optimized for HI collisions. OS charge lepton pairs are used to create a signal-enriched sample, while SS charge pairs serve as a representation of background contamination.

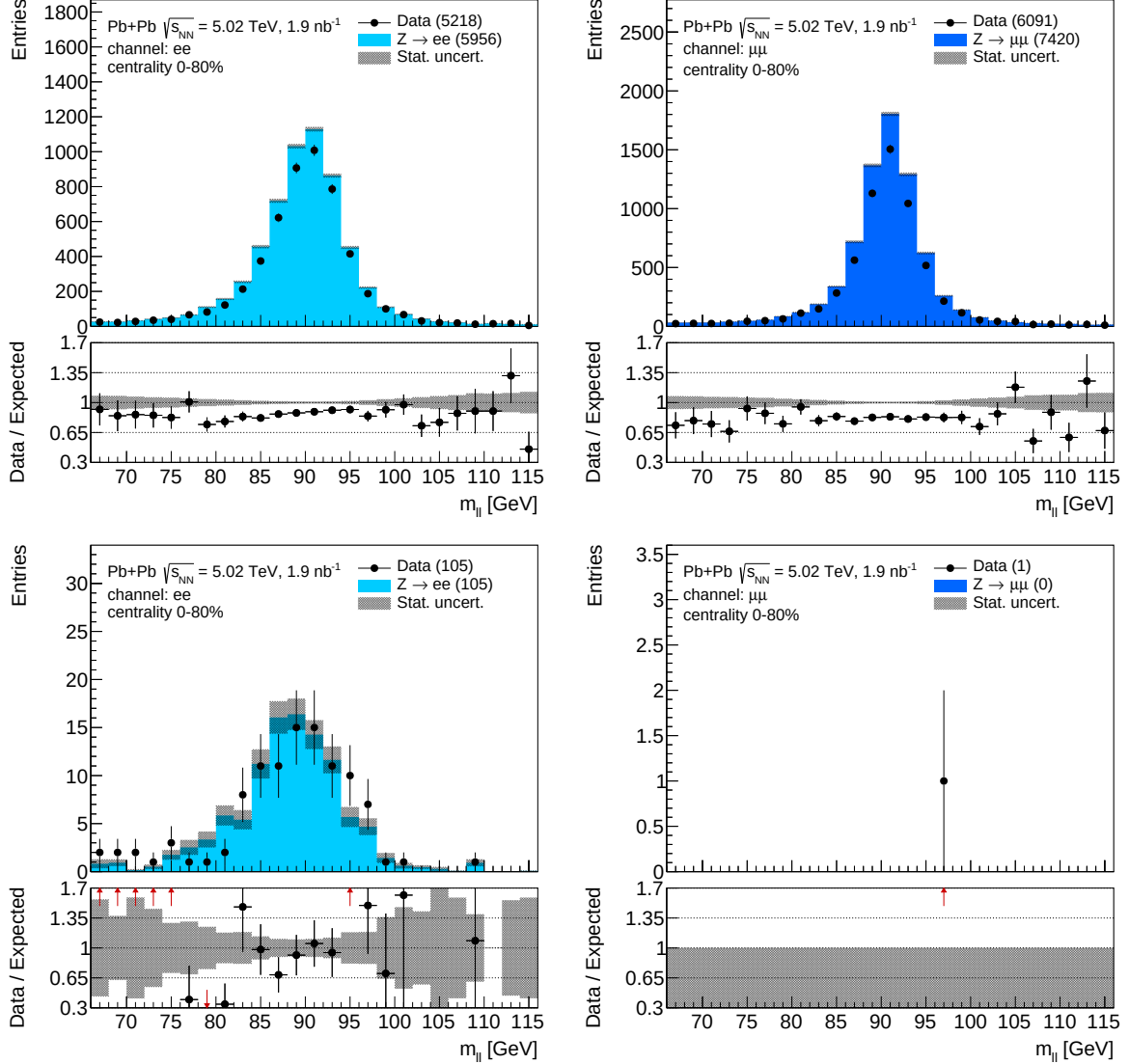


Figure 4.6: Invariant mass distributions of lepton pairs forming the nominator in the isolation studies. Top row: OS charge pairs for electrons (left) and muons (right), used to obtain signal-enriched samples. Bottom row: SS charge pairs for electrons (left) and muons (right). Error bars and shaded boxes correspond to statistical uncertainties in data and MC, respectively.

The invariant mass distributions of OS and SS charge pairs, presented in Figure 4.6, are analyzed to estimate the background contribution in data and MC simulation. As seen in the plots, the contribution from SS charge leptons is significantly larger for electrons, where background processes are more prominent. In contrast, for muons, the SS contribution is

negligible. We also observe a leftward shift in the peak of OS electrons, arising from the residual miscalibration effect.

Similarly to the procedure used for calculating identification scale factors, mass windows play a crucial role in evaluating systematic uncertainties. Figure 4.7 presents event yields of Z boson candidates as a function of the mass window when both leptons are isolated. The broadest window, spanning 70–110 GeV and corresponding to the up variation, captures the maximum number of events. This trend highlights the relationship between the size of the mass window and the event count, emphasizing the impact of systematic variations on the analysis. The number of event candidates increases with the widening of the measurement window. As a result, the broadest window, referred to as the "Up variation," exhibits the highest count rate. Conversely, the first window ("Down variation"), with the narrowest invariant mass range, contains the fewest events.

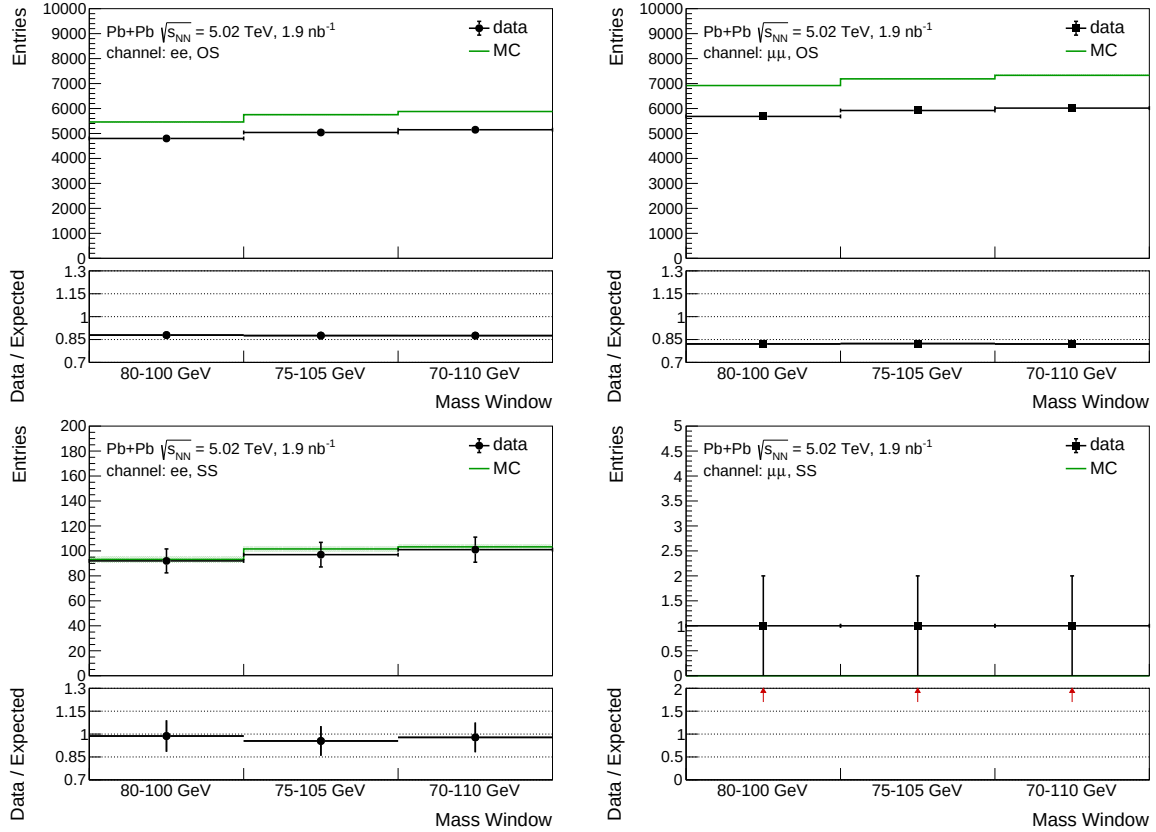


Figure 4.7: Comparison of Z boson event yields in data and MC simulation for both leptons isolated, for ee (left) and $\mu\mu$ (right) channels as a function of the Z boson mass. Error bars correspond to statistical uncertainties in data.

Isolation efficiencies are determined by evaluating the fraction of lepton candidates passing the calorimeter- and track-based isolation criteria relative to the total number of identified leptons. To evaluate isolation performance, events are divided based on whether both leptons, only the positively charged lepton, or only the negatively charged leptons meet the isolation criteria. Table 4.2 summarizes these categories, where the "Both" category consti-

tutes the numerator of the isolation efficiency, while the "Positive" and "Negative" categories form the denominator. It is worth noting that in this case, there is a difference of one categorized lepton between the numerator and denominator, unlike for the identification efficiency.

Table 4.2: Explanation of isolation categories and their corresponding labels, with "Both" defining the numerator and "Positive" and "Negative" the denominators in the isolation efficiency calculation.

Category	Label	Explanation
Both leptons isolated	Both	Both leptons in the event are isolated.
One lepton isolated	Positive	Only positively-charged leptons are isolated.
	Negative	Only negatively-charged leptons are isolated.

Figure 4.8 illustrates Z boson event yields as a function of the mass window and the isolation category applied. As expected, the broadest window, 70–110 GeV, contains the highest number of events. Within each mass window, the most events are observed for the "Negative" isolation category, however they remain consistent within the statistical uncertainty with the event yields in the "Positive" category, which aligns with the assumption of the lack of noticeable differences in lepton and antilepton production at high LHC energies.

The isolation efficiencies are evaluated as functions of various lepton kinematic variables. Figure 4.9 illustrates the p_T -dependent isolation efficiencies. The error bars for data and the shaded boxes for MC simulation represent the total uncertainties, with statistical uncertainties being the dominant contribution. For both electrons and muons, the efficiency initially exhibits a gradual increase as a function of p_T . This increase range is wider for electrons compared to muons, primarily due to the more significant effects of electromagnetic showering in the calorimeter and the complexities of isolating electron tracks from nearby energy deposits. These factors contribute to a slower convergence of the efficiency at lower p_T .

As p_T increases further, the efficiencies approach a plateau, indicating near-maximal isolation efficiency. The plateau reflects the reduced influence of background processes and the improved isolation of high-momentum leptons. The trend is more pronounced for electrons, which benefit from stronger rejection of background at higher p_T .

Figure 4.10 presents the efficiency as a function of pseudorapidity (η). The efficiency is observed to decrease within the central detector region and towards the edges of the detector acceptance ($|\eta| > 2$), primarily due to the reduced coverage of the calorimeter and tracking systems in these regions. The data show a strong alignment with the detector simulation, indicating good agreement between observed and predicted isolation efficiencies. Notably, in the transition region between the barrel and endcap, specifically around $1.37 < |\eta| < 1.52$, where both calorimeter and tracking coverage are more limited, larger uncertainties are present in electron efficiency. This region also exhibits a reduced isolation efficiency, which

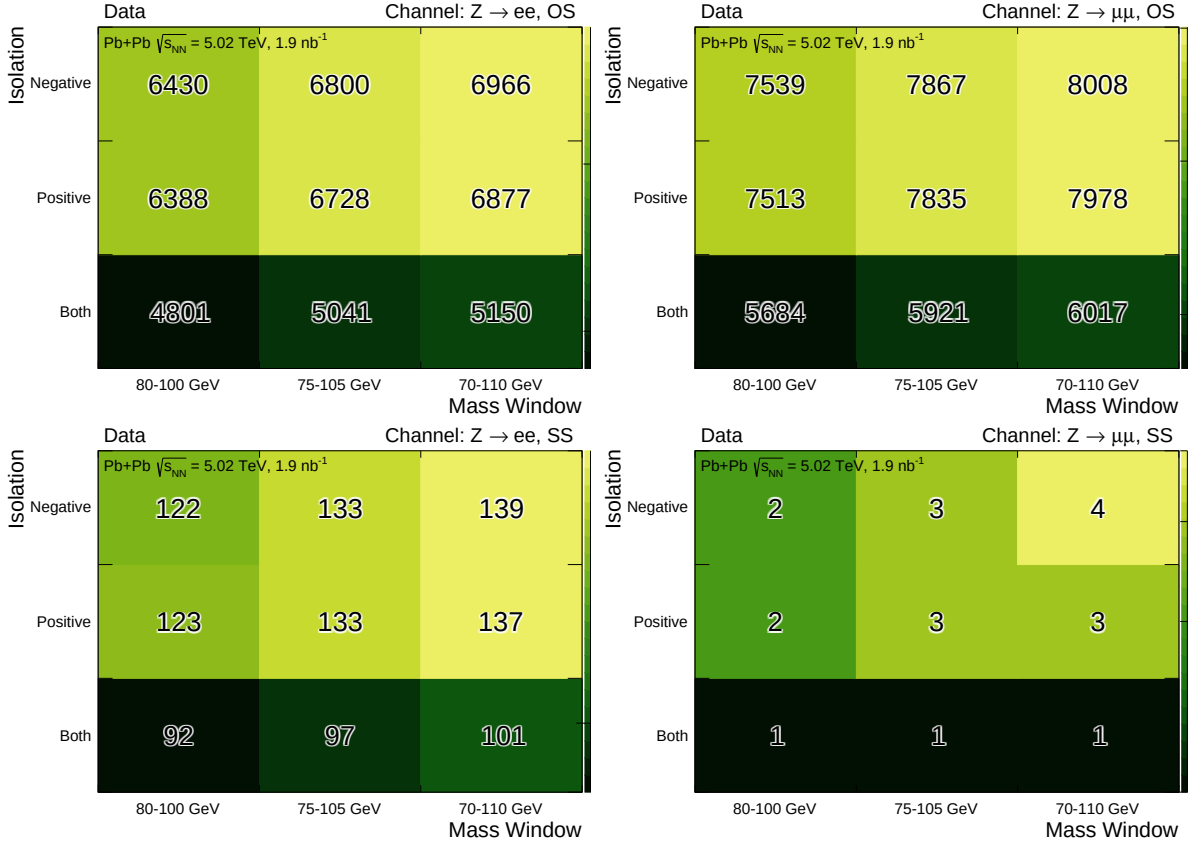


Figure 4.8: Event yields for Z bosons in three isolation categories and mass windows considered in the systematic uncertainty calculations. The data are presented for both the ee (left) and $\mu\mu$ (right) channels, with OS (top) and SS (bottom) charged leptons taken into account.

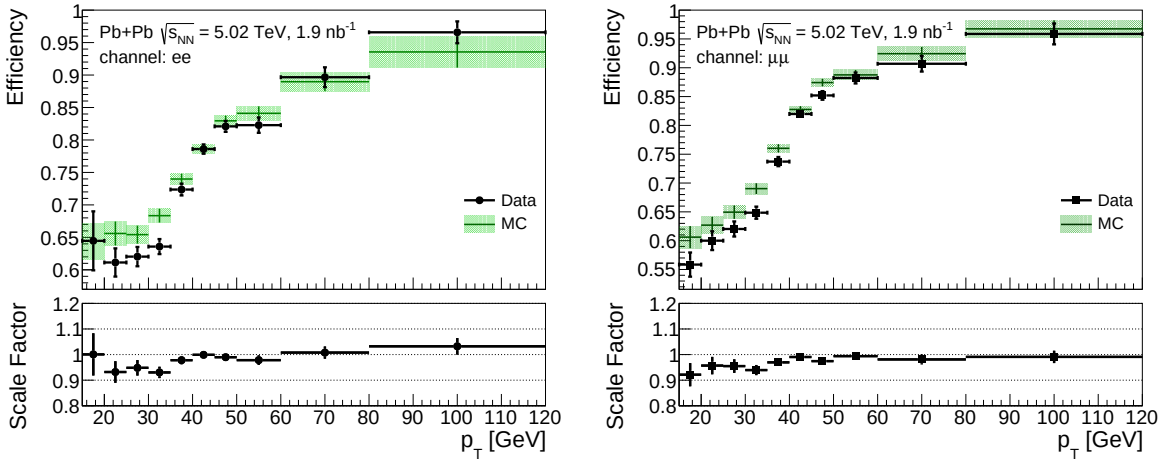


Figure 4.9: Isolation efficiency as a function of p_T for electrons (left) and muons (right) in data and MC simulation. Error bars and shaded boxes correspond to total uncertainties in data and MC simulation, respectively.

can be partly attributed to the scarcity of data in this area, highlighting the challenges in detector performance at these intermediate pseudorapidities.

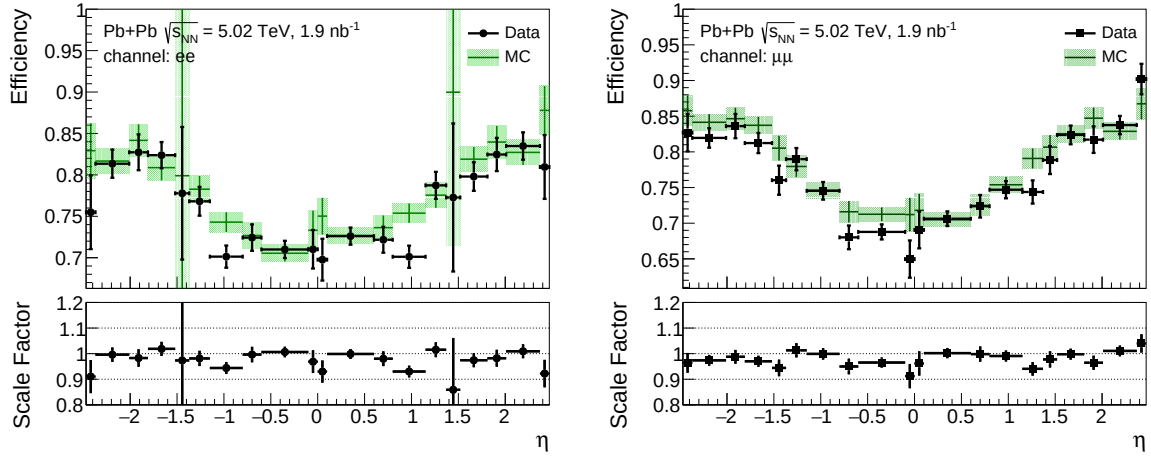


Figure 4.10: Isolation efficiency as a function of pseudorapidity (η) for electrons (left) and muons (right) in data and MC simulation. Error bars and shaded boxes correspond to total uncertainties in data and MC simulation, respectively.

The data-to-MC isolation efficiency in the η - p_T plane is presented in Figure 4.11. In both channels, the simulation aligns reasonably well with the data in most of the detector regions. For the $\mu\mu$ channel, slightly smaller fluctuations in efficiency are observed compared to the ee data. The MC simulation overestimates the real detector response, especially at low p_T . The reduced efficiency ratio is also evident for $|\eta| < 0.1$, where the data diverge more prominently from the simulation.

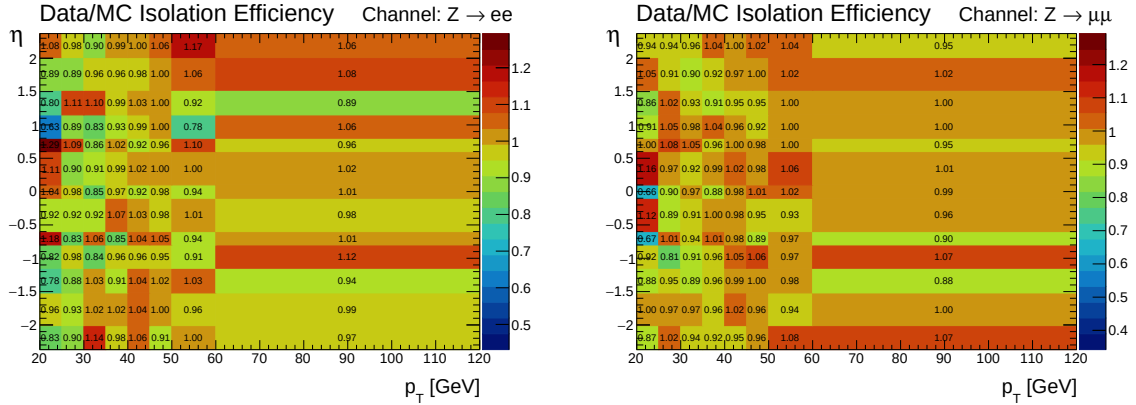


Figure 4.11: The data-to-MC ratio of lepton isolation efficiency as a function of η and p_T for electron (ee) and muon ($\mu\mu$) channels.

The total isolation scale factors are calculated, taking into account both statistical and systematic uncertainties, with a predominant contribution from the statistical uncertainties. Moreover, the uncertainties decrease as the integrated luminosity increases. The final results for the combined 2015+2018 data set are cross-checked for consistency with the individual data sets. Figure 4.12 presents the SF_{iso} values, showing good agreement within the uncertainties between the combined and individual data sets.

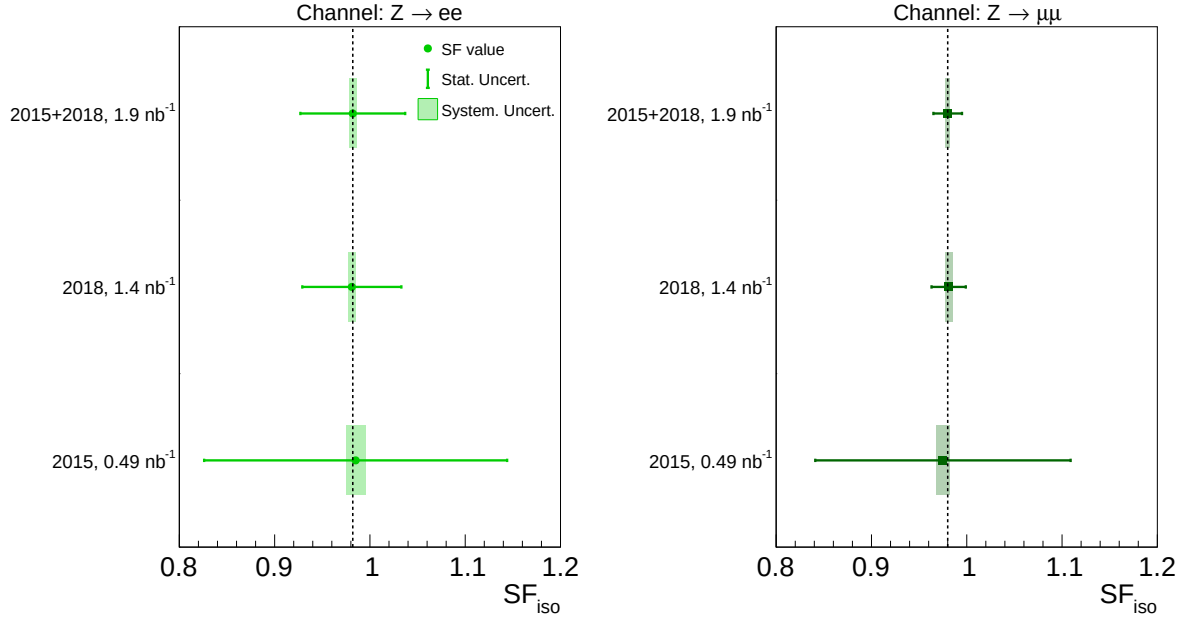


Figure 4.12: Isolation scale factors (SF_{iso}) for electrons (left) and muons (right). The vertical dashed line represents the central value of the combined data set for 2015+2018. Error bars and shaded boxes represent statistical and systematic uncertainties, respectively.

The total isolation scale factor for the combined 2015+2018 data set with an integrated luminosity of 1.9 nb^{-1} for electrons is

$$SF_{\text{iso}}^{ee} = 0.982 \pm 0.055 (\text{stat.})^{+0.0022}_{-0.0026} (\text{syst.})$$

and for muons

$$SF_{\text{iso}}^{\mu\mu} = 0.980 \pm 0.015 (\text{stat.})^{+0.0043}_{-0.0024} (\text{syst.}).$$

4.6 Trigger Efficiencies

Unlike previous efficiency and scale factor measurements, the trigger efficiency analysis in this study is based exclusively on the 2018 data set. This choice is due to the different triggers used across the data-taking periods and the fact that the MC simulation was generated for the specific conditions of 2018 data-taking period including only the triggers used during that year.

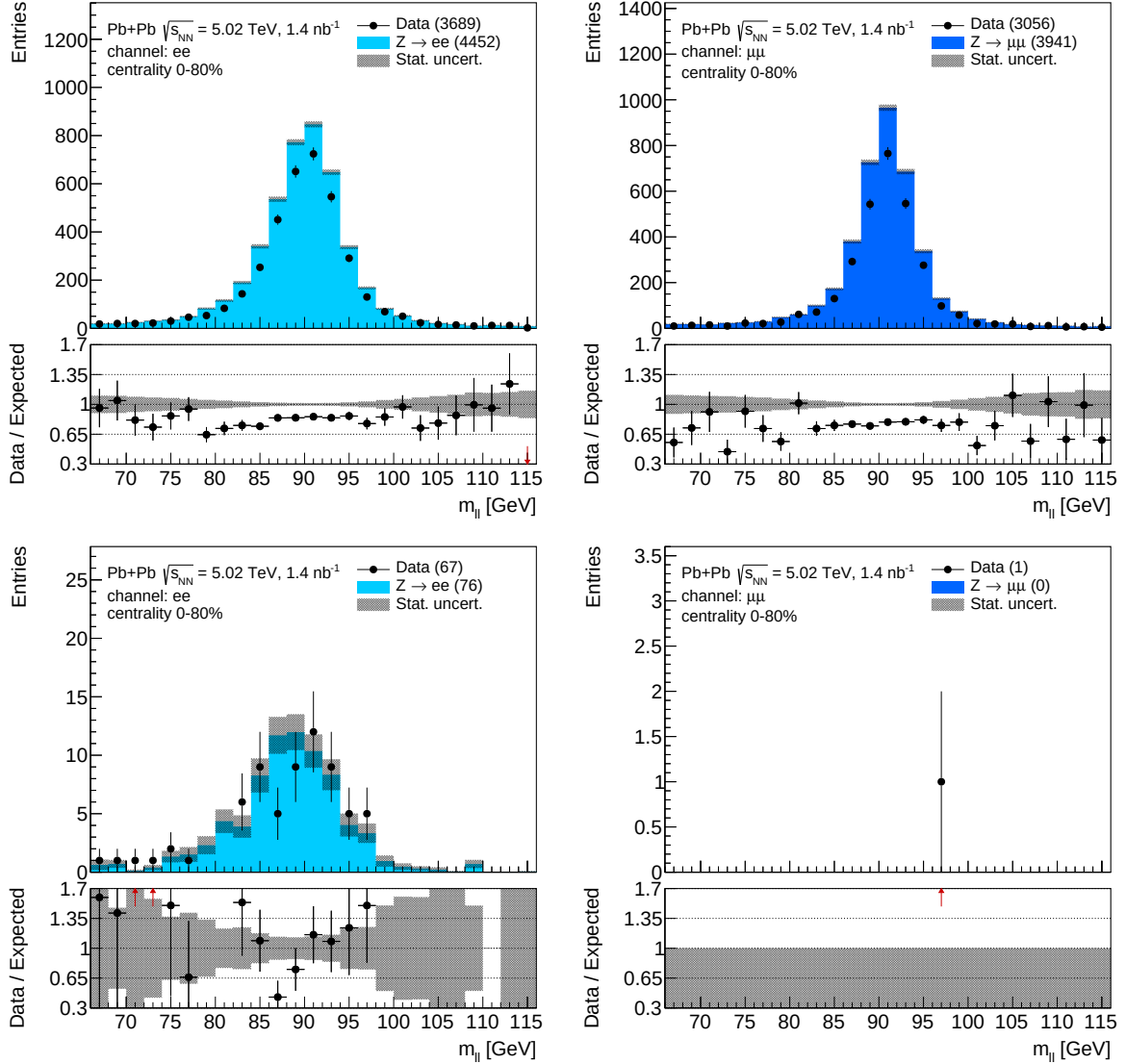


Figure 4.13: Invariant mass distributions of triggered lepton pairs used in the numerator of trigger efficiency calculations. Top row: OS charged pairs for electrons (left) and muons (right), used to obtain signal-enriched samples. Bottom row: SS charged pairs for electrons (left) and muons (right). Error bars and shaded boxes correspond to statistical uncertainties in data and MC simulation, respectively.

The invariant mass distribution of lepton pairs is once again used in this study, serving as the basis for trigger efficiency calculations. These calculations are similar to the isolation SF measurements and are performed using three categories: both leptons triggered (Both),

negative lepton triggered (Negative), and positive lepton triggered (Positive). Figure 4.13 presents the invariant mass distributions of the triggered lepton pairs, where the top row corresponds to OS charged pairs for electrons (left) and muons (right), and the bottom row shows the SS charged pairs for electrons (left) and muons (right).

In the distributions, we observe that the data show fewer events than predicted by the MC simulations, which can be attributed to differences in efficiencies between the data and simulation. Additionally, the SS distribution is well-populated for electrons, but for muons, only one data event is observed that survived the trigger selection, highlighting the challenges in capturing sufficient statistics for this category.

For the ee channel, two triggers are considered for each event, at least one of the trigger conditions must be satisfied for the event to be considered valid. For muons, only one trigger is utilized, which is necessary for the event to be considered further. A summary of the triggers used for both the ee and $\mu\mu$ channels is provided in Table 4.3.

Table 4.3: Summary of triggers used for ee and $\mu\mu$ channels in the analysis.

Lepton	Trigger	Description
Electron	Loose electron trigger <code>HLT_e15_loose_ion</code>	$p_T \geq 15$ GeV, cut-based criteria
	Likelihood-based electron trigger <code>HLT_e15_lhloose_ion_L1EM12</code>	$p_T \geq 15$ GeV, loose identification with Level-1 EM calorimeter threshold of 12 GeV
Muon	Muon trigger <code>HLT_mu8</code>	$p_T \geq 8$ GeV, captured by the HLT system

Statistical uncertainties and total SF values are calculated within the second, nominal mass window, with the results for data and MC simulation for each mass window and both leptons triggered shown in Figure 4.14. Compared to isolation, significantly larger differences between data and MC simulation are observed, particularly in the $\mu\mu$ channel, since the MC simulation does not perfectly model the trigger performance in real data. Furthermore, the differences may also stem from the smaller data sample used in this analysis, as it is restricted by the exclusion of 2015 data. In the ee channel, we also observe a substantial number of SS events, which contribute significantly to the background in this analysis.

Similarly to the isolation study, systematic uncertainties are evaluated using specific categories and mass windows. The corresponding event counts for both channels, as well as for SS and OS charged pairs, are shown in Figure 4.15. As expected, the largest number of events is observed in the broadest mass window (70–110 GeV). For the negatively charged leptons triggered, only a slight difference is observed compared to the positively charged lepton category. A single event in the $Z \rightarrow \mu\mu$ SS channel, visible in the invariant mass distribution, contributes to every possible category. Small fluctuations in event counts across the mass windows are observed.

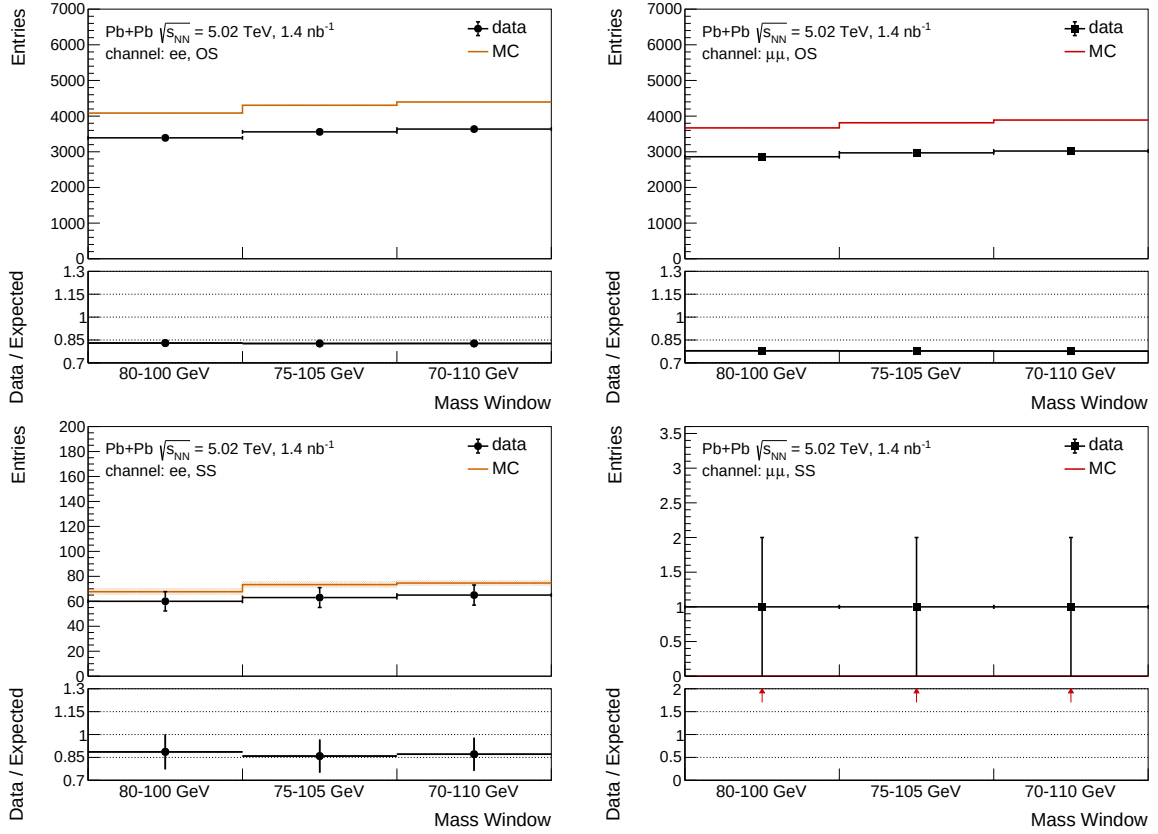


Figure 4.14: Comparison of Z boson yields in data and MC simulation for both leptons triggered, for ee (left) and $\mu\mu$ (right) channels as a function of the Z boson mass. Error bars correspond to statistical uncertainties in data.

The trigger efficiencies are examined using the kinematic variables p_T and η , ensuring that the trigger selection criteria are properly applied across different kinematic regions. Figure 4.16 shows the efficiency as a function of p_T , where we observe stable values of scale factors, close to unity throughout the whole range p_T , with slightly more deviations for muons at low p_T .

For electrons, the turn-on occurs rapidly, with the plateau being reached already at $p_T > 30$ GeV. In contrast, for muons, no visible turn-on is observed due to the trigger threshold applied at $p_T = 8$ GeV, which causes the efficiency to stabilize almost immediately. This difference reflects the distinct kinematic and trigger selection criteria for electrons and muons.

The trigger efficiency as a function of lepton η , presented in Figure 4.17, exhibits minor variations across the detector acceptance range for electrons. For muons, however, a more complex pattern is observed. The trigger efficiency is lowest near $|\eta| \approx 0$, which corresponds to the acceptance gap. This presents challenges due to geometric complexity and overlapping subdetector coverage, making track reconstruction more difficult. Efficiency improves as $|\eta|$ approaches ± 1.5 , where the detector's magnetic field and acceptance are optimal for muon triggering. However, beyond $|\eta| > 2$, trigger efficiency drops sharply due to reduced coverage

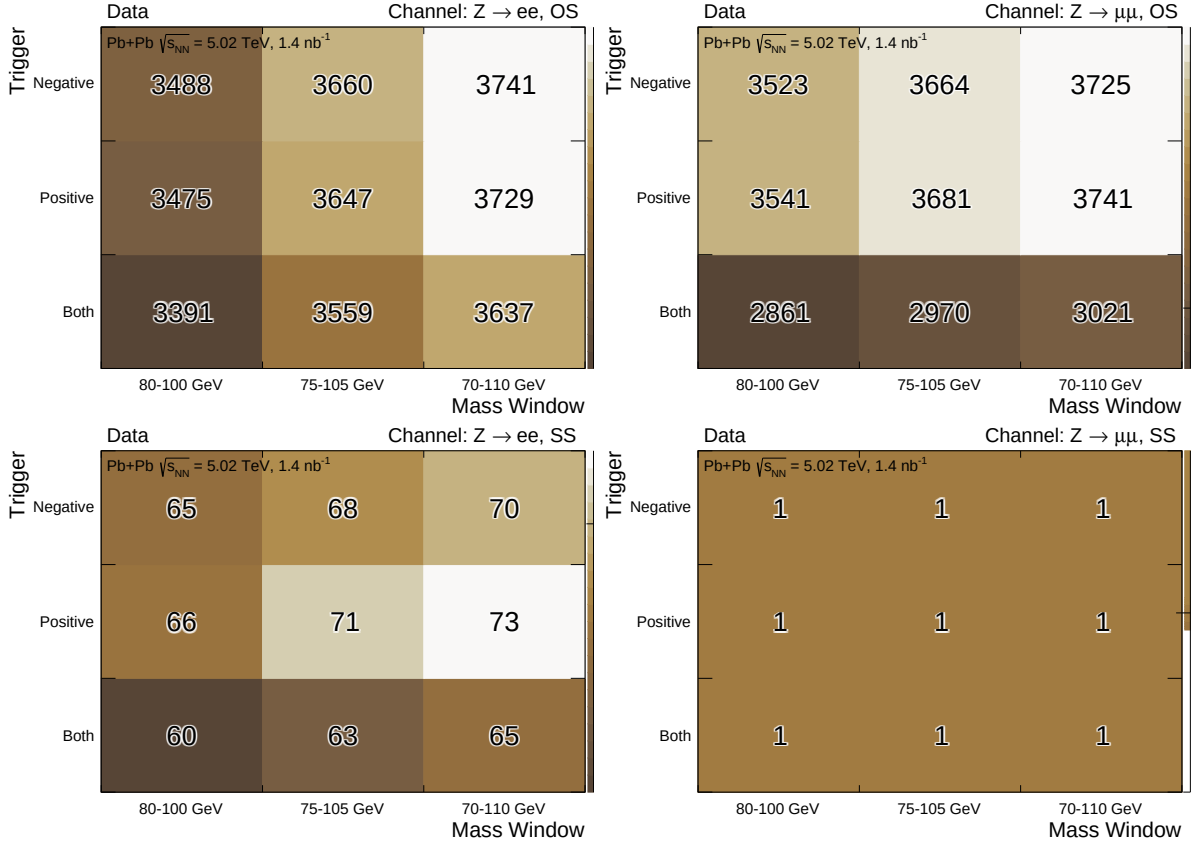


Figure 4.15: Number of Z boson event candidates for three trigger categories and windows considered in the systematic uncertainty evaluation. The data are presented for both the ee (left) and $\mu\mu$ (right) channels, with OS (top) and SS (bottom) charged leptons taken into account.

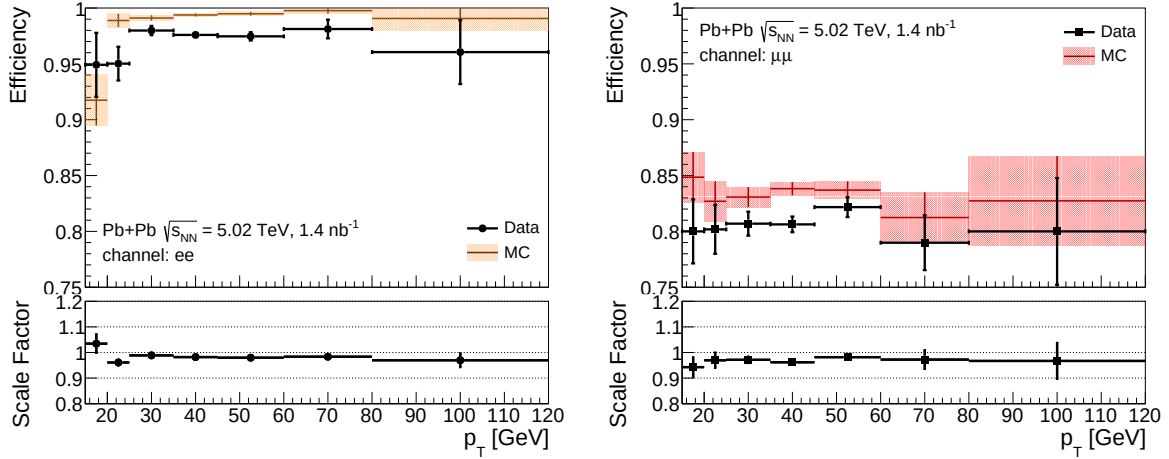


Figure 4.16: Trigger efficiency as a function of lepton p_T for electrons (left) and muons (right) after the tag-and-probe selection. Error bars and shaded boxes correspond to total uncertainties in data and MC simulation, respectively.

and the MS's limited performance in the high- η regions.

The data-to-MC ratios of trigger efficiency as a function of η and p_T are presented in

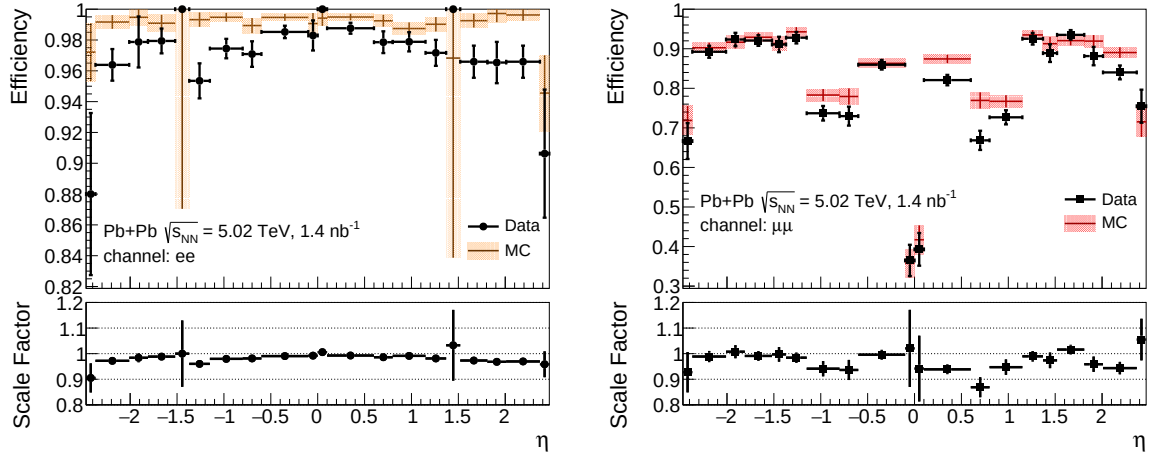


Figure 4.17: Trigger efficiency as a function of η for electrons (left) and muons (right) after the tag-and-probe selection. Error bars and shaded boxes correspond to total uncertainties in data and MC simulation, respectively.

Figure 4.18, providing a detailed map of the trigger SFs across the kinematic parameter space. In the ee channel, the simulation reproduces the data well, with SFs showing good agreement across most regions of the detector. Slight drops in SF values are observed in the transition region ($1.37 < |\eta| < 1.52$) and for low- p_T , high- η regions, which are areas of reduced detector efficiency. For muons, data efficiency exceeds the MC efficiency in specific regions, particularly for $|\eta| < 0.1$, while the ratio is closest to unity for $|\eta| \approx 1.5$ and high- p_T , indicating optimal agreement in these kinematic regions.

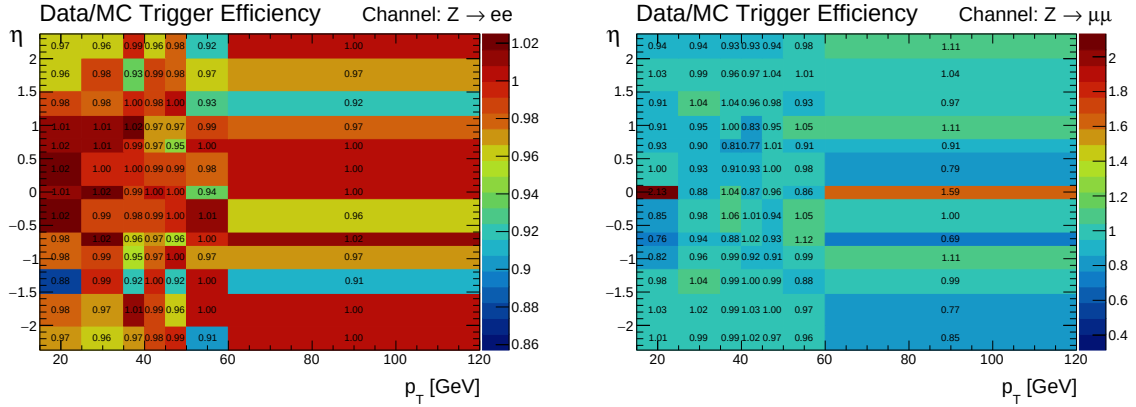


Figure 4.18: The data-to-MC ratios of trigger efficiency as a function of η and p_T for electron (ee) and muon ($\mu\mu$) channels.

The total trigger scale factor for the 2018 data with an integrated luminosity of 1.4 nb^{-1} for electrons is

$$\text{SF}_{\text{trig}}^{ee} = 0.983 \pm 0.055 (\text{stat.})^{+0.0022}_{-0.0026} (\text{syst.})$$

and for muons

$$\text{SF}_{\text{trig}}^{\mu\mu} = 0.968 \pm 0.021 (\text{stat.})^{+0.0043}_{-0.0024} (\text{syst.}).$$

4.7 Discussion of Results

The efficiency and scale factor measurements for lepton identification, isolation, and trigger selection have been performed using data from the 2015 and 2018 Pb+Pb collision runs. For identification, the scale factors are derived for both electrons and muons, with good agreement observed between the combined 2015+2018 data set and the individual data sets within the statistical and systematic uncertainties.

For isolation, both electron and muon candidates are required to meet calorimeter- and track-based isolation criteria. The calculated isolation scale factors show stable efficiency across different kinematic regions. The background contribution from SS charged lepton pairs, especially in the ee channel, is found to be significant. In contrast, for muons, the background contribution is minimal, resulting in more consistent efficiency values.

The trigger efficiencies are calculated using only the 2018 data set due to the different trigger configurations across data-taking periods. For electrons, the event is accepted if either of the two triggers is satisfied, while for muons, only one trigger is used. The trigger efficiencies show stable values across the p_T spectrum.

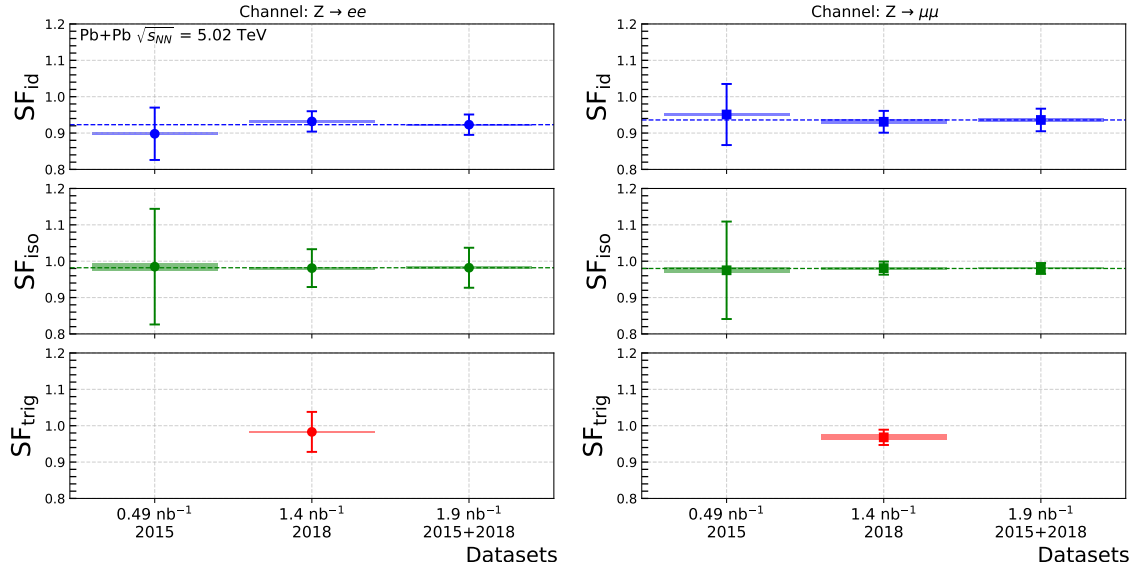


Figure 4.19: Total scale factors for electrons (left) and muons (right) derived for identification (SF_{id}), isolation (SF_{iso}) and trigger (SF_{trig}) efficiencies in the individual 2015, 2018 and combined 2015+2018 data sets. The horizontal dashed line represents the central value of the combined data set. Error bars and shaded boxes represent statistical and systematic uncertainties, respectively.

In general, the derived scale factors, as shown in Figure 4.19, are consistent within the uncertainties between the two data-taking periods, confirming the robustness of the detector's performance in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV during Run 2.

5 Analysis of Run 3 Data

5.1 LHC 2024 Heavy-Ion Run

The analysis of pp and Pb+Pb data collected during the November 2024 LHC heavy-ion run with the ATLAS detector is presented, specifically focused on the electron channel in Z boson dileptonic decays at a center-of-mass energy of 5.36 TeV per nucleon pair. The hard-probes stream was deployed in Pb+Pb collisions to ensure efficient selection of events containing high-invariant-mass lepton pairs, such as those from Z boson decays. Hard processes provide probes within the Standard Model that can be calculated using perturbative methods, providing valuable insights into high-momentum-transfer phenomena in HI collisions [23].

The objective is to analyze and validate the response of the ATLAS detector to high-density particle environments and test the baseline for lepton identification under HI conditions. For this analysis, the **TagAndProbe** framework [24], part of the new ATLAS e/γ software in release 25.2.19, is used, with a specialized configuration optimized for pp and HI collisions. The triggers employed in the analysis are summarized in Table 5.1. The tag-and-probe pairs are required to satisfy the OS charge condition, with $p_T > 15$ GeV and η within the range of $-2.47 < \eta < 2.47$. Key kinematic variables are used, that directly characterize lepton and detector performance.

Table 5.1: Names of the triggers used for electron selection in the analysis of pp and Pb+Pb collision data collected during the LHC HI run in November 2024.

Interaction Type	pp Collisions	Pb+Pb Collisions
Trigger Name	HLT_e15_loose_L1eEM15	HLT_2e20_loose_nogsf_ion_L12eEM18
	HLT_e15_lhloose_L1eEM15	HLT_e15_etcut_ion_L1eEM15
	HLT_2e20_lhloose_L12eEM18	HLT_e15_loose_nogsf_ion_L1eEM15
	HLT_2e20_lhmedium_L12eEM18	HLT_e15_lhloose_nogsf_ion_L1eEM15

5.2 Proton-Proton Reference Run

In parallel to the HI analysis, pp reference data at the same center-of-mass energy are analyzed to provide a benchmark for comparison. These reference data are critical for understanding the performance of electrons in Pb+Pb collisions, as they enable the calibration of detector response under lower multiplicity conditions typical of pp interactions. This approach is akin to studies in vacuum, where controlled conditions allow researchers to isolate specific effects and calibrate instruments before applying them to more complex environments, such as the high-energy, high-density states created in HI collisions. In total, 14 stable collision runs from pp reference collisions are analyzed.

In all the following studies, a tag electron is required to satisfy the Tight identification (id) working point (WP), ensuring a high-purity sample. The probe electron, on the other hand, is evaluated under varying conditions, starting from reconstruction (Reco) and progressing through the id WPs: VeryLoose, Loose, Medium, and Tight WPs. This approach allows to systematically study the effect of tightening identification criteria on signal purity and background suppression.

The transformed LH discriminant (d'_L) distribution, shown in Figure 5.1, highlights the impact of varying WPs on reconstructed probes. As seen, tighter WPs correspond to a more prominent peak at $d'_L \approx 1$, which signifies a better signal with a reduced background contribution. However, this improvement in signal purity comes at the cost of a slight reduction in data efficiency, as some signal events are lost due to the stricter selection criteria.

For the id WPs, the signal-to-background ratio is significantly improved, demonstrating the effectiveness of stricter selection criteria. In contrast, reconstructed (Reco) probes exhibit a broader tail extending towards lower d'_L values ($d'_L < 0$), indicating a higher level of background contamination.

This distribution matches the simulation-based results, as shown in Figure 3.2, confirming that the methods applied to the pp data set are reliable and well-calibrated. This consistency ensures that the analysis can serve as a robust benchmark for subsequent investigations of Pb+Pb collisions.

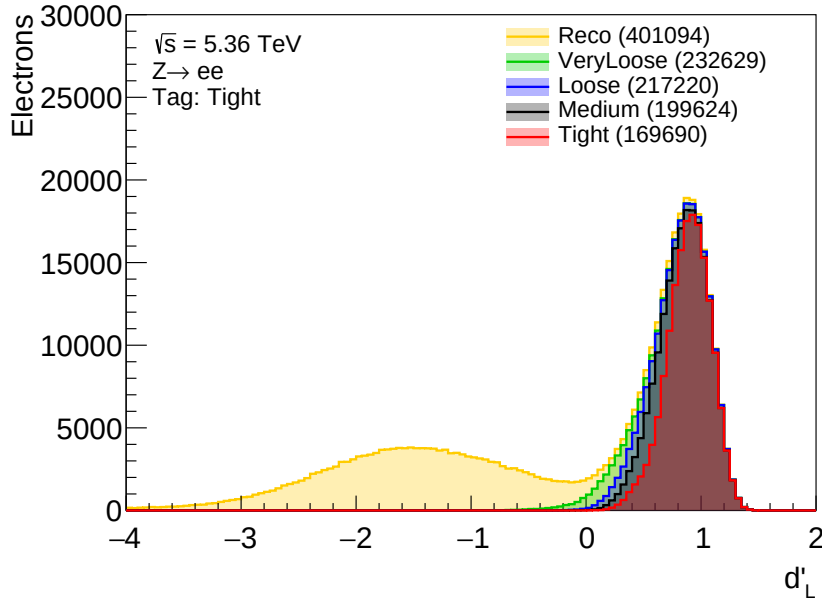


Figure 5.1: Transformed LH discriminant (d'_L) distribution of probe electrons for varying WPs and Tight tag in pp collisions. The total number of probes is given in parentheses.

The invariant mass distribution of electron pairs from Z boson decays is presented in Figure 5.2. A prominent peak at 91 GeV is visible for all WPs and the total number of tag-and-probe pairs for each identification WP. As the probe WP becomes more stringent,

from Reco to VeryLoose and finally Tight, the background in the invariant mass distribution diminishes significantly, resulting in a cleaner signal with reduced contributions in the sidebands. Each tighter WP improves the signal-to-background ratio by filtering out events inconsistent with $Z \rightarrow ee$ decays, albeit at the cost of a slight reduction in statistics.

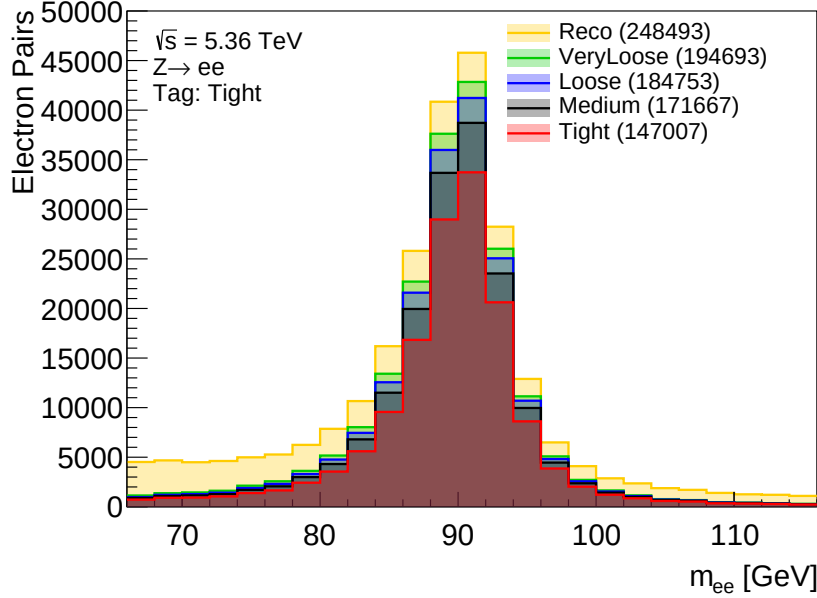


Figure 5.2: Invariant mass (m_{ee}) distribution of electron pairs for varying probe WPs and Tight tag in pp collisions. The total number of tag-and-probe pairs is given in parentheses.

In Figure 5.3, the p_T distribution of probe electrons is presented. The distribution peaks at around 45 GeV which is a feature of electrons originating from Z boson decays. The background is predominantly associated with low- p_T probes, which are largely removed upon applying the VeryLoose WP. As the identification WP becomes more stringent, the suppression of background at low p_T is further enhanced, resulting in a cleaner signal.

In Figure 5.4, a noticeable reduction in the electron yield is observed with the rising $|\eta|$ values, with the smallest number of events near $|\eta| \approx 2.47$, corresponding to the edge of detector acceptance. The geometric shape of the distribution remains consistent across all working points, with each cut progressively reducing the total number of events.

As depicted in Figure 5.5, the ϕ distribution of probe electrons exhibits a generally uniform behavior across most of the azimuthal range. However, a notable dip is observed around $\phi \approx 2$. This reduction in events can be attributed to an inactive region in the ECALs, clearly visible in the η - ϕ map of Figure 5.6 at $(\eta, \phi) = (-2, 2)$. Despite this localized deficiency, the overall distribution confirms the azimuthal symmetry of the detector. Successive WP requirements lead to a decrease in the number of events but do not significantly alter the shape of the distribution.

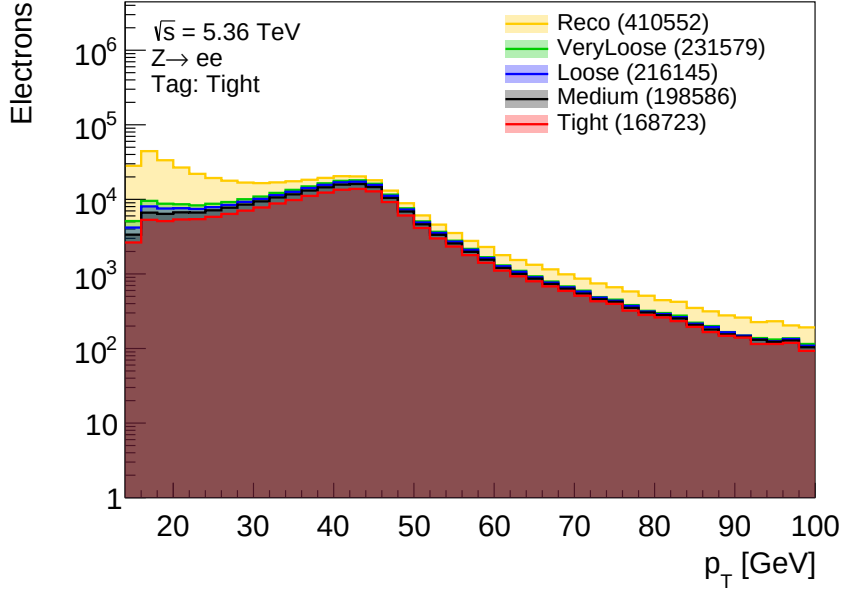


Figure 5.3: Transverse momentum (p_T) distribution of probe electrons for varying WPs and Tight tag in pp collisions. The total number of probes is given in parentheses.

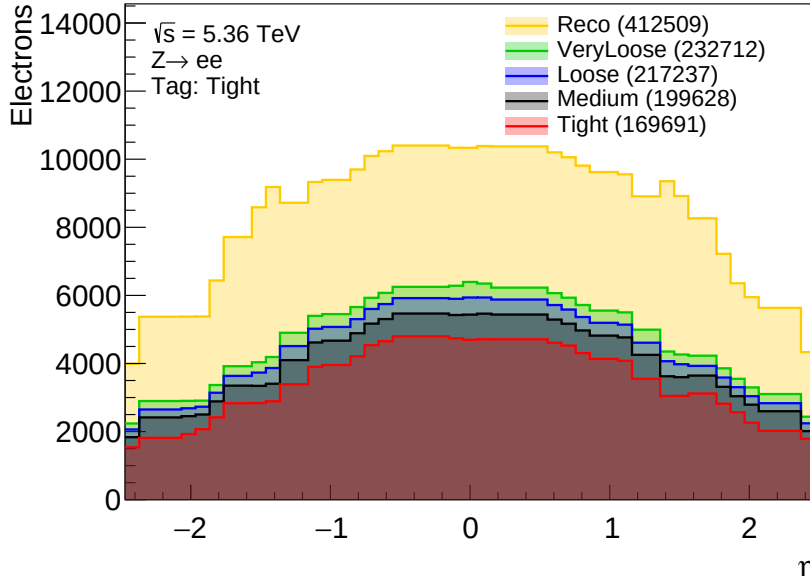


Figure 5.4: Pseudorapidity (η) distribution of probe electrons with $p_T > 15$ GeV for varying WPs and Tight tag in pp collisions. The total number of probes is given in parentheses.

5.3 Lead-Lead Collisions at 5.36 TeV

In the analysis of the Pb+Pb data set, multiple electron identification working points optimized for HI collisions are applied to measure electron performance and background rejection under high-density collision conditions. These working points, ranging from HIVeryLoose to HITight, were evaluated within the hard-probes stream. In all the following plots, the tag electron is required to satisfy the HIMedium WP. The total of 41 stable 2024 Pb+Pb runs

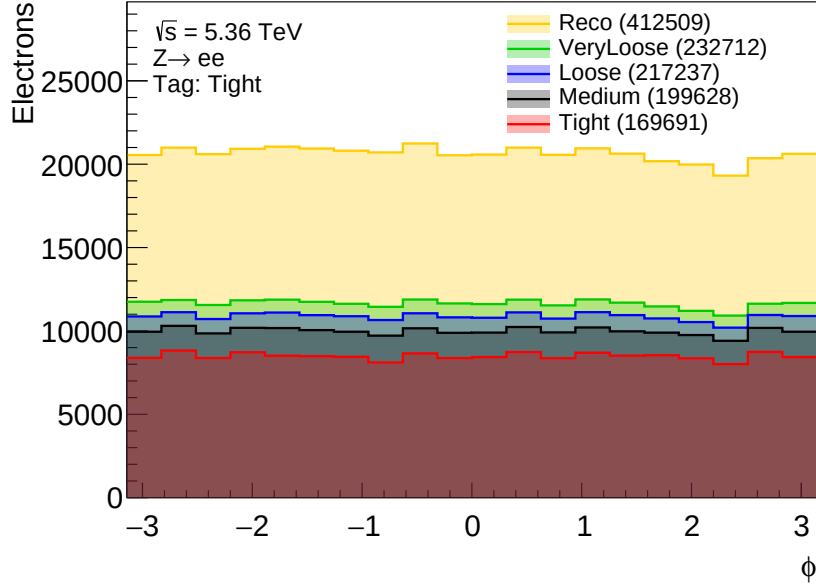


Figure 5.5: Azimuthal angle (ϕ) distribution of probe electrons with $p_T > 15$ GeV for varying WPs and Tight tag in pp collisions. The total number of probes is given in parentheses.

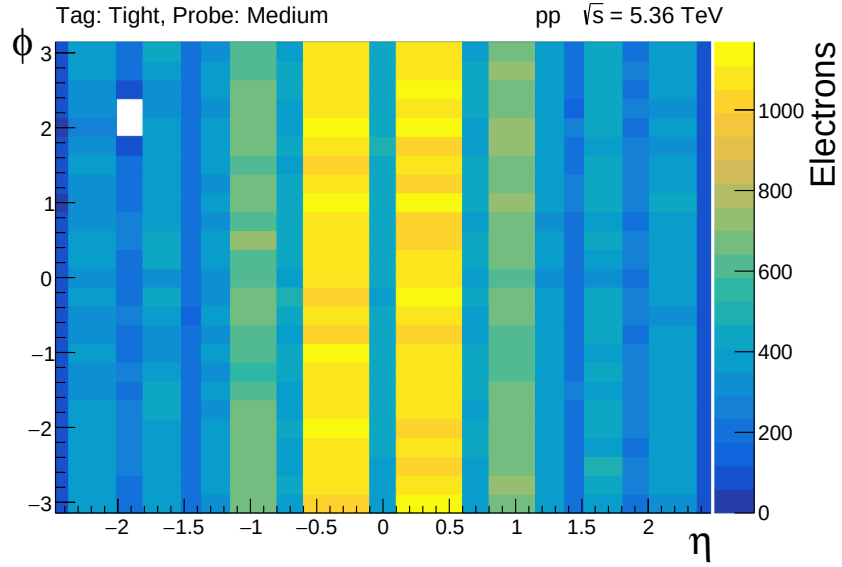


Figure 5.6: Two-dimensional maps of pseudorapidity (η) and azimuthal angle (ϕ) for Medium probe electrons associated with Tight tag electrons in pp collisions.

are analyzed, that achieved a significant milestone, with 1240 bunches per beam spaced 50 ns apart, leading to unprecedented luminosity of 1.67 nb^{-1} .

Figure 5.7 illustrates best the challenging nature of HI collisions, showing the d'_L distribution for various identification criteria imposed on the probe electron. Unlike in pp collisions, the data-to-background ratio is significantly smaller, and only for the HIMedium and HITight WPs imposed on the probe sample a clear signal peak is observed, free from

background dominance. This demonstrates the challenges faced in the analysis and underscores the importance of accurate calibration, including the use of the pp reference run for this purpose.

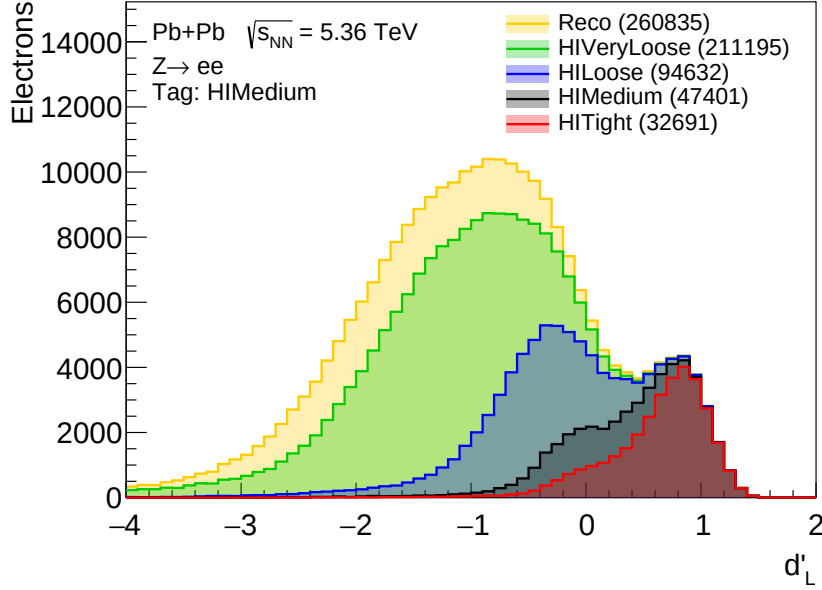


Figure 5.7: Transformed LH discriminant (d'_L) distribution of probe electrons for varying identification WPs and HIMedium tag in Pb+Pb collisions. The total number of probes is given in parentheses.

In the distribution of m_{ee} , presented in Figure 5.8, the Z boson peak is less pronounced and wider compared to the pp case. A significant contribution from background processes is observed, particularly in the tails of the distribution. As seen in the plot, applying tighter identification WPs results in a substantial improvement of the signal-to-background ratio, but also significantly reduces the number of Z boson candidates, leading to a decrease in selection efficiency in data. This highlights the trade-off between background rejection and loss of statistics, which is a common challenge in HI collision analyzes.

As seen in Figure 5.9, the p_T distribution of probe electrons shows a significant contribution from low- p_T electrons. This behavior is characteristic of the dense, hadronic environment present in HI collisions, which contrasts with pp collisions, where high- p_T probes dominate after applying tighter identification criteria. The increased presence of low- p_T particles in Pb+Pb collisions is due to the collective effects and soft particle production specific to HI environments.

An additional variable analyzed for HI collisions is the FCal ΣE_T , a measure of centrality, as presented in Figure 5.10. Unlike the typical centrality distribution shown in Figure 2.6, our distribution reflects the selection of events with two electrons, which biases the sample toward higher FCal ΣE_T values and event centralities. The distributions for tighter identification WPs appear relatively flat, which might simply be a visual artifact.

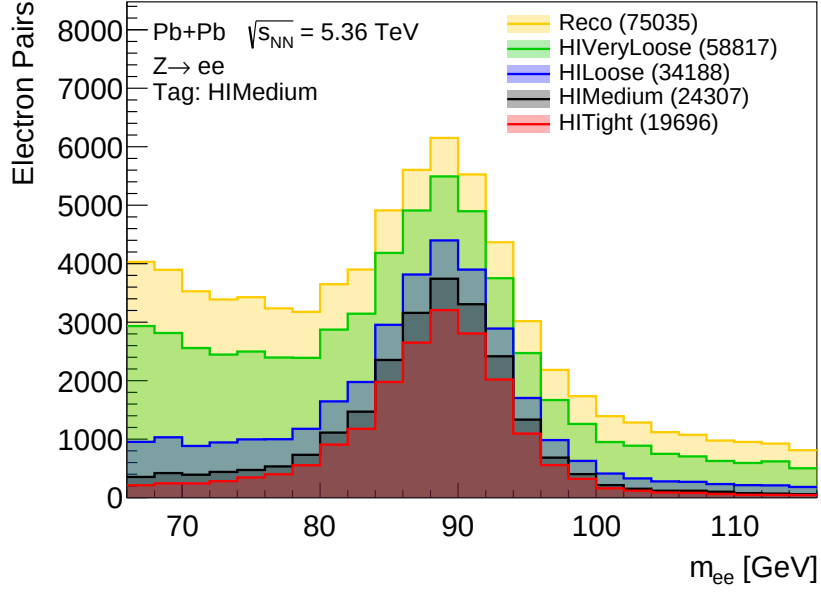


Figure 5.8: Invariant mass (m_{ee}) distribution of electron pairs for varying identification WPs for probe electrons and HIMedium tag in Pb+Pb collisions. The total number of tag-and-probe pairs is given in parentheses.

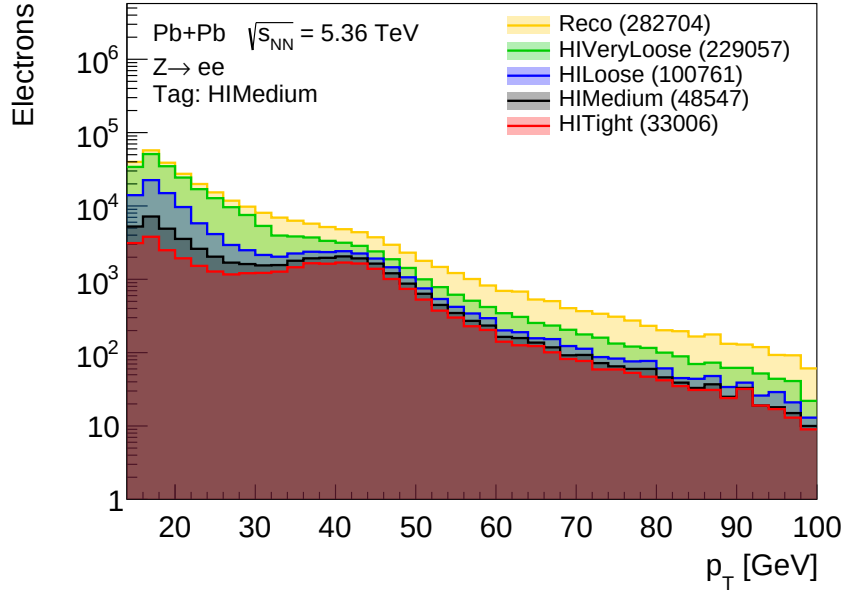


Figure 5.9: Transverse momentum (p_T) distribution of probe electrons for varying identification WPs and HIMedium tag in Pb+Pb collisions. The total number of tag-and-probe pairs is given in parentheses.

The next two plots, presented purely for control purposes, display the η and ϕ maps, shown in Figures 5.11 and 5.12, respectively. The η and ϕ distributions maintain their shape as tighter cuts are applied, with only a reduction in the number of events observed. The η distribution shows a decrease in events in the endcap-barrel transition region, whereas the

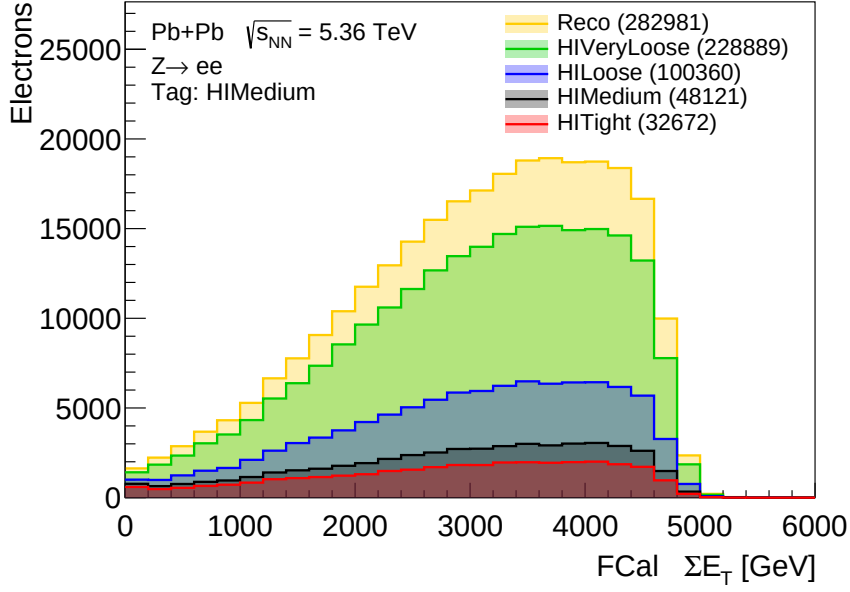


Figure 5.10: Distribution of the transverse energy in the Forward Calorimeter ($\text{FCal } \Sigma E_T$) of probe electrons for varying identification WPs and HIMedium tag in Pb+Pb collisions. The total number of probes is given in parentheses.

uniform ϕ distribution suggests that the identification criteria are consistently applied across the full azimuthal range. A slight dip in events is observed for the $\phi \approx 2$ region, which is also evident in Figure 5.13 and is manifested by the lack of visible events for $(\eta, \phi) \approx (-2, 2)$.

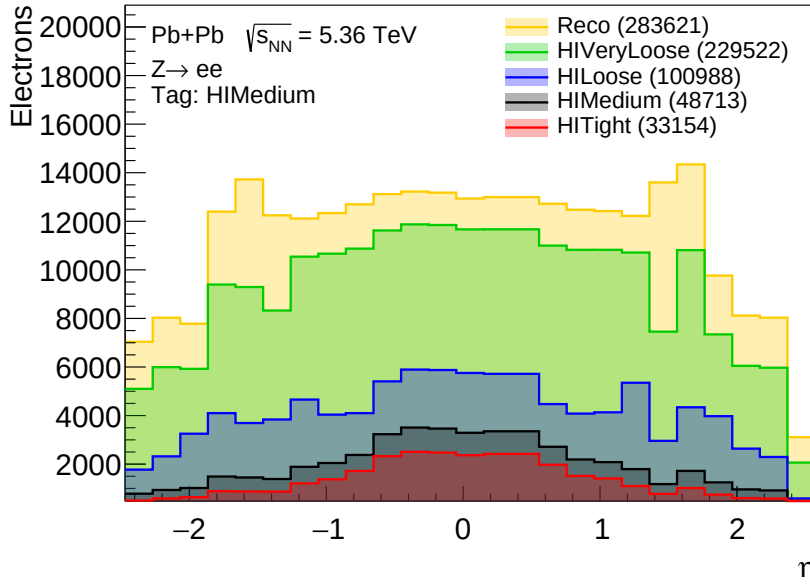


Figure 5.11: Pseudorapidity (η) distribution of probe electrons with $p_T > 15$ GeV for varying identification WPs and HIMedium tag in Pb+Pb collisions. The total number of probes is given in parentheses.

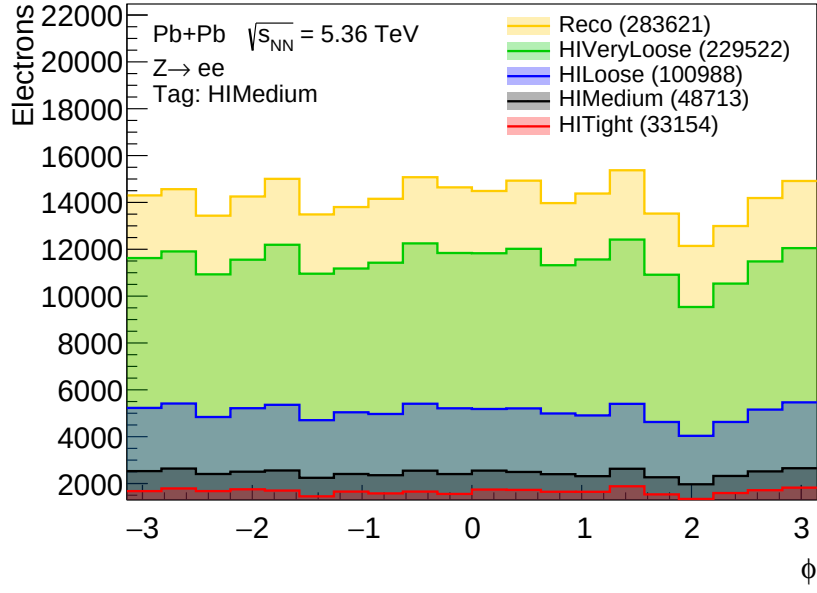


Figure 5.12: Azimuthal angle (ϕ) distribution of probe electrons with $p_T > 15$ GeV for varying identification WPs and HIMedium tag in Pb+Pb collisions. The total number of probes is given in parentheses.

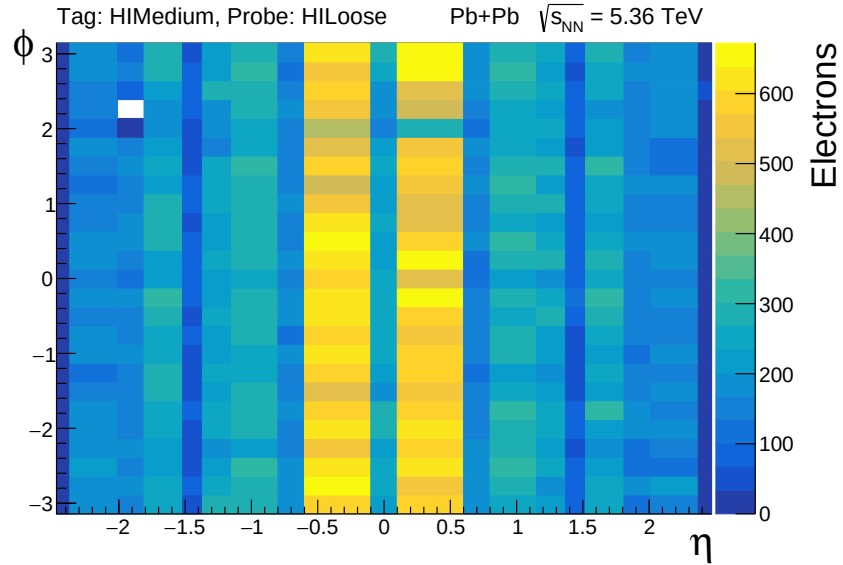


Figure 5.13: Two-dimensional maps of pseudorapidity (η) and azimuthal angle (ϕ) for HILoose probe electrons associated with HIMedium tag electrons in Pb+Pb collisions.

5.4 Summary of Results

The analysis of Run 3 data has provided key insights into the electron performance of the ATLAS detector during the 2024 HI run, specifically focusing on the $Z \rightarrow ee$ decay using the **TagAndProbe** framework. Overall, the results demonstrate robust calibration and detector performance, providing a strong foundation for future studies of the HI data set.

For pp collisions, the Tight identification WP is shown to effectively suppress background, while maintaining a clear signal, as demonstrated in the d'_L and m_{ee} distributions. The Pb+Pb analysis highlights the challenges of HI environments, with increased low- p_T background contamination compared to pp collisions. The HITight identification WP provides substantial improvements in signal-to-background ratios, particularly in d'_L and m_{ee} distributions.

Additional variables, such as the $\text{FCal} \Sigma E_T$, reveal correlations with collision centrality, emphasizing the importance of centrality-dependent analyses in HI physics. Control distributions for η and ϕ confirm consistent detector performance across different identification WPs, with expected reductions in yields in the calorimeter transition and acceptance edge regions.

6 Summary

The analysis of lepton efficiencies—for electrons and muons—measured in Pb+Pb collisions at a center-of-mass energy of $\sqrt{s_{\text{NN}}} = 5.02$ TeV, collected during Run 2 at the LHC using the ATLAS detector and MC simulation is presented. Combined datasets from 2015 and 2018 were analyzed using the tag-and-probe method, focusing on high lepton p_{T} values, leveraging Z boson decaying into electron (ee) and muon ($\mu\mu$) pairs for studies. Efficiencies were calculated at three stages of the detection chain: identification, isolation, and trigger. The trigger efficiency was studied using only 2018 data due to differing trigger configurations across the run.

Systematic uncertainties are evaluated using the mass-window technique. Efficiencies are analyzed as functions of key kinematic variables such as p_{T} and η , demonstrating good agreement between data and MC simulation. The final output of each analysis was the calculation of SFs for each stage, along with statistical and systematic uncertainties, with the former dominating. The calculated SFs are crucial for top-quark pair production studies, contributing to the first observation of this process with a significance of 5 standard deviations [2].

The second part of the analysis focused on Run 3 data from Pb+Pb collisions at $\sqrt{s_{\text{NN}}} = 5.36$ TeV collected in November 2024. The ATLAS TagAndProbe framework was used. Leptons from Z boson decays were studied, focusing on the ee channel and analyzing distributions of fundamental kinematic variables. Data from 41 Pb+Pb runs, with an integrated luminosity of 1.67 nb^{-1} , provided a large number of high-quality records focused on hard probes, enabling precise studies and further detailed analyses. A total of 75,035 electron pairs from $Z \rightarrow ee$ events were recorded for the HIMedium tag and the reconstructed probe, with the event yield decreasing as tighter probe identification working points were applied: 58,817 for HIVeryLoose, 34,188 for HILoose, 24,307 for HIMedium, and 19,696 for HITight.

Prior to the HI collision analysis, a study of reference pp collisions at the same center-of-mass energy was conducted using data from 14 runs, corresponding to an integrated luminosity of 425 pb^{-1} and recording a yield of 248,493 electron pairs with the Tight tag and reconstructed probe, providing yields for the probe at progressively more restrictive identification working points: VeryLoose (194,693), Loose (184,753), Medium (171,667), and Tight (147,007). This analysis ensured a proper detector response and revealed minor imperfections in the detection geometry within $(\eta, \phi) = (-2, 2)$, attributed to a small fraction of inactive electromagnetic calorimeter modules.

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A Appendix

A.1 Lepton Efficiency in 5.02 TeV Pb+Pb Collisions

A.1.1 Identification Scale Factor

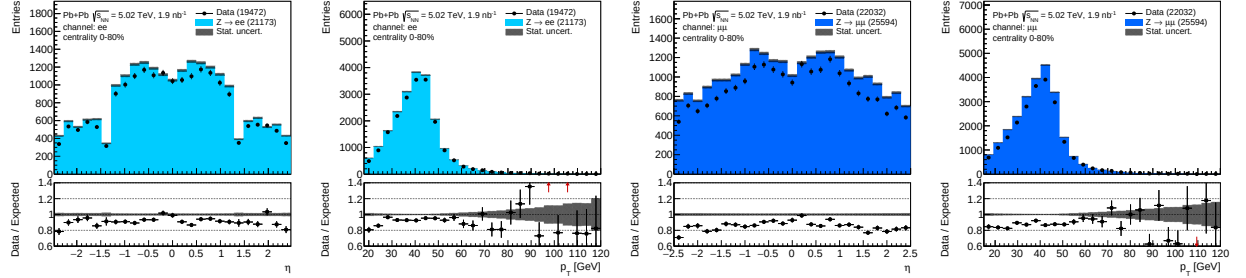


Figure A.1: Pseudorapidity (η) and transverse momentum (p_T) distribution of identified electrons passing the tag-and-probe selection in the 0–80% centrality class of Pb+Pb data, for electron (ee) and muon ($\mu\mu$) channels.

A.1.2 Isolation and Trigger Efficiencies

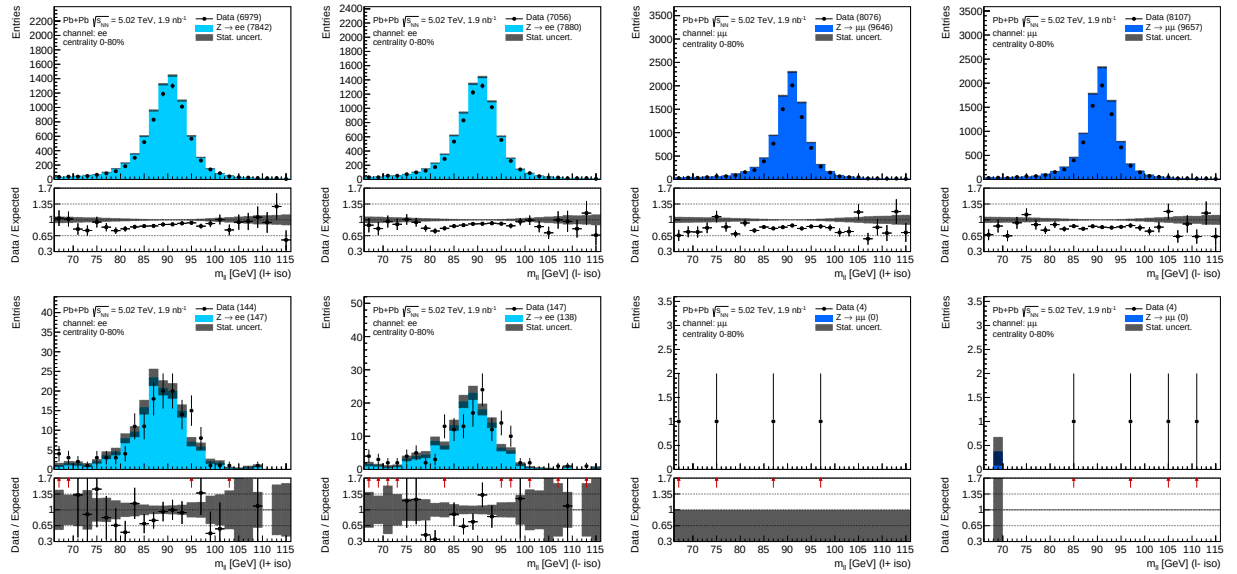


Figure A.2: Invariant mass distributions of lepton pairs forming the denominator in the isolation studies. Top row: OS charge pairs for electrons (left) and muons (right), used to obtain signal-enriched samples. Bottom row: SS charge pairs for electrons (left) and muons (right). The " $l+$ iso" corresponds to only positively charged leptons isolated, while " $l-$ iso" corresponds to negatively charged leptons isolated. Error bars and shaded boxes correspond to statistical uncertainties in data and MC, respectively.

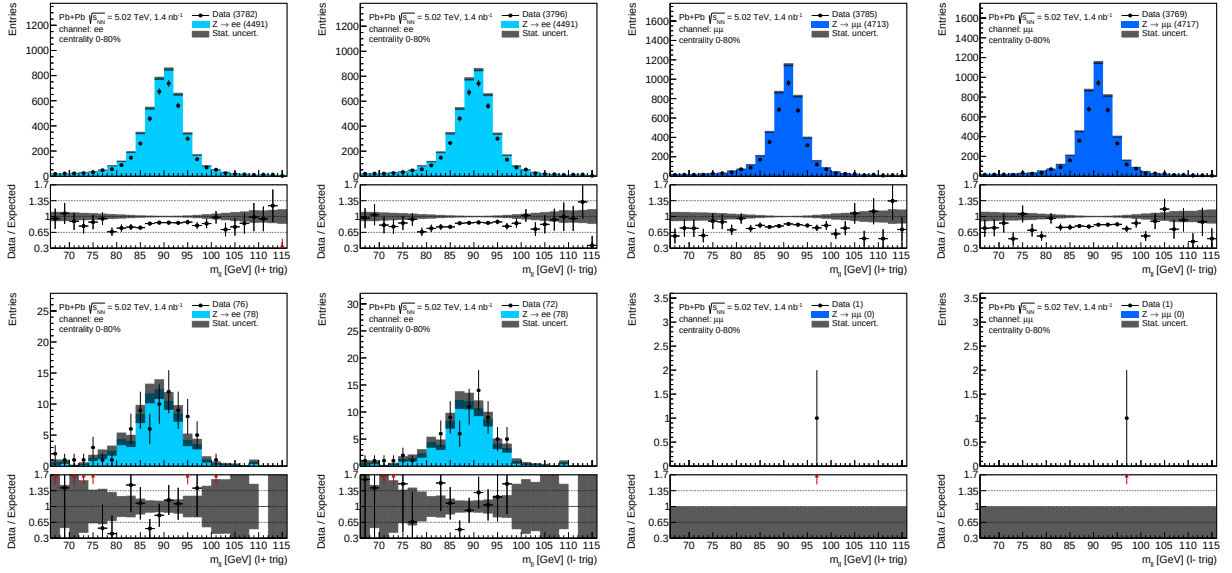


Figure A.3: Invariant mass distributions of lepton pairs forming the denominator in the trigger studies. Top row: OS charge pairs for electrons (left) and muons (right), used to obtain signal-enriched samples. Bottom row: SS charge pairs for electrons (left) and muons (right). The "l+ trig" corresponds to only positively charged leptons triggered, while "l- trig" corresponds to negatively charged leptons triggered. Error bars and shaded boxes correspond to statistical uncertainties in data and MC, respectively.

A.2 Analysis of Run 3 Data

A.2.1 Proton-Proton Reference Run

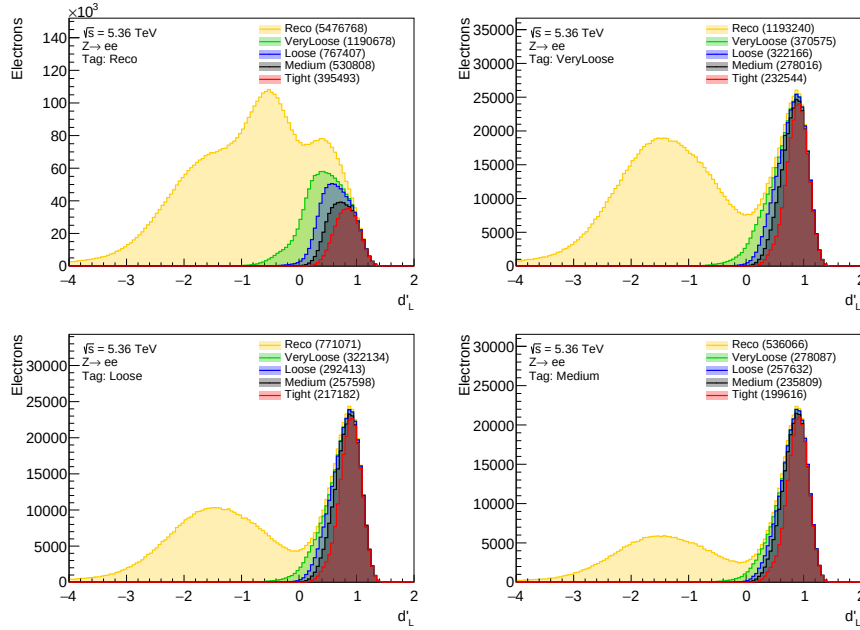


Figure A.4: Transformed LH discriminant (d'_L) distribution of probe electrons for varying WPs and fixed tag WPs in pp collisions. The total number of probes is given in parentheses.

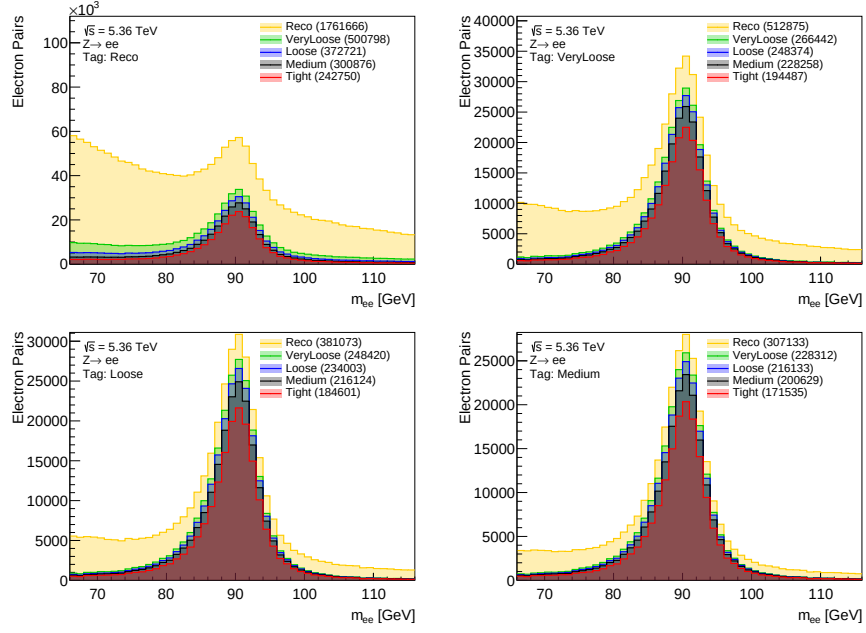


Figure A.5: Invariant mass (m_{ee}) distribution of electron pairs for varying probe WPs and fixed tag WPs in pp collisions. The total number of tag-and-probe pairs is given in parentheses.

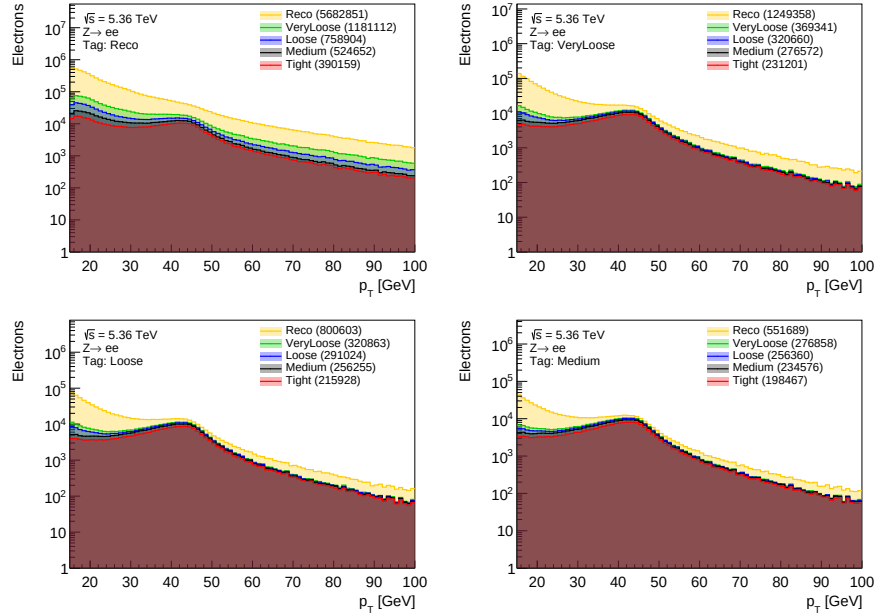


Figure A.6: Transverse momentum (p_T) distribution of probe electrons for varying WPs and fixed tag WPs in pp collisions. The total number of probes is given in parentheses.

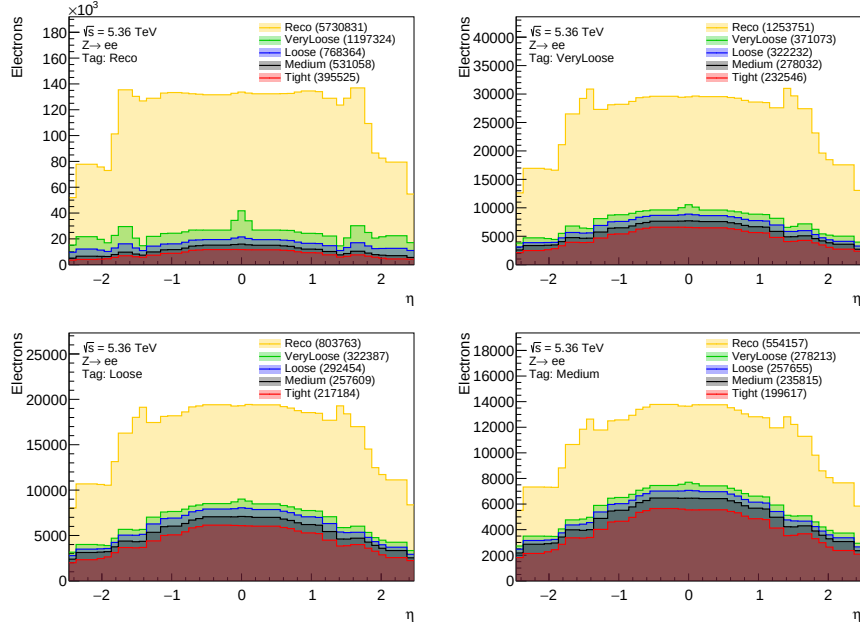


Figure A.7: Pseudorapidity (η) distribution of probe electrons with $p_T > 15$ GeV for varying WPs and fixed tag WPs in pp collisions. The total number of probes is given in parentheses.

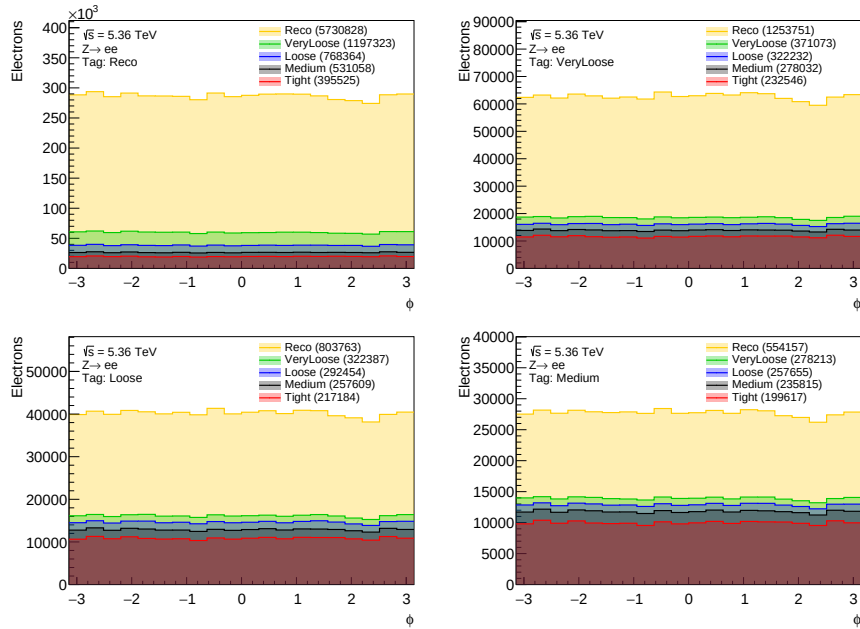


Figure A.8: Azimuthal angle (ϕ) distribution of probe electrons with $p_T > 15$ GeV for varying WPs and fixed tag WPs in pp collisions. The total number of probes is given in parentheses.

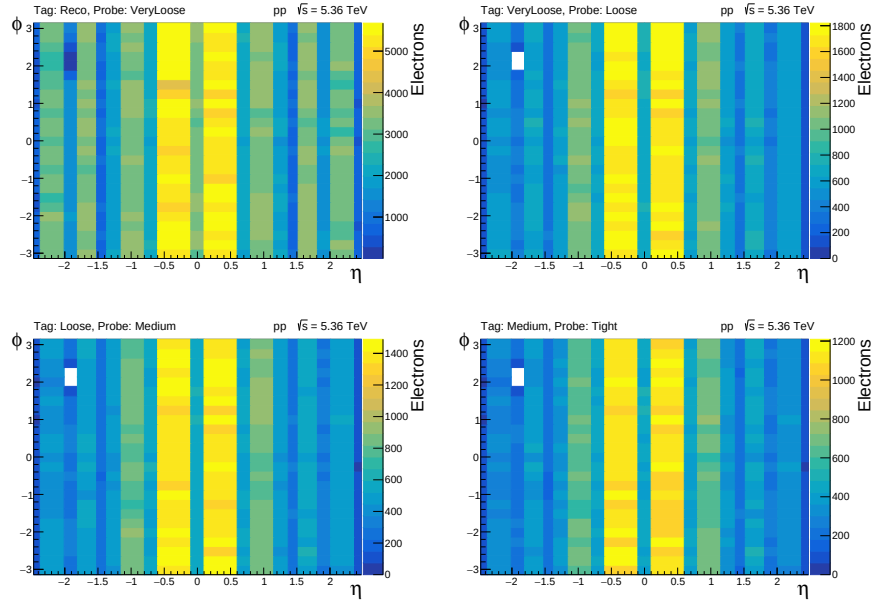


Figure A.9: Two-dimensional maps of pseudorapidity (η) and azimuthal angle (ϕ) for varying probe electrons associated with different tag electrons in pp collisions.

A.2.2 Lead-Lead Collisions at 5.36 TeV

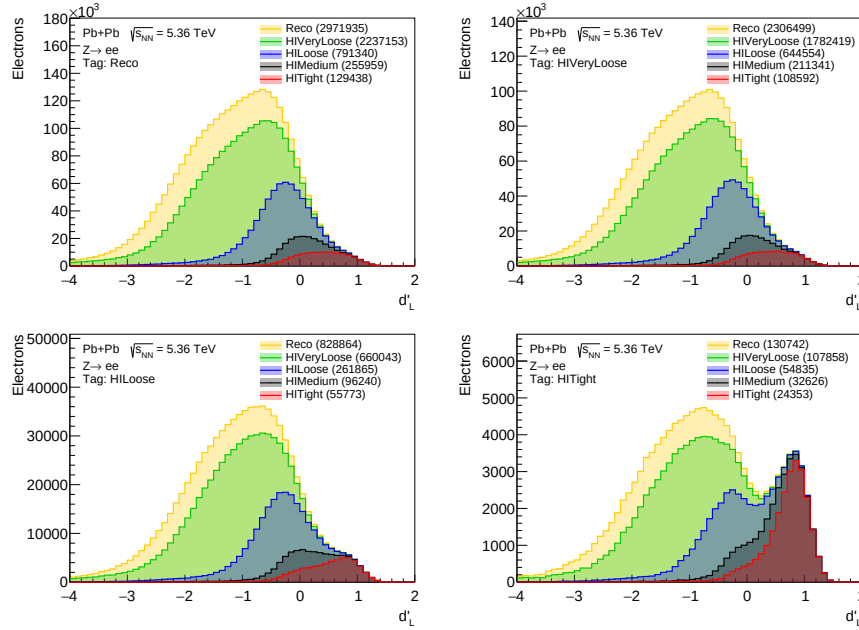


Figure A.10: Transformed LH discriminant (d'_L) distribution of probe electrons for varying identification WPs and fixed tag WPs in Pb+Pb collisions. The total number of probes is given in parentheses.

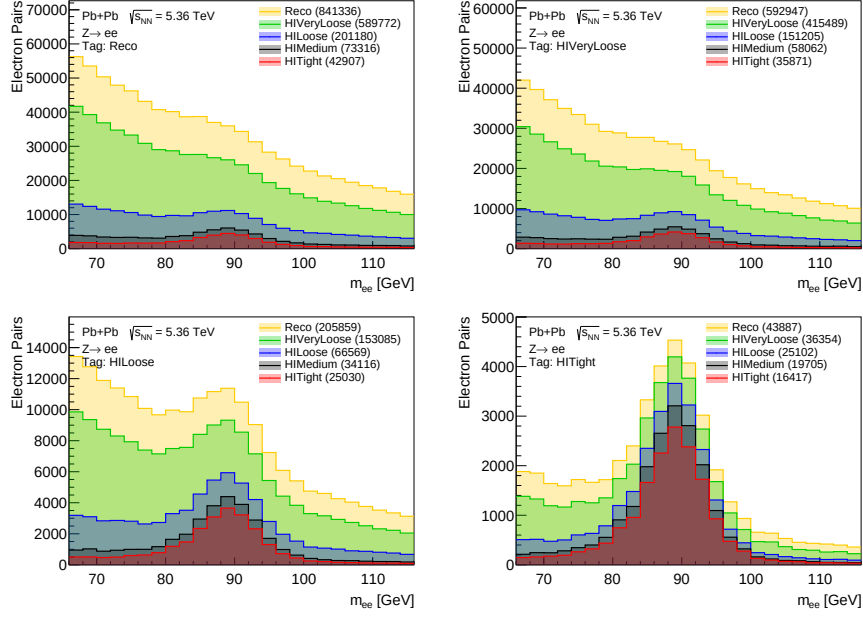


Figure A.11: Invariant mass (m_{ee}) distribution of electron pairs for varying identification WPs for probe electrons and fixed tag WPs in Pb+Pb collisions. The total number of tag-and-probe pairs is given in parentheses.

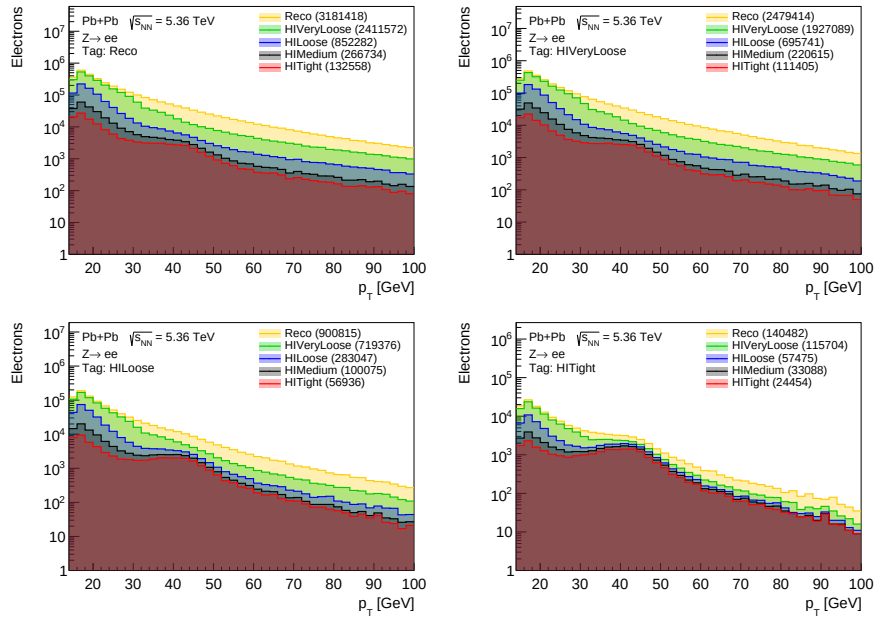


Figure A.12: Transverse momentum (p_T) distribution of probe electrons for varying identification WPs and fixed tag WPs in Pb+Pb collisions. The total number of tag-and-probe pairs is given in parentheses.

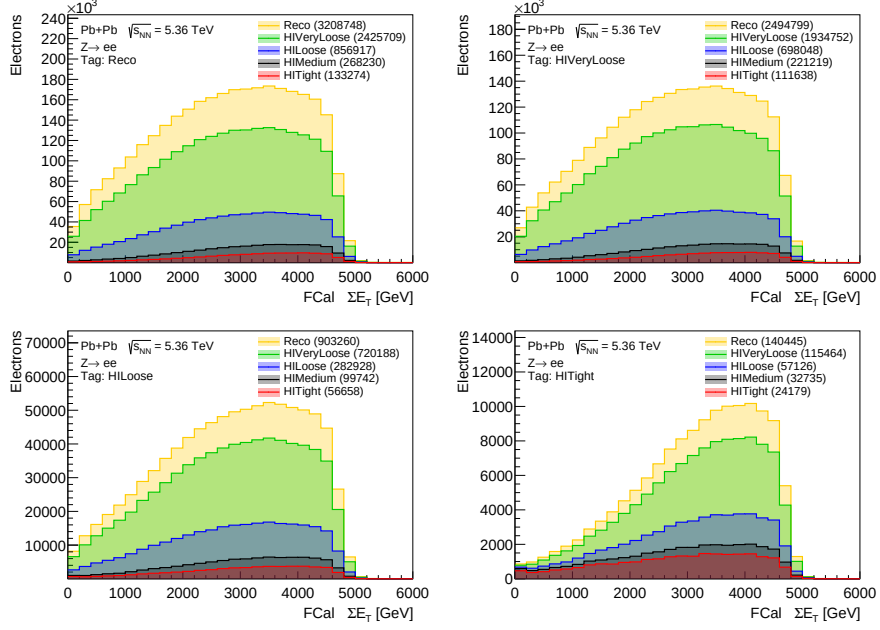


Figure A.13: Distribution of the transverse energy in the Forward Calorimeter ($\text{FCal } \Sigma E_T$) of probe electrons for varying identification WPs and fixed tag WPs in Pb+Pb collisions. The total number of probes is given in parentheses.

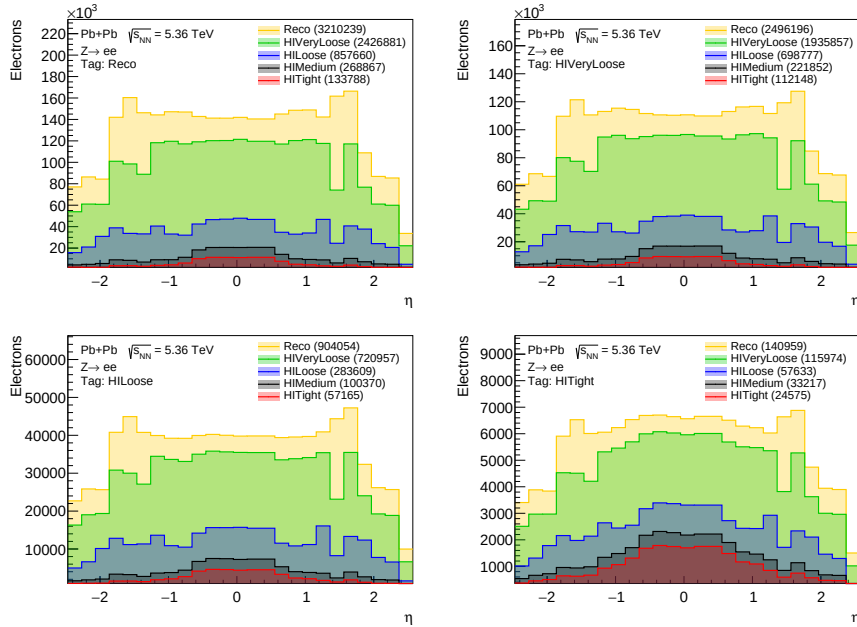


Figure A.14: Pseudorapidity (η) distribution of probe electrons with $p_T > 15$ GeV for varying identification WPs and fixed tag WPs in Pb+Pb collisions. The total number of probes is given in parentheses.

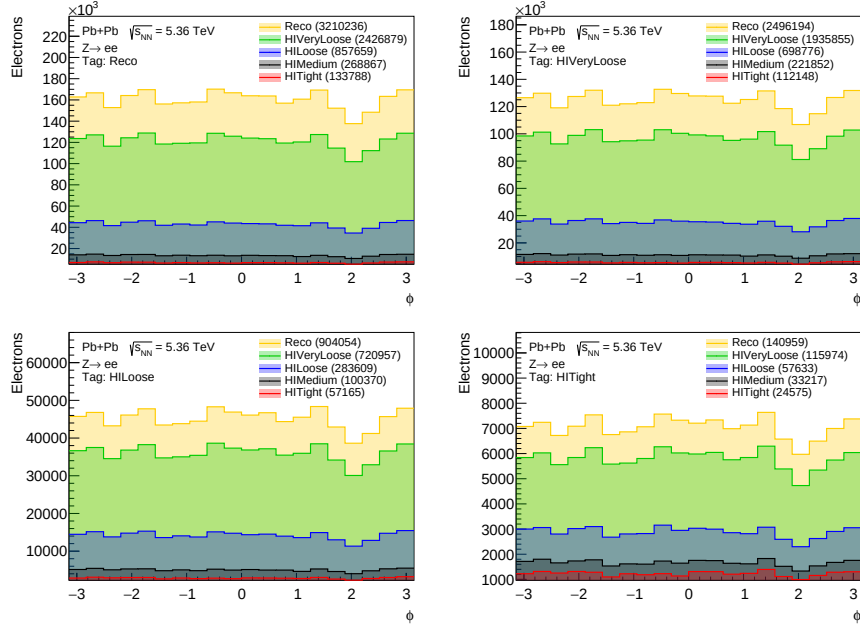


Figure A.15: Azimuthal angle (ϕ) distribution of probe electrons with $p_T > 15$ GeV for varying identification WPs and fixed tag WPs in Pb+Pb collisions. The total number of probes is given in parentheses.

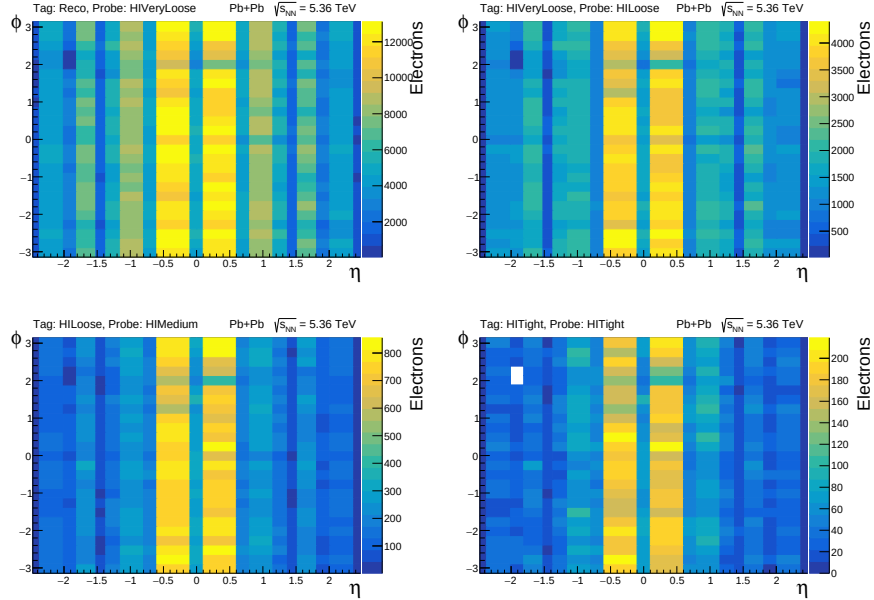


Figure A.16: Two-dimensional maps of pseudorapidity (η) and azimuthal angle (ϕ) for varying probe electrons associated with different tag electrons in Pb+Pb collisions.