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Doctoral thesis

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Measurement of W boson production in Pb+Pb collisions at 5.02 TeV with the ATLAS detector

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Declaration of the author of this dissertation:

Aware of legal responsibility for making untrue statements I hereby declare that I have written this dissertation myself and all the contents of the dissertation have been obtained by legal means.

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This dissertation is ready to be reviewed.

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Dedicated to my wife Asia, my Parents and my Brother for their support and patience for my permanent lack of time.

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Streszczenie

W rozprawie doktorskiej zaprezentowano pomiar procesu $W^\pm \rightarrow \ell^\pm \nu$ w kanale rozpadu elektronowym i mionowym w zderzeniach ołów-ołów przy energii 5.02 TeV w układzie środka masy na parę nukleonów. Rozkłady zostały zmierzone w przestrzeni fazowej ograniczonej przez pęd poprzeczny naładowanego leptonu $p_T^\ell > 25$ GeV i jego pseudopośpieszność $|\eta_\ell| < 2.5$, pęd poprzeczny neutrina $p_T^\nu > 25$ GeV oraz masę poprzeczną układu lepton–neutrino $m_{T} > 40$ GeV. Znormalizowane rozkłady, poprawione na tło i efekty detektorowe, są pokazane w funkcji bezwzględnej pseudopośpieszności naładowanego leptonu oraz w funkcji średniej liczby nukleonów biorących udział w zderzeniu N_{part} . Znormalizowane rozkłady produkcji bozonów $W^\pm$ są zgodne pomiędzy dwoma leptonowymi kanałami rozpadu i zostały one razem połączone. Połączony pomiar jest dobrze opisany przez przewidywania teoretyczne uwzględniające efekt izospinowy oraz wykorzystujące parametryzację CT14NLO funkcji PDF, podczas gdy przewidywania uzyskane przy pomocy jądrowych parametryzacji EPPS16 i nCTEQ15 funkcji nPDF zaniżają zmierzone rozkłady o 10–20%. Zmierzone rozkłady posłużyły także do wyznaczenia asymetrii ładunkowej, która jest dobrze opisywana przez wspomniane przewidywania. Asymetria ładunkowa przyjmuje wartości ujemne dla $|\eta_\ell| > 2$, co jest wynikiem efektu izospinowego. Spodziewane jest skalowanie się produkcji bozonów $W^\pm$ wraz ze średnią wartością funkcji przekrywania $\langle T_{AA} \rangle$ wyznaczoną z modelu Glaubera. Znormalizowana produkcja bozonów $W^\pm$ jest w zgodzie ze skalowaniem z $\langle T_{AA} \rangle$ dla zderzeń centralnych. W zakresie $N_{\text{part}} < 200$ został zaobserwowany systematyczny wzrost znormalizowanej produkcji bozonów $W^\pm$ w stosunku do przewidywań. Efekt jest największy w najbardziej peryferycznym zakresie zderzeń dla bozonów W^- gdzie nadmiar wynosi 1.7 odchylenia standardowego. Porównanie znormalizowanej produkcji dla parametrów geometrycznych wyznaczonych dla wersji v2.4 i v3.2 modelu Glaubera pokazuje, że wyniki modelu v3.2 są bliższe przewidywaniom. Jednakże, różnice pomiędzy dwoma wynikami są mniejsze niż precyzja pomiaru. Wpływ efektu skórki neutronowej został oszacowany z wykorzystaniem osobnych rozkładów radialnych protonów i neutronów dostarczonych przed model Glaubera v3.2. Efekt jest na poziomie -1.4%(1%) dla bozonów W^+ (W^-) w stosunku do przewidywań zakładających jednorodny stosunek protonów do neutronów. Precyzja pomiaru nie jest wystarczająca aby potwierdzić efekty pochodzące od skórki neutronowej.

Abstract

In this thesis measurement of inclusive production of $W^\pm \rightarrow \ell^\pm \nu$ in the electron and muon channels in Pb+Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV is presented. The fiducial production yields are measured in the phase space region defined by the charged lepton transverse momentum $p_T^\ell > 25$ GeV and pseudorapidity $|\eta_\ell| < 2.5$, the transverse momentum of the neutrino $p_T^\nu > 25$ GeV and the transverse mass of the charged lepton–neutrino system $m_T > 40$ GeV. After background subtraction and efficiency correction, the normalised production yields, corrected for background and efficiency, are presented as a function of the absolute pseudorapidity of the charged lepton and the average number of nucleons participating in the collision, the later being a measure of the collision centrality. The normalised production yields for $W^\pm$ bosons are consistent between the two leptonic decay channels which are combined in this analysis. The combined normalised production yields are consistent with theoretical predictions based on the CT14NLO PDF set, while predictions obtained with the EPPS16 and nCTEQ15 nPDF sets underestimate the measured yields by 10–20%. The measured yields for $W^\pm$ bosons are also used to obtain the lepton charge asymmetry, which is well described by the above mentioned theoretical predictions. The lepton charge asymmetry changes sign and becomes negative for $|\eta_\ell| > 2$, which is a result of the isospin effect. It is expected that W production should scale with the average value of nuclear thickness function $\langle T_{\text{AA}} \rangle$ evaluated from the Glauber model. Normalised production yields for $W^\pm$ bosons are in agreement with the expected scaling with $\langle T_{\text{AA}} \rangle$ for central events. In the range $N_{\text{part}} < 200$, a systematic excess of the normalised production yields of $W^\pm$ bosons is observed in the data in comparison to the theory predictions. The effect is largest in the most peripheral bin for W^- bosons where the excess amounts to 1.7 standard deviations. A comparison of normalised production yields for geometric parameters obtained with two versions of the Glauber model v2.4 and v3.2 shows that the Glauber v3.2 results are somewhat closer to the predictions. However, the difference between the two results is smaller than the measurement uncertainties. Impact of the neutron-skin effect evaluated using the separate radial distributions for protons and neutrons provided by the Glauber model v3.2 was found to be at the level -1.4% (1%) for W^+ (W^-) bosons with respect to predictions calculated using a constant proton-to-neutron ratio. Given current measurement precision data are not sensitive enough to confirm the neutron-skin effect.

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0 Author's contribution to the ATLAS experiment

I have been involved in the work for the ATLAS experiment already since my master studies of Technical Physics. At the beginning of my PhD study in 2015 I started a yearly qualification task, which is obligatory for all new members of the ATLAS Collaboration, in order to become co-author of ATLAS publications. The subject of my qualification task was "Development of a trigger menu for heavy-ion collisions and performance studies of b -jet triggers in lead-lead collisions", and in mid of 2016 I became a full member of the ATLAS Collaboration and co-author of all its publications. As a part of the qualification task I was working on trigger menu used in 2015 Pb+Pb data taking, implementation of b -jet triggers and evaluation of performance of muon+jet triggers in the collected data. After qualification period I have continued working on trigger menu and trigger performance in heavy ion data taking periods in 2016, 2017, and 2018 and also taking part in trigger shifts during pp data taking. The main task during the shifts was checking quality of the collected data and analysing events for which the correct decisions was not taken by the ATLAS trigger and acquisition systems. My another contribution to the ATLAS experiment was work on software for production of derivation data sets, which serve as an intermediate data format in the data analysis chain. In total I have spent 5 months at CERN during my PhD studies.

The results presented in this thesis are based on the physics analyses to which I made major contributions. It includes:

- evaluation of MC samples needs (Section 3.2),
- studies of muon momentum issue (Section 4.2.2),
- optimisation of an electron isolation (Section 5.2),
- studies of reconstructed objects performance (Sections 6 and 7),
- evaluation of background contributions (Sections 9 and 10) and efficiency corrections (Section 11),
- studies of systematic uncertainties (Section 12),
- analysis and combination of muon and electron decay channels and calculation of theoretical predictions (Section 13),
- preparation of the internal documentation and paper draft.

Most of the results were presented during international conferences and are published or will be published soon. This thesis is based on the following scientific work:

- ATLAS Collaboration (P. Janus), *Measurement of $W^\pm$ boson production in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector*, work in progress.
- ATLAS Collaboration (P. Janus), *Performance of ATLAS Electron and Photon triggers during LHC Run 2*, work in progress.
- ATLAS Collaboration, M. Aaboud *et al.* (P. Janus), *Measurements of W and Z boson production in pp collisions at $\sqrt{s} = 5.02$ TeV with the ATLAS detector*, Eur. Phys. J. C **79** (2019) 128.

- Zvi Citron *et al.* (P. Janus), *Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams*, arXiv:1812.06772 [hep-ph] (2018).
- ATLAS Collaboration (P. Janus), *Measurement of W boson production in the muon channel in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV*, ATLAS-CONF-2017-067, <http://cdsweb.cern.ch/record/2285571>
- P. Janus (on behalf of the ATLAS Collaboration), *Measurement of W boson production in Pb+Pb collisions at 5.02 TeV with the ATLAS detector*, PoS LHCP2018 (2018) 022.
- P. Janus (on behalf of the ATLAS Collaboration), *Measurement of W and Z Boson Production in 5.02 TeV pp, p+Pb and Pb+Pb Collisions with the ATLAS Detector*, KnE Energ. Phys. 3 (2018) 345-351.
- P. Janus (on behalf of the ATLAS Collaboration), *Measurement of angular correlations in proton-proton and proton-lead collisions with the ATLAS detector at the LHC*, PoS DIS2017 (2018) 162.
- P. Janus (on behalf of the ATLAS Collaboration), *Light-by-light scattering in ultra-peripheral Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector*, Nucl. Part. Phys. Proc. 289-290 (2017) 479-482.
- P. Janus (on behalf of the ATLAS Collaboration), *Measurement of electroweak boson production in pp, p+Pb and Pb+Pb collisions with the ATLAS detector*, IV international conference on particle physics and astrophysics, 22-26.10.2018, Moscow, Russia (talk).
- P. Janus (on behalf of the ATLAS Collaboration), *Measurement of W boson production in Pb+Pb collisions at 5.02 TeV with the ATLAS detector*, The Sixth Annual Large Hadron Collider Physics conference LHCP 2018, 4-9.6.2018, Bologna, Italy (poster).
- P. Janus (on behalf of the ATLAS Collaboration), *Measurement of W and Z boson production in 5 TeV pp, p+Pb and Pb+Pb collisions with the ATLAS detector*, The 3rd International Conference on Particle Physics and Astrophysics, 2-5.10.2017, Moscow, Russia (talk).
- P. Janus (on behalf of the ATLAS Collaboration), *Electroweak boson production in heavy ion collisions with the ATLAS detector*, 4th International Conference on the Initial Stages in High-Energy Nuclear Collisions, 18-22.09.2017, Cracow, Poland (talk).
- P. Janus (on behalf of the ATLAS Collaboration), *Measurement of angular correlations in proton-proton and proton-lead collisions with the ATLAS detector at the LHC*, 25th International Workshop on Deep Inelastic Scattering and Related Topics, 3-7.4.2017, Birmingham, England (talk).
- P. Janus (on behalf of the ATLAS Collaboration), *Light-by-light scattering in ultra-peripheral Pb+Pb collisions at 5.02 TeV with the ATLAS detector*, 8th International Conference on Hard and Electromagnetic Probes of High-energy Nuclear Collisions, 22-27.9.2016, Wuhan, China (poster, flash talk).

1 Introduction

1.1 Standard Model of particle physics

The research in the field of high-energy physics concentrates on the most fundamental blocks of matter and laws that govern their interactions. The current understanding of the field was first formulated in 1970s and is called the Standard Model (SM) of particle physics. The SM provides a unified description in which forces between particles are governed by the exchange of particles. According to this model there are two groups of particles: fermions and bosons. Fermions are half-integer spin particles which obey Fermi-Dirac statistics [1] and thus they obey Pauli exclusion principle [2]. On the other hand, bosons are integer spin particles that follow the Bose-Einstein statistics [3, 4]. Within the SM, bosons are particles carrying forces while all the surrounding us matter is composed of fermions.

Further, fermions are classified as leptons and quarks according to fundamental interactions in which they can participate. There are six leptons which are grouped in three generations ordered according to their masses as shown in Table 1. Neutrinos do not carry electrical charge and their masses are below current experimental precision, while other leptons have integer charge and sizeable masses. Quarks follow similar pattern, namely there are six particles paired in three generations with increasing masses also shown in Table 1. Within each generation, one of the quarks has charge $+2/3$ and other $-1/3$. Despite the electric charge, the quarks carry quantum number called colour charge and each quark has one of three colours, denoted red, green and blue. Moreover, each lepton and quark has an associated antiparticle with the same mass but with opposite electric charge.

The electroweak theory (EW), included in the SM, describes the electromagnetic and weak forces. Photons, which are massless and chargeless spin one particles, mediate the electromagnetic interaction between electrically charged particles. The weak interaction is mediated by massive vector bosons W^+ , W^- and neutral Z . All the fermions can interact weakly but the strength of the weak force is $\sim 10^4$ times smaller comparing to the electromagnetic force. The

Leptons			Quarks		
	Mass [GeV]	Electric charge [e]		Mass [GeV]	Electric charge [e]
First Generation					
ν_e	$< 10^{-8}$	0	u	0.00216	$2/3$
e	0.000511	-1	d	0.00467	$-1/3$
Second Generation					
ν_μ	< 0.0002	0	c	1.27	$2/3$
μ	0.106	-1	s	0.093	$-1/3$
Third Generation					
ν_τ	< 0.02	0	t	173	$2/3$
τ	1.78	-1	b	4.18	$-1/3$

Table 1: Masses, and electric charges expressed as a fraction of an electron absolute electric charge of the SM fermions [5].

weak interaction is the only interaction capable of changing the flavour of quark. Last force which enters to the SM is strong force responsible for the interactions between colour charged particles and it is described by theory of Quantum Chromodynamics (QCD). This interaction is mediated by spin one gluons which carry colour and anti-colour charge. Gluons interact with each other what confines quarks in hadrons.

The generation of mass of the elementary particles is explained by the SM Brout-Englert-Higgs (BEH) mechanism [6, 7]. As an effect of interactions with the Higgs field the weak bosons and the fermions acquire their masses, which exact values depend on the strength of their couplings to the Higgs field. The Higgs boson is the quantum excitation of the Higgs field. The BEH mechanism was experimentally confirmed after the discovery of the Higgs boson by ATLAS [8] and CMS [9] Collaborations in 2012.

Quantum electrodynamics

One of the first formulated quantum field theory (QFT) was Quantum Electrodynamics (QED) which describes interactions between electrically charged fermions and photons. According to QFT the motion of free half-integer spin particle with mass m is described by the Dirac equation [10]:

$$(i\gamma^\mu \partial_\mu - m)\psi = 0, \quad (1)$$

and the corresponding Lagrangian is:

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi, \quad (2)$$

where ψ is the four-component spinor describing the fermion, γ^μ denotes the four-dimensional gamma matrices, and Einstein's sum convention is used for repeating indices. The gauge transformation is a transformation which changes the field configuration to another one but does not change the observable quantities. Since the QED is a gauge theory the Lagrangian should be invariant under the gauge transformation of the field $\psi \rightarrow e^{iq\alpha}\psi$. The invariance can be satisfied by replacing the derivative ∂_μ with a covariant derivative $\mathcal{D}_\mu = \partial_\mu - iqA_\mu$, where the new vector field A_μ couples to fermions with a coupling strength q . The requirement for the Lagrangian to be invariant under given transformation leads to additional term for the gauge field of the form $F_{\mu\nu}F^{\mu\nu}$, with $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$. The free field can be interpreted as the photon field, which must be massless, as otherwise local gauge invariance would not hold. Finally, the QED Lagrangian is given by:

$$\mathcal{L}_{QED} = \bar{\psi}(i\gamma^\mu \mathcal{D}_\mu - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}. \quad (3)$$

In the $\mathcal{L}_{QED}$ three components can be identified which corresponds to free Lagrangian of the Dirac field, the free Lagrangian of the massless photon field and an interaction term between the photon and the Dirac field.

Quantum chromodynamics

The QCD is a theory of interactions between quarks and gluons described by a non-Abelian $SU(3)$ colour symmetry. The conserved quantum number related to this symmetry group is the colour charge. The gluons mediate the strong interaction in which they couple to the colour charges, defined as red, green, and blue. The quark wave function is given by three vector:

$$\psi = \begin{pmatrix} \psi_1 \\ \psi_2 \\ \psi_3 \end{pmatrix}, \quad (4)$$

where ψ_i is Dirac spinor for a quark of colour i . Gluons carry a superposition of both the colour and the anti-colour charge, leading to eight different states. Following the analogy to QED, a local gauge invariance can be achieved by replacing ∂_μ with a covariant derivative $\mathcal{D}_\mu = \partial_\mu - ig_s G_\mu^a \lambda_a$, where λ_a are eight generators of $SU(3)$ that satisfy general commutation relation $[\lambda_a, \lambda_b] = if_{abc}\lambda_c$, and g_s is the coupling strength of the gluon field. The QCD Lagrangian is given by:

$$\mathcal{L}_{QCD} = \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi - \frac{1}{4}G_{\mu\nu}^k G_k^{\mu\nu} - \frac{g_s}{2}\bar{\psi}\gamma^\mu \lambda_k G_\mu^k \psi, \quad (5)$$

where the second term describes a free gluon Lagrangian and the third term is responsible for quark–gluon interaction. This Lagrangian is invariant under the non-Abelian $SU(3)$ transformations. The gluon fields can be expressed in terms of field strength tensor [11]:

$$G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a - g_s f_{abc} G_\mu^b G_\nu^c, \quad (6)$$

where f_{abc} are the $SU(3)$ structure constants that form a totally antisymmetric tensor. Unlike to QED the field tensor of the QCD includes the gluon triplet and quartic self-interactions what leads to the property of asymptotic freedom. It means that the coupling of quarks and gluons is large at large distances therefore they are not observed as free particles.

Electroweak interactions

The electroweak theory unifies the electromagnetic and weak interactions and it is derived from the combination of $SU(2) \times U(1)$ symmetries [12–14]. Following the procedures applied in the QED and QCD it is required that the Lagrangians of the left-handed L and right-handed R fermions are invariant under global and local transformation of the gauge group. A local gauge invariance can be achieved by replacing ∂_μ with a covariant derivative $\mathcal{D}_\mu = \partial_\mu - ig\frac{\tau_a}{2}W_\mu^a + i\frac{g'Y}{2}B_\mu$, where W_μ^a are the gauge bosons of $SU(2)$ group and B_μ is the gauge boson of $U(1)$ group. The generators of these groups are presented by the Pauli matrices τ_a and the hypercharge Y .

The electroweak Lagrangian can be written as:

$$\mathcal{L}_{EW} = -\frac{1}{4}W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \bar{\psi}_L\gamma^\mu(i\partial_\mu - \frac{1}{2}g\tau W_\mu - g'\frac{Y}{2}B_\mu)\psi_L + \bar{\psi}_R\gamma^\mu(i\partial_\mu - g'\frac{Y}{2}B_\mu)\psi_R, \quad (7)$$

where first two terms contain kinetic energy and the self coupling of the W_μ fields and the kinetic energy of the B_μ field. Later terms correspond to the fermion kinetic energy and fermions interactions with fields W_μ and B_μ . Similarly as in QCD the weak bosons can self-interact. The field strength tensors have the form:

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu, \quad (8)$$

$$W_{\mu\nu}^i = \partial_\mu W_\nu^i - \partial_\nu W_\mu^i - g\epsilon_{ijk}W_\mu^jW_\nu^k. \quad (9)$$

1.2 Proton structure

A proton is a composite object which structure depends on the probing energy scale Q . It behaves like a point-like particle without any substructure at energies $Q \ll 1$ GeV. Especially, the proton electric charge and its quantum numbers [15] are defined by the three valence quarks: two up quarks and one down quark. This idea of valence quark was firstly postulated, and later experimentally confirmed what gave a rise to the parton model [16] which explains the proton structure at high energies.

The valence quarks are bounded with gluons which additionally can split into quark-antiquark ($q\bar{q}$) pairs producing so-called sea quarks. At high energies these additional contributions from the sea quarks and the gluons needs to be taken into account. In that picture the proton structure is understood in terms of the fractional momentum distributions of the constituent partons. The Parton Distribution Functions (PDFs) give probability distributions of the fraction of the momentum carried by a given parton. The PDFs depend on Q^2 and at low energies the momentum of the proton is carried to a good approximation by the three valence quarks. With an increase of energy the proton momentum is also distributed over gluons and sea quarks.

1.3 Hadronic cross section and W boson production

The factorization theorem enables the derivation of cross sections for hard processes in hadronic collisions by separating a process dependent partonic cross section calculable in perturbative QCD (pQCD) from a part corresponding to the distribution of partons given by PDFs, what is schematically shown in Figure 1. The factorization theorem was firstly proposed by Drell and Yan [17]. It postulates that the cross section for the process $\sigma_{AB \rightarrow X}$ can be determined from the convolution of the PDFs of the hadrons, $f_{a/A}(x_a, \mu_F)$ for hadron A and $f_{b/B}(x_b, \mu_F)$ for hadron

B, and the cross section of the interacting partons a and b , $\sigma_{ab \rightarrow X}$:

$$\sigma_{AB \rightarrow X} = \sum_p \int \int dx_a dx_b f_{a/A}(x_a, \mu_F) f_{b/B}(x_b, \mu_F) \sigma_{ab \rightarrow X}, \quad (10)$$

where x_a and x_b are the momentum fractions of hadrons A and B carried by partons a and b , respectively, and μ_F is a factorization scale. The μ_F scale separates regimes where perturbative and non-perturbative calculations apply. The hard-scattering process which is represented by $\sigma_{ab \rightarrow X}$ may be expressed as a power series expansion in the coupling α_s . Higher-order terms of the strong coupling correspond to contributions from higher order emissions. Thus it can be written as series of terms proportional to subsequent powers of the strong coupling constant:

$$\sigma_{ab \rightarrow X} = [\sigma_0 + \alpha_s(\mu_R^2)\sigma_1 + \dots]_{ab \rightarrow X}, \quad (11)$$

where μ_R is the renormalization scale.

In general the choice of μ_R and μ_F does not have impact on the cross section calculated to all orders of perturbative expansion. It happens due to the compensation of the scale dependence of the PDFs and of the coupling constant. In practise, the processes of lepton pair production through mechanism of $q\bar{q}$ annihilation are only known to the certain order giving a rise to a theoretical uncertainty from higher order contributions. In the given case it is necessary to make a choice of μ_R and μ_F values and the standard choices are $\mu_R = \mu_F = M_Z$ or M_W , where $M_{Z,W}$ are masses of Z or W bosons, respectively.

Based on the factorization theorem one can calculate the W boson production cross-section in nucleon-nucleon collisions within QCD by convolution of PDFs with the partonic cross sections.

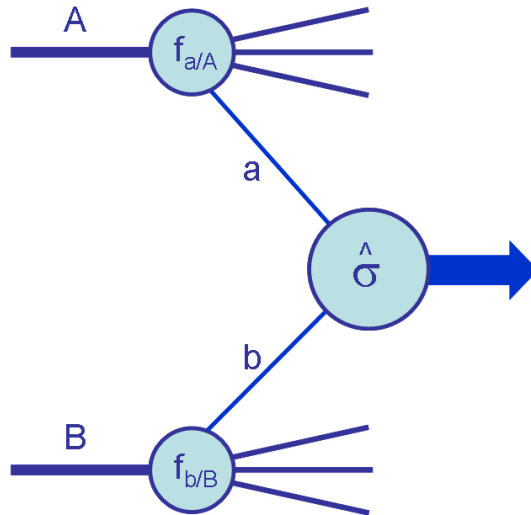


Figure 1: Schematic diagram for particle production in hadronic collisions. PDFs of hadrons A and B are represented by $f_{a/A(b/B)}$ and $\hat{\sigma}$ represents the cross section for the hard-scattering process [18].

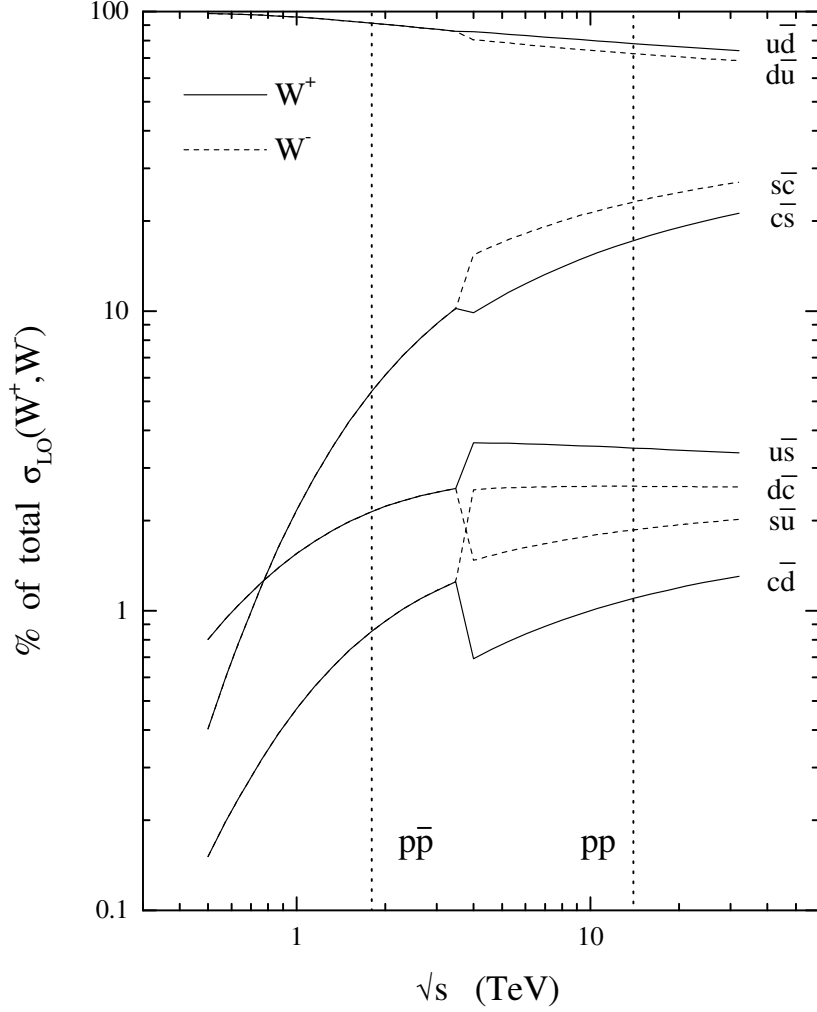


Figure 2: Parton decomposition of the W^+ (solid line) and W^- (dashed line) total cross sections in pp and $p\bar{p}$ collisions as a function of the centre-of-mass energy. Individual contributions are shown as a percentage of the total cross section [19].

In proton-proton (pp) collisions, W bosons at leading order (LO) are produced in the Drell-Yan (DY) process of $q\bar{q}$ annihilation. Charge conservation requires $u\bar{d}$ and $d\bar{u}$ interaction in order to produce W^+ and W^- , respectively. Since protons consist of two u and one d valence quark in pp collisions at the LHC, the total number of produced W^+ bosons is larger than W^- bosons. However, note that this is not the case for neutron-neutron interactions as neutrons consist of two d and one u valence quark. The parton decomposition for W boson production total cross sections is shown in Figure 2. It can be noticed that second largest contribution to the production comes from c and s sea quarks which give more than 10% at the LHC energies.

The high mass of the W boson is reflected in its short mean life time. Therefore, in practise only the decay products of W can be measured. The W boson decay modes are shown in Table 2. The decays are almost equally distributed over different lepton channels and their contribution to the total cross section is roughly 11% per mode. The hadronic decays are challenging to be measured in pp or Pb+Pb collisions due to high background coming from processes with di-jets

Decay mode	Branching ratio [%]
$W \rightarrow e\nu$	10.71 ± 0.16
$W \rightarrow \mu\nu$	10.63 ± 0.15
$W \rightarrow \tau\nu$	11.38 ± 0.21
$W \rightarrow \text{hadrons}$	67.41 ± 0.27

Table 2: The W boson decay modes [20].

in the final state. Subject of this thesis are W decays with a muon or electron in the final state. In particular events with high- p_T muon or electron are relatively rare therefore leptonic decay channels provide a clean signature. The $W \rightarrow \tau\nu$ decay is also not used for measurement since there are two neutrinos in the final states (one from W decay and one from τ decay) what is challenging to reconstruct in heavy-ion environment.

1.4 Parton Distribution Functions

As it was stated in previous section PDFs provide probability densities of finding in the proton a parton carrying a fraction x of the proton momentum. They also depend on energy scale Q^2 . The evolution of these function with Q^2 starting from Q_0^2 is well know and described by the DGLAP (Dokshitzer, Gribov, Lipatov, Altarelli and Parisi) evolution equations [21–23]. The evolution is given by a system of integro-differential equations and describes the dependence of the PDFs as a function of Q :

$$Q^2 \frac{d}{dQ^2} \begin{pmatrix} f_i(x, Q^2) \\ f_g(x, Q^2) \end{pmatrix} = \sum_j \frac{\alpha_s}{\pi} \int_x^1 \frac{d\xi}{\xi} \begin{pmatrix} P_{q_i q_j}(\frac{x}{\xi}) & P_{q_i g}(\frac{x}{\xi}) \\ P_{g q_j}(\frac{x}{\xi}) & P_{g g}(\frac{x}{\xi}) \end{pmatrix} \begin{pmatrix} f_j(\xi, Q^2) \\ f_g(\xi, Q^2) \end{pmatrix}, \quad (12)$$

where $P(\frac{x}{\xi})$ are the splitting functions which describe the transition probability of the parton a into a parton b by emitting a quark or gluon. The DGLAP evolution is applicable in perturbative regime and when all terms involving powers of $\log(1/x)$ are negligible.

It is important to note that the x dependence is not calculable analytically. However, it can be fitted to experimental data. Figure 3 shows the $Q^2 - x$ map probed by the various experiments. Also the contribution of W boson production at LHC energies is also marked.

1.5 Nuclear modifications to Parton Distribution Functions

The PDFs introduced in the previous sections apply to free nucleons. However, the European Muon Collaboration discovered that the momentum distributions of quarks and gluons in nucleons confined in heavy ions were different from those in free nucleons [26]. It means that atomic nuclei are not a simple superposition of the free nucleons. The experimental data can be described after adding nuclear modifications to the pre-existing PDFs (nPDFs). The evolution of nPDFs is also given by the DGLAP equations. However, the factorization theorem was not rigorously proven in nuclei collisions and it is assumed to hold. The nuclear modifications are typically categorized into four distinct regions [27]:

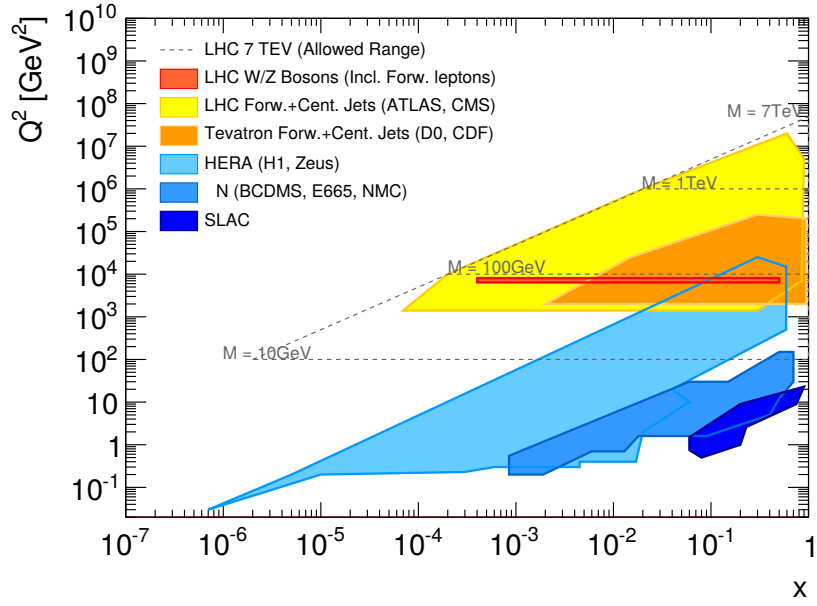


Figure 3: Illustration of kinematic plane probed by Drell-Yan processes at the Tevatron and the LHC and the deep inelastic scattering experiments [24].

- **Shadowing:** it is dominating at low x ($x \lesssim 0.1$) and results in suppression of nPDFs with respect to PDFs. It arises from the multiple interactions between the scattered partons and also the ones from the different nucleons.
- **Anti-shadowing:** this effect results in the enhancement visible in the region $0.1 \lesssim x \lesssim 0.2$. It is usually understood as a restoration of the momentum sum rule which compensates for degradation caused by the shadowing and EMC effect.

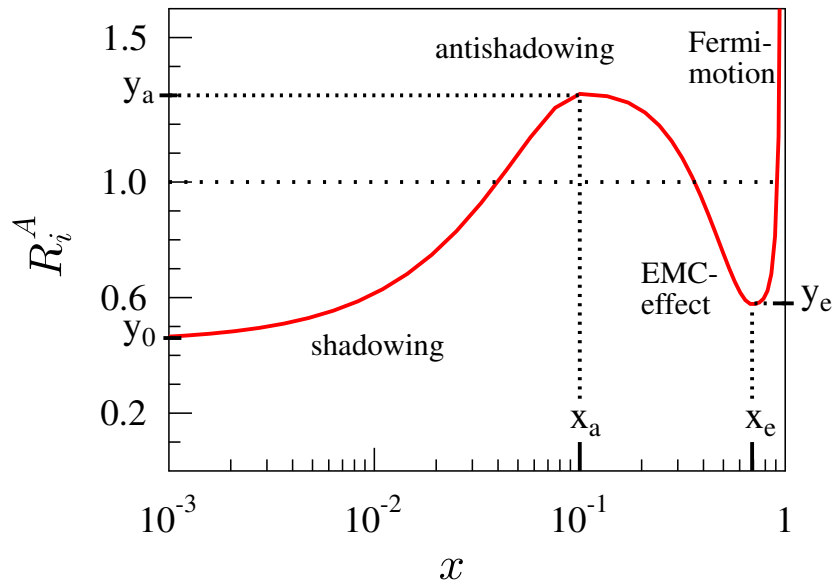


Figure 4: Illustration of the different nuclear effects to the free nucleon PDFs [25].

- **EMC effect:** it is suppression observed at moderate x ($0.2 \lesssim x \lesssim 0.7$). The effect is not well understood and it might arise from the short range correlations between nucleons.
- **Fermi motion effect:** the dominant effect at $x \lesssim 0.7$ comes the Fermi motion of the nucleons inside the nucleus.

Different regions of nuclear modifications observed experimentally are shown in Figure 4. Note that there is no unique theoretical description of the nuclear effects.

The nPDFs are defined for confined protons in the nucleus therefore the nPDFs for confined neutrons are evaluated using isospin symmetry (the up quarks PDFs are exchanged with down quark PDFs). The nPDFs for a whole nucleus made of Z protons and $A - Z$ neutrons can be expressed by a superposition of the confined protons nPDFs ($f_i^{p/A}$) and the confined neutrons nPDFs ($f_i^{n/A}$):

$$f_i^A = \frac{Z}{A} f_i^{p/A} + \frac{A - Z}{A} f_i^{n/A}, \quad (13)$$

where i designates the parton flavour.

At the leading order the W bosons are produced from a $q\bar{q}$ annihilation what makes them an excellent tool for probing PDFs. The subject of this thesis is W boson production in Pb+Pb collisions therefore it should provide means to study nuclear modifications.

1.6 The phase transition

As it was stated in the previous sections quarks and gluons exist only in the confined state for the commonly known hadronic matter. However, it is possible to form a deconfined state in the regime of high-energy density and temperature [29]. The limiting temperature (usually called critical temperature) is understood as a transition from the hadronic matter to a new state where quarks and gluons are the degrees of freedom. The order of the phase transition from hadronic matter to a quark-gluon plasma (QGP) is still under discussions. It is convenient to present QCD

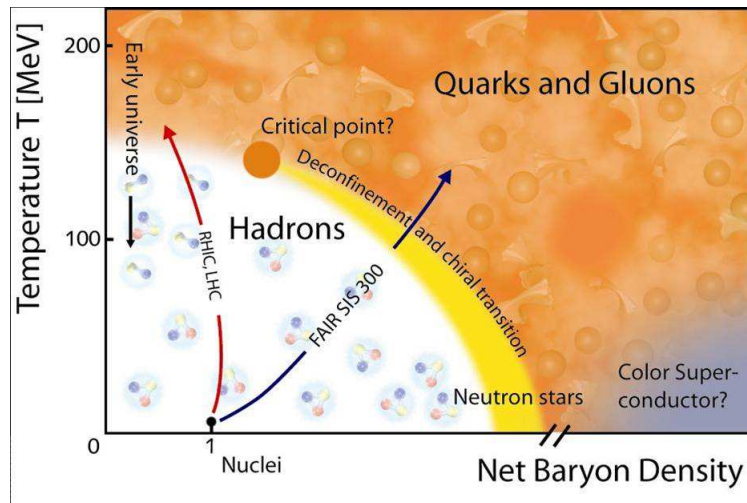


Figure 5: A schematic phase diagram of QCD matter in the plane of temperature and the net baryon density [28].

phase diagram as a function of the temperature and net baryon density n_b (difference of baryons and antibaryons densities), as shown in Figure 5. Matter is presented as a gas of hadrons at low temperatures and low n_b . As temperature increases, for a given n_b , the phase transition occurs when reaching critical temperature (T_c). Calculations within a lattice QCD predict a smooth crossover at zero chemical potential around $T_c = 155$ MeV [30]. On the other side, at high n_b a colour superconducting state is expected to form [31]. The only possible way of probing QCD phase diagram in the laboratory is through ultra-relativistic heavy-ion collisions. The high n_b conditions might be possibly found in the core of neutron stars.

1.7 Nucleus-Nucleus Collisions

Nuclei are composed objects made of protons and neutrons, therefore the number of nucleon-nucleon (NN) interactions is higher for more central collisions and lower for less central collisions. Participants are the nucleons which participate in the collision, while spectators are those which do not participate in the collision. The size of the interaction region may affect the final state observables, therefore it is required to control the collision geometry. An impact parameter $\vec{b}$ is the transverse distance between the centres of the two colliding nuclei as shown in Figure 6. The features of the collision geometry like the impact parameter $\vec{b}$ and number of participants (N_{part}) are not measurable. However, they may be modelled with the Glauber model [32, 33], which assumes nucleus-nucleus collisions as the superposition of independent NN interactions.

The Glauber model can be implemented with two approaches. The first one is an optical approach, which assumes a continuous nucleon density distribution. The limitation of this approach is that the correlations between nucleon positions are not taken into account. Also, event-by-event fluctuations are neglected, e.g. N_{part} is fixed for a given $\vec{b}$. The later approach makes use of Monte Carlo (MC) methods. In the Glauber MC nucleons are located according to their nuclear density. The created nuclei centres are shifted by random impact parameter $\vec{b}$ and then

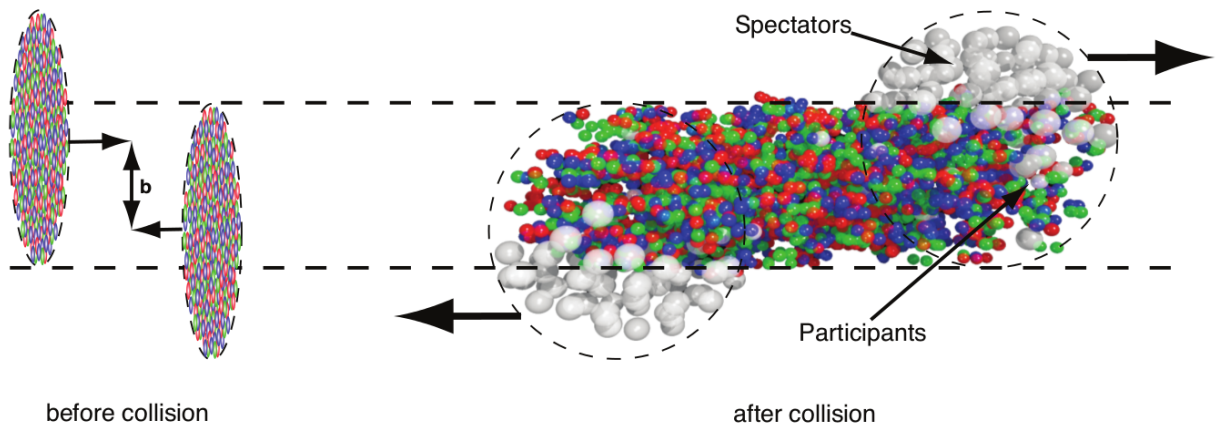


Figure 6: Illustration of two nucleus with impact parameter $\vec{b}$ before (left) and after (right) collision. The spectators are unaffected, while in the interaction region particle production takes places [34].

the nucleus-nucleus collision is modelled by performing independent inelastic NN collisions. The total number of binary NN collisions is denoted by N_{coll} .

The geometry of nucleus-nucleus collision can be determined knowing the inelastic nucleon-nucleon cross-section σ_{NN} and the nuclear density distribution of a given nucleus $\rho(r)$. In general, the density is parametrised using Woods-Saxon distribution:

$$\rho(r) = \rho_0 \frac{1 + w(r/R)}{1 + \exp(\frac{r-R}{a})}, \quad (14)$$

where ρ_0 corresponds to the nucleon density in the centre of the nucleus, R corresponds to the nuclear radius, a to the "skin depth" and w characterizes deviations from a spherical shape.

The Glauber formalism can be described with help of σ_{NN} and $\rho(r)$, as follows. Consider Figure 7, where two nuclei are shown colliding at relativistic speeds with impact parameter $\vec{b}$. The probability per unit transverse area of a given nucleon being located at transverse position $\vec{s}$ is:

$$T_A(\vec{s}) = \int \rho(\vec{s}, z) dz. \quad (15)$$

The nuclear thickness function for nuclei A (with A nucleons) and B (with B nucleons) separated by an impact parameter $\vec{b}$, can be defined as:

$$T_{AB}(\vec{b}) = \int T_A(\vec{s}) T_B(\vec{s} - \vec{b}) d\vec{s}. \quad (16)$$

It can be interpreted as the effective overlap area for which a specific nucleon in A can interact

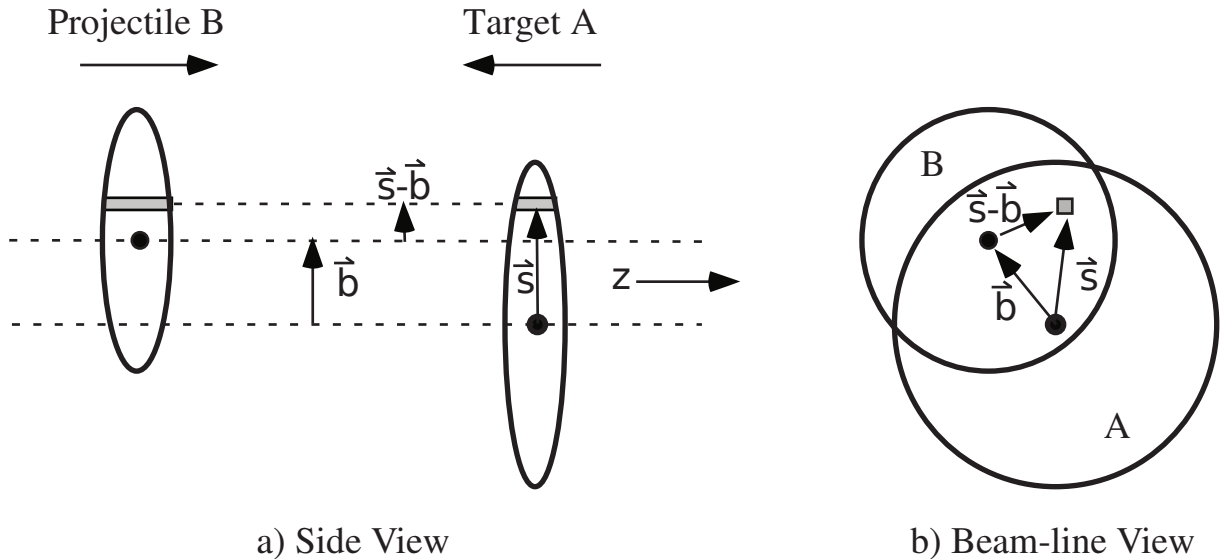


Figure 7: Schematic representation of the Optical Glauber Model geometry, with transverse (a) and longitudinal (b) views [33].

with a nucleon in B. Given a σ_{NN} the N_{coll} can be calculated as:

$$N_{\text{coll}}(\vec{b}) = T_{AB}(\vec{b})\sigma_{NN}. \quad (17)$$

Given $T_{AB}(\vec{b})$ the probability for n inelastic NN collisions at impact parameter $\vec{b}$ out of AB possible collisions is a binomial distribution:

$$P(n, \vec{b}) = \binom{AB}{n} (T_{AB}(\vec{b})\sigma_{NN})^n (1 - T_{AB}(\vec{b})\sigma_{NN})^{AB-n}. \quad (18)$$

Integrating $P(n, \vec{b})$ over the $\vec{b}$ gives the total inelastic cross section for a heavy-ion collision:

$$\sigma_{AB} = \int (1 - (1 - T_{AB}(\vec{b})\sigma_{NN})^{AB}) d\vec{b}. \quad (19)$$

Then the N_{part} at impact parameter $\vec{b}$ is given by:

$$N_{\text{part}} = A \int T_A(\vec{s}) \left(1 - (1 - T_B(\vec{s} - \vec{b})\sigma_{NN})^B\right) d^2s + \\ B \int T_B(\vec{s} - \vec{b}) \left(1 - (1 - T_A(\vec{s})\sigma_{NN})^A\right) d^2s. \quad (20)$$

In the optical approach to the Glauber model defined above integrals are evaluated analytically or numerically.

Mean values of N_{part} , N_{coll} and T_{AB} can be extracted via mapping for classes of measured events. In the ATLAS experiment a measured distribution of sum of the transverse energy col-

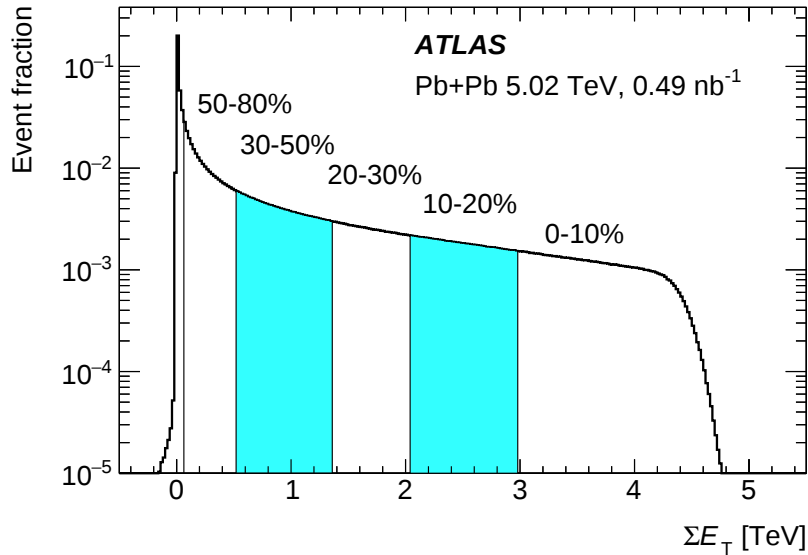


Figure 8: Measured $\sum E_T$ distribution in the ATLAS forward calorimeters in minimum-bias Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The shaded and unshaded regions denote the 0–10%, 10–20%, 20–30%, 30–50%, and 50–80% centrality classes. [35].

lected in the forward calorimeters is mapped to the corresponding distribution obtained from Glauber model calculations. To do that one needs to define centrality classes in the measured and calculated distributions and then connect the mean values in the same centrality classes in both distributions. The assumption is that impact parameter $\vec{b}$ is monotonically changing with the sum of the transverse energy collected in the forward calorimeters. Once the transverse energy is measured and the total integral of the distribution is known, centrality classes are defined by binning the distribution based upon the fraction of the total integral. Figure 8 shows measured $\sum E_T$ distribution in the ATLAS forward calorimeters in minimum-bias Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with marked several centrality classes. For example, 0-10% centrality range correspond to the 10% of events with the highest values of N_{part} , or with the lowest value of the impact parameter.

The production of W bosons is expected not to be affected by the later stages of the collision therefore it carries information about the collision geometry. The product of nuclear thickness function T_{AB} and number of inelastic events N_{evt} can be thought of as an integrated luminosity¹ for events of given centrality classes. Especially, W bosons production yields measured as a function of centrality provides a test of the Glauber model as they should scale with $T_{AB} \cdot N_{\text{evt}}$.

In this analysis the colliding nuclei are the same, therefore $A = B$. It is convenient to define an observable which compares the yield of particles in a given centrality of nucleus-nucleus collision to the yield observed in pp collision, scaled by $\langle T_{AA} \rangle$ in that centrality bin:

$$R_{AA} = \frac{(N_X/N_{\text{evt}})}{\langle T_{AA} \rangle \cdot \sigma_X^{pp}}, \quad (21)$$

where R_{AA} is called the nuclear modification factor, N_X is the number of observed events of process X in nucleus-nucleus collisions, N_{evt} is the total number of observed inelastic events, $\langle T_{AA} \rangle$ is the mean of the nuclear thickness function and σ_X^{pp} is the cross section for the process X in pp collisions. In general, R_{AA} below unity is referred to as a suppression of a given process, while R_{AA} above unity is referred to as an enhancement of a given process.

¹The luminosity definition is given in Section 2.1.2.

2 The ATLAS experiment at the LHC

This chapter reviews the basic parameters of the LHC and presents the ATLAS detector, including a summary of the geometry and technologies used in its main subdetectors.

2.1 The Large Hadron Collider

The Large Hadron Collider (LHC) [36] is the largest hadronic accelerator ever built. It is located at the European Laboratory for Particle Physics (CERN) on the French-Swiss border close to Geneva, Switzerland. The accelerator is placed at a depth of 50 – 175 m under ground with a circumference of about 27 km and provides two counter-rotating beams of protons or heavy-ions, colliding at four points. The LHC was designed to achieve centre-of-mass energies of 14 TeV and 5.5 TeV per nucleon pair for protons and heavy ions, respectively.

At four interaction points (IP) of the colliding beams the main detectors are located: ATLAS (A Toroidal LHC Apparatus) [37], CMS (Compact Muon Solenoid) [38], ALICE (A Large Ion Collider Experiment) [39] and LHCb (Large Hadron Collider Beauty) [40]. First two of them, the ATLAS and the CMS, are general purpose detectors intended to allow for high precision measurements of QCD, electroweak interactions, and flavour physics at high luminosity in both pp and Pb+Pb collisions. Especially, the both experiments are able to cross-check their results and validate their discoveries. The ALICE is a detector specialised in heavy-ion physics which studies the physics of strongly interacting matter and the quark-gluon plasma. The LHCb is dedicated to measurements of CP violation and rare hadronic B decays. Its geometry covers only forward region where the probability to observe B meson decay is maximal.

The magnet system uses superconducting NbTi coils cooled to 1.9 K in order for the dipole to generate a maximum magnetic field of 8 T. Approximately 96 tonnes of liquid helium keep the magnets at their operating temperature, making the LHC the largest cryogenic facility in the world at liquid helium temperature. The LHC dipoles are constructed with novel two-in-one design where the two magnetic coils share a common cryostat. The resulting design is economical and compact, allowing the accelerator to fit in the existing tunnel. The machine is comprised of 9593 magnets, of which 1232 are main dipoles for bending the beam, and the remaining, including 392 quadrupoles and other superconducting and non-superconducting magnets, perform tasks such as beam corrections and focusing. To protect the superconducting magnets from the spray particles, there are two dedicated cleaning sections in the ring, where the absorbers remove protons significantly deviated from the reference orbit before they reach the sections with magnets.

2.1.1 The LHC Lead Injection Chain

Heavy-ion collisions were included in the conceptual design of the LHC from an early stage. Since the LHC is operating below the designed energy the maximum magnetic field of the dipole magnets allow for a beam energy of 2.51 TeV/nucleon yielding a total centre-of-mass energy of 1.04 PeV.

$$\frac{dN}{dt} = \mathcal{L}\sigma, \quad (22)$$

where $\mathcal{L}$ represents the instantaneous luminosity. The instantaneous luminosity is process independent quantity, which is entirely determined by the beam parameters:

$$\mathcal{L} = \frac{f_{\text{rev}} n_b N_{b1} N_{b2}}{2\pi\sigma_x\sigma_y} F(\phi, \sigma_x, \sigma_y, \sigma_s), \quad (23)$$

where f_{rev} denotes the revolution frequency of the accelerated ions, n_b is the number of bunches per beam, N_{b1} and N_{b2} are number of particles in the colliding bunches, σ_x and σ_y are the transverse RMS beam sizes at the IP and $2\pi\sigma_x\sigma_y$ represents the effective transverse area in which collisions take place assuming the particles in each beam are Gaussian distributed. The F is the geometrical reduction factor that depends on the crossing angle ϕ between two beams, transverse beam sizes, σ_x and σ_y , and the bunch length σ_s . The integrated luminosity is derived by integrating the instantaneous luminosity over a given period of time.

In 2015, the LHC programme dedicated to heavy-ion physics took place during four weeks between November and December. The first week was dedicated to pp collisions at $\sqrt{s} = 5.02$ TeV to collect a reference sample for the Pb+Pb collision data. Then, the LHC beam settings were modified to collide two beams of Pb ions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The Pb beam lifetime was shorter than for protons because of the loss of the Pb beams intensity. The losses are due to the large ultraperipheral electromagnetic interactions between Pb ions. The integrated luminosity as a function of time for the Pb+Pb and pp collisions is shown in Figure 10. In total, integrated luminosity of collected data was 0.49 nb^{-1} and 25 pb^{-1} for Pb+Pb and pp collisions, respectively.

2.2 The ATLAS detector

The ATLAS [37] detector at the LHC was designed and built for general physics studies in high energy proton-proton collisions. It included confirmation or exclusion of existence of the

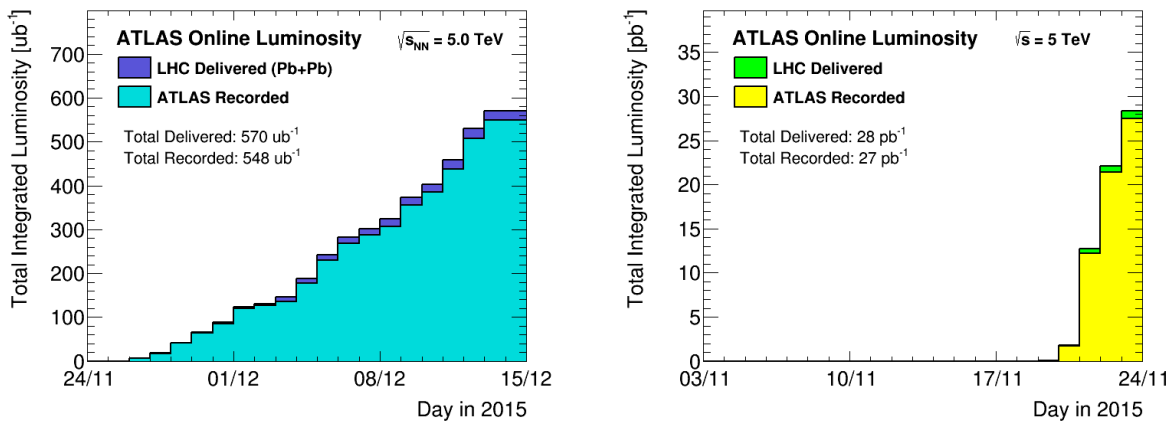


Figure 10: Total integrated luminosity as a function of time delivered by the LHC and recorded by ATLAS during Pb+Pb (left) and pp (right) data taking in 2015 at centre-of-mass energy of 5.02 TeV per nucleon pair.

Higgs boson, searches for new physics signatures at the TeV energy scale such as new heavy-gauge bosons or supersymmetric particles. Achievement of these goals is guaranteed by good performance of measurement high- p_T objects including electrons, photons, jets and muons. The detector is also able to estimate missing transverse momentum and to identify primary and secondary vertices.

The ATLAS detector consists of different types of sub-detectors ordered concentrically in layers around the beam axis with forward-backward symmetric cylindrical geometry and almost full coverage in the solid angle around the IP. The schematic view of the ATLAS detector is shown in Figure 11. The innermost system is the inner detector (ID) which measures the trajectory and momentum of charged particles in a 2 T magnetic field produced by a surrounding solenoid magnet. The next system is the electromagnetic and hadronic calorimeter for detection of electrons, photons and hadrons and measurement of their energy via electromagnetic or hadronic showers. The outer layer is the muon spectrometer (MS) for high-precision tracking of muons. The muon system is submerged into magnetic field created with the air-core toroid system which consists of barrel and two endcap magnets.

2.2.1 Coordinate system and kinematic variables

The nominal interaction point within the ATLAS detector determines the origin of the coordinate system, while the beam direction defines the z -axis and $x - y$ plane is transverse to the beam direction. The positive x -axis points from the interaction point to the centre of the

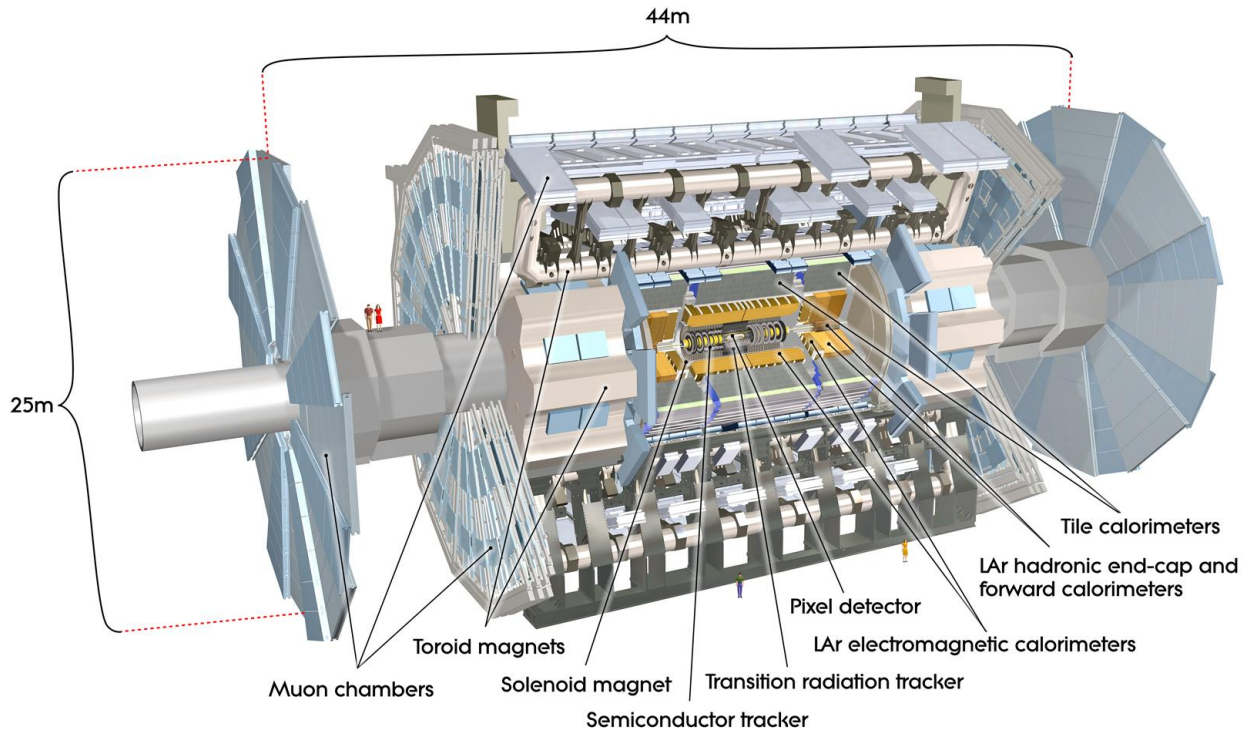


Figure 11: Cut-away view of the ATLAS detector. The dimensions of the detector are 25 m in height and 44 m in length. The overall weight of the detector is approximately 7000 tonnes [37].

LHC ring and the positive y -axis points upwards such that coordinate system is right-handed. The detector is split into two sides where side-A is defined as that with positive z and side-C is that with negative z . The symmetry of the detector makes cylindrical coordinates useful. The azimuthal angle ϕ is measured in the $x - y$ plane around the beam axis, and the polar angle θ corresponds to the angle from the beam axis. The pseudorapidity is defined as:

$$\eta = -\ln[\tan(\theta/2)]. \quad (24)$$

For massless particles, it is identical to the rapidity:

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right). \quad (25)$$

In the limit where the particle is travelling close to the speed of light (highly relativistic particles), or equivalently in the approximation that the mass of the particle is negligible, pseudo-rapidity converges to the definition of rapidity. An important feature of rapidity is that differences in y are invariant under Lorentz boosts along the z -axis. The distance ΔR in the $\eta - \phi$ space is defined as:

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}. \quad (26)$$

Two more parameters for the reconstructed tracks of the charged particles should be defined: the longitudinal impact parameter z_0 which is the z position of the track at the point of closest approach and the transverse impact parameter d_0 defined as the distance in the transverse plane of the closest approach (perigee) to the z -axis of the helix produced by the particle.

Finally, it may be noted that the transverse momentum p_T , the transverse energy E_T and the missing transverse momentum p_T^{miss} are components defined in the $x - y$ plane.

2.2.2 Inner Detector

Thousands of particles are produced in the most central Pb+Pb collisions creating a very large tracks density in the detector. To achieve the momentum and vertex resolution requirements imposed by the benchmark physics processes, high-precision measurements must be made with fine granularity detector. In order to meet these requirements, the ID consists of three specialized sub-detectors, from inside out the Pixel Detector, the Semiconductor Tracker (SCT), and the Transition Radiation Tracker (TRT), as shown in Figure 12.

ID is divided into the barrel part ($|z| < 80$ cm) and two endcaps covering the pseudorapidity range $|\eta| < 2.5$. It is immersed in a 2 T axial magnetic field generated by the central solenoid (not shown in Figure 12), which extends a length of 5.3 m and a diameter of 2.5 m. The active tracking detector elements record the position of charged particles traversing it, and this information is used to reconstruct the particle's trajectory as a track. The charged particles bend in the presence of the magnetic field, and the radius of curvature determined by the tracking is used to derive the transverse momentum of the particle.

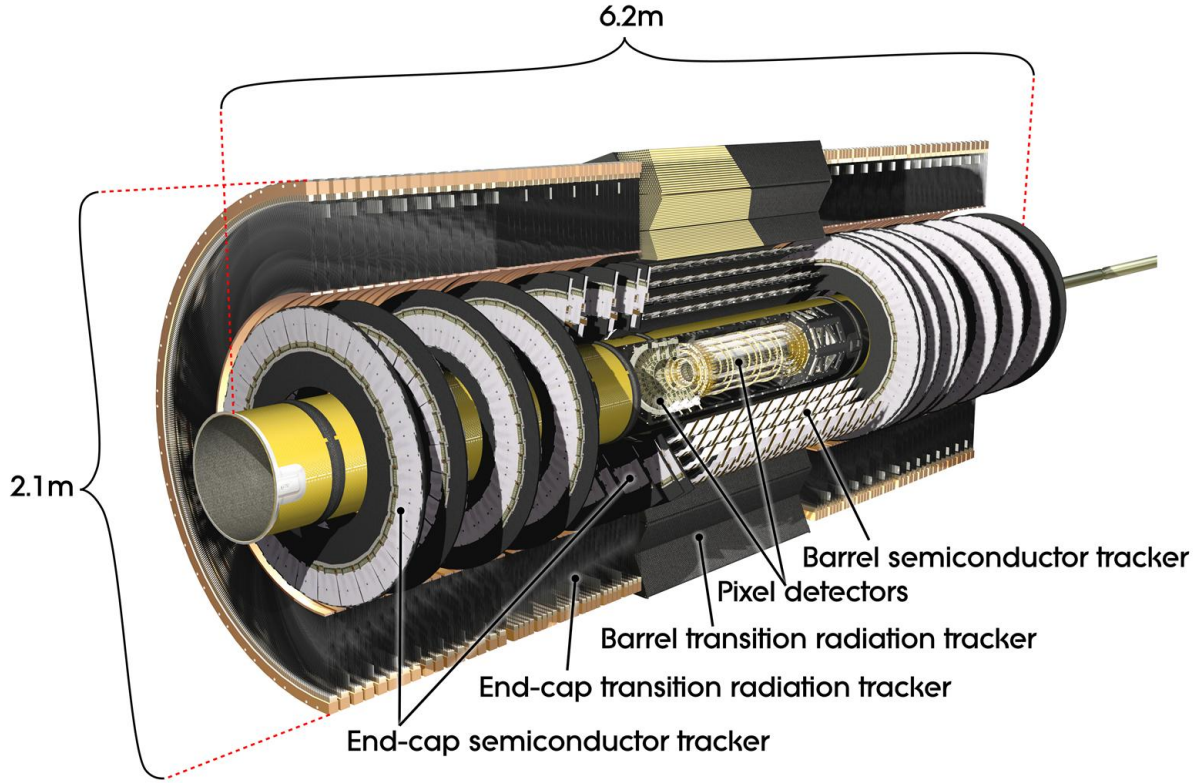


Figure 12: Cut-away view of the ATLAS inner detector [37].

Pixel Detector

The 3-Layer pixel modules are arranged around the beam axis in three concentric cylinders for the barrel region (at radii of 50.5, 88.5, and 122.5 mm) and in three disks (at $|z|$ positions of 495, 580 and 650 mm) for the endcaps. Each of the 1744 modules contains 47 232 pixels each, forming 46 080 readout channels. In total, this equals approximately 80 M readout channels, corresponding to 80% of the total readout channels of ATLAS. Approximately 90% of the pixels have a size of $50\text{ }\mu\text{m} \times 400\text{ }\mu\text{m}$, with the remaining pixels of a size of $50\text{ }\mu\text{m} \times 600\text{ }\mu\text{m}$. This is due to geometry constraints from the readout electronics.

During the first Long Shutdown a number of upgrades have been applied to the ATLAS ID. One of the main improvements was mounting the Insertable B-layer (IBL) [43] which is a fourth layer added to the present Pixel Detector. It reduced the distance of the first sensitive layer to the interaction point from 5 cm to 3.3 cm. The principal motivation of the project was a better determination of the track impact parameters due to a closer positioning from the interaction point and the maintenance of high tracking performance in the case of failures of some modules of the B-Layer, the former innermost pixel layer.

Semiconductor Tracker

The silicon strip tracker surrounding the pixel detector is arranged in four concentric cylinders for the barrel (at radii of 299, 371, 443, and 514 mm) and in six endcap disks on both sides of the IP (at $|z|$ positions of 890, 1091, 1350, 1771, 2115 and 2608 mm). It has coarser granularity as

the track density decreases with increasing the radius. Each module has 1536 silicon strips 12.6 cm long and 80 μm wide. A charged particle track typically traverses eight strip sensors corresponding to four space points. The intrinsic resolutions per module are 17 μm (ϕ) and 580 μm (z) for the barrel and 17 μm (ϕ) and 580 μm (R) for the endcap disks. The total number of readout channels in the SCT is approximately 6.3 million.

Transition Radiation Tracker

The TRT consists of a barrel part and two endcaps, formed by nine wheel-like structures. It consists of proportional drift tubes (straws) of 4 mm in diameter, which are oriented in the z axis in the barrel and radially in the endcaps. The straws are filled with gas mixture consisting of 70% Xe, 27% CO_2 and 3% O_2 . The xenon gas provides an electron identification capability by detecting transition-radiation photons created by radiator between the straws. To keep the TRT performance at a constant level, the close-loop gas system is used maintaining the correct gas fractions. During 2015 Pb+Pb data taking argon-based mixture instead of xenon was used due its better performance in high occupancy conditions. There are about 50k straws in the barrel and 320k straws in the endcap providing a large number of hits for each track.

2.2.3 Calorimeters

The aim of the calorimeter system in ATLAS (shown in Figure 13) is to measure accurately the energy and position of electrons and photons as well as jets. It also allows to measure the missing transverse energy and provides the separation of electrons and photons from hadrons and jets. The ATLAS Calorimeter system consists of an electromagnetic (EM) calorimeter covering the rapidity region $|\eta| < 3.2$, barrel hadronic calorimeter covering $|\eta| < 1.7$, hadronic endcap calorimeters covering $1.5 < |\eta| < 3.2$, and forward calorimeters covering $3.1 < |\eta| < 4.9$. The calorimeters provide good containment of electromagnetic and hadronic showers, limiting punch-through into the muon system.

Electromagnetic Calorimeters

The EM calorimeter is designed for precise energy measurement of electromagnetically interacting particles (electrons and photons) and exploits liquid argon (LAr) as active material and lead as an absorber. LAr was chosen because of its linear response and radiation hardness. The EM calorimeter consists of two half barrels ($|\eta| < 1.475$) and inner ($1.375 < |\eta| < 2.5$) and outer ($2.5 < |\eta| < 3.2$) endcaps. The region $1.37 < |\eta| < 1.52$ has a lot of dead material (cables, services, support, etc.) which reduces the calorimeter performance, it is referred as the crack region. In order to maintain the argon in liquid state, it is cooled to about 87 K, so the calorimeters are located in cryostats composed of two concentric aluminium vessels, an inner cold vessel and an outer warm vessel. The barrel and endcap/forward calorimeters are enclosed in separate cryostats to allow access to the inner detector and space for services.

The electromagnetic calorimeter has an accordion geometry, offering a full coverage with respect to ϕ without any cracks. Moreover, it allows for a fast extraction of the obtained signal.

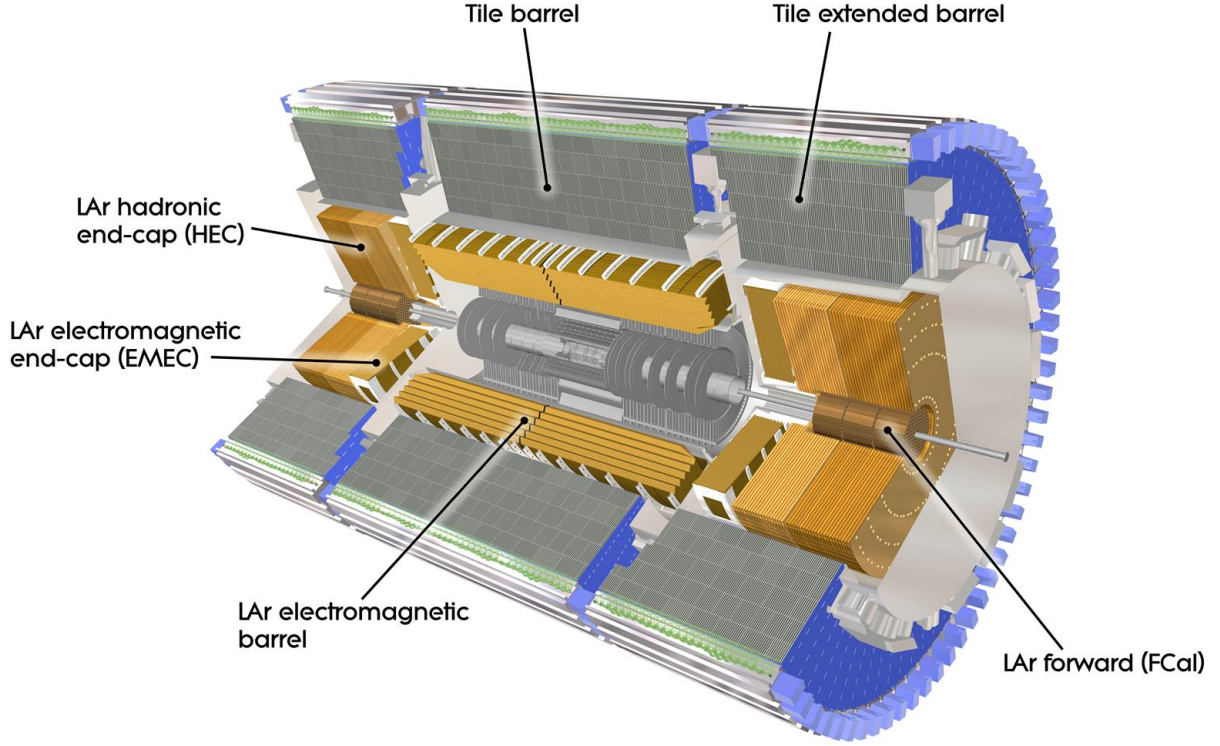


Figure 13: Cut-away view of the ATLAS calorimeter system [37].

The structure of the accordion geometry was optimized for large uniformity in terms of linearity and resolution as a function of ϕ . The electromagnetic calorimeters consist of several layers with different granularity. It should be noted that the granularity with respect to ϕ is usually larger than with respect to η . This is because the inner detector is immersed in a solenoidal magnetic field, which deflects electrons along the ϕ direction. The bremsstrahlung emitted by these electrons will therefore encompass a larger area in ϕ than η . In addition in the region $|\eta| < 2.5$, relevant for precision physics, the EM calorimeter is longitudinally segmented into three layers. The first layer is finely segmented along η allowing for a precise position measurements. It also gives an opportunity for individual photon reconstruction. The second layer collects the largest fraction of the electromagnetic shower energy, while the third layer collects the tail of the shower, therefore it is coarsely segmented in η .

Hadronic Calorimeters

The Tile calorimeter is situated behind the EM barrel calorimeter. The signal is provided by scintillating tiles as active material while the iron is used as an absorber. The tiles are placed perpendicular to the beam-pipe and are 3 mm thick. The total thickness of iron in each period is 14 mm. The tile calorimeter is divided into a barrel region covering the range $|\eta| < 1.0$ and two endcaps covering the range $0.8 < |\eta| < 1.7$. In the radial direction it is extending in radius from 2.28 m to 4.25 m.

The hadronic endcap calorimeter (HEC) covers the range $1.5 < |\eta| < 3.2$ and is comprised of

two wheels per side within the same cryostat as the endcap EM calorimeter. In order to increase the material coverage, the HEC overlaps with the tile calorimeter in the region $1.5 < |\eta| < 1.7$ and with the forward calorimeter in the range $3.1 < |\eta| < 3.2$. The front and back wheels made up of 24 copper plates of 25 mm thickness for the front wheel and 16 plates of 50 mm thickness for the wheel further away, with LAr as the active medium filling the 8.5 mm gaps between the plates. Each wheel is divided into 32 wedge sections in ϕ and in two sections in depth, providing 4 independently read out segments in total.

Forward Calorimeters

They are located in endcap cryostats and provide coverage over the region $3.1 < |\eta| < 4.9$. The active material is LAr and the absorber is copper for the first EM module and tungsten for the two subsequent hadronic modules. The modules are made up of copper or tungsten plates held together in a matrix by regularly spaced rods inside tubes of the same material that are placed parallel to the beam. The FCal modules are located at a distance of approximately 4.7 m from the interaction point and is approximately 10 interaction lengths deep.

Zero Degree Calorimeters

The Zero Degree Calorimeters (ZDC) detect neutral particles (mainly spectator neutrons) at $|\eta| > 8.3$ and are used in heavy-ion collisions for triggering on minimum bias events and rejecting pile-up events. It is located at ± 140 m from the interaction point, just beyond the point where the LHC beam-pipe is divided into two separate pipes. The ZDC modules consist of layers of alternating quartz rods and tungsten plates. The rods pick up the Cerenkov light generated by the shower and transmit it to multi-anode phototubes at the top of the module. The intensity of the light corresponds to the energy of the incident particle.

2.2.4 Muon Spectrometer

Muons are the only charged particles, which can traverse the whole detector without being absorbed. The MS is the largest detector system of ATLAS, with a length of 44 m and 25 m in diameter, and forms the outermost part of the ATLAS detector. It is used for muon identification and precise muon momentum measurement for transverse momenta between 3 GeV up to a few TeV in the magnetic field of superconducting air-core toroid magnets. The created magnetic field varies from 0.15 T to 2.5 T in the barrel region, and from 0.2 to 3.5 T in the endcap region. A schematic view of the MS is shown in Figure 14.

Over the range $|\eta| < 1.4$, magnetic bending is provided by the large barrel toroid. For $1.6 < |\eta| < 2.7$ region muon tracks are bent by two smaller endcap magnets inserted into both ends of the barrel toroid. Over $1.4 < |\eta| < 1.6$, usually referred to as the transition region, magnetic deflection is provided by a combination of barrel and endcap fields. This magnet configuration provides a field that is mostly orthogonal to the muon trajectories, while minimizing the degradation of resolution due to multiple scattering.

MS consists of monitored drift tube chambers (MDT) and cathode strip chambers (CSC) for precision tracking measurements. MDT covers $|\eta| < 2.7$ region, while CSC is used only in the forward region $2.0 < |\eta| < 2.7$. As a trigger system resistive plate chambers (RPC) and thin gap chambers (TGC) are used in the barrel ($|\eta| < 1.05$) and endcap ($1.05 < |\eta| < 2.4$) region, respectively.

The MDT consists of 3 cm in diameter aluminium tubes operating with Ar/CO₂ gas (93:7) at 3 bar. The 50 μ m in diameter tungsten-rhenium wire is in the centre of the tube. Traversing charged particle ionises the gas inside the tube and ions drift to the wire in electric field. Fine position resolution is enabled by determination of the drift time.

The CSC in the muon system are used to detect tracks at large pseudorapidities ($2.0 < |\eta| < 2.7$). The CSCs can tolerate counting rates up to ~ 1000 Hz/cm², while the MDT are designed to work at rate below ~ 150 Hz/cm². The CSC are multi-wire proportional chambers aligned radially, 8 large and 8 small trapezoid chambers have full azimuth coverage. The chambers are filled with Ar/CO₂ (80:20) gas mixture, with two types of segmented cathode strips allowing measurement in both η and ϕ directions.

The RPC are gaseous detectors covering the region up to $|\eta| < 1.05$. It consist of two resistive plates on a 2 mm distance, filled with gas mixture of C₂H₂F₄, Iso – C₄H₁₀, and SF₆ (94.7:5:0.3). Muons travelling the gas induce an avalanche towards the anode and thin gas gap allows quick

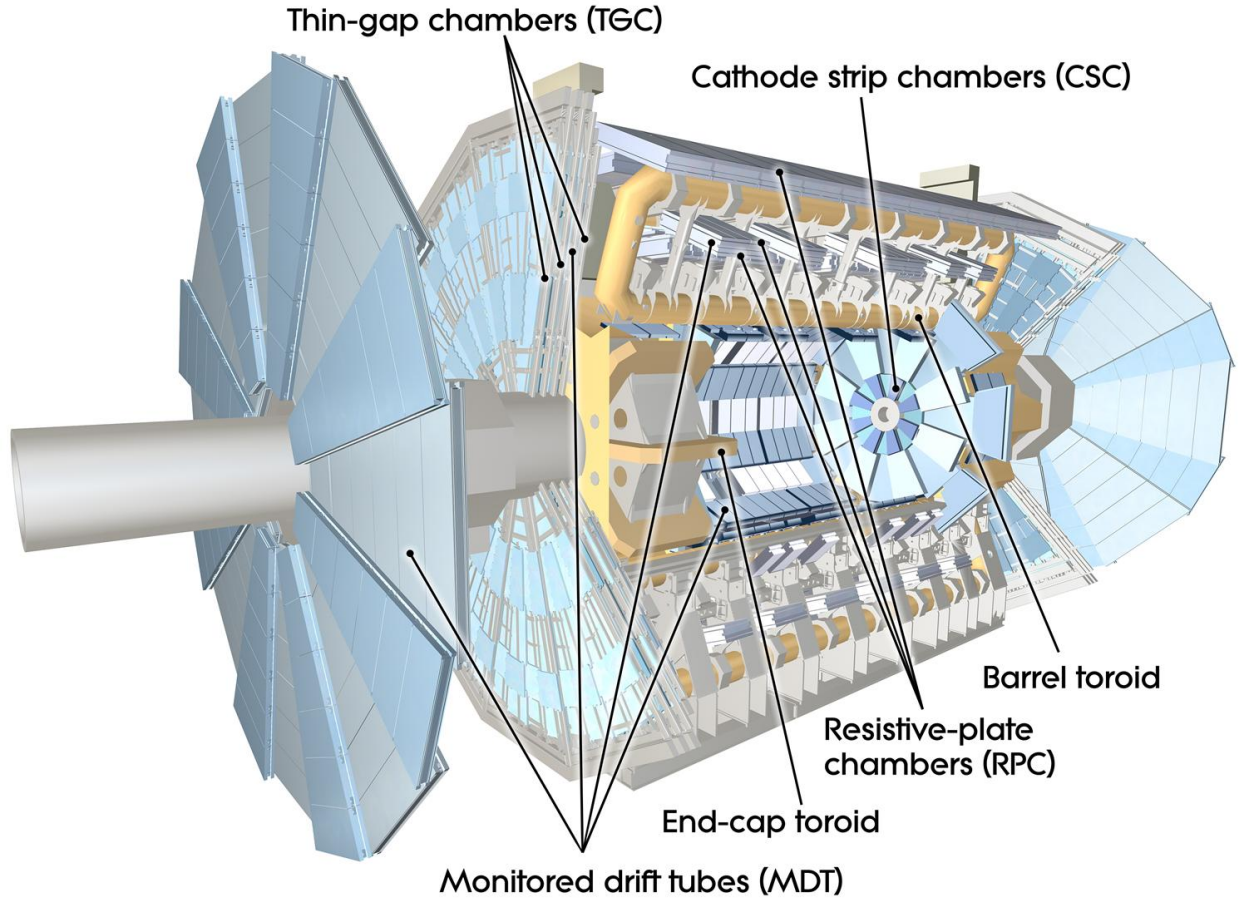


Figure 14: Cut-away view of the ATLAS muon system [37].

response time which is ideal for triggering. There are 544 RPCs arranged in three layers, referred as three trigger stations, allowing for threshold set up in low and high p_T trigger.

The TGC are multiwire proportional chambers with the smaller wire-to-cathode distance (1.4 mm) than the wire-to-wire distance (1.8 mm). The TGC are filled with mixture of CO_2 and n-pentane in high electric field for good time resolution. The operational principle is similar to the CSC. In the endcaps they are located in the inner and middle layer and have a dual application: as a trigger system and for azimuth coordinate measurement.

2.2.5 Trigger and Data Acquisition

The purpose of the Trigger and Data Acquisition (TDAQ) system [44] is to reduce the rate of data stored from ~ 40 MHz down to the level of ~ 2 kHz. Many of the rejected events are soft physics events which are not of high interest for most analyses. The ATLAS detector is equipped with a two-level trigger system based on hardware and software information. The Level-1 (L1) trigger is based on Regions-of-Interest (RoI) in the detector which are used for the trigger decision. It uses coarse calorimeter information and muon spectrometer information as input. This decision is made within $2.5 \mu\text{s}$ and reduces the event rate to approximately 100 kHz. The high level trigger (HLT) receives the RoI information of the L1 trigger and can make use of the full calorimeter granularity, tracking and muon spectrometer information for the decision and reduces the event rate further down to 2 kHz. Decisions in the HLT are made within 200 ms and events passing this trigger are stored for offline analysis using the data acquisition (DAQ) system. This system is interdependent with the triggers and follows different stages. If an event is accepted by the L1 trigger, data is transported from the front-end electronics at the detector to the readout system. There, the event data is buffered and can be accessed by the HLT. If the HLT accepts the event, the data is sent to permanent storage via the data logger.

For certain physics objects that ATLAS triggers on, the production rate might be still too high to record every single event passing the trigger. In such cases, prescaled triggers exist, which record only a certain fraction of the events that would normally pass the trigger, effectively reducing the recorded luminosity.

3 Data and Monte Carlo samples

3.1 Data sets

The analysis which is the main subject of this thesis is done with the full set of 2015 Pb+Pb data at $\sqrt{s_{NN}} = 5.02$ TeV. ATLAS online data-taking can be divided into sub-periods. The fundamental time interval is Luminosity Block (LB) which corresponds to roughly 1 minute of data-taking. A run is a period of collecting data which starts after LHC is filled and lasts till a beam dump. A typical run is a collection of few hundreds LB's. In total 33 runs were taken and on average each run was lasting for ~ 6.5 h. The integrated luminosity recorded by ATLAS was 0.49 nb^{-1} . Only data taken during stable beam conditions and with a fully operating magnet system, tracking, calorimeter and muon sub-detectors were considered. For this purpose, a Good Run List (GRL) is prepared by the ATLAS data quality group which defines good LB in each run.

During online data-taking, the triggers were segmented into streams in order to enrich the data samples with pertinent physics information and facilitate end-user analysis:

- The *HardProbes* stream contain high- p_T triggers for jets, photons, electrons and muons. The HardProbes stream data sample corresponds to an integrated luminosity of $487 \mu\text{b}^{-1}$. The total number of events in the sample is 202.8 million.
- The *MinBias* stream contain several triggers that added together correspond to the minimum-bias (MB) event sample. Details are explained in this section. The MB sample was taken in each run. In total the MinBias stream contains about 284.2 million events.
- The *MinBiasOverlay* stream contain events enhanced towards the most central collision. This sample contains about 23.1 million events. It is used for embedding simulated signal and background events into MB events in this analysis. Details are given in the Section 3.2.

The HLT_e15_loose_ion_L1EM12 and the HLT_mu8 triggers are used by the electron and muon channels, respectively. The first one required single electron with $p_T > 15$ GeV, while the later one required single muon with $p_T > 8$ GeV at the HLT. This triggers are part of the HardProbes stream. The full integrated luminosity for this analysis is $486 \mu\text{b}^{-1}$ for the muon channel and $485 \mu\text{b}^{-1}$ for the electron channel. Difference is due to turned off electron trigger in the first two runs.

The results of heavy-ion data analyses are usually presented not in the form of cross sections, but as a number of counts per MB event, N_{evt} . This number is extracted from the MinBias stream using events triggered by the MB trigger: an OR between HLT_noalg_mb_L1TE50 and HLT_mb_sptrk_ion_L1ZDC_A_C_VTE50 triggers. L1TE50 implies that the total transverse energy in the event is $E_T > 50$ GeV, whereas VTE50 means that the $E_T < 50$ GeV. L1ZDC_A_C is a coincidence trigger requirement in which at least one neutron is required in both the A and C sides of the ZDC. The suffix noalg implies that no further event processing is performed from L1 to the HLT, and the sptrk suffix signifies that the online selection relays on counting hits in the ID. Each MB event is weighted by its prescale value, and N_{evt} corresponds to the total number of prescale-weighted MB events which were probed during the heavy-ion runs. A measurement of N_{evt} is the subject of an independent analysis [45] and was done according

to the procedure utilized in Run 1 [46]. For the integrated luminosity probed in this analysis and the 0–80% centrality range, N_{evt} amounts to 2.99×10^9 events.

3.2 Monte Carlo samples

Monte Carlo methods are widely used in experimental and theoretical high-energy physics, since they allow to simulate events according to a physics process of interest or to calculate its cross-section. Additionally, a detailed simulation of the detector is necessary to study the detector response for a wide range of physics processes. The ATLAS experiment uses a chain of algorithms for the detector simulation, which consists of several steps. Within this chain, events generated using a MC event generator are passed through a full simulation of the detector response and reconstructed like events from collision data. This procedure is enabled in the ATLAS simulation infrastructure [47], which is integrated into the ATLAS software framework, ATHENA [48], and uses the GEANT4 simulation toolkit [49, 50].

The ATLAS simulation chain consists of four main steps: event generation, detector simulation, event digitalization, and event reconstruction. The event generation steps typically uses multi-purpose event generators, which can simulate the full proton–proton interaction. These programs usually offer a modelling of the hard scattering, interfaces to PDFs, parton showering models, hadronisation and decays of particles produced in the interaction. At the simulation step, the generated particles are propagated through the ATLAS detector, and their interactions with detector material are simulated using the GEANT4 package. The digitalization step transforms the results of these interactions into digital signals in a format produced by the detector electronics. Following digitalization, the simulated events are reconstructed using the same software packages as used for the reconstruction of collision data.

The nominal MC event samples used in this analysis were produced using the PYTHIA8 [51] and POWHEG [52] generators with CT10 [53] PDFs. These programs were used to generate events containing W and Z bosons produced in pp , pn , np and nn interactions. In order to study detector effects in the heavy-ion environment, the generated events were embedded into minimum-bias Pb+Pb events from the 2015 dataset. The HIJING event generator, commonly used in the heavy-ion community, can produce full Pb+Pb events. However, passing a MB HIJING event through the GEANT4 simulation of ATLAS requires approximately 6 h of CPU time, while the most central events may take up to 30 h. Due to the high CPU demand it is difficult to produce large MC samples. Therefore, generated events are instead embedded into real MB events recorded in parallel with the nominal dataset. This procedure of *data overlay* has the additional benefit of detector conditions in the simulation being identical to those during data taking. Despite a considerable gain in the CPU processing time, the embedding and reconstruction of data overlay events still require large resources and the resulting size of MC samples is limited. The MC samples used in this analysis are listed in Tables 3 and Table 4. At the time when MC samples for the muon channel analysis were generated, trigger simulation was not available in the ATLAS data overlay software, and thus MC samples listed in Table 3 do not have simulated trigger decisions. The lack of this information is compensated by measuring the trigger efficiency in

data and then reweighting MC samples. More details are given in Section 6.2.

Since the signal and background processes have been generated independently for various charge and nucleon combinations, a weighting procedure is applied for each process of interest in order to combine all MC sub-samples into one. For each sub-process a global event weight is derived based on the mass (A) and atomic (Z) numbers of the colliding nuclei, and on the total number of generated events. In the lead nuclei used at the LHC, $A = 208$ and $Z = 82$. This corresponds to a collision rate of $f_{pp} = (Z/A)^2 = 15.5\%$ for proton–proton, $f_{pn,np} = 2Z(A - Z)/A^2 = 47.8\%$ for proton–neutron or neutron–proton, and $f_{nn} = ((A - Z)/A)^2 = 36.7\%$ for neutron–neutron interactions. Therefore, the global event weight for each sub-process is proportional to the ratio of the corresponding collision rate and the total number of MC events for that sub-process:

$$w = \frac{\langle T_{AA} \rangle^{0-80\%} \cdot N_{\text{evt,MB}}^{0-80\%} \cdot \sigma}{N_{\text{gen}}^{0-80\%}} f_{xy}, \quad (27)$$

where f_{xy} stands for f_{pp} , $f_{pn,np}$ or f_{nn} , $N_{\text{gen}}^{0-80\%}$ is the number of generated events for the given sub-process in the 0–80% centrality class reweighted according to the weight described in Section 3.4, $N_{\text{evt,MB}}^{0-80\%}$ is the total number of MB events in the 0–80% centrality class, and σ is the

Process	Isospin combination	Events $\times 10^3$	σ [nb]
$W^+ \rightarrow \mu^+ \nu$	pp	190.813	4.299
	np	294.745	3.550
	pn	293.253	3.551
	nn	451.866	2.823
$W^- \rightarrow \mu^- \nu$	pp	190.814	2.863
	np	294.545	3.598
	pn	294.645	3.598
	nn	452.957	4.356
$Z \rightarrow \mu^+ \mu^-$	pp	98.801	0.642
	pn	296.638	0.656
	np	296.737	0.656
	nn	443.891	0.665
$W^+ \rightarrow \tau^+ \nu$	pp	49.345	4.298
	np	74.165	3.551
	pn	74.066	3.549
	nn	110.729	2.823
$W^- \rightarrow \tau^- \nu$	pp	49.444	2.810
	np	74.165	3.598
	pn	74.066	3.598
	nn	110.629	4.357
$Z \rightarrow \tau^+ \tau^-$	pp	197.362	0.643
$t\bar{t}$ production	pp	69.214	0.056

Table 3: MC samples used in the muon channel analysis, with the respective total cross sections times branching ratios and initial number of events. Presented cross sections of W boson processes are scaled to an NNLO QCD calculation.

Process	Isospin combination	Events $\times 10^3$	σ [nb]
$W^+ \rightarrow e^+ \nu$	pp	425.445	4.300
	np	585.172	3.551
	pn	587.291	3.551
	nn	901.402	2.823
$W^- \rightarrow e^- \nu$	pp	388.419	2.863
	np	584.635	3.598
	pn	585.668	3.598
	nn	897.095	4.356
$Z \rightarrow e^+ e^-$	pp	39.552	0.643
	pn	58.386	0.656
	np	59.078	0.656
	nn	92.903	0.665
$W^+ \rightarrow \tau^+ \nu$	pp	68.760	4.298
	np	107.814	3.550
	pn	107.272	3.549
	nn	156.752	2.823
$W^- \rightarrow \tau^- \nu$	pp	68.760	2.865
	np	108.032	3.598
	pn	108.765	3.598
	nn	155.627	4.356
$Z \rightarrow \tau^+ \tau^-$	pp	48.962	0.642
$t\bar{t}$ production	pp	194.383	0.057

Table 4: MC samples used in the electron channel analysis, with the respective total cross sections times branching ratios and initial number of events. Presented cross sections of W boson processes are scaled to an NNLO QCD calculation.

production cross section for the given sub-process. Cross sections for all sub-processes are given in Table 3 and Table 4. The cross sections for W boson production are scaled from an NLO QCD approximation (POWHEG+PYTHIA8 simulation with the CT10 PDF set) to an NNLO QCD approximation (DNNLO 1.5 [54, 55] calculations with the CT14nnlo PDF set). It should be noted that the scaling factors (k -factors) can be calculated only for the pp isospin combination. For other isospin combinations, the same scaling as for pp collisions is assumed to be valid. The k -factors take the following values: 1.026 for W^+ boson production, 1.046 for W^- boson production.

3.3 Centrality association in the data

Centrality is defined in the following way. All events are ordered according to the impact parameter between centres of the colliding nuclei. A percentile of all events is called the event centrality. Conventionally, a low percentile corresponds to central collisions and a high percentile to peripheral ones. Particular centrality classes used in the analysis depend on the statistics of the sample. Due to the nature of heavy-ion collisions, variations of N_{part} for a given centrality class are weak with $\sqrt{s_{\text{NN}}}$ over a wide range of incident energies, however it significantly changes depending on the colliding species. Therefore, the centrality dependence of measured quantities

Centrality	FCal ΣE_T [TeV]	$\langle N_{\text{part}} \rangle$	$\delta \langle N_{\text{part}} \rangle$	$\langle T_{\text{AA}} \rangle$ [mb $^{-1}$]	$\delta \langle T_{\text{AA}} \rangle$
0–2%	4.7–4.081	399.0 ± 1.2	0.29%	28.30 ± 0.25	0.87%
2–4%	4.081–3.764	380.2 ± 2.0	0.54%	25.47 ± 0.21	0.84%
4–6%	3.764–3.481	358.9 ± 2.4	0.67%	23.07 ± 0.21	0.89%
6–8%	3.481–3.224	338.1 ± 2.7	0.79%	20.93 ± 0.20	0.97%
8–10%	3.224–2.989	317.8 ± 2.9	0.92%	18.99 ± 0.19	0.97%
10–15%	2.989–2.477	285.2 ± 2.9	1.0%	16.08 ± 0.18	1.1%
15–20%	2.477–2.047	242.9 ± 2.9	1.2%	12.59 ± 0.17	1.4%
20–25%	2.047–1.681	205.6 ± 2.9	1.4%	9.77 ± 0.18	1.8%
25–30%	1.681–1.369	172.8 ± 2.8	1.6%	7.50 ± 0.17	2.3%
30–40%	1.369–0.875	131.4 ± 2.6	2.0%	4.95 ± 0.15	3.0%
40–50%	0.875–0.525	87.0 ± 2.4	2.7%	2.63 ± 0.11	4.3%
50–60%	0.525–0.290	53.9 ± 2.0	3.7%	1.281 ± 0.074	5.8%
60–80%	0.290–0.0637	23.0 ± 1.3	5.5%	0.394 ± 0.032	8.2%
0–80%	4.7–0.064	141.3 ± 2.1	1.5%	7.00 ± 0.11	1.5%

Table 5: Centrality, 2015 FCal cuts and MC Glauber parameters with uncertainties used in the analysis.

is usually presented as a function of $\langle N_{\text{part}} \rangle$ rather than centrality itself to allow for easier comparisons between different colliding systems. For example, the most "peripheral" events, the pp collisions, correspond to $N_{\text{part}} = 2$.

Centrality association in the 2015 data was done following the method applied to the 2010 and 2011 data which is described in Ref. [45]. The centrality determination is based on the total transverse energy measured by the FCal detector (FCal ΣE_T). Since the calorimeter is located at very forward region ($3.2 < |\eta| < 4.9$) there is no risk of auto-correlation while using objects reconstructed in the central region ($|\eta| < 2.5$) of the ATLAS detector. The centrality class definitions used in this analysis are given in Table 5.

For each centrality class geometric parameters and their systematic uncertainties are assigned, based on the Glauber model by matching it to the measured FCal ΣE_T distribution. The model assumes the nuclear geometry and the inelastic pp cross section. In recent years the same model was used by all heavy-ion experiments. The uncertainties on the model related parameters are coming from two main sources: the uncertainties of the Glauber model itself, such as in measured parameters of the Woods-Saxon distribution, and the uncertainties of mapping the model onto the FCal distribution. The latter contribution is largely defined by the uncertainty of the MB trigger efficiency and its possible contamination from the photo-nuclear processes in very peripheral events. Table 5 lists the main Glauber model parameters relevant to this analysis. The first centrality parameter listed in the table is the average number of participating nucleons, $\langle N_{\text{part}} \rangle$, in both colliding lead nuclei which are involved in the collision. The next column gives the average value of the nuclear overlap function $\langle T_{\text{AA}} \rangle$. All parameters are presented with their respective uncertainties.

The most peripheral class (80–100%) of Pb+Pb collisions has not been studied in this analysis due to expected low statistics of W bosons, and a large uncertainty on the Glauber model

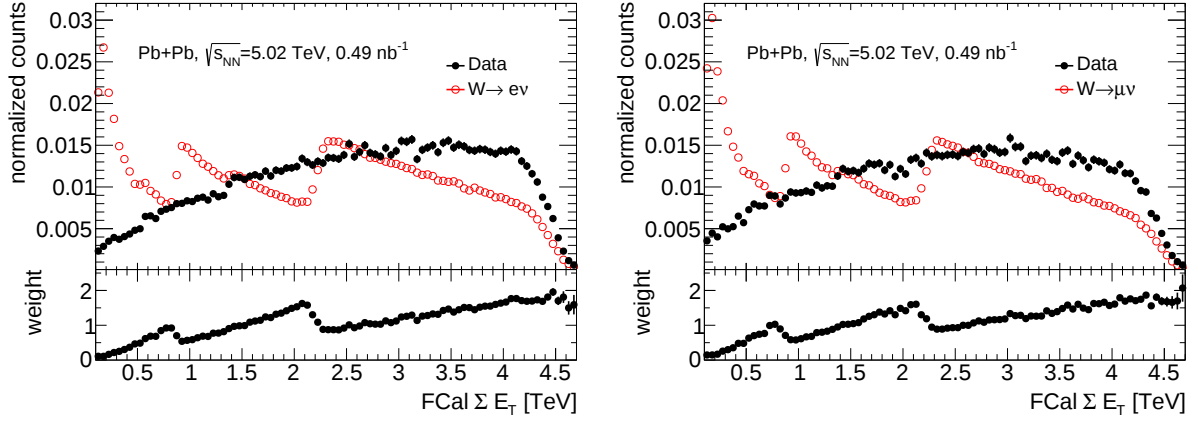


Figure 15: $\text{FCal } \Sigma E_T$ distributions of W boson candidate events in data (full circles) and signal MC samples (open circles) normalized to unity. The distributions are shown for the electron (left) and muon channel (right) candidates. The bottom panels present event-by-event weights used to reweight MC samples in this analysis.

parameters which are associated with that bin.

The probability of additional hard interactions (pile-up) to occur in the 2015 data taking conditions was below the percent level. The fraction of pile-up events in the selected event sample is estimated using the ZDC detector. In the most central class of events were rejected events with $\text{FCal } \Sigma E_T > 4.7$ TeV, while further rejection in all centrality classes is achieved by using the anti-correlation between the $\text{FCal } \Sigma E_T$ and the number of neutrons detected in ZDC. Events with a number of ZDC neutrons much higher than the number expected from the bulk of events for a given value of $\text{FCal } \Sigma E_T$ are rejected. The fraction of rejected events is about 0.4% in both the electron and muon channels.

3.4 Centrality association in the Monte Carlo

As a first step for using the MC samples, the $\text{FCal } \Sigma E_T$ distribution needs to be corrected to provide a reliable measure of centrality. Such a procedure is motivated by the event composition of the MinBiasOverlay stream which does not match the data. The latter is significantly enhanced towards more central events. Figure 15 shows distributions of $\text{FCal } \Sigma E_T$ for data events with W boson candidates and signal MC samples in both electron and muon channels. A significant difference between data and simulation is observed which leads to a need of applying an event-by-event weight in the MC samples. Such weights are presented as a function of $\text{FCal } \Sigma E_T$ in the bottom panels of plots in Figure 15. Three regions of $\text{FCal } \Sigma E_T$ can be identified where the weights raise almost linearly from 0.1 to about 1.8. These three regions correspond to $\text{FCal } \Sigma E_T$ values where a different trigger mix was used to collect data for MinBiasOverlay stream in the 2015 heavy-ion runs.

4 Reconstruction of physics objects

In the W boson production measurement objects like electrons, muons and missing transverse momentum are reconstructed using the detector information from all sub-detectors of the ATLAS. In the following sections, the identification and reconstruction of such objects will be explained.

4.1 Track reconstruction

A charged particle is bent in the solenoid magnetic field inside the ID and follows a circular trajectory in the transverse plane. The trajectory is parametrised by a set of five parameters, namely ratio of particle's charge to its transverse momentum, the azimuthal angle $\phi = \arctan(y/x)$, the polar angle θ measured relative to the positive z -axis, and the transverse and the longitudinal impact parameters, d_0 and z_0 , respectively. Track reconstruction algorithms are using the information from the entire ID (Pixel, SCT, TRT), therefore they are only reconstructed in the range $|\eta| < 2.5$.

The primary track reconstruction algorithm [56, 57] starts from pattern recognition of ID hits with seeding in the inner part of the tracker and performs hit finding towards the outer border of the ID, referred to as the inside-out algorithm. In case of detector hits being in a window of interest, where additionally other hits are expected, a simplified Kalman filter [58, 59] is used for further selection. Detector hits are considered to be part of a track or being rejected, respectively, based on the decision of the Kalman filter, and similar is done for so-called holes, where the track traversed a silicon layer without producing an actual hit in the detector material. This procedure results in a collection of tracks, where a track can share the same hits or holes with other tracks. These ambiguities are resolved by assigning track scores, similar to likelihoods, based on refitting of each track candidate using a finer geometry. Only track candidates with the highest scores are accepted. The surviving track candidates are then extrapolated to search for additional hits in the TRT. The full collection of hits and holes are added iteratively, and the track is refitted every time a new hit or hole is added. The standard track-fit used in ATLAS assumes that tracks come from pions, affecting the fitted momentum through the estimation of their energy loss in the detector.

Two track selections have been defined: *HILoose* and *HITight*. *HILoose* characterize with higher tracking efficiency but allows for more fake tracks which are reconstructed due to random coincidence of the hits in the ID. However, this fake rate is significant only for $p_T < 1$ GeV, and this region is excluded from the analysis. Detail requirements of the *HILoose* selection:

- $|\eta| < 2.5$,
- if expected require hit in the innermost layer,
- $N_{\text{Pix}} \geq 1$,
- $N_{\text{SCT}} \geq 2, 4, 6$ for $p_T > 0, 300, 400$ MeV, respectively,
- $d_0 < 1.5$ mm,
- $z_0 \sin \theta < 1.5$ mm.

HITight selection requirements include:

- $|\eta| < 2.5$,
- if expected require hit in the innermost layer,
- $N_{\text{Pix}} \geq 2$,
- $N_{\text{SCT}} \geq 4, 6, 8$ for $p_T > 0, 300, 400$ MeV, respectively,
- $d_0 < 1.0$ mm,
- $z_0 \sin \theta < 1.0$ mm,
- $\chi^2/\text{n.d.f.} < 6$.

Where N_{Pix} – number of pixel hits, N_{SCT} – number of SCT hits, d_0 – transverse impact parameter, z_0 – longitudinal impact parameter, $\chi^2/\text{n.d.f.}$ – quality of a track fit.

4.2 Muon reconstruction

Muon reconstruction is first performed independently in the ID and MS [60]. The information from individual subdetectors is then combined to form the muon tracks that are used in physics analyses. In the ID, muons are reconstructed like any other charged particles as described in Section 4.1.

Muon reconstruction in the MS starts with a search for hit patterns inside each muon chamber to form segments. In each MDT chamber and nearby trigger chamber, a Hough transform [61] is used to search for hits aligned on a trajectory in the bending plane of the detector. The MDT segments are reconstructed by performing a straight-line fit to the hits found in each layer. The RPC or TGC hits measure the coordinate orthogonal to the bending plane. Segments in the CSC detectors are built using a separate combinatorial search in the η and ϕ detector planes. The search algorithm includes a loose requirement on the compatibility of the track with the luminous region. Muon track candidates are then built by fitting together hits from segments in different layers. The algorithm used for this task performs a segment-seeded combinatorial search that starts by using as seeds the segments generated in the middle layers of the detector where more trigger hits are available. The search is then extended to use the segments from the outer and inner layers as seeds. The segments are selected using criteria based on hit multiplicity and fit quality, and are matched using their relative positions and angles. At least two matching segments are required to build a track, except in the barrel–endcap transition region where a single high-quality segment with η and ϕ information can be used to build a track. The same segment can initially be used to build several track candidates. Later, an overlap removal algorithm selects the best assignment to a single track, or allows for the segment to be shared between two tracks. To ensure high efficiency for close-by muons, all tracks with segments in three different layers of the spectrometer are kept when they are identical in two out of three layers but share no hits in the outermost layer. The hits associated with each track candidate are fitted using a global χ^2 fit. A track candidate is accepted if the χ^2 of the fit satisfies the selection criteria. Hits providing large contributions to the χ^2 are removed and the track fit is repeated. A hit recovery procedure

is also performed looking for additional hits consistent with the candidate trajectory. The track candidate is refit if additional hits are found.

The combined ID–MS muon reconstruction is performed according to various algorithms based on the information provided by the ID, MS and calorimeters. Four muon types are defined depending on which subdetectors are used in reconstruction:

- **Combined (CB) muon:** track reconstruction is performed independently in the ID and MS, and a combined track is formed with a global refit that uses the hits from both the ID and MS subdetectors. During the global fit procedure, MS hits may be added to or removed from the track to improve the fit quality. Most muons are reconstructed following an outside-in pattern recognition, in which the muons are first reconstructed in the MS and then extrapolated inward and matched to an ID track. An inside-out combined reconstruction, in which ID tracks are extrapolated outward and matched to MS tracks, is used as a complementary approach if the outside-in reconstruction fails.
- **Segment-tagged (ST) muons:** a track in the ID is classified as a muon if, once extrapolated to the MS, it is associated with at least one local track segment in the MDT or CSC chambers. ST muons are used when muons cross only one layer of MS chambers, either because of their low p_T or because they fall in regions with reduced MS acceptance.
- **Calorimeter-tagged (CT) muons:** a track in the ID is identified as a muon if it can be matched to an energy deposit in the calorimeter compatible with a minimum-ionizing particle. This type has the lowest purity of all the muon types but it recovers acceptance in the region where the MS is only partially instrumented to allow for cabling and services to the calorimeters and ID. The identification criteria for CT muons are optimised for that region ($|\eta| < 0.1$) and a momentum range of $15 < p_T < 100$ GeV.
- **Extrapolated (ME) muons:** the muon trajectory is reconstructed based only on the MS track and a loose requirement on compatibility with originating from the IP. The parameters of the muon track are defined at the interaction point, taking into account the estimated energy loss of the muon in the calorimeters. In general, the muon is required to traverse at least two layers of MS chambers to provide a track measurement, but three layers are required in the forward region. ME muons are mainly used to extend the acceptance for muon reconstruction into the region $2.5 < |\eta| < 2.7$, which is not covered by the ID.

Overlaps between different muon types are resolved before producing the collection of muons used in physics analyses. When two muon types share the same ID track, preference is given to CB muons, then to ST, and finally to CT muons. The overlap with ME muons in the MS is resolved by analysing the track hit content and selecting the track with better fit quality and larger number of hits.

4.2.1 Muon identification

Muon identification is performed by applying quality requirements that suppress background muons, mainly from pion and kaon decays, while selecting prompt muons with high efficiency

and/or guaranteeing a robust momentum measurement. Muon candidates originating from in-flight decays of charged hadrons in the ID are often characterized by the presence of a distinctive "kink" topology in the reconstructed track. As a consequence, it is expected that the fit quality of the resulting combined track will be poor and that the momentum measurements in the ID and MS may not be compatible. Several variables offering good discrimination between prompt muons and background muon candidates are used in muon identification:

- q/p significance, defined as the absolute value of the difference between the ratio of the charge and momentum of the muons measured in the ID and MS divided by the sum in quadrature of the corresponding uncertainties,
- ρ , defined as the absolute value of the difference between the transverse momentum measurements in the ID and MS divided by the p_T of the combined track,
- normalised χ^2 of the combined track fit.

To guarantee a robust momentum measurement, specific requirements on the number of hits in the ID and MS are used. For the ID, the quality cuts require at least one Pixel hit, at least five SCT hits and fewer than three Pixel or SCT holes. Figure 16 presents distributions of the hits in the ID. Pixel and SCT hits are well simulated in the signal MC while for the TRT hits significant

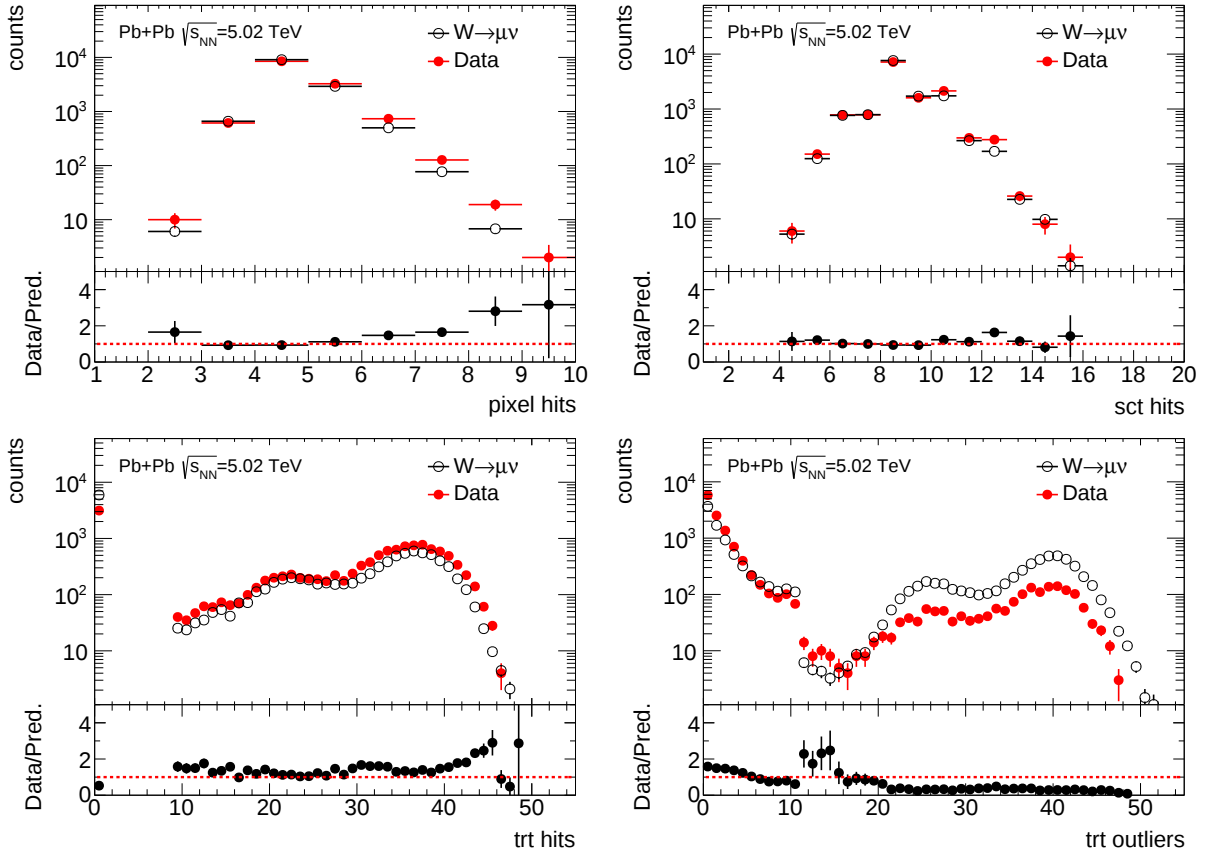


Figure 16: Distributions of the number of Pixel (top, left), SCT (top, right), and TRT (bottom, left) hits and TRT outliers (bottom, right) for reconstructed muon tracks in data (full points) and signal MC simulation (open points). The signal MC is normalized to the number of events in data.

differences can be noticed. They originate in a different gas mixture used in the TRT during the 2015 Pb+Pb data taking compared to pp operations. Due to these differences this analysis does not use information from TRT to identify muons.

Three muon identification selections have been defined: *Tight*, *Medium*, *Loose*. They represent inclusive categories in that muons identified with tighter requirements are also included in the looser categories.

- ***Tight muons:*** *Tight* muons are selected to maximise the purity of muons at the cost of some efficiency loss. Only CB muons with hits in at least two stations of the MS and satisfying the *Medium* selection criteria (defined below) are considered. The normalised χ^2 of the combined track fit is required to be less than 8 to remove pathological tracks. A two-dimensional cut in the ρ and q/p significance variables is performed as a function of the muon p_T to ensure stronger background rejection for momenta below 20 GeV where the misidentification probability is higher.
- ***Medium muons:*** The *Medium* identification criteria provide the default selection for muons in ATLAS. This selection minimises the systematic uncertainties associated with muon reconstruction and calibration. Only CB and ME tracks are used. The former are required to have at least 3 hits in at least two MDT layers, except for tracks in the $|\eta| < 0.1$ region, where tracks with at least one MDT layer but no more than one MDT hole layer are allowed. The latter are required to have at least three MDT/CSC layers, and are employed only in the $2.5 < |\eta| < 2.7$ region to extend the acceptance outside the ID geometrical coverage. For combined muons, a loose selection on the compatibility between ID and MS momentum measurements is applied to suppress the contamination due to hadrons misidentified as muons. Specifically, the q/p significance is required to be less than seven. In the pseudorapidity region $|\eta| < 2.5$, about 0.5% of the muons classified as *Medium* originate from the inside-out combined reconstruction strategy. This analysis uses medium muon identification w/o TRT requirements.
- ***Loose muons:*** The *Loose* identification criteria are designed to maximise the reconstruction efficiency while providing good-quality muon tracks. All muon types are used. All CB and ME muons satisfying the *Medium* requirements are included in the *Loose* selection. CT and ST muons are restricted to the $|\eta| < 0.1$ region. In the region $|\eta| < 2.5$, about 97.5% of the *Loose* muons are combined muons, approximately 1.5% are CT, and the remaining 1% are reconstructed as ST muons.

4.2.2 Muon momentum issue

During work on this analysis, an issue with the muon momentum performance has been identified. Figure 17 shows the average value of the difference between muon p_T measured in the ID and MS systems divided by the combined muon p_T (i.e. the signed value of ρ introduced in Section 4.2.1) as a function of the combined muon p_T . This variable can be treated as a measure of the muon momentum scale. In case of the MC simulation the scale is close to 0 on average, while for data a 2% charge-dependent shift is observed. The muon p_T measured using the ID

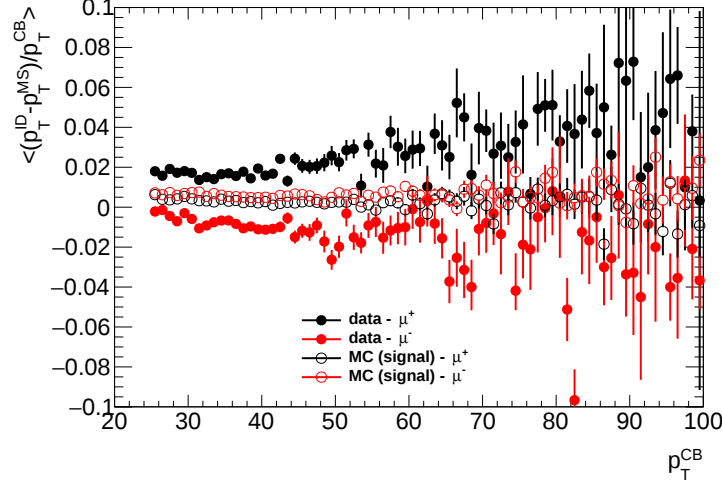


Figure 17: Average value of the difference between muon p_T measured in the ID and MS systems divided by the combined muon p_T as a function of combined muon p_T for data and $W \rightarrow \mu\nu$ MC simulation. Black and red markers correspond to positive and negative muons, respectively.

track is too high for positive muons and too low for negative muons with respect to the measurement performed only using the MS track. This difference is non-negligible as the combined muon p_T is constructed from both systems. The issue has been tracked down to originate from the suboptimal ID alignment used in the reprocessing of the Pb+Pb data. To minimize the impact of this issue on the analysis, the ME kinematics (see Section 4.2) are used per recommendation from the ATLAS Muon Combined Performance group.

4.3 Electron reconstruction

Electron reconstruction in the central region of the ATLAS detector ($|\eta| < 2.47$) starts from energy deposits (clusters) in the electromagnetic (EM) calorimeter which are then associated to reconstructed tracks of charged particles in the inner detector [62, 63].

The first step is to reconstruct the EM clusters. The basic building blocks are longitudinal calorimeter towers of size 0.025×0.025 in $\eta - \phi$ plane, corresponding to the granularity of the middle layer of the electromagnetic calorimeter. Total cluster transverse energy above 2.5 GeV are searched for by a sliding-window algorithm [64]. The window size is 3×5 in units of 0.025×0.025 in $\eta - \phi$ space. Cluster reconstruction is expected to be very efficient for true electrons. In MC simulations, the efficiency is about 95% for electrons with a transverse energy $E_T = 7$ GeV and reaches 99% at $E_T = 15$ GeV and 99.9% at $E_T = 45$ GeV.

The next step is to reconstruct track associated with a given electron. First, the electron track candidates are identified in the ID using the standard ATLAS track reconstruction algorithms described in Section 4.1. Then, tracks are extrapolated to the electromagnetic calorimeter and loosely matched to the seed clusters. A track and a cluster are considered to be successfully matched if the distance between the track and the EM cluster is $\Delta\eta < 0.05$. To account for the effect of bremsstrahlung losses on the azimuthal distance, the size of the $\Delta\phi$ track–cluster matching window is 0.1 on the side where the extrapolated track bends as it traverses the solenoidal

magnetic field. An electron candidate is considered to be reconstructed if at least one track is matched to the seed cluster. In the case where more than one track is matched to a cluster, tracks with hits in the pixel detector or the SCT are given priority, and the match with the smallest $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ distance is chosen.

The track parameters are precisely re-estimated using an optimised electron track fitter, the Gaussian Sum Filter (GSF) [65], which is a non-linear generalisation of the Kalman filter [58]. It yields a better estimate of the electron track parameters, especially those in the transverse plane, by accounting for the non-linear bremsstrahlung effects. These final tracks are used to perform the final track – cluster matching to build electron candidates and also to provide information for particle identification.

The reconstructed electron energy is determined from the sum of the energy deposits in the cluster. The cluster energy is determined by summing four different contributions: (1) the estimated energy deposit in the material in front of the EM calorimeter, (2) the measured energy deposit in the cluster, (3) the estimated external energy deposit outside the cluster (lateral leakage), and (4) the estimated energy deposit beyond the EM calorimeter (longitudinal leakage). The electron direction, in terms of η and ϕ angles, is determined from the direction of the reconstructed ID track

4.3.1 Electron identification

Not all objects built by the electron reconstruction algorithms are signal electrons. Background objects include hadronic jets as well as background electrons from photon conversions, Dalitz decays and heavy flavour hadron decays. In order to reject as much of these backgrounds as possible while keeping the efficiency for signal electrons high, electron identification in ATLAS is based on discriminating variables. The different background sources can be discriminated with variables describing the longitudinal and transverse shapes of the electromagnetic showers in the calorimeters (shower shapes), the properties of the tracks in the inner detector, as well as the matching between tracks and energy clusters. The variables used in electron identification are listed in Table 6.

In Run 1, the electron identification in ATLAS relied on a cut-based method, both in pp and Pb+Pb collisions. However, in the Run 2 the likelihood (LH) approach has been chosen for electron identification. The LH method is a multivariate analysis (MVA) technique. MVAs are used extensively in physics analyses to separate signal from background, since they allow, in contrast to cut-based methods, the simultaneous evaluation of several properties when making a selection decision. LH method make use of signal and background probability density functions of discriminating variables. Based on these probability density functions, an overall probability is calculated for the event or object to be signal or background. The signal and background probabilities are combined into a discriminant on which a cut is applied. The choice of the discriminant cut value determines the signal efficiency and background rejection of a given likelihood-based operating point

Conditions in the Pb+Pb collisions are characterized by a wide spectrum of the detector occupancy: from just few tracks in the peripheral collisions up to thousands of tracks in the most

Name	Description
R_{had}	Ratio of E_T in the hadronic calorimeter ($ \eta < 0.8$ and $ \eta > 1.37$: first layer of hadronic calorimeter) to E_T of the EM cluster.
R_η	Ratio of the energy in 3×7 cells over the energy in 7×7 cells centred at the electron cluster position.
R_ϕ	Ratio of the energy in 3×3 cells over the energy in 3×7 cells centred at the electron cluster position.
f_1	Ratio of the energy in the first EM calorimeter layer to the total energy.
f_3	Ratio of the energy in the third EM calorimeter layer to the total energy.
w_{η_2}	Lateral shower width calculated in a window of 3×5 cells in the second EM calorimeter layer.
E_{ratio}	Ratio of the energy difference between the largest and second largest energy deposits in the first EM calorimeter layer over the sum of these energies.
$\Delta\eta_1$	$\Delta\eta$ between the cluster position in the first EM calorimeter layer and the extrapolated track.
$\Delta\phi_{\text{res}}$	$\Delta\phi$ between the cluster position in the second EM calorimeter layer and the extrapolated track (with the track momentum rescaled to the cluster energy before extrapolation).
d_0	Transverse impact parameter of electron track.
d_0 significance	Significance of transverse impact parameter defined as the ratio of d_0 over its uncertainty.
TRT PID	Likelihood probability based on transition radiation in the TRT.
$\Delta p/p$	Momentum lost by the track between the perigee and the last measurement point divided by the original momentum.

Table 6: Electron variables used in the LH identification.

central collisions. Therefore, dedicated studies have been performed in order to optimize working points of the LH method. As a result are prepared two requirements: *LooseLH* and *MediumLH*. The *LooseLH* requirement is designed to give 90% efficiency of the electron identification, while the later one gives 80% efficiency of electron the identification. These studies are subject of a separate thesis [66].

5 Lepton isolation

The lack of activity in the detector around a lepton is called isolation. Leptons from $W \rightarrow \ell\nu$ decays are supposed to be isolated as opposed to leptons from various QCD multi-jet backgrounds. Therefore, the use of an isolation variable to enhance the signal-to-background ratio is investigated.

The following isolation variables are defined by ATLAS Collaboration to assess lepton isolation:

- calorimeter based isolation – calorimetric isolation variable $etcone20/pt$ is defined as the sum of the transverse energy deposited in the calorimeter cells in a cone of $\Delta R = 0.2$ around the lepton, excluding the contribution of the lepton itself. It is corrected for energy leakage from the lepton to the isolation cone. pt is a p_T of a given lepton.
- track based isolation – the track isolation variable $ptcone20/pt$ is the sum of the transverse momentum of the tracks with $p_T > 1$ GeV in a cone of $\Delta R = 0.2$ around the lepton, excluding the track of the lepton itself. The tracks considered in the sum be of good quality; i.e. they must have at least four hits in the pixel and silicon strip detectors. pt is a p_T of a given lepton.

5.1 Muon isolation optimization

In the Pb+Pb environment, the default ATLAS isolation requirements dedicated to pp collisions have been found to introduce a lot of inefficiency with increasing centrality (detector occupancy is increasing what cause widening of the isolation distributions). In the extreme case of the most central events, the signal efficiency drops by a factor of two. Therefore, a dedicated optimisation of working points better suited for Pb+Pb collisions is done as part of this measurement. Signal distributions of isolation variables are extracted from the W boson signal MC samples, while QCD multi-jet MC samples with $c\bar{c}$ and $b\bar{b}$ production and subsequent decays to high- p_T muons are used to extract isolation variable distributions for backgrounds representing non-isolated muons.

Usage of a common set of isolation requirements for all events would introduce a dependence of the signal efficiency on centrality. Therefore, the optimisation analysis is performed in several centrality classes. The selection on $ptcone20/pt$ is optimised in bins of centrality to preserve a constant signal efficiency of 90%. Table 7 summarizes the cuts imposed on $ptcone20/pt$ for each centrality class. Further studies shown that introducing additional cut on calorimetric isolation variable does not improve significantly background reduction.

centrality	0–5%	5–10%	10–15%	15–20%	20–30%	30–50%	50–80%
max $ptcone20/pt$	0.446	0.391	0.329	0.284	0.226	0.147	0.063

Table 7: Summary of selection requirements imposed on $ptcone20/pt$ corresponding to 90% signal efficiency for seven centrality classes.

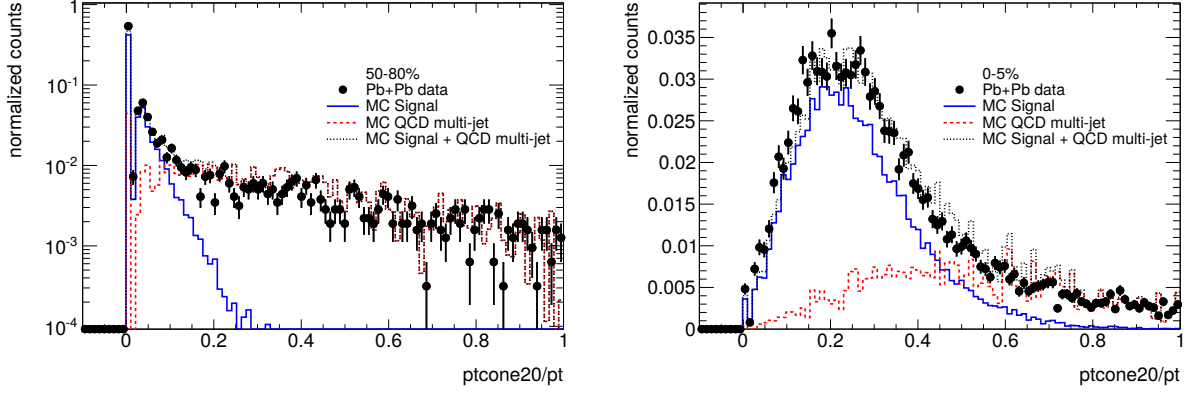


Figure 18: Distribution of $ptcone20/pt$ for muons from W boson decays from data (points), signal (solid line) and background (dashed line) from MC for two centrality classes: 50–80% (left) and 0–5% (right). The sum of the signal and background components is also shown.

Figure 18 presents distributions of $ptcone20/pt$ isolation variable in 50–80% and 0–5% centrality classes. The background MC sample is normalised to the number of events in data for $ptcone20/pt > 0.8$ where the contribution from signal is expected to be negligible. The signal MC sample is normalised to the number of muon candidates in the data in the signal region defined by the cuts in Table 7 after background subtraction. One can notice that $ptcone20/pt$ distributions is widening with centrality. A good agreement between data and MC predictions is found in the shape of the two distributions.

5.2 Electron isolation optimization

As in the case of muons, the electron isolation requirements have also been optimized. No precise simulation of multi-jet background processes with electrons in the final state is available, so the W boson signal MC is used together with data-driven techniques. Figure 19 shows the mean value of the given isolation variable as a function of electron p_T . The electrons used for these studies are required to pass the W boson analysis selection defined in Section 8 removing the isolation condition. The multi-jet background is not subtracted from data, so that the mean values of the isolation variables are expected to be higher than in the signal MC. In particular, the local minimum visible in the $etcone20/pt$ distribution in data around 40 GeV results from the fact that electrons from W boson decays dominate over background. One can notice that the calorimetric isolation variable provides discrimination between signal and background electrons, since the mean value in data (which can be treated as a composition of signal and background electrons) differs significantly from the mean value extracted from signal MC. It is not the case for the tracking isolation variable for which the mean value in data and signal MC is not much different above 35 GeV. Based on these studies, the $etcone20/pt$ isolation variable is selected to prepare isolation cuts. Similarly to the muon case, the requirements on $etcone20/pt$ are optimised in bins of centrality to preserve a constant signal efficiency at 95%.

With the prepared isolation working point, the estimated fraction of the multi-jet background in W boson candidates is around 30%. Such a huge background contamination in data can result

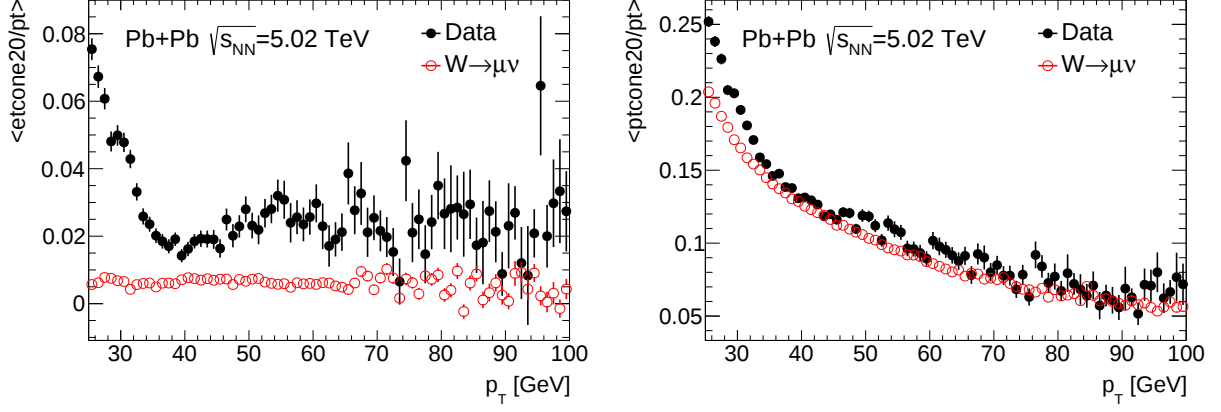


Figure 19: Mean value of $etcone20/pt$ (left) and $ptcone20/pt$ (right) as a function of electron p_T for electrons from W boson candidate events in data (black markers) and signal (red markers) MC.

in a significant systematic uncertainty on the W boson production yields. In order to further reduce the multi-jet background contamination, tighter isolation requirements are tested. It is found that tightening isolation selection affects mainly the signal efficiency, while the background fraction is not reduced significantly. Another way of reducing the multi-jet background contamination is redefining the tracking isolation variable in a way that increases its discriminative power. The Run 1 W boson measurement [67] showed that tracking isolation has a better performance in the Pb+Pb environment when using tracks with $p_T > 2$ GeV (1 GeV is the default cut). Following this approach, the tracking isolation is re-calculated using tracks satisfying the 2 GeV cut and passing HI Loose track quality requirements (for definition see Section 4.1). One needs to consider the track which is originating from the signal electron, and therefore the track matched best to the electron EM cluster is not taken into account while calculating the redefined tracking isolation variable. Electrons can also radiate bremsstrahlung, and the radiated pho-

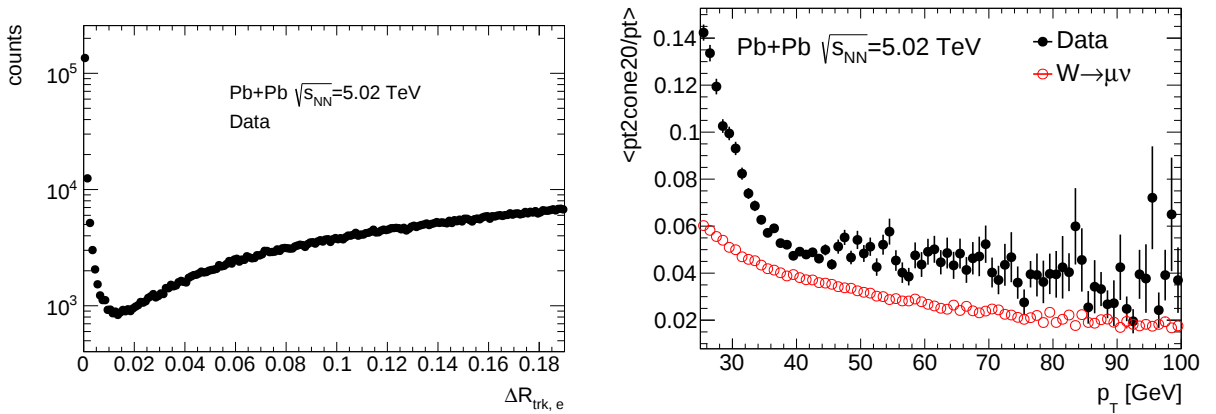


Figure 20: (Left) Distribution of distance between all reconstructed ID tracks passing HI Loose track quality requirements (for definition see Sec. 4.1) and electrons passing W boson analysis requirements in data. (Right) Mean value of $pt2cone20/pt$ as a function of electron p_T for electrons from W boson candidate events in data (black markers) and signal (red markers) MC.

centrality [%]	max $etcone20/pt$	max $pt2cone20/pt$
0–5	0.2	0.1
5–10	0.185	0.1
10–15	0.17	0.1
15–20	0.155	0.1
20–25	0.14	0.1
25–30	0.125	0.1
30–40	0.11	0.1
40–45	0.095	0.1
45–50	0.08	0.1
50–60	0.065	0.1
60–80	0.05	0.1

Table 8: Summary of selection requirements imposed on the $etcone20/pt$ and $pt2cone20/pt$ for given centrality classes.

tons can subsequently convert into secondary electrons which should also not be counted in an isolation variable. Therefore, tracks which are within $\Delta R_{\text{trk},e} < 0.01$ distance from the considered electron are rejected from the isolation calculations. Figure 20 (left) shows the distribution of $\Delta R_{\text{trk},e}$ between all reconstructed ID tracks passing HILoose track quality requirements and electrons passing W boson analysis requirements (Section 8). This distribution contains both the tracks which are originating from signal electrons and tracks from the underlying event. It can be noticed that the minimal distance of 0.01 is justified as above that value tracks from the underlying event are dominating.

The mean value of the redefined tracking isolation variable, $pt2cone20/pt$, is presented in Figure 20 (right) as a function of electron p_T . By comparing it to the right panel of Figure 19 it can be noticed that the new tracking isolation variable has better separation power. Moreover, the performance of this variable does not depend strongly on centrality, and therefore a constant cut on it is imposed in the analysis.

Table 8 summarizes the optimised isolation requirements for electrons. Using cuts on both the calorimetric and tracking isolation variables helps to reduce the multi-jet background contamination from 30% to 18%. The studies of efficiency of the electron isolation selection are described in Sec 6.7.

6 Lepton performance

Various aspects of the muon and electron performance, including trigger, reconstruction, identification and isolation efficiencies, have been studied extensively in both the data and simulation for $\sqrt{s_{\text{NN}}} = 5.02$ TeV Pb+Pb collisions. A summary of these performance studies can be found in the following subsections. The W boson analyses in both channels use efficiency corrections derived in-situ for $\sqrt{s_{\text{NN}}} = 5.02$ TeV collisions.

The efficiency corrections are applied to simulated events in the form of per-lepton scale factors (SF) defined as the ratio of efficiencies measured in data and in MC simulation:

$$\text{SF} = \frac{\epsilon^{\text{data}}}{\epsilon^{\text{MC}}}. \quad (28)$$

Efficiencies which form the input for SF calculation are measured as a function of lepton η or two-dimensionally as a function of both lepton η and p_{T} . The detector occupancy dependence of efficiencies is also checked. The SFs are then calculated separately for each efficiency type and finally combined in a single event weight. In the $W \rightarrow e\nu$ analysis the total per-event SF is calculated as:

$$\text{SF}_{\text{total}}^e = \text{SF}_{\text{reco}}^e \cdot \text{SF}_{\text{ID}}^e \cdot \text{SF}_{\text{iso}}^e \cdot \text{SF}_{\text{trig}}^e, \quad (29)$$

while in the $W \rightarrow \mu\nu$ analysis it is equal to:

$$\text{SF}_{\text{total}}^\mu = \text{SF}_{\text{reco/ID}}^\mu \cdot \text{SF}_{\text{iso}}^\mu \cdot \text{SF}_{\text{trig}}^\mu. \quad (30)$$

6.1 Muon reconstruction and identification efficiency

The efficiencies of muon reconstruction and identification are measured in both the data and MC simulation with the Tag-and-Probe (TP) method, which serves as a data-driven approach and allows for a direct comparison of efficiencies measured in data and MC simulation [60]. The method is based on the selection of a very pure sample of muons produced in $Z \rightarrow \mu^+\mu^-$ decays, requiring one leg of the decay (tag) to be identified as a *Medium* quality muon and the second leg (probe) to be reconstructed by a system independent of the one under study. The efficiency measurements for *Medium* quality muons consist of two stages. First, the efficiency $\epsilon(\text{medium}|\text{CT})$ of reconstructing these muons is measured assuming a reconstructed CT muons as probes. The efficiency is defined as the ratio of the number of CT probes which are matched to a *Medium* quality muon to the total number of CT probes.:

$$\epsilon(\text{medium}|\text{CT}) = \frac{N_{\text{CT probes}}^{\text{medium matched to CT}}}{N_{\text{CT probes}}} \quad (31)$$

Geometrical matching of *Medium* quality muons with CT muons is performed by requiring $\Delta R_{\text{CT,medium}} < 0.05$. To reduce the impact of backgrounds, both the tag and the probe are required to match the signature of a Z boson decay, i.e. probes must have a charge opposite to the tag muon and form together with it a pair with an invariant mass in the range

$81 < m_{\mu\mu} < 101$ GeV. The underlying idea of using $Z \rightarrow \mu^+\mu^-$ decays is identify muons by using event topology rather than cuts on the identification variables. Then, this result is multiplied by the efficiency $\epsilon(\text{CT}|\text{MS})$ of the CT muon reconstruction, measured using MS tracks as probes:

$$\epsilon(\text{CT}|\text{MS}) = \frac{N_{\text{MS probes}}^{\text{CT matched to MS}}}{N_{\text{MS probes}}} \quad (32)$$

As in the case of $\epsilon(\text{medium}|\text{CT})$ the MS probes must have a charge opposite to the tag muon and form together with it a pair with an invariant mass in the range $81 < m_{\mu\mu} < 101$ GeV. The reconstruction and identification efficiency of *Medium* quality muons is given by:

$$\epsilon(\text{medium}) = \epsilon(\text{medium}|\text{CT}) \cdot \epsilon(\text{CT}) = \epsilon(\text{medium}|\text{CT}) \cdot \epsilon(\text{CT}|\text{MS}) \quad (33)$$

This approach is valid if the CT muon reconstruction efficiency is independent from the muon spectrometer track reconstruction ($\epsilon(\text{CT}) = \epsilon(\text{CT}|\text{MS})$). This assumption is fulfilled as CT muons are reconstructed by tracker and calorimeter which are systems fully independent from the muon spectrometer.

The efficiency $\epsilon(\text{medium})$ is measured in data and MC simulation. The level of agreement between these two measurements is quantified with reconstruction and identification scale factors:

$$\text{SF}_{\text{reco/ID}}^{\mu} = \frac{\epsilon^{\text{data}}(\text{medium})}{\epsilon^{\text{MC}}(\text{medium})} \quad (34)$$

This quantity describes the deviation of the simulated muon reconstruction and identification performance from the one in data. If SFs are found to be different from unity, they can be used to reweight the simulation. The TP method defines the tag as follows:

- *Medium* quality muons,
- $p_{\text{T}} > 24$ GeV,
- $|\eta| < 2.4$
- $|d_0|/\sigma(d_0) < 3$,
- $|z_0| < 10$ mm,
- matched to the HLT_mu8 trigger (data only, since trigger is not simulated in MC samples).

Figure 21 presents invariant mass distributions of TP pairs build from CT probes in data and MC simulation for both the efficiency numerator and denominator, see Eq. (31). The same-charge distributions, which are used to estimate the combinatorial background, are also presented. The impact of the combinatorial background is almost negligible, however in order to remove the background contamination in data the same-charge distribution is subtracted. Such an approach is valid since the multijet background, which contributes most of the combinatorial same-charge pairs, is dominant over $Z \rightarrow \tau^+\tau^-$ and $t\bar{t}$ backgrounds [68]. The combinatorial background is subtracted from both the numerator and denominator. The efficiency measured in data and MC simulation is presented in Figure 22 as a function of the probe η and p_{T} . The ratios of efficiencies measured in data and simulation are presented in the bottom panels of the plots. The efficiency

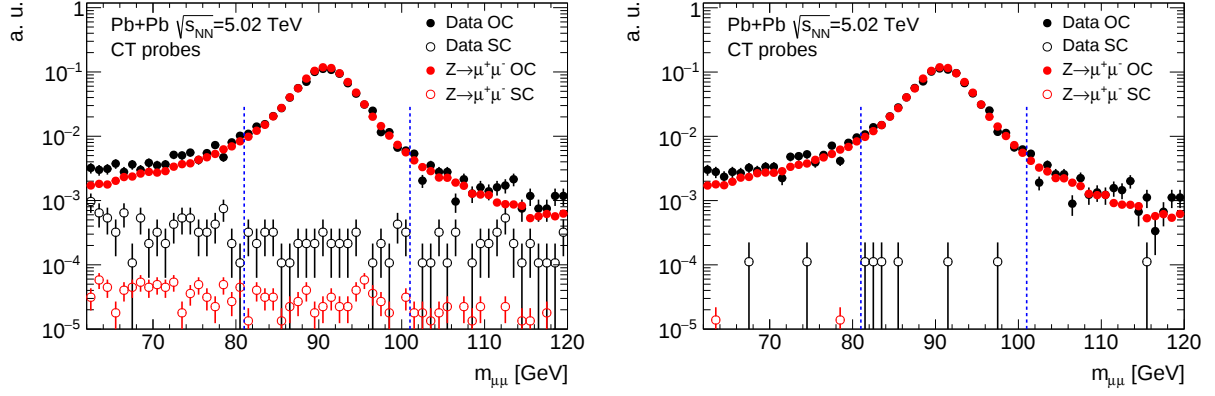


Figure 21: Invariant mass distributions of tag and probe pairs with CT muons as probes, shown for both the opposite-charge and same-charge pairs. The $Z \rightarrow \mu^+\mu^-$ MC simulation is represented by red markers while for data black markers are used (open - same charge, solid - opposite charge). Distributions are presented for the efficiency denominator (left) and numerator (right).

in data is measured to be above 98% and constant as a function of both the probe η and p_T . The MC simulation describes data well in the range $-1.85 < \eta < 1.85$, while in the forward region the simulated efficiency is $\sim 3\%$ lower than in data. The right plot in Figure 22 shows that the decrease of efficiency in simulation is not p_T dependent. In order to correct for the observed discrepancy, scale factors for the reconstruction and identification efficiency are introduced to the analysis only as a function of muon η .

The efficiency of the CT muon reconstruction is measured using MS probes. The invariant mass distributions of TP pairs in data and MC simulation are presented in Figure 23 for both the efficiency numerator and denominator. The same-charge distributions are also shown and they indicate a weak impact of the level of combinatorial background on the efficiency measurements. The efficiency is defined as the number of MS probes which are matched to a CT muon divided by the number of all MS probes. Figure 24 shows the efficiency measured in data and MC

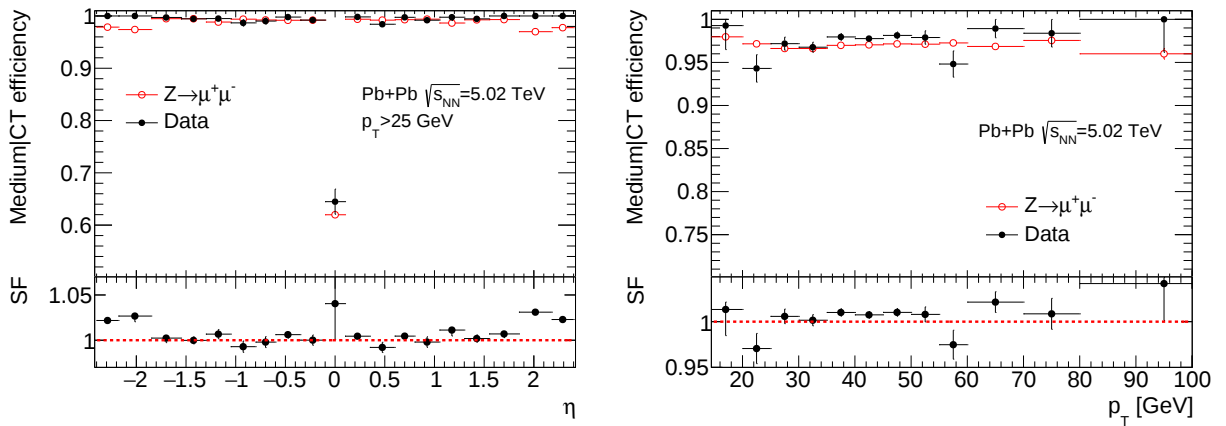


Figure 22: Reconstruction and identification efficiency of *Medium* quality muons with respect to CT muons as a function of η (left) and p_T (right). Bottom panels show the data to MC simulation ratios.

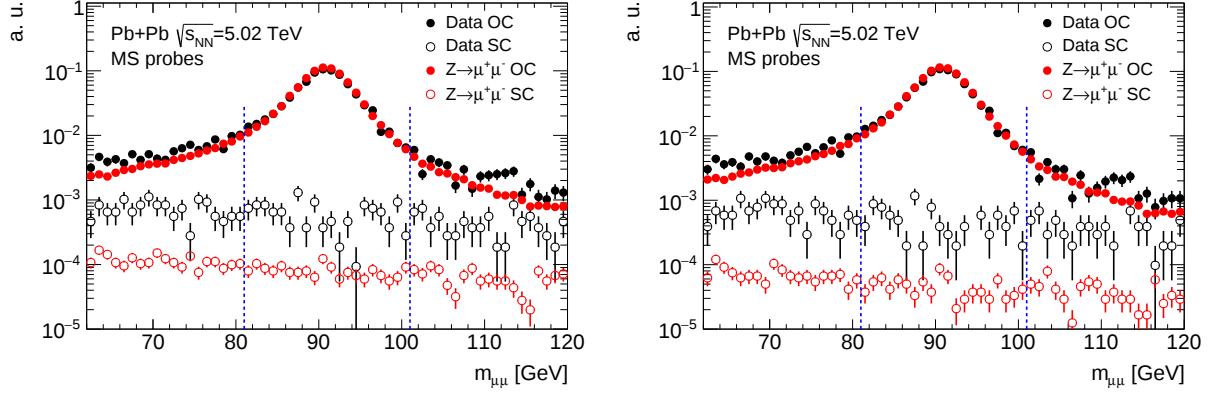


Figure 23: Invariant mass distributions of tag and probe pairs with MS tracks as probes, shown for both the opposite-charge and same-charge pairs. The $Z \rightarrow \mu^+ \mu^-$ MC simulation is represented by red markers while for data black markers are used (open - same charge, solid - opposite charge). Distributions are presented for the efficiency denominator (left) and numerator (right).

simulation as a function of the probe η and p_T . The efficiency is measured to be $\sim 98\%$ in the central region and is slowly falling in the forward region reaching $\sim 92\%$ at $|\eta| = 2.4$. The MC simulation seems to describe data well in the entire η and p_T range in contrast to the efficiency $\epsilon(\text{medium}|\text{CT})$ which shows 2–3% differences in the forward region.

According to Eq. (33), the total efficiency can be obtained as a product of two components presented in Figure 22 and Figure 24. Figure 25 presents the total efficiency of reconstructing *Medium* quality muons as a function of η , while the bottom panels show scale factors with propagated statistical errors. Figure 26 presents a comparison of SFs measured separately for the two muon charges. In order to test the compatibility between SFs obtained for the two charges the χ^2 test was performed, which gives $\chi^2/\text{n.d.f.} = 20.2/18$. Therefore it can be concluded that there are no significant differences between positive and negative muons, thus charge-integrated SFs are used in the analysis.

The dependence of reconstruction SFs on FCal ΣE_T is also tested as shown in Figure 25.

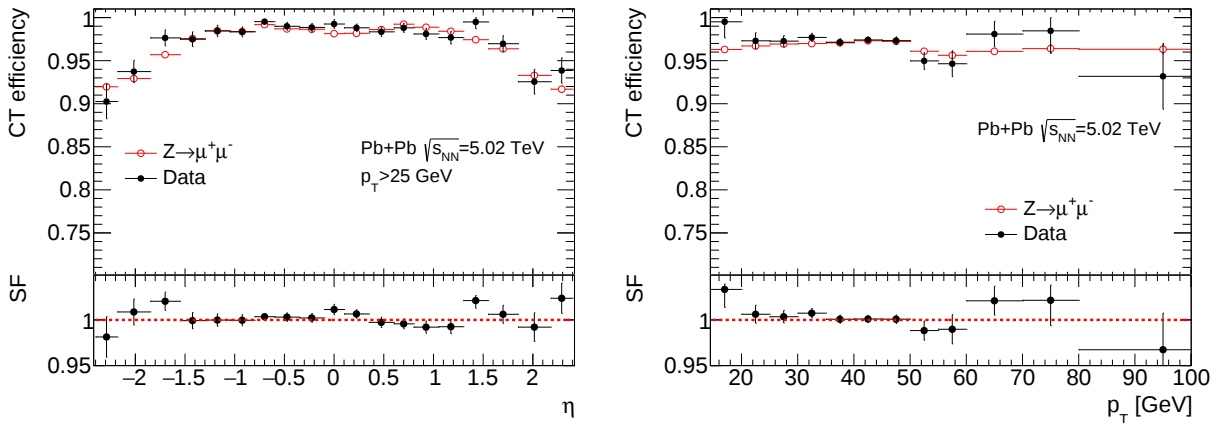


Figure 24: Efficiency of reconstructing CT muons with respect to the MS muons as a function of η (left) and p_T (right). Bottom panels show data to MC simulation ratio.

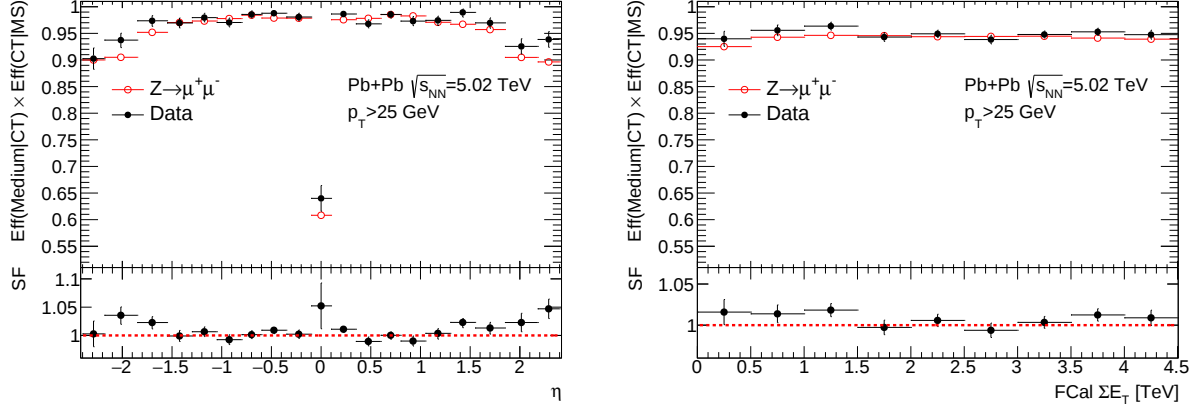


Figure 25: Total reconstruction and identification efficiency for *Medium* quality muons as a function of muon η (left) and FCal ΣE_T (right). The bottom panel shows efficiency SFs.

It can be concluded that the SFs do not dependent on detector occupancy within the statistical precision of the measurement.

Contributions from systematic effects considered for the *Medium* quality muon reconstruction and identification efficiency SFs are estimated following the methodology applied to SF measurements in $\sqrt{s} = 13$ TeV pp collisions [60]. The following sources of systematic uncertainties are considered:

- variation of the background scaling factor to 0 or 2 (by default the same-charge distribution is not scaled by any factor),
- variation of cone size ΔR for probe matching to 0.025 or 0.1 (default value is 0.05).

The summary of statistical and systematic uncertainties of the *Medium* quality muon reconstruction and identification scale factors is presented in Figure 27 as a function of muon η . The

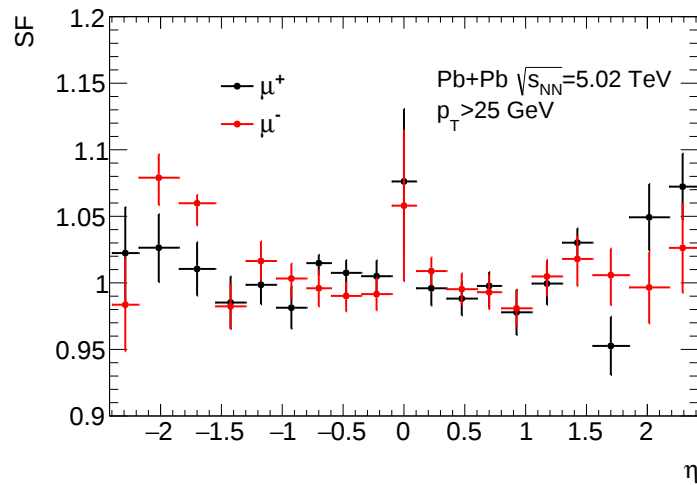


Figure 26: Comparison of reconstruction and identification SFs measured separately for positive and negative muons.

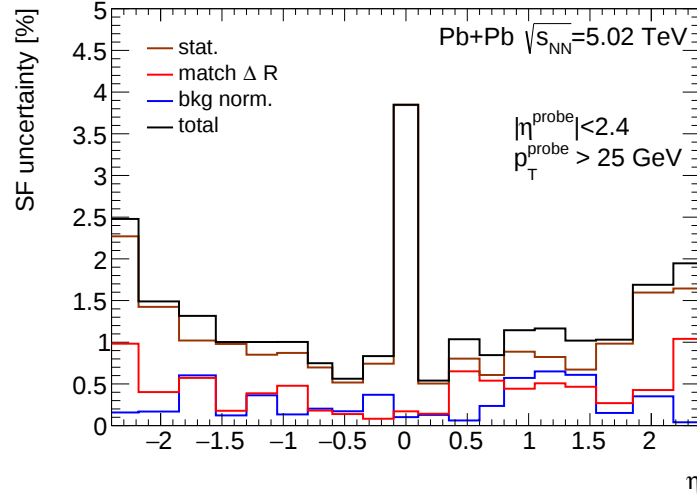


Figure 27: Summary of uncertainties of the *Medium* quality muon reconstruction and identification scale factors as a function of muon η . The black histogram corresponds to the total uncertainty which is a result of adding in quadrature statistical and systematic uncertainties.

uncertainties are dominated by the statistical component, while the contributions from systematic effects are mostly at the permille-level. Since the statistical uncertainty is dominant, the systematic uncertainties are neglected in the further analysis.

6.2 Muon trigger efficiency

At the HLT, the HLT_mu8 trigger chain selects events containing a muon with $p_T > 8$ GeV. It is seeded from the Level-1 trigger L1_MU6 requiring a muon with $p_T > 6$ GeV. The efficiency of the single-muon trigger is measured with the TP method using $Z \rightarrow \mu^+\mu^-$ candidate events [44] in data only, since the trigger decision is not simulated in the muon channel MC samples. By selecting events in which one of the decay muons (tag) is required to pass a stricter selection, while both opposite-charge muons fall into the Z boson mass window, one obtains a pure sample of muons (probes) to study the trigger performance. The selection of TP candidate events and requirements on the tag and probe muons are summarised in Table 9. The trigger efficiency is defined as a ratio of probes matched to the object reconstructed online at the level of trigger (HLT muon) over all probes satisfying the given requirements:

$$\epsilon(\text{HLT_mu8}) = \frac{N_{\text{matched probes}}}{N_{\text{probes}}} \quad (35)$$

In principle one of the muon is used to select event sample, while the another one is used to study trigger performance.

The measurement of the single-muon trigger efficiency is performed using opposite-charge TP pairs. Same-charge TP pairs are used for an estimate of the possible combinatorial background contribution. The sample of events selected for the measurement is very pure, since the number of observed same-charge pairs is negligible as shown in Figure 28.

	Tag muon	Probe muon
Quality	<i>Medium</i> identification	
Kinematics	$p_T > 24 \text{ GeV}, \eta < 2.4$	
Impact parameter	$ \frac{d_0}{\sigma(d_0)} < 3$ and $ z_0 < 10 \text{ mm}$	
trigger match		$\Delta R < 0.1$
Pair invariant mass	$81 < m_{\text{tag+probe}} < 101 \text{ GeV}$	

Table 9: Requirements for selecting tag-and-probe pairs from $Z \rightarrow \mu^+ \mu^-$ candidate events for the measurement of the single-muon trigger efficiency.

The measurements of the trigger efficiency as a function of the probe muon p_T and η are presented in Figures 29 and 30. The turn-on of the trigger efficiency can be noticed around muon $p_T = 8 \text{ GeV}$. Within statistical precision there is no dependence of the trigger efficiency in a plateau from the muon p_T (what is the expected behaviour of the trigger). The trigger efficiency is measured to be around 70% in the barrel region ($|\eta| < 1.05$) and around 90% in the endcap region ($1.05 < |\eta| < 2.4$) of the detector. This large difference between the trigger efficiency measured in the barrel and endcap regions can be attributed to different types of the L1 trigger systems used in these two regions.

Collisions of lead nuclei can be characterized by a broad spectrum of detector occupancy. In order to compare the muon trigger performance in peripheral and central events, the trigger efficiency is measured as a function of FCal ΣE_T , which is shown in Figure 30. A constant fit to the data is performed to test the dependence of trigger efficiency on FCal ΣE_T and the fit parameters are given in the plot. The resulting $\chi^2/\text{n.d.f.} = 11.98/8$ translates to a p -value of 0.152 which allows to conclude that the FCal ΣE_T dependence of the efficiency can be neglected in the further analysis.

The possible dependence of the trigger efficiency on the muon charge is studied in Figure 31. The statistically limited precision of the measurement does not allow to draw firm conclusions,

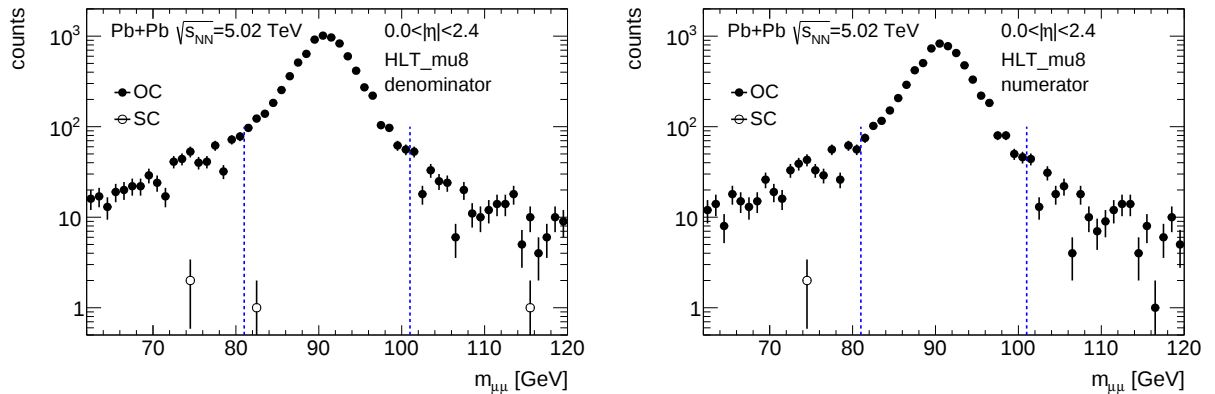


Figure 28: Invariant mass distributions of TP muon pairs used in the trigger efficiency measurement. Distributions are presented for pairs with the probe muon reconstructed for the efficiency denominator (left) and numerator (right). Both the opposite-charge and same-charge pairs are shown.

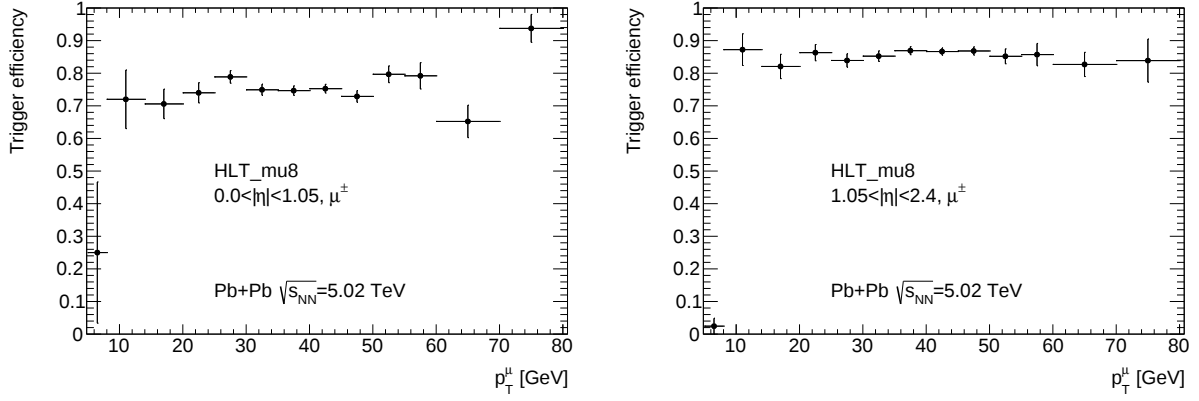


Figure 29: Efficiency of the single-muon trigger HLT_mu8 measured as a function of muon p_T in the barrel region (left) and in the endcap region (right) in data.

however small differences between efficiencies measured for positive and negative muons are visible in the barrel region. The measured efficiency is applied as a weight to signal MC samples as a function of η and charge.

Contributions from systematic effects considered for the HLT_mu8 trigger efficiency are estimated following the methodology applied to trigger efficiency measurements in $\sqrt{s} = 13$ TeV pp collisions [44]. The following sources of systematic uncertainties are considered:

- variation of pair invariant mass range to $76 < m_{\text{tag+probe}} < 106$ GeV or $86 < m_{\text{Tag+Probe}} < 96$ GeV,
- variation of cone size ΔR for matching probes to HLT muons to 0.05 or 0.15 (default is 0.1),
- additional cut $\Delta\phi_{\text{tag, probe}} < \pi - 0.1$ (default is no cut) to check possible impact of tag-probe correlation.

For efficiency measurements at $\sqrt{s} = 13$ TeV also a change of the background scaling factor to 0.5 or 2 is considered. In this study it is neglected since only one event with a same-charge

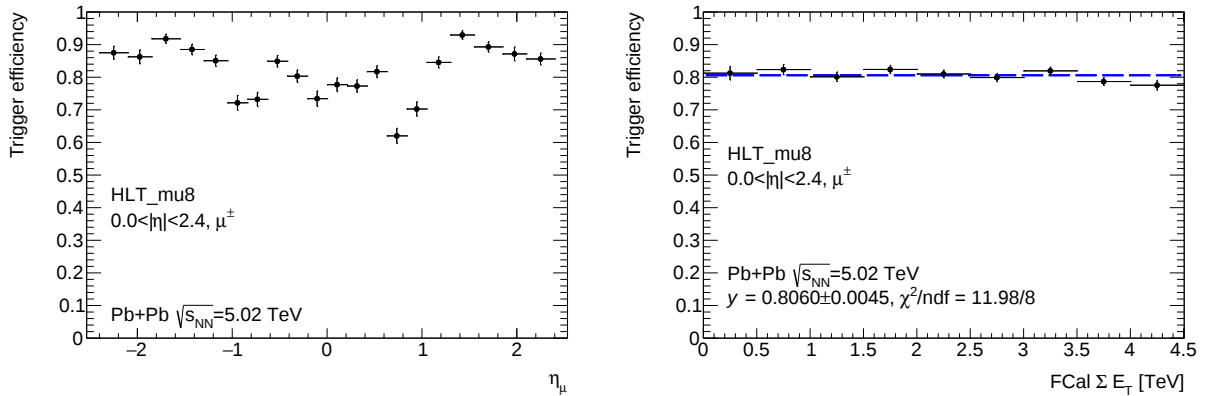


Figure 30: Efficiency of the single-muon trigger HLT_mu8 measured as a function of muon η (left) and FCal ΣE_T (right) in data. A constant fit to the data is performed to test the dependence of trigger efficiency on FCal ΣE_T and the fit parameters are given in the plot.

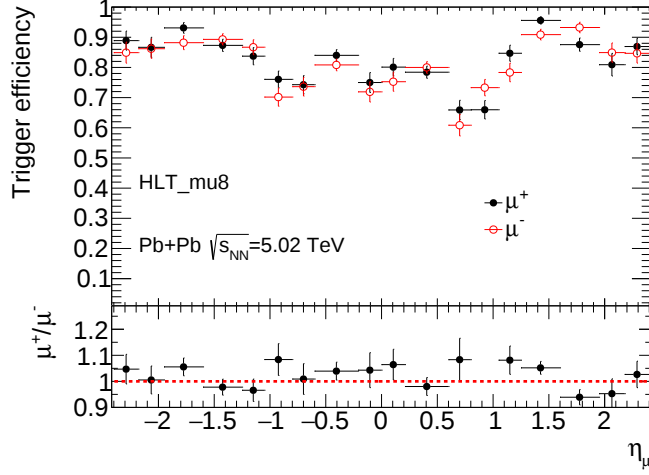


Figure 31: Efficiency of the single-muon trigger HLT_mu8 measured as a function of muon η . Presented are efficiencies measured separately for positive and negative muons in data.

pair falls into the $81 < m_{\text{tag+probe}} < 101$ GeV mass range. The impact of a tag-probe correlation in ϕ on the measured trigger efficiency is tested by dividing the sample of Z boson candidates into two statistically independent subsamples. TP pairs in one of the subsamples are satisfying the requirement $\Delta\phi_{\text{tag, probe}} < \pi - 0.1$, while for the other subsample this cut is inverted. A comparison of trigger efficiencies measured using the two subsamples is shown in Figure 32 for both muon charges. One can notice that there is no sensitivity to possible tag-probe correlations within the statistical precision of the measurement.

The summary of statistical and systematic uncertainties of the measured HLT_mu8 trigger efficiency is presented in Figure 33 as a function of muon η . The uncertainties are dominated by the statistical component and the only non-zero systematic effect is related to the definition of the pair invariant mass range. Since the statistical uncertainty is dominant, the systematic uncertainties are neglected in the further analysis.

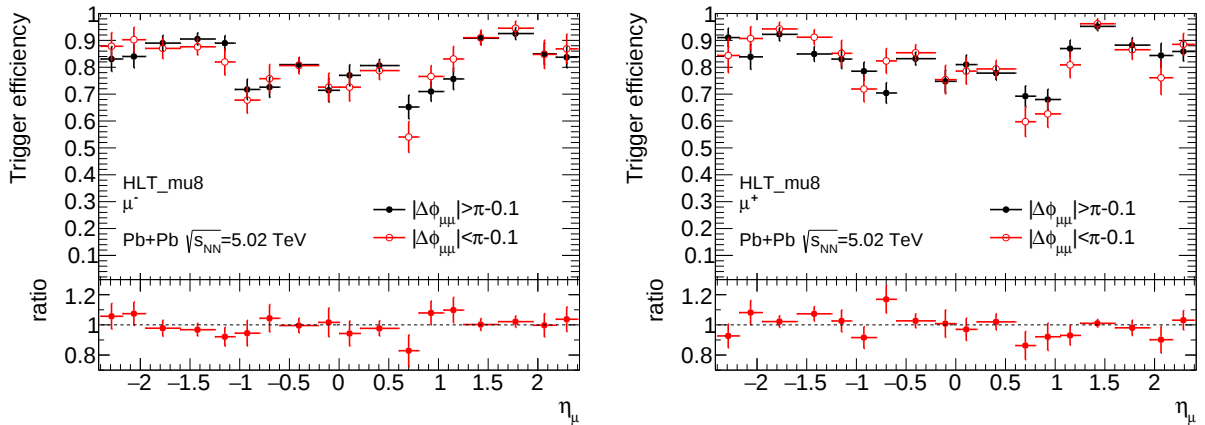


Figure 32: Efficiency of the single-muon trigger HLT_mu8 measured in events with TP pairs satisfying $\Delta\phi_{\text{tag, probe}} < \pi - 0.1$ (red markers) and in events selected with an inverted cut (black markers) for negative (left) and positive (right) muons.

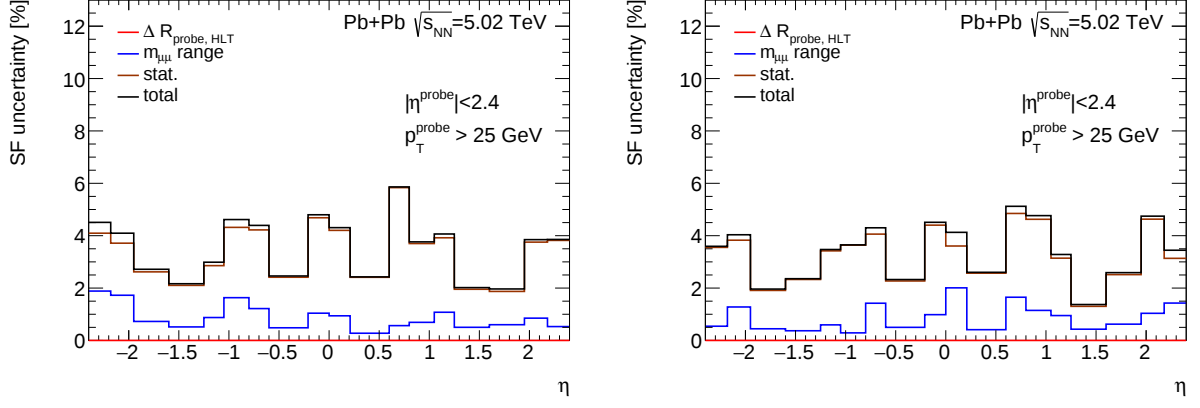


Figure 33: Summary of uncertainties of the HLT_mu8 trigger efficiency as a function of muon η for negative (left) and positive (right) muons. The black histogram corresponds to the total uncertainty which is a result of adding in quadrature statistical and systematic uncertainties.

6.3 Muon isolation efficiency

The efficiency of the optimised isolation selection (Section 5.1) is measured with the TP method in $Z \rightarrow \mu^+ \mu^-$ candidate events in both the data and MC simulation [60]. In principle the idea is very similar to the measurement of the trigger efficiency given in the Section 6.2. The isolation efficiency is defined as a ratio of isolated probes over all probes satisfying given requirements

$$\epsilon(iso) = \frac{N_{\text{isolated probes}}}{N_{\text{probes}}} \quad (36)$$

The selection of TP candidate events and requirements on the tag and probe muons are summarised in Table 10. Opposite-charge muon pairs are used to obtain the isolation efficiency, while same-charge pairs are used to estimate background, however their contribution is negligible as shown in Figure 34.

The measurements of the isolation efficiency measured in data and the $Z \rightarrow \mu^+ \mu^-$ signal MC sample as a function of the probe muon p_T , η and FCal ΣE_T are presented in Figures 35 and 36. In both the data and MC simulation, the measured isolation efficiency increases from around 80% at $p_T^\mu = 25$ GeV to around 98% at $p_T^\mu = 50$ GeV and then slowly increases further approaching 100%. The efficiency "steps" in a function of FCal ΣE_T are due to that applied isolation cuts are in a wider bins than presented measurement. It is not affecting W boson measurement since results

	Tag muon	Probe muon
Quality	Medium identification	
Kinematics	$p_T > 25$ GeV, $ \eta < 2.4$	
Pair invariant mass	$81 < m_{\text{tag+probe}} < 101$ GeV	
Pair distance ΔR	$\Delta R_{\text{tag+probe}} > 0.4$	

Table 10: Requirements for selecting tag-and-probe pairs from $Z \rightarrow \mu^+ \mu^-$ candidate events for the measurement of the isolation efficiency.

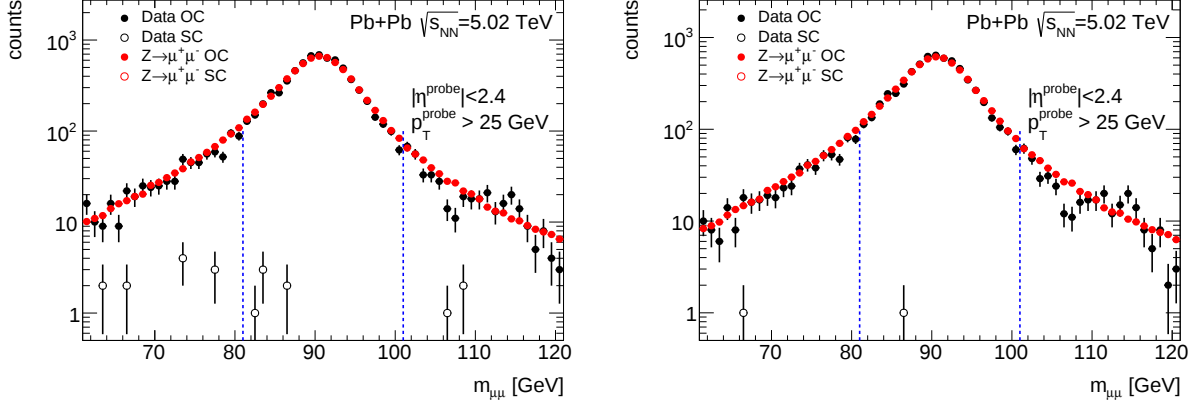


Figure 34: Invariant mass distributions of TP muon pairs used in the isolation efficiency measurement. Distributions are presented for the efficiency denominator (left) and numerator (right). Both the opposite-charge and same-charge pairs are shown and the MC simulation distributions are normalized to the number of counts in data.

are corrected for that effect. The efficiency scale factors are consistent with unity within the statistical precision of the measurement, and are thus not applied to MC samples in the analysis. However, the isolation SF uncertainties are propagated to the final results as a function of η .

The possible dependence of the isolation SFs on the muon charge is studied as presented in Figure 37. It is found that the isolation efficiency scale factors do not depend on the muon charge.

Contributions from systematic effects considered for the isolation efficiency scale factors are estimated following the methodology applied to scale factor measurements in $\sqrt{s} = 13$ TeV pp collisions [60]. The following sources of systematic uncertainties are considered:

- variation of the pair invariant mass range to $76 < m_{\text{tag+probe}} < 106$ GeV or $86 < m_{\text{tag+probe}} < 96$ GeV,
- variation of minimal ΔR distance between tag and probe to 0.3 or 0.5 (default value is 0.4),

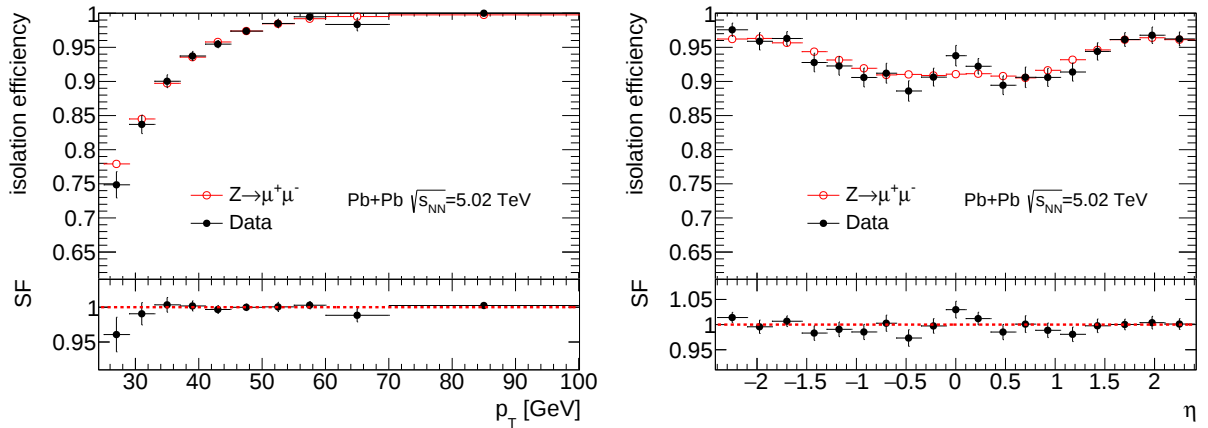


Figure 35: Efficiency of the isolation selection measured as a function of muon p_T (left) and η (right) in data and the $Z \rightarrow \mu^+ \mu^-$ MC sample. The bottom panels present efficiency scale factors.

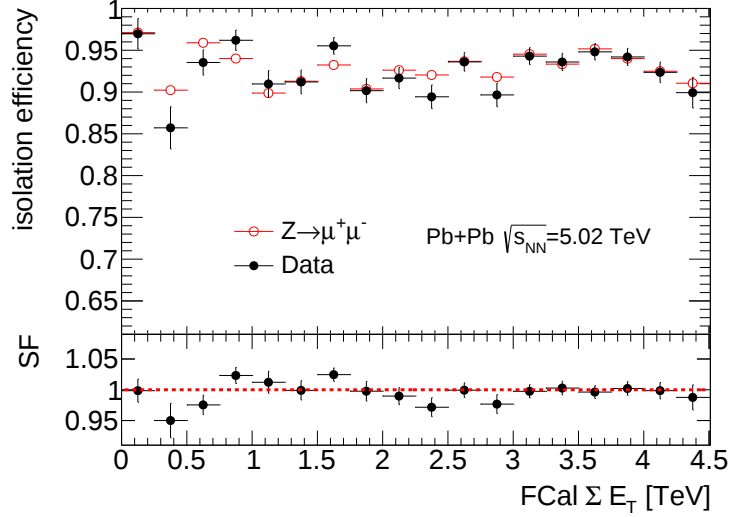


Figure 36: Efficiency of the isolation selection measured as a function of $\text{FCal } \Sigma E_T$ in data and the $Z \rightarrow \mu^+ \mu^-$ MC sample. The bottom panel presents efficiency scale factors.

- variation of the background scaling factor to 0.5 or 2 (by default the same-charge distribution is not scaled by any factor).

The summary of statistical and systematic uncertainties of the isolation scale factors is presented in Figure 38 as a function of muon η . There is found no effect from varying ΔR distance between tag and probe. The uncertainties are dominated by the statistical component, while the contributions from systematic effects are mostly at the permille-level. Only statistical uncertainties are propagated in the analysis and systematic uncertainties are neglected.

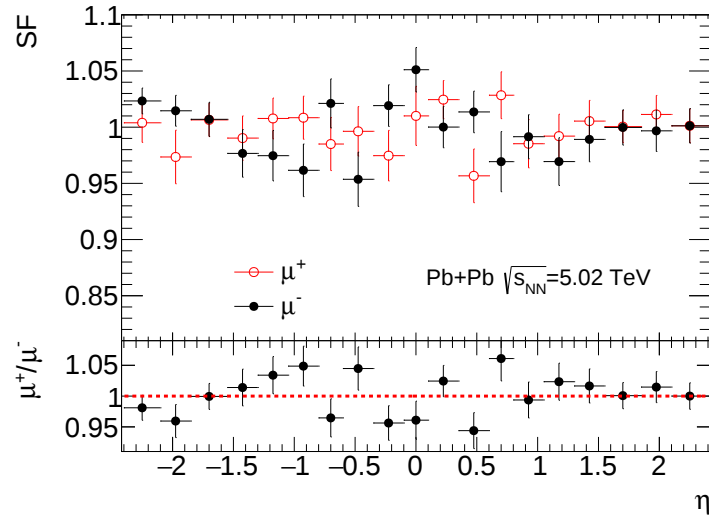


Figure 37: Isolation efficiency scale factors measured as a function of muon η , separately for positive and negative muons. The bottom panel presents the ratio of SFs measured for both charges.

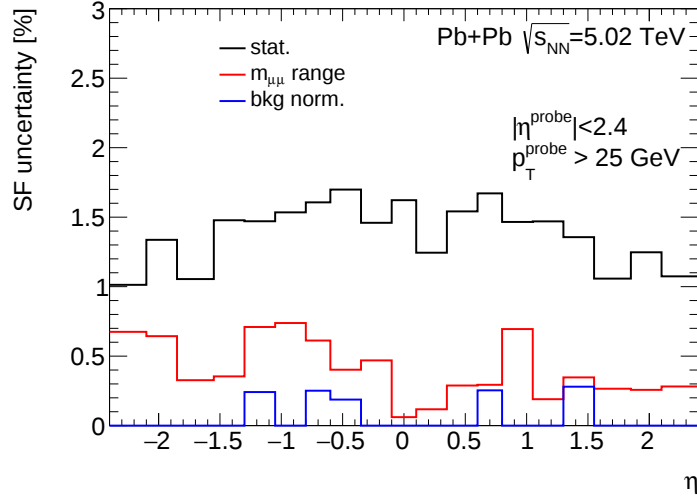


Figure 38: Summary of uncertainties of the isolation scale factors as a function of muon η .

6.4 Electron performance

The measurements of electron-related efficiencies follow a general ATLAS procedure of measuring electron performance described in Ref. [69]. Some adjustments are applied to the measurement methodology in order to take into account specifics of the Pb+Pb environment and statistical limitations of the sample of $Z \rightarrow e^+e^-$ candidates in data. The most important change is the use of the FCal ΣE_T reweighting described in Section 3.4 instead of the default pile-up reweighting procedure for pp collisions.

The TP method in $Z \rightarrow e^+e^-$ events is used in all of the analyses described in following subsections. A strict selection on one of the electron candidates, tag, together with a requirement on the dielectron invariant mass allows for a loose pre-identification of the other electron candidate, probe. The probe is used for the measurement of the reconstruction, identification, isolation and trigger efficiencies, after accounting for the residual background contamination. This method is similar to the method of extracting efficiencies for muons. However, there are some differences resulting from different reconstruction of electrons and muons in the ATLAS detector. Usually, electron sample contaminate more background events since EM calorimeter is the first system just after tracker. This is not the case for the muons, where most of the background particles are stopped in a EM or hadronic calorimeter. The second important difference is charge misidentification, where the charge of an electron is incorrectly identified. It is known generally that muon charge misidentification is negligible while electron charge misidentification is not negligible. Therefore, one can not use same-charge distribution as a background template.

The efficiency ϵ is defined as the fraction of probe electrons satisfying the tested criteria. It is divided into different components, namely trigger, isolation, identification and reconstruction efficiencies. The total efficiency for a single electron can be written as:

$$\epsilon_{\text{total}} = \epsilon_{\text{reco}} \times \epsilon_{\text{id}} \times \epsilon_{\text{iso}} \times \epsilon_{\text{trig}} = \frac{N_{\text{reco}}}{N_{\text{clusters}}} \times \frac{N_{\text{id}}}{N_{\text{reco}}} \times \frac{N_{\text{iso}}}{N_{\text{id}}} \times \frac{N_{\text{trig}}}{N_{\text{iso}}}. \quad (37)$$

The efficiency components are measured in a specific order to preserve consistency. The reconstruction efficiency ϵ_{reco} is measured with respect to electron clusters reconstructed in the EM calorimeter N_{clusters} , the identification efficiency ϵ_{id} is determined with respect to reconstructed electrons N_{reco} , the isolation efficiency ϵ_{iso} is calculated for reconstructed electrons passing a given identification criterion N_{id} , and the trigger efficiency ϵ_{trig} is calculated for reconstructed electrons satisfying given isolation and identification criteria N_{iso} .

6.5 Electron reconstruction efficiency

Electrons are reconstructed in ATLAS from the combination of a cluster of energy deposits in the EM calorimeter and a matching ID track (details are given in Section 4.3). The TP method is employed for estimating the electron reconstruction efficiency which is measured with respect to EM clusters. The efficiency to detect an energy cluster with the sliding window algorithm in the EM calorimeter is found to be above 99% for $E_T > 15$ GeV [70]. Therefore, EM clusters are the starting point of the reconstruction efficiency measurement. The reconstruction efficiency ϵ_{reco} is defined as:

$$\epsilon_{\text{reco}} = \frac{N^{\text{Quality-Track}} - B^{\text{Quality-Track}}}{(N^{\text{Quality-Track}} - B^{\text{Quality-Track}}) + (N^{\text{No-Quality}} - B^{\text{No-Quality}}) + (N^{\text{No-Track}} - B^{\text{No-Track}})} \quad (38)$$

where $N(B)$ represents the number of reconstructed (background) probes, "Quality-Track" represents probes associated with a good quality track having at least 7 precision hits and 1 pixel hit, "No-Quality" refers to probes with a track with silicon hits but no pixel or less than 7 precision hits, and "No-Track" refers to probes with no associated track. The "No-Quality" terms are equal

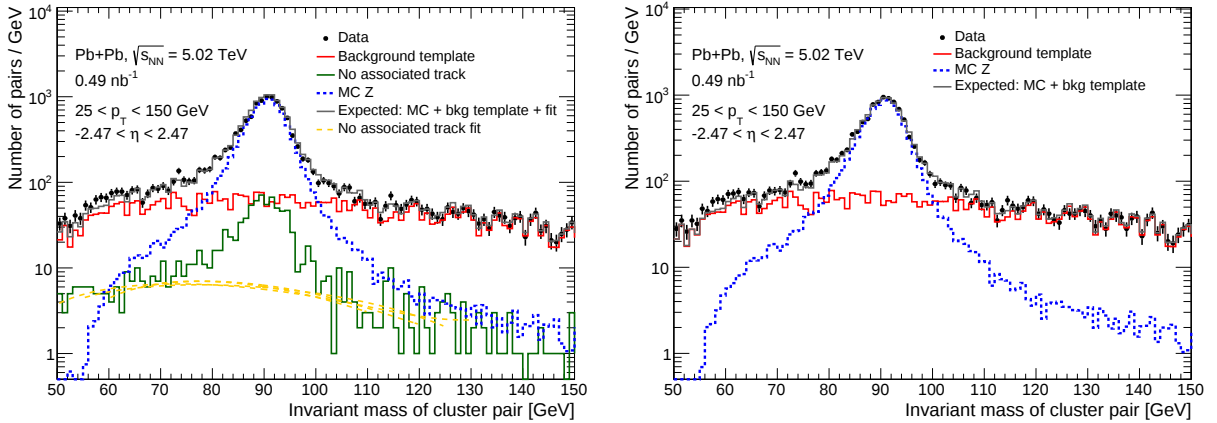


Figure 39: Invariant mass distributions of TP electron pairs used in the reconstruction efficiency measurement for data (black markers), MC simulation (blue dashed histogram), normalized $B^{\text{Quality-Track}}$ template (red histogram), probes with no associated track (green histogram) and polynomial fits to 4 different sidebands of no associated track distribution (yellow dashed lines). The sum of the normalized templates and the MC signal prediction is shown as the grey histogram. Distributions are presented for the efficiency denominator (left) and numerator (right).

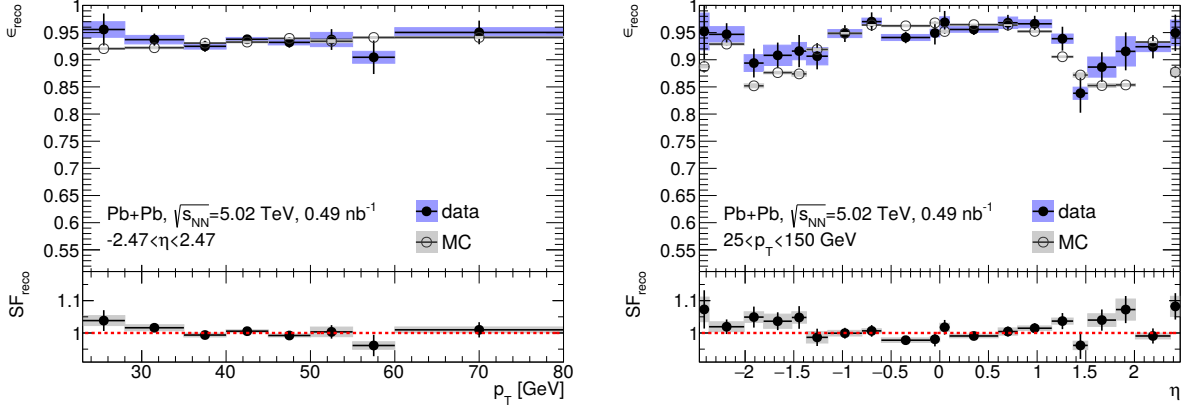


Figure 40: Measured reconstruction efficiencies as a function of electron p_T integrated over the full pseudorapidity range (left) and as a function of η for $25 < p_T < 150$ GeV (right) for the 2015 dataset. The shown uncertainties are statistical (bars) and systematic (boxes).

to 0, since the Pb+Pb track reconstruction uses by default tighter requirements on track quality than the pp reconstruction. Splitting the denominator into 2 terms allows for an optimized background determination for each case.

The background component $B^{\text{No-Track}}$ is modelled by a third order polynomial. The polynomial parameters are estimated from a fit which is performed in an invariant mass region excluding the Z-peak, resulting in sidebands of low ($m_{ee} < 80$ GeV) and high masses ($m_{ee} > 100$ GeV). The residual signal contamination in the sideband regions is subtracted using $Z \rightarrow e^+e^-$ MC simulation. The background component $B^{\text{Quality-Track}}$ is estimated using a template which is built from poor quality electrons failing identification requirements and passing an inverted isolation requirement (they are required to be non-isolated). The template is normalized to the high mass tail of the dielectron invariant mass distribution following ATLAS procedure given in Ref. [69].

Figure 39 shows invariant mass distributions for data and MC simulation for both the efficiency denominator and numerator. The background components estimated using the template and polynomial fits in 4 different sidebands are also depicted.

In order to estimate the impact of the analysis choices and potential imperfections in the background modelling, different variations of the efficiency measurement are carried out, modifying for example the selection of the tag electron or the background estimation method. For the measurement of the data-to-MC correction factors, the same variations of the selection are applied consistently in data and MC simulation. The central value of a given efficiency measurement is taken to be the average value of the results from all variations. The systematic uncertainty is estimated to be equal to the root mean square (RMS) of all considered variations. The statistical uncertainty is taken to be the average of the statistical uncertainties over all investigated variations of the measurement.

The following systematic variations are performed for the measurement:

- Tag identification requirement is varied between working points optimized for Pb+Pb collisions (see Section 4.3.1): *LooseLH*, *MediumLH* and *MediumLH* with isolation requirement described in 5.2.

- Invariant mass ranges of 80-100 GeV, 75-105 GeV and 70-110 GeV.
- Two background templates build from poor quality electrons failing different identification requirements.
- Four different sideband ranges for the background polynomial fit: $[70,80] \cup [100,110]$ GeV, $[60,80] \cup [100,120]$ GeV, $[50,80] \cup [100,130]$ GeV and $[55,70] \cup [110,125]$ GeV

Figure 40 shows the efficiency to reconstruct an electron with a good track quality in data and MC simulation as a function of p_T and η , while the bottom panels show reconstruction scale factors. The efficiency measured as a function of electron p_T in data is above 92% and depends only weakly on the p_T , however it varies as a function of electron η between 90 and 95%. The MC simulation describes data well in the barrel region, while in the forward region the simulated efficiency is lower by $\sim 4\%$ than in data. A similar effect is observed in the muon reconstruction and identification efficiency measurement presented in Section 6.1, which may point to differences in tracking between data and MC simulation.

Some concerns may be related to the estimation of the background term $B^{\text{No-Track}}$, which represents photons, using a polynomial fit. If scale factors are derived in too many bins, the polynomial fits may not give a proper background estimation due to limited statistics in each of the bins. The scale factor integrated over the entire η and p_T range (based on Figure 39) is equal to 1.016 if $B^{\text{No-Track}}$ is subtracted in the efficiency denominator or 1.003 otherwise. Therefore, this term has a non-negligible impact of roughly 1% on scale factors. The following procedure, summarised in Figure 41, is proposed to check whether the evaluation of the photon background is correct. Polynomial fits used to estimate the background are performed either using the full available statistics or separately in each bin in which scale factors are derived. Then the number of photon background events obtained from a single fit is compared to the sum of background events obtained from separate fits. Figure 41 presents two comparisons which use different sets of bins: 18 bins in η or 12 bins in η and p_T . If more bins are used, the total number of photon

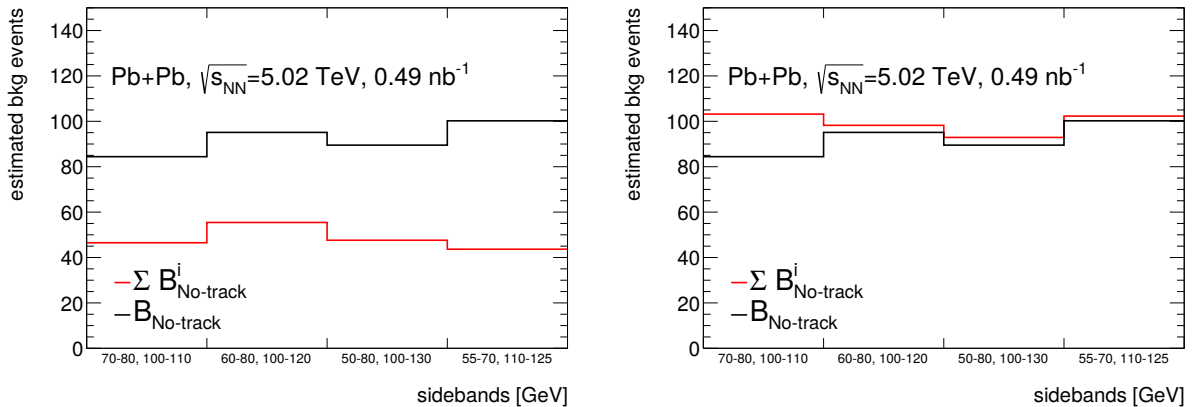


Figure 41: Total number of photon background events $B^{\text{No-Track}}$ estimated with a polynomial fit using full available statistics (black histogram) and as a sum over estimations made separately in each bin (red histogram) for various definitions of sidebands. The left plot presents the background estimation for 18 η bins, while in the right plot 12 $\eta - p_T$ bins are used.

background events is underestimated, which is related to a limited number of $Z \rightarrow e^+e^-$ events in each of the kinematic bins. On the other hand, with a smaller number of bins there are still differences with respect to the amount of background estimated with a single fit, but they are covered by the systematic uncertainty related to the sideband definition. In the analysis, scale factors derived using the second set of bins (four in η , excluding the calorimeter crack, and three in p_T) are applied to correct MC simulation events.

Figure 42 presents the reconstruction efficiency measured as a function of electron η in three different ranges of electron p_T . The scale factors shown in the bottom panels are the ones used in the analysis.

The dependence of the reconstruction efficiency and scale factors on FCal ΣE_T is presented in Figure 43. A small dependence of the efficiency measured in data is found, but it is well simulated. Therefore, no impact of FCal ΣE_T on the scale factors is observed within statistical uncertainties.

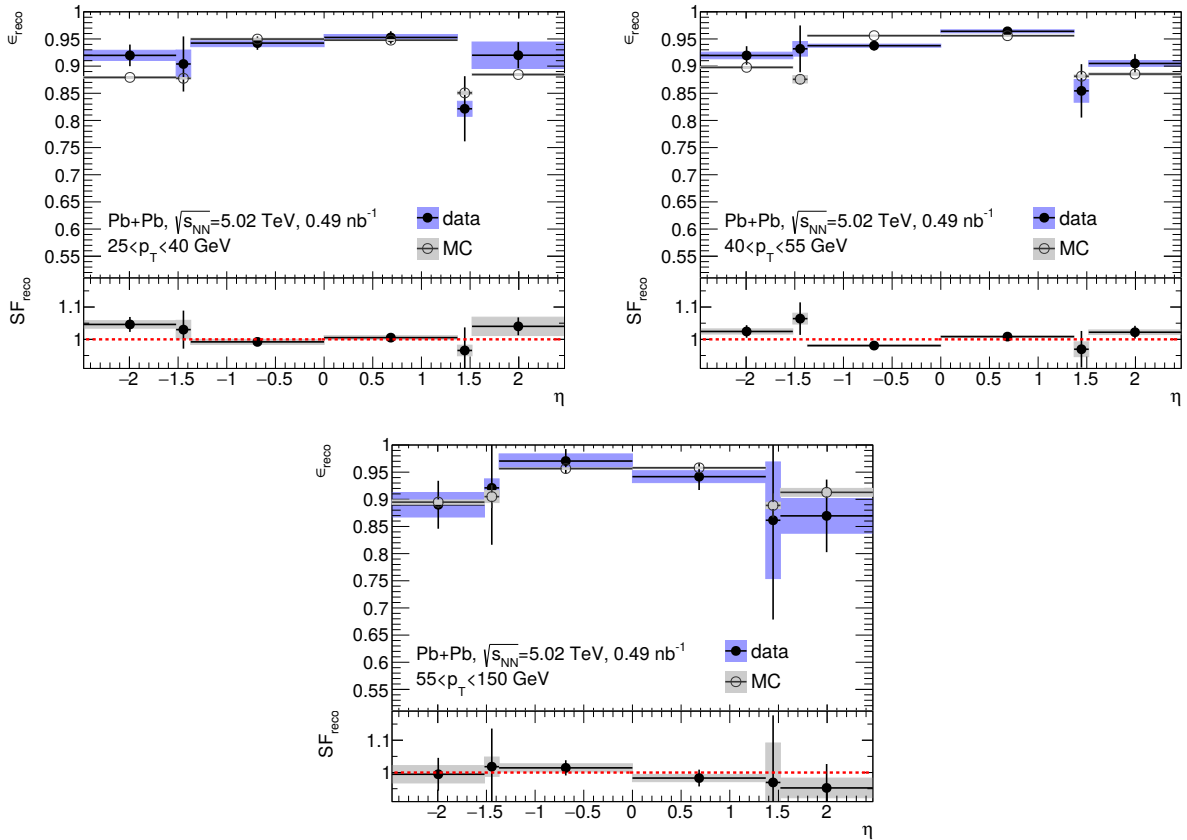


Figure 42: Reconstruction efficiency measured as a function of electron η three electron p_T ranges in data (black solid markers) and MC simulation (black open markers). The bottom panels present efficiency scale factors. Statistical uncertainties are shown as bars and systematic uncertainties are shown as a blue or grey band for efficiency and scale factors, respectively.

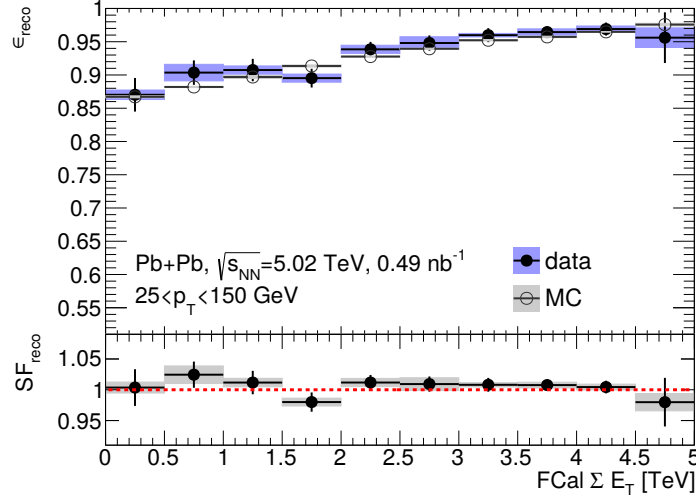


Figure 43: Reconstruction efficiency measured as a function of $\text{FCal } \Sigma E_T$ in data (black solid markers) and MC simulation (black open markers). The bottom panel presents efficiency scale factors. Statistical uncertainties are shown as bars and systematic uncertainties are shown as a blue or grey band for efficiency and scale factors, respectively.

6.6 Electron identification efficiency

To determine whether reconstructed electron candidates are signal-like objects or background-like objects such as hadronic jets or converted photons, algorithms for electron identification are applied. The baseline identification algorithm used for Run-2 data analyses is the likelihood (LH) method, which description is given the Section 4.3.1. Two working points are provided which are referred to, in order of increasing background rejection, as *LooseLH* and *MediumLH*. By design, the sample of electron candidates selected by the *MediumLH* working point is a subset of the sample selected by the *LooseLH* working point.

Electron identification scale factors are derived for the *MediumLH* working point used in the analysis. The measurement is performed following the procedure documented in Refs. [63, 70] with the same software package as for the reconstruction efficiency measurement. Below the main points of the measurement strategy are recapped.

The efficiency of the identification selection is determined in data and in the simulated samples with respect to reconstructed electrons with associated tracks that have at least 1 hit in the pixel detector and at least 7 hits in the pixel or SCT detectors. The efficiencies are calculated as the ratio of the number of electrons passing the *MediumLH* identification selection (numerator) to the number of electrons with a matching track passing the track quality requirements (denominator):

$$\epsilon_{\text{id}} = \frac{N^{\text{MediumLH}} - B^{\text{MediumLH}}}{N^{\text{Quality-Track}} - B^{\text{Quality-Track}}}, \quad (39)$$

where N^{MediumLH} (B^{MediumLH}) is the number of reconstructed (background) electrons passing the *MediumLH* requirement, while $N^{\text{Quality-Track}}$ ($B^{\text{Quality-Track}}$) is the number of reconstructed (background) electrons passing track quality requirements.

To form a background template the reconstructed electron candidates with an associated

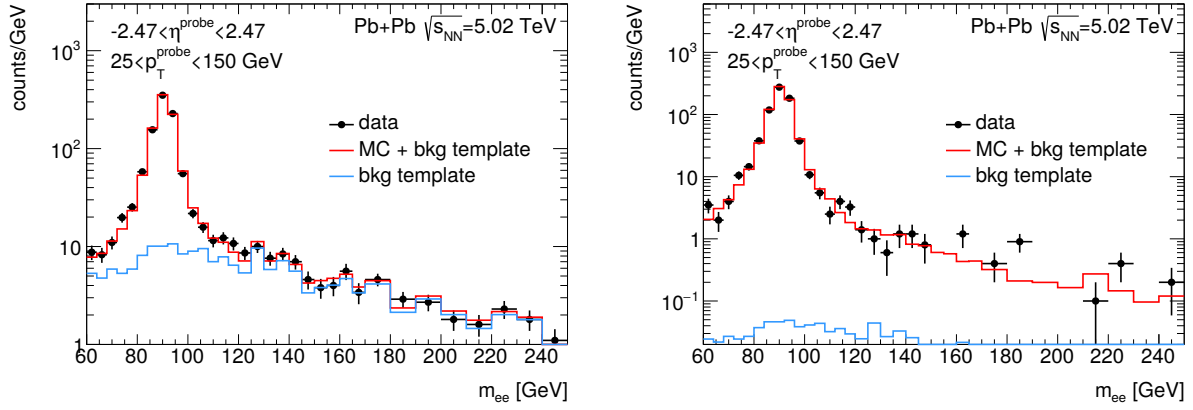


Figure 44: Invariant mass distributions of TP pairs used in the *MediumLH* identification efficiency measurement for data (black markers), signal MC simulation with added background (red histogram) and normalized background template (blue histogram). Distributions are presented for the efficiency denominator (left) and numerator (right).

track, satisfying track quality criteria, are chosen as probes. In addition, identification and isolation requirements are inverted to minimize the contribution of signal electrons. The remaining signal electron contamination in the background templates is estimated using simulated events. The signal MC simulation and the background templates need to be normalized to data in order to estimate the background in the Z -peak region. The normalization approach is different for numerator and denominator.

In the numerator, the normalization factor is obtained by normalizing the background template to same-charge data (to avoid signal contamination) in the high-mass tail region of the invariant mass distribution ($120 \text{ GeV} < m_{ee} < 250 \text{ GeV}$). In case of the denominator, the back-

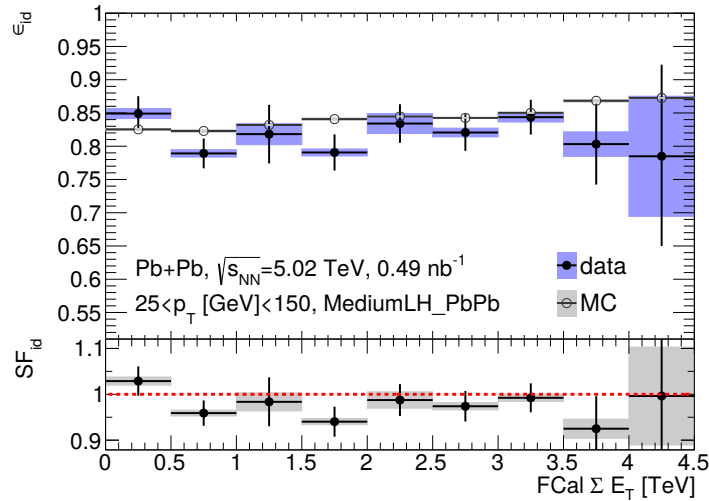


Figure 45: Identification efficiency measured as a function of $\text{FCal } \Sigma E_T$ in data (black solid markers) and MC simulation (black open markers). The bottom panel presents efficiency scale factors. Statistical uncertainties are shown as bars and systematic uncertainties are shown as a blue or grey band for efficiency and scale factors, respectively.

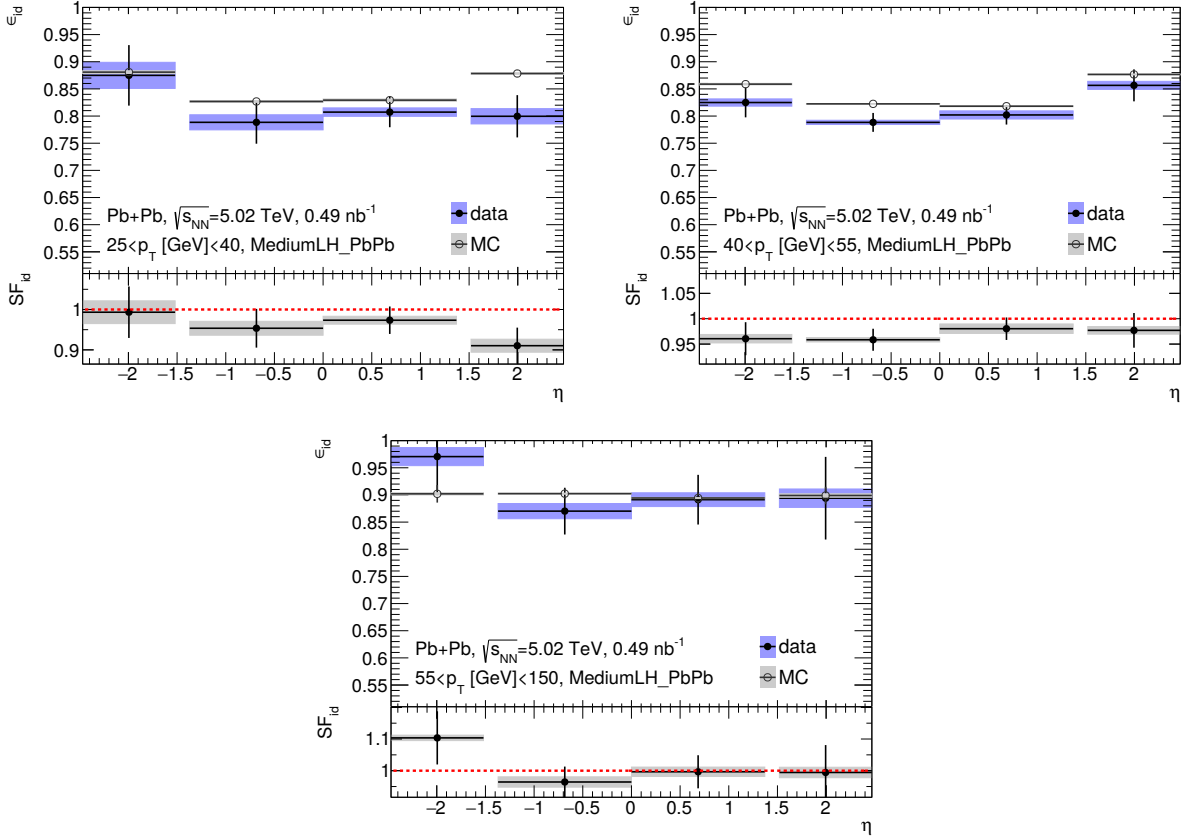


Figure 46: Identification efficiency measured as a function of electron η in three electron p_T ranges in data (black solid markers) and MC simulation (black open markers). The bottom panels present efficiency scale factors. Statistical uncertainties are shown as bars and systematic uncertainties are shown as a blue or grey band for efficiency and scale factors, respectively.

ground template is normalized to opposite-charge data, also in the high-mass tail region of the invariant mass distribution ($120 \text{ GeV} < m_{ee} < 250 \text{ GeV}$). However, in this case the signal contamination is subtracted before normalization. The invariant mass distributions of tag-and-probe pairs in the efficiency numerator and denominator are shown in Figure 44 with normalized background templates.

Similarly to the reconstruction efficiency measurement, the central value of the identification efficiency is taken to be the average value of results from all variations listed below. The systematic uncertainty is estimated to be equal to the RMS of all considered variations. The statistical uncertainty is taken to be the average of statistical uncertainties over all investigated variations.

The following systematic variations are performed for the identification efficiency measurement:

- Tag identification requirement is varied between *LooseLH* and *MediumLH* with an isolation requirement described in 5.2.
- Invariant mass ranges of 80-100 GeV, 75-105 GeV and 70-110 GeV.
- Two background templates defined from poor quality electrons failing different identification requirements and inverted isolation cuts on $etcone20/pt$ from Table 8 are applied.

The dependence of the identification efficiency and scale factors on $\text{FCal } \Sigma E_T$ is presented in Figure 45. The *LooseLH* and *MediumLH* working points have been optimized to have an efficiency independent of $\text{FCal } \Sigma E_T$. A small centrality dependence can be noticed for the efficiency of *MediumLH* measured in the simulation, which may come from the fact that HIJING overlay samples have been used for the identification optimisation, while current MC samples have been produced with data overlay. However, the scale factors measured at all $\text{FCal } \Sigma E_T$ values agree with each other within statistical uncertainties.

Figure 46 presents the identification efficiency measured as a function of electron η in three different ranges of electron p_T . The scale factors shown in the bottom panels are used to correct MC simulation events in the analysis.

6.7 Electron isolation efficiency

Efficiency scale factors are measured for the isolation working point described in Section 5.2. The measurement is performed with the same software package as for the reconstruction and identification measurements. The isolation efficiency is defined as the fraction of *MediumLH* identified electrons passing the isolation criterion:

$$\epsilon_{\text{iso}} = \frac{N^{\text{MediumLH}+\text{iso}} - B^{\text{MediumLH}+\text{iso}}}{N^{\text{MediumLH}} - B^{\text{MediumLH}}}, \quad (40)$$

where $N^{\text{MediumLH}+\text{iso}}$ ($B^{\text{MediumLH}+\text{iso}}$) is the number of reconstructed (background) electrons passing the *MediumLH* and isolation requirements, while N^{MediumLH} (B^{MediumLH}) is the number of reconstructed (background) electrons passing the *MediumLH* requirement.

The invariant mass distributions of tag-and-probe pairs in the efficiency numerator and denominator are shown in Figure 47 with normalized background templates. In the numerator and denominator, the normalization factor is obtained by normalizing the background template to

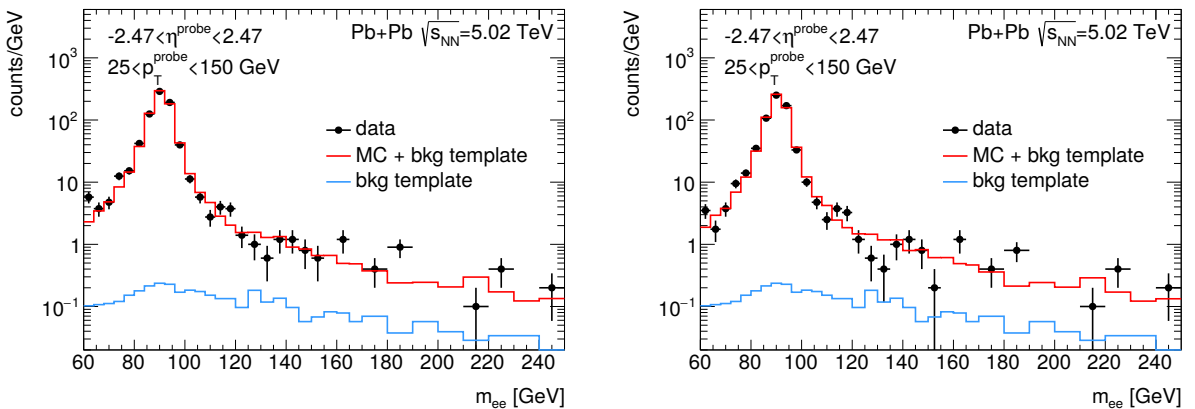


Figure 47: Invariant mass distributions of TP pairs used in the isolation efficiency measurement for data (black markers), signal MC simulation with added background (red histogram) and normalized background template (blue histogram). Distributions are presented for the efficiency denominator (left) and numerator (right).

same-charge data (to avoid signal contamination) in the high-mass tail region of the invariant mass distribution ($120 \text{ GeV} < m_{ee} < 250 \text{ GeV}$).

The following systematic variations are performed for the isolation efficiency measurement:

- Tag identification requirement is varied between *LooseLH* and *MediumLH*.
- Invariant mass ranges of 80-100 GeV, 75-105 GeV and 70-110 GeV.
- Two background templates defined from poor quality electrons failing different identification requirements and inverted isolation cuts on $etcone20/pt$ from Table 8 are applied.

Figure 48 presents the isolation efficiency measured as a function of electron η in three different ranges of electron p_T . The bottom panels show efficiency scale factors.

Dependences of the isolation efficiency and scale factors on FCal ΣE_T are presented in Figure 49. The cuts on the calorimetric isolation variable $etcone20/pt$ are optimized to have a signal efficiency independent of FCal ΣE_T , as described in Section 5.2, however the cut on the tracking isolation variable $pt2cone20/pt$ is constant. Therefore, some centrality dependence of the isolation efficiency can be noticed, but the measured scale factors do not depend on FCal ΣE_T within statistical precision.

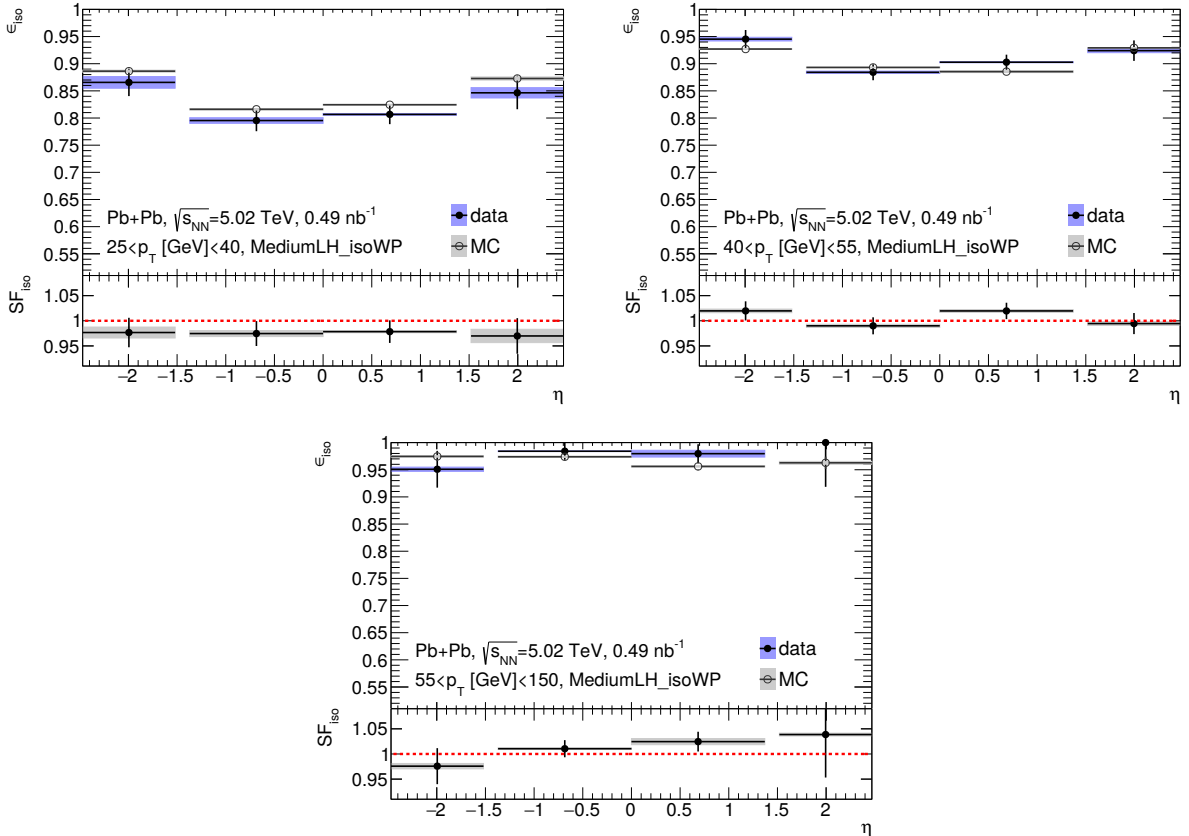


Figure 48: Isolation efficiency measured as a function of electron η in three electron p_T ranges in data (black solid markers) and MC simulation (black open markers). The bottom panels present efficiency scale factors. Statistical uncertainties are shown as bars and systematic uncertainties are shown as a blue or grey band for efficiency and scale factors, respectively.

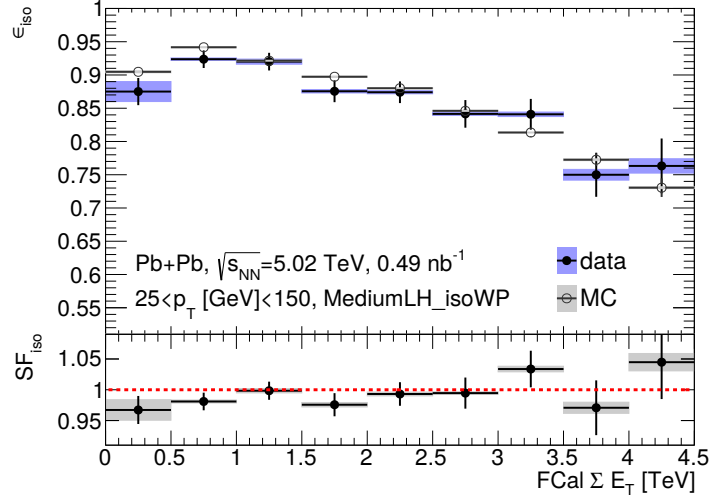


Figure 49: Isolation efficiency measured as a function of $\text{FCal } \Sigma E_T$ in data (black solid markers) and MC simulation (black open markers). The bottom panel presents efficiency scale factors. Statistical uncertainties are shown as bars and systematic uncertainties are shown as a blue or grey band for efficiency and scale factors, respectively.

Within the precision of the measurement, the isolation scale factors are consistent with unity. It is an expected behaviour, as the isolation scale factors for pp data deviate from unity by no more than few permilles. Moreover, Figure 50 presents distributions of the calorimetric and tracking isolation variables obtained from $Z \rightarrow e^+e^-$ events in data and MC simulation. A good agreement is observed, which supports the consistency of isolation scale factors with unity. In further analysis, the isolation scale factors are assumed to be equal 1, and only scale factor uncertainties are propagated to the final results.

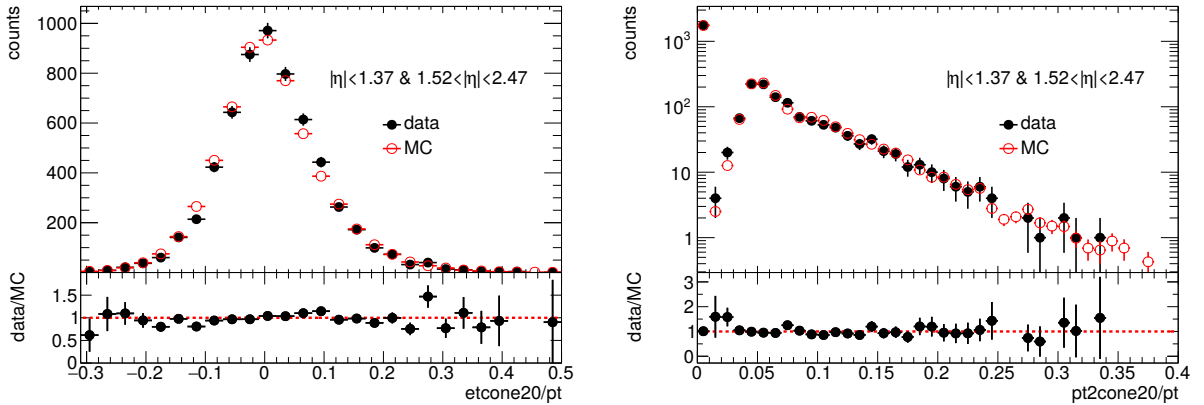


Figure 50: Distributions of calorimetric (left) and tracking (right) isolation variables for electrons forming TP pairs in data (black markers) and MC simulation (red markers).

6.8 Electron trigger efficiency

The `HLT_e15_loose_ion_L1EM12` trigger efficiency is determined in $Z \rightarrow e^+e^-$ events using the same tag-and-probe method as in the isolation efficiency measurement with similar background subtraction. The trigger efficiency is defined as the ratio of the number of probe electrons that match to the given HLT electron to the total number of probe electrons. In addition to the common selection, all offline probe electrons are required to pass an isolation and identification criterion. The exact formula is the following:

$$\epsilon_{\text{trig}} = \frac{N^{\text{MediumLH}+\text{iso}+\text{trig}} - B^{\text{MediumLH}+\text{iso}+\text{trig}}}{N^{\text{MediumLH}+\text{iso}} - B^{\text{MediumLH}+\text{iso}}}, \quad (41)$$

where N^{MediumLH} (B^{MediumLH}) is the number of reconstructed (background) electrons passing the *MediumLH* and isolation requirements, while $N^{\text{MediumLH}+\text{iso}+\text{trig}}$ ($B^{\text{MediumLH}+\text{iso}+\text{trig}}$) is the number of reconstructed (background) electrons passing the *MediumLH*, isolation and trigger requirements

The invariant mass distributions of tag-and-probe pairs in the efficiency numerator and denominator are shown in Figure 51 with normalized background templates. In the numerator and denominator, the normalization factor is obtained by normalizing the background template to same-charge data (to avoid signal contamination) in the high-mass tail region of the invariant mass distribution ($120 \text{ GeV} < m_{ee} < 250 \text{ GeV}$).

The following systematic variations are performed for the trigger efficiency measurement:

- Tag identification requirement is varied between *LooseLH* and *MediumLH*.
- Invariant mass ranges of 80-100 GeV, 75-105 GeV and 70-110 GeV.
- Two background templates defined from poor quality electrons failing different identification requirements and inverted isolation cuts on *etcone20/pt* from Table 8 are applied.

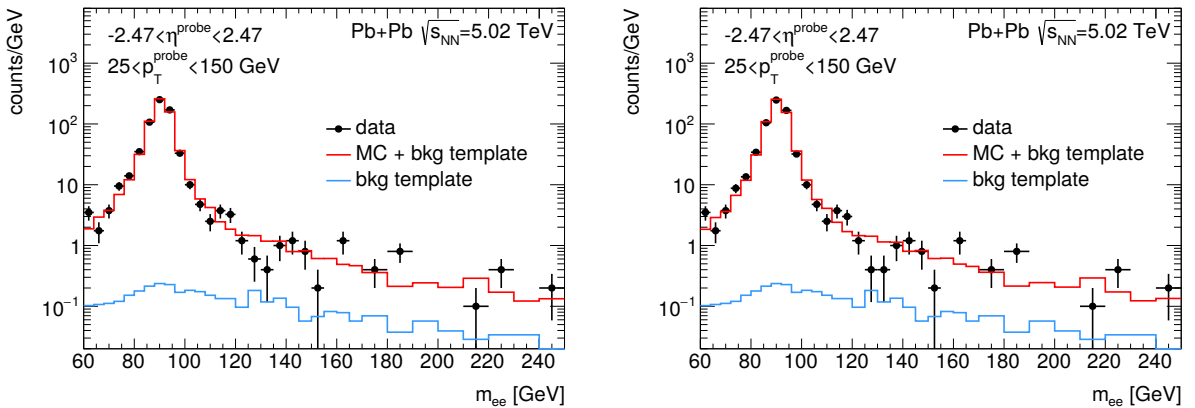


Figure 51: Invariant mass distributions of TP pairs used in the trigger efficiency measurement for data (black markers), signal MC simulation with added background (red histogram) and normalized background template (blue histogram). Distributions are presented for the efficiency denominator (left) and numerator (right).

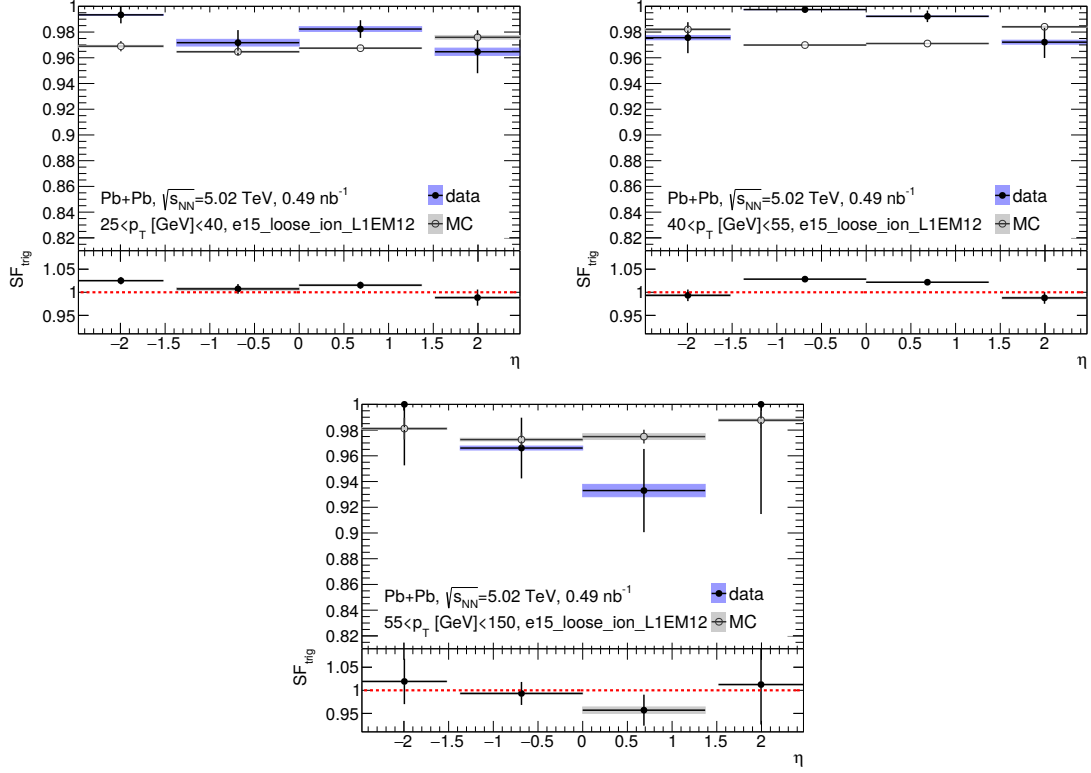


Figure 52: Trigger efficiency measured as a function of electron η in three electron p_T ranges in data (black solid markers) and MC simulation (black open markers). The bottom panels present efficiency scale factors. Statistical uncertainties are shown as bars and systematic uncertainties are shown as a blue or grey band for efficiency and scale factors, respectively.

Figure 52 presents the trigger efficiency measured as a function of electron η in three different ranges of electron p_T . The scale factors shown in the bottom panels are used to correct MC events in the analysis. The efficiency in data is measured to be around 98%. Small deviations of the simulated efficiency can be noticed which are more pronounced in the barrel region for

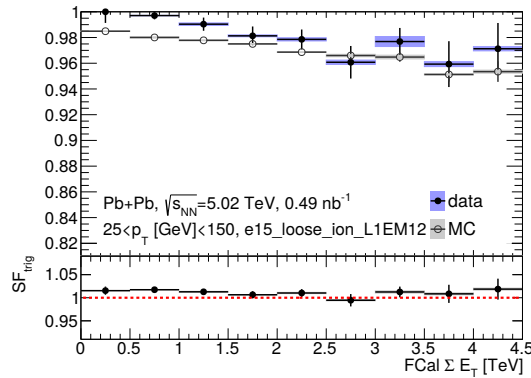


Figure 53: Trigger efficiency measured as a function of FCal ΣE_T in data (black solid markers) and MC simulation (black open markers). The bottom panel presents efficiency scale factors. Statistical uncertainties are shown as bars and systematic uncertainties are shown as a blue or grey band for efficiency and scale factors, respectively.

electrons with $p_T < 55$ GeV.

Dependences of the trigger efficiency and scale factors on $\text{FCal } \Sigma E_T$ are presented in Figure 53. The measured efficiency is slowly falling with $\text{FCal } \Sigma E_T$, however the effect is well simulated and there is no impact on scale factors which are roughly 1% above unity.

7 Missing transverse momentum

Neutrinos from W decays are undetectable for the ATLAS detector. However, momentum conservation is expected in the transverse plane, and thus the momentum vectors of undetected particles can be estimated by measuring the missing transverse momentum (MET, p_T^{miss}) of the event. The MET reconstruction based on calorimeter information is not run by default in the reconstruction chain of heavy-ion events. Moreover, MET performance is drastically affected by the particle multiplicity of the event, in particular as centrality increases. This leads to very poor resolution of the calorimeter based MET. The p_x^{miss} and p_y^{miss} resolutions as a function of the total transverse energy per event (ΣE_T) are shown in Figure 54. They can reach up to 60 GeV in the most central events.

Instead, an alternative method has been developed which evaluates MET using ID tracks (so called *track MET*). This approach was first utilized by CMS in the 2010 Pb+Pb W measurement at 2.76 TeV [72] and later by ATLAS in 2011 Pb+Pb collisions at 2.76 TeV [67]. This analysis has reoptimized the track MET technique to the 5.02 TeV Pb+Pb collisions. The track MET calculation uses all tracks in the event which pass the *HITight* selection criteria (for definition see Section 4.1) with several $p_T^{\text{min}} = 1, 2, 3, 4, 5$ GeV thresholds considered in this analysis. The total momentum components p_x^{tot} and p_y^{tot} are computed using all tracks which pass the above selection following the formulae:

$$p_x^{\text{tot}} = \sum_{i=1}^n p_x^i, \quad p_y^{\text{tot}} = \sum_{i=1}^n p_y^i, \quad (42)$$

where n stands for the number of tracks passing the selection criteria.

The algorithm also checks if tracks originating from signal leptons are included in this computation (so called lepton recovery procedure). If their associated ID tracks pass the standard track quality criteria but fail the stringent *HITight* track quality criteria, the lepton p_x and p_y

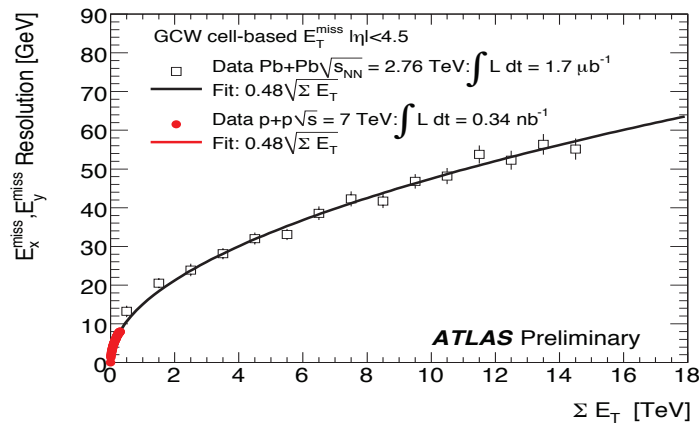


Figure 54: E_x^{miss} and E_y^{miss} resolution as a function of the total transverse energy (ΣE_T) for Pb+Pb and pp collision events. For Pb+Pb, due to low statistics, RMS values are plotted instead of sigma from the fit. The line represents independent fits to the resolution obtained in Pb+Pb data and in pp data at 7 TeV [71]. E_x^{miss} , E_y^{miss} and ΣE_T are computed from cells with energy $> 2\sigma(\text{noise})$.

components are explicitly included in the p_x^{tot} and p_y^{tot} sums. This is done for electrons with $p_T > 10$ GeV and combined muons with $p_T > 6$ GeV which are considered after the loop over all tracks has been executed. After the lepton recovery procedure, track MET is defined as follows:

$$p_x^{\text{miss}} = -p_x^{\text{tot}}, \quad p_y^{\text{miss}} = -p_y^{\text{tot}}, \quad (43)$$

with $p_T^{\text{miss}} = \sqrt{(p_x^{\text{miss}})^2 + (p_y^{\text{miss}})^2}$ and azimuthal angle $\phi^{\text{miss}} = \arctan(p_y^{\text{miss}}/p_x^{\text{miss}})$. The transverse mass of the lepton- p_T^{miss} system is defined as:

$$m_T = \sqrt{2p_T^\mu p_T^{\text{miss}}(1 - \cos \phi)}, \quad (44)$$

where ϕ is the azimuthal angle between directions of the lepton transverse momentum and p_T^{miss} .

Shortcomings of this method are that it neglects neutral particles in the vector summation and is limited to the ID coverage.

7.1 p_T^{miss} performance in MB events

The performance of p_T^{miss} reconstruction is studied in a MB sample of events written into the MinBias stream. Several $p_T^{\text{min}} = 1, 2, 3, 4, 5$ GeV thresholds of track p_T are investigated to identify the optimal one for the nominal W boson analysis. Figure 55 shows p_x^{miss} and p_y^{miss} distributions for various p_T^{min} thresholds integrated over 0–80% centralities. All distributions tend to be symmetric and centred close to zero.

Figure 56 show mean values of $p_{x,y}^{\text{miss}}$, and their distributions width $\sigma_{p_{x,y}^{\text{miss}}}$ evaluated with RMS as a function of FCal ΣE_T for various p_T^{min} thresholds used to evaluate track MET in the MB sample. For each p_T^{min} threshold both the mean and resolution grow with centrality. Even the highest p_T^{min} threshold tends to have a non-zero mean for the most central events. This feature may come from regions in the ID where dead detector modules were present during heavy-ion data taking. For $p_T^{\text{min}} = 1$ GeV the resolution increases with centrality from 12 GeV to 45 GeV. For $p_T^{\text{min}} = 5$ GeV this raise is from 5 GeV to about 10 GeV. The optimal choice is $p_T^{\text{min}} = 4$ GeV

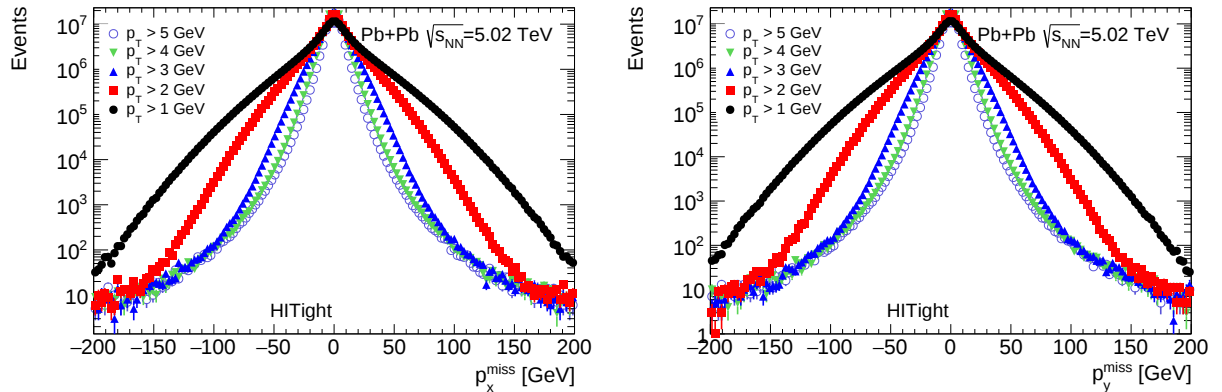


Figure 55: p_x^{miss} (left) and p_y^{miss} (right) distributions for various minimum p_T track thresholds used to evaluate track MET in MB events.

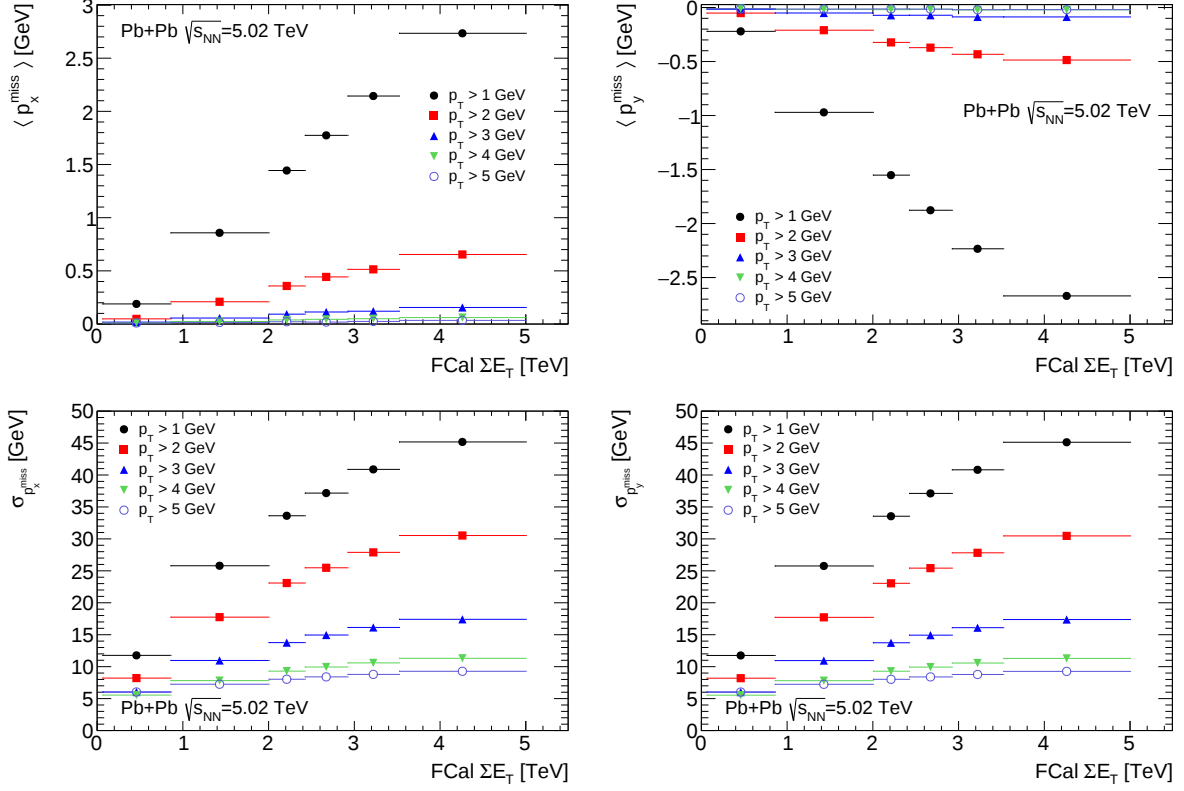


Figure 56: $\langle p_{x,y}^{\text{miss}} \rangle$ (top) and $\sigma_{p_{x,y}^{\text{miss}}}$ (bottom) as a function of $\text{FCal } \Sigma E_T$ for various p_T^{min} thresholds used to evaluate track MET in MB events.

for which mean values of $p_{x,y}^{\text{miss}}$ are at the level of ~ 20 MeV and the resolution slowly grows with centrality. For $p_T^{\text{min}} = 3$ GeV deviations of $\langle p_{x,y}^{\text{miss}} \rangle$ from 0 are more significant and also one can notice worse resolution than for $p_T^{\text{min}} = 4$ GeV. The $p_T^{\text{min}} = 5$ GeV threshold is also not the best choice as it only slightly improves track MET performance in MB events while in $W \rightarrow \ell\nu$ events it leads to non-negligible fraction of events with reconstructed missing transverse momentum only using the signal lepton.

7.2 p_T^{miss} performance in $W \rightarrow \mu\nu$ events

The performance of p_T^{miss} reconstruction is studied with the signal $W \rightarrow \mu\nu$ MC events. Figure 57 shows the correlation between true neutrino p_T and reconstructed p_T^{miss} for two selected p_T^{min} thresholds for events from the 0–5% and 50–80% centrality classes. In each p_T^{miss} bin, the average true neutrino p_T is extracted. The dashed lines represent linear functions with a 100% correlation coefficient. As the p_T^{min} requirement grows, the $p_T^{\text{miss, true}}$ and p_T^{miss} distributions tend to be slightly more correlated. In each panel the linear correlation coefficient is given. In general, very poor correlation is found. In the 50–80% centrality class, the correlation coefficient varies between 0.091 and 0.159, while for 0–5% centralities it amounts to 0.027–0.053. The correlation weakens as the p_T^{min} threshold decreases due to a larger track multiplicity contributing to the p_T^{miss} calculation. In the heavy-ion environment a majority of tracks comes from the underlying event.

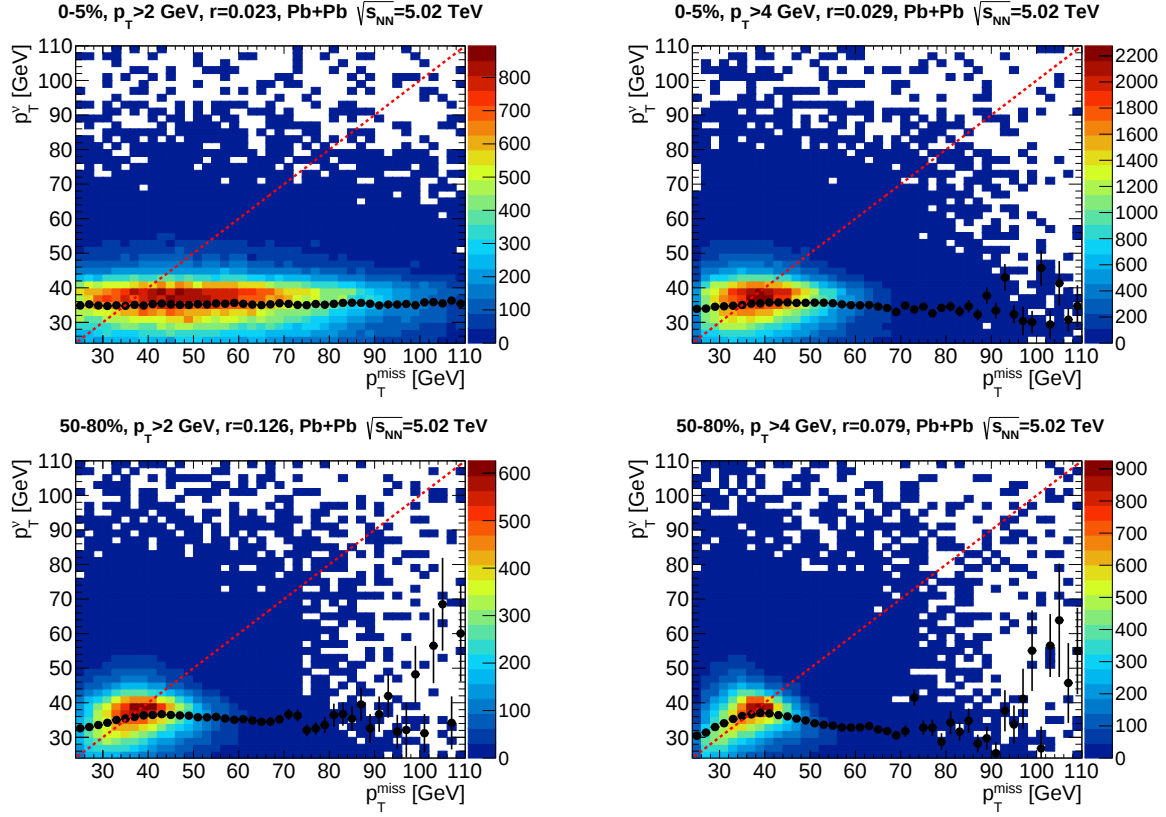


Figure 57: Correlation between true neutrino p_T and reconstructed p_T^{miss} from the signal MC sample for the 0–5% (top) and 50–80% (bottom) centrality class and two selected p_T^{min} thresholds used to define p_T^{miss} . Solid points represent the average true neutrino p_T in each p_T^{miss} bin. The dashed line represents the scenario with a linear correlation.

Figure 58 presents p_T^{miss} distributions extracted from signal and background MC samples for varying p_T^{min} requirements for events from 0–80% centralities. Each panel gives fractions of rejected background and accepted signal events for $p_T^{\text{miss}} > 25$ GeV. With increasing p_T^{min} threshold a larger fraction of background events tends to be rejected and more signal events get accepted. These fractions change from 22.3% and 84.8% for $p_T^{\text{min}} = 1$ GeV to 51.3% and 89.1% for $p_T^{\text{min}} = 5$ GeV for background rejection and signal efficiency, respectively. This leads to a conclusion that a higher p_T^{min} threshold will perform better in rejecting background events. However, the gain in background rejection and signal efficiency is not significant for $p_T^{\text{min}} = 5$ GeV with respect to the lower threshold. For the nominal analysis, the $p_T^{\text{min}} = 4$ GeV threshold is chosen, while $p_T^{\text{min}} = 3$ GeV and $p_T^{\text{min}} = 5$ GeV are used for systematic studies discussed in Section 12.

7.3 p_T^{miss} performance in $Z \rightarrow \mu^+ \mu^-$ events

The performance of p_T^{miss} reconstruction is also studied with Z boson candidates in data and MC simulation. The main advantage of $Z \rightarrow \mu^+ \mu^-$ events is a low background contamination in the selected sample. The dimuon pairs are selected by requiring:

- $p_T > 25$ GeV,

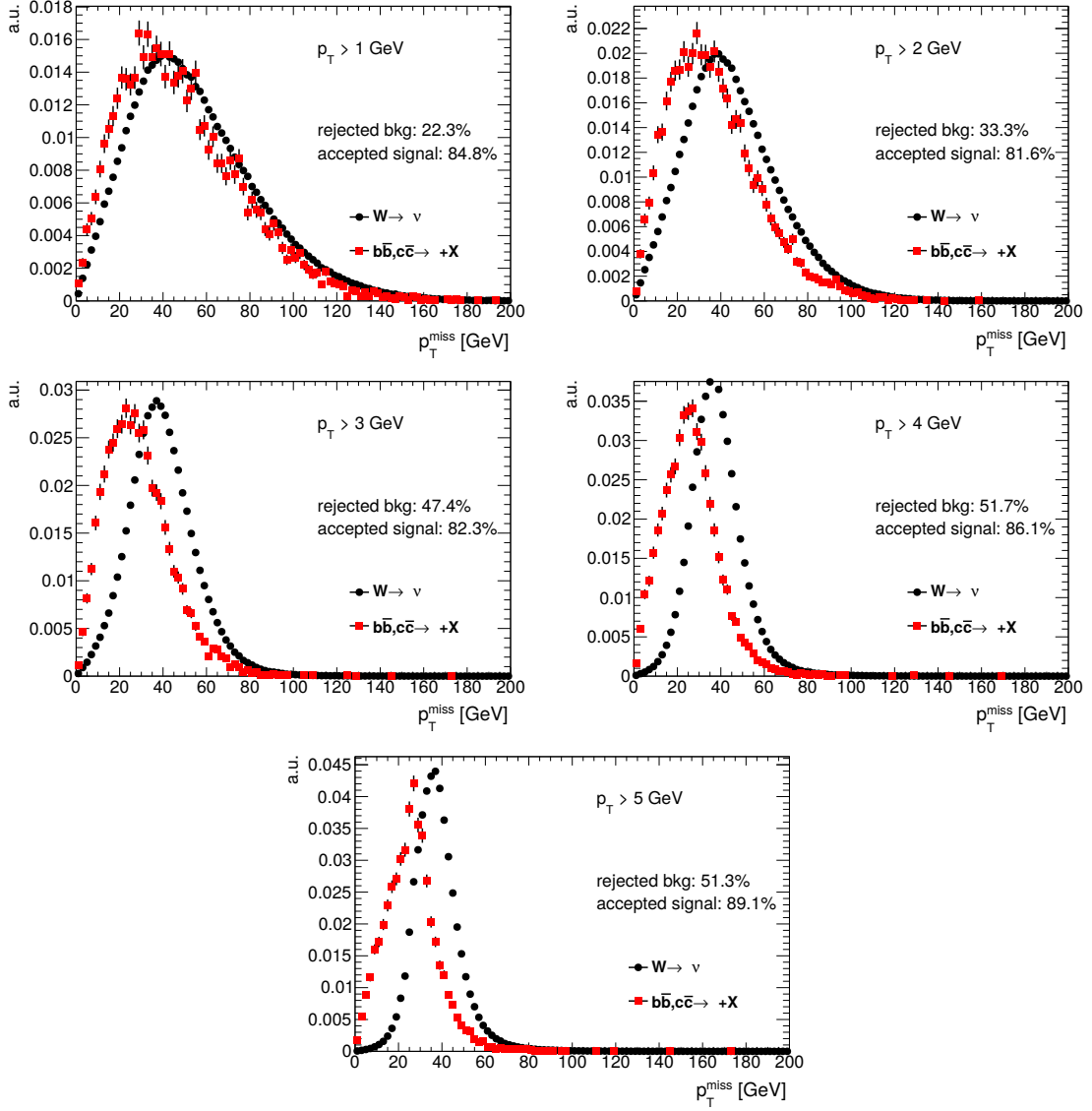


Figure 58: p_T^{miss} distribution for signal (circles) and $c\bar{c}$ and $b\bar{b}$ pairs with decays to muons (squares) MC events for increasing p_T^{min} thresholds used in the definition of p_T^{miss} . The fractions of accepted signal and rejected background events for $p_T^{\text{miss}} > 25$ GeV are given in each panel.

- $|\eta| < 2.4$,
- at least one of the muons is matched to the single muon trigger (HLT_mu15_msonly),
- both muons are passing the isolation requirement defined in Section 5.1,
- oppositely charged muons have a pair invariant mass in the range $61 < m_{\mu^+\mu^-} < 121$ GeV.

In the selected events, the missing transverse momentum is reconstructed using the track MET algorithm in both data and MC simulation. Distributions of p_x^{miss} , p_y^{miss} and p_T^{miss} are presented in Figure 59 after normalization to the number of entries to compare their shapes. Data and MC simulation are in good agreement, however differences are visible. The distributions of p_x^{miss} and p_y^{miss} components are slightly wider in data than in MC simulation. It is also reflected in the p_T^{miss} distribution. The main cause for such behaviour is the ID misalignment reported in Section 4.2.2. The reconstructed p_T of ID tracks and combined muons is shifted by 2% and

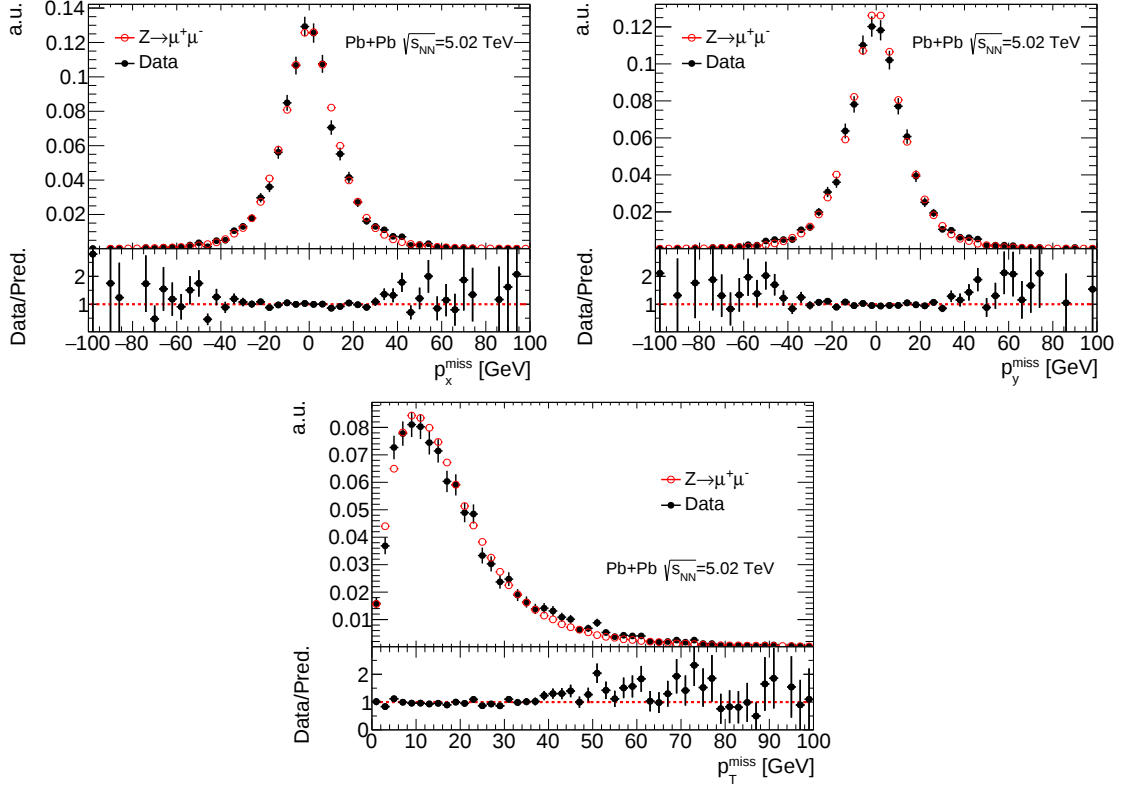


Figure 59: p_x^{miss} (top left), p_y^{miss} (top right) and p_T^{miss} (bottom) distributions in events with $Z \rightarrow \mu^+\mu^-$ candidates in data (black markers) and signal MC (red markers).

-2% for positive and negative charges, respectively. Leptons coming from Z boson decays can be treated approximately as produced back-to-back. In such a configuration the reconstructed track MET (bearing in mind that it is a vector sum) has to be overestimated, since one of the leptons has its p_T shifted by 2% while the other has its p_T shifted by -2% . This would not be the case if the p_T shift introduced by the misalignment would be charge independent. The ID alignment issue explains why the resolutions of p_x^{miss} and p_y^{miss} components in data are worse than in MC.

7.4 p_T^{miss} performance in $Z \rightarrow e^+e^-$ events

For completeness, the performance of p_T^{miss} reconstruction is also studied with Z boson candidates in the electron decay channel. The dielectron pairs are selected by requiring:

- $p_T > 25$ GeV,
- $|\eta| < 2.47$,
- at least one of the electrons is matched to the electron trigger,
- oppositely charged electrons pair invariant mass is in the range $61 < m_{e^+e^-} < 121$ GeV.

Distributions of p_x^{miss} , p_y^{miss} and p_T^{miss} are presented in Figure 60 after normalization to the number of entries to compare their shapes. Similarly to the muon case, the data distributions are wider than in the MC simulation. The electron reconstruction is largely unaffected by the

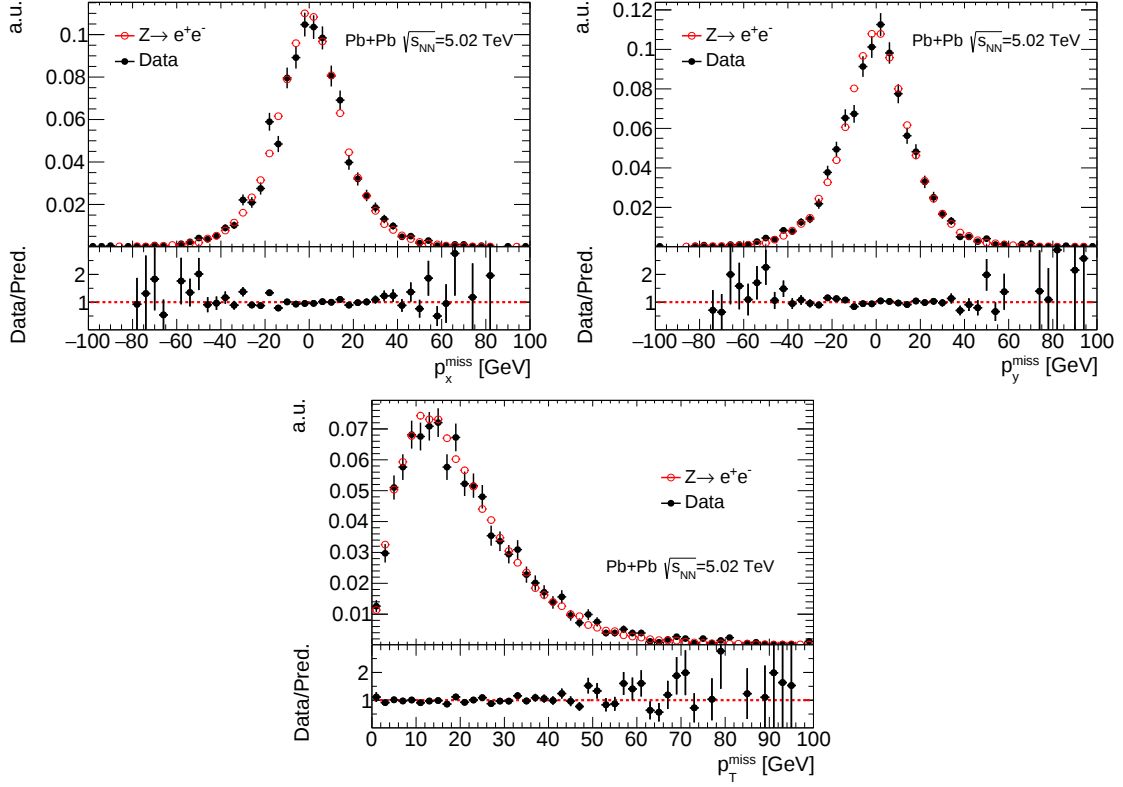


Figure 60: p_x^{miss} (top left), p_y^{miss} (top right) and p_T^{miss} (bottom) distributions in events with $Z \rightarrow e^+e^-$ candidates in data (black markers) and signal MC (red markers).

ID misalignment as the reconstructed electron E_T comes mainly rather from clusters than the associated ID tracks. However, the track MET reconstruction is applying the lepton recovery procedure to electrons only if the track matched to the electron fails the *HITight* track quality requirements. Therefore, the missing transverse momentum reconstructed in events with electrons is also biased but the effect is slightly less pronounced than in events with muons.

8 Event selection

Muon channel

Events considered to be $W \rightarrow \mu\nu$ candidates have to pass the following selection criteria:

- *Preselection* - Good Run List selection as defined in Section 3.1, 0–80% centrality range
- *MuonQuality* - a muon with $p_T^\mu > 25$ GeV (ME kinematics are used) falling into the pseudorapidity region $0 < |\eta_\mu| < 2.4$, passing the *Medium* identification, matched to HLT_mu8 trigger object,
- *IsoCut* - a muon passing the isolation selection defined in Section 5.1,
- *METCut* - $p_T^{\text{miss}} > 25$ GeV, where p_T^{miss} is calculated using tracks with $p_T > 4$ GeV,
- *ZVeto* - if a muon passing the *MuonQuality* requirements forms a Z boson candidate with an oppositely charged muon of any quality with $p_T > 20$ GeV, the event is rejected if the mass of the dimuon system exceeds 66 GeV,
- *MtCut* - the transverse mass of the muon- p_T^{miss} system must satisfy $m_T > 40$ GeV.

The number of $W^+ \rightarrow \mu^+\nu$ and $W^- \rightarrow \mu^-\nu$ candidate events in data passing the subsequent selection criteria is summarised in Table 11. In total 27394 $W^+ \rightarrow \mu^+\nu$ candidates and 25385 $W^- \rightarrow \mu^-\nu$ candidates satisfy all criteria.

Electron channel

Events considered to be $W \rightarrow e\nu$ candidates have to pass the following selection criteria:

- *Preselection* - Good Run List selection as defined in Section 3.1, 0–80% centrality range
- *ElectronQuality* - an electron with $p_T^e > 25$ GeV falling into the pseudorapidity region $0 < |\eta_e| < 1.37$ or $1.52 < |\eta_e| < 2.47$, passing the *MediumLH* identification, matched to HLT_15_loose_ion_L1EM12 trigger object,
- *IsoCut* - an electron passing the isolation selection defined in Section 5.2,
- *METCut* - $p_T^{\text{miss}} > 25$ GeV, where p_T^{miss} is calculated using tracks with $p_T > 4$ GeV,
- *ZVeto* - if an electron passing the *ElectronQuality* requirements forms a Z boson candidate with an oppositely charged electron of any quality with $p_T > 20$ GeV, the event is rejected if the mass of the dielectron system exceeds 66 GeV,

Requirement	$W^+ \rightarrow \mu^+\nu$ candidates	$W^- \rightarrow \mu^-\nu$ candidates
<i>Preselection</i>	2087875	2016966
<i>MuonQuality</i>	56423	53450
<i>ZVeto</i>	49704	46878
<i>IsoCut</i>	32902	30881
<i>METCut</i>	27532	25529
<i>MtCut</i>	27394	25385

Table 11: Cutflow for selections of $W^+ \rightarrow \mu^+\nu$ and $W^- \rightarrow \mu^-\nu$ candidate events in data.

Requirement	$W^+ \rightarrow e^+\nu$ candidates	$W^- \rightarrow e^-\nu$ candidates
<i>Preselection</i>	15258800	15677430
<i>ElectronQuality</i>	52566	49763
<i>ZVeto</i>	47827	44988
<i>IsoCut</i>	33460	31737
<i>METCut</i>	20299	19014
<i>MtCut</i>	19751	18465

Table 12: Cutflow for selections of $W^+ \rightarrow e^+\nu$ and $W^- \rightarrow e^-\nu$ candidate events in data.

- *MtCut* - the transverse mass of the electron- p_T^{miss} system must satisfy $m_T > 40$ GeV.

The number of $W^+ \rightarrow e^+\nu$ and $W^- \rightarrow e^-\nu$ candidate events in data passing the subsequent selection criteria is summarised in Table 12. In total 19751 $W^+ \rightarrow e^+\nu$ candidates and 18465 $W^- \rightarrow e^-\nu$ candidates satisfy all criteria.

Selection Stability

Figure 61 shows the stability of the event selection for both the $W \rightarrow \mu\nu$ and $W \rightarrow e\nu$ channels defined as the number of W boson candidates per $1 \mu\text{b}^{-1}$ of data as a function of run number. The runs number are ordered by a time when they were taken. It means that the lowest run number correspond to the first run of Pb+Pb collisions while the highest run number correspond to the last taken run of Pb+Pb collisions. Statistical uncertainties are shown only. Constant fits yield about 53.2 ($\chi^2/\text{n.d.f.} = 47.9/31$) $W^+ \rightarrow \mu^+\nu$ and 49.4 ($\chi^2/\text{n.d.f.} = 32.6/31$) $W^- \rightarrow \mu^-\nu$ candidates per $1 \mu\text{b}^{-1}$ in the case of the muon channel, and about 41.9 ($\chi^2/\text{n.d.f.} = 31.7/29$) $W^+ \rightarrow e^+\nu$ and 39.2 ($\chi^2/\text{n.d.f.} = 24.6/29$) $W^- \rightarrow e^-\nu$ candidates per $1 \mu\text{b}^{-1}$ for the electron channel. Within the considered uncertainties, no deviations from the fitted constant values are observed. The single electron trigger used in the analysis was not collecting data during the first

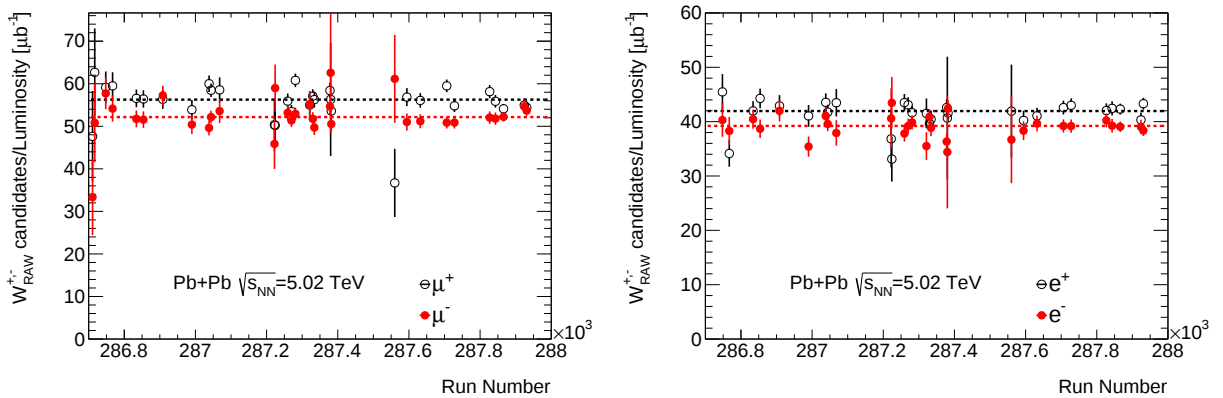


Figure 61: Number of events passing the muon (left) and electron (right) channel event selections per $1 \mu\text{b}^{-1}$ of data, separated by charges. Error bars represent statistical uncertainties only. The lines are fits of constant values.

two runs (286711, 286717), therefore these runs are not shown in Figure 61. However, the impact of missing runs is negligible, since the integrated luminosity of the first two runs is $1 \mu\text{b}^{-1}$.

9 Backgrounds in the muon channel

9.1 Multi-jet production

QCD multi-jet production (MJ) processes usually have a very large production cross-section and give a finite probability of fake W -boson-like signatures from jets mimicking the isolated lepton selection, and p_T^{miss} generated through energy/momentum mis-measurement in the event. In the case of the muon channel, the MJ background has significant contributions from muons produced in semi-leptonic decays of heavy quarks and in-flight pion decays. Although this type of background processes is effectively rejected by the selection of an isolated lepton, large p_T^{miss} and m_T , some contamination of the signal region due to these processes remains. Because of the difficulties in the precise simulation of these processes, data-driven techniques are often used for the MJ estimate in W boson measurements. This is possible due to the expectation that leptons produced in QCD multi-jet events are more likely to be non-isolated in comparison to signal leptons. The contribution from QCD multi-jet production to the sample of events selected in data is evaluated using a data-driven approach utilized in the W boson mass measurement by the ATLAS Collaboration [73].

9.1.1 General procedure

A generic recipe for the data-driven estimate is based on the selection of a jet-enriched data sample obtained by relaxing or inverting one of the isolated lepton selection cuts, then the newly selected MJ background template is normalized using data in a fit region selected to have a sizeable MJ background fraction. The normalization can be extracted using the fit of a kinematic distribution able to separate the signal from the MJ background, where the MJ background shape is derived from the MJ background template and the signal shape from MC. The normalization scaling factor extracted from the fit region is then applied to the number of MJ background template events passing the signal region selection. However, this general approach is not very well defined due to several reasons:

- arbitrariness of MJ background template lepton selection,
- biases in composition and kinematics of MJ background template with respect to events containing non-prompt leptons or fakes passing the signal selection,
- subtraction from the MJ background template of contamination coming from prompt leptons produced by W signal or other electroweak processes.

The method of estimating the MJ background contribution is made more robust by following a procedure similar to the one proposed and applied in Ref. [73]. Several MJ background templates are defined slicing the lepton isolation variables for values greater than the one used in the signal region and progressively further away from the signal region lepton selection. The MJ background extraction fit on a kinematic distribution is then repeated for each of the MJ background templates corresponding to each slice. The result is a "scan" of the MJ background

extractions with templates closer and closer to the signal region lepton selection. It is then possible to linearly extrapolate the MJ background estimate into the signal region. This procedure addresses the following points:

- The MJ background template selection is not arbitrary any more, in fact ideally the MJ background estimate coming from the extrapolation is the one with the signal region selection.
- The biases in the event kinematics or in the composition of the MJ background template become reduced as the MJ background selection gets closer to the signal region selection.

The normalization of the contribution from MJ background to the signal region is obtained from template fits to the p_T^μ distribution. Due to the limited resolution of the missing transverse momentum reconstruction fits to p_T^{miss} or m_T are not converging properly (signal and background templates are not different enough to discriminate between them). For the fitting procedure several phase-space regions are defined:

- signal region (SR): isolated muons (see Section 5.1), requirement on p_T^μ as described in Section 8;
- fit region (FR): isolated muons, relaxed $p_T^\mu > 20$ GeV requirement;
- control region (CR): anti-isolated muons (the isolation requirement is inverted) with relaxed $p_T^\mu > 20$ GeV requirement;

Events in these regions are required to pass all non-kinematic selection criteria. The relaxed requirements on p_T^μ in FR and CR are necessary to have a sufficient number of events for performing the fits to kinematic distributions. As described previously, the properties of the extracted MJ background can vary with the amount of muon isolation, so the control regions are not defined with all anti-isolated muons, but rather in slices of an isolation variable, and an "isolation scan" over these slices is performed for a final estimate of the MJ background.

In general, the procedure of evaluating the MJ background using a template from a single isolation slice is the following:

- CR is used to obtain a MJ background template:

$$N_{\text{MJ}}^{\text{uncorrected}} = N_{\text{data}}^{\text{CR}} - N_{\text{EW}}^{\text{CR}}, \quad (45)$$

where $N_{\text{MJ}}^{\text{uncorrected}}$ is the number of events in the MJ background template, $N_{\text{data}}^{\text{CR}}$ is the number of events in CR in data, while $N_{\text{EW}}^{\text{CR}}$ is the number of events contributed to CR by electroweak (EW) and top-quark processes. This contribution is estimated using MC samples scaled to their respective cross-sections.

- The shape of the MJ template obtained from the p_T^μ distribution is corrected by reweighting with a weight w binned in p_T^μ :

$$N_{\text{MJ}}^{\text{template}}(p_T^\mu) = N_{\text{MJ}}^{\text{uncorrected}}(p_T^\mu) \cdot w(p_T^\mu)^{d/D}. \quad (46)$$

The weight is scaled using the ratio of the distance d from the centre of the isolation slice to the mean of the signal isolation and the distance D between centres of slices used to determine the weight. Both distances are measured in units of the isolation variable used in the scan.

- A sum of two contributions is fitted to the number of data events in FR $N_{\text{data}}^{\text{FR}}$:

$$N_{\text{data}}^{\text{FR}}(p_T^\mu) = \alpha \cdot N_{\text{EW}}^{\text{FR}}(p_T^\mu) + T \cdot N_{\text{MJ}}^{\text{template}}(p_T^\mu). \quad (47)$$

One of the contributions is the number of events from EW and top-quark processes in FR $N_{\text{EW}}^{\text{FR}}$ estimated from MC samples. Prior to the fit the MC samples are normalized to the cross-sections of the respective processes, but in the fit the normalization of this contribution defined by α is allowed to float. The second contribution comes from the MJ background template scaled by the fit parameter T and allows to obtain the number of MJ background events in FR:

$$N_{\text{MJ}}^{\text{FR}} = T \cdot N_{\text{MJ}}^{\text{template}}. \quad (48)$$

- Since the p_T^μ requirements imposed to define SR and FR are different, the number of MJ background events in SR is calculated by integrating the p_T^μ distribution fitted in FR starting from the nominal cut.

9.1.2 Isolation slices

The isolation scan is performed in slices of pt_{cone20}/pt with a width of 0.1 units, starting from 0.4. Figure 62 presents the p_T^μ distributions for positive and negative muons which fall into a selected isolation slice ($0.4 < pt_{\text{cone20}}/pt < 0.5$). The MC samples are normalized to the to their expected number of events in the data according to Eq. (27). It can be noticed that a small fraction of events in CR comes from the signal process with much smaller contributions

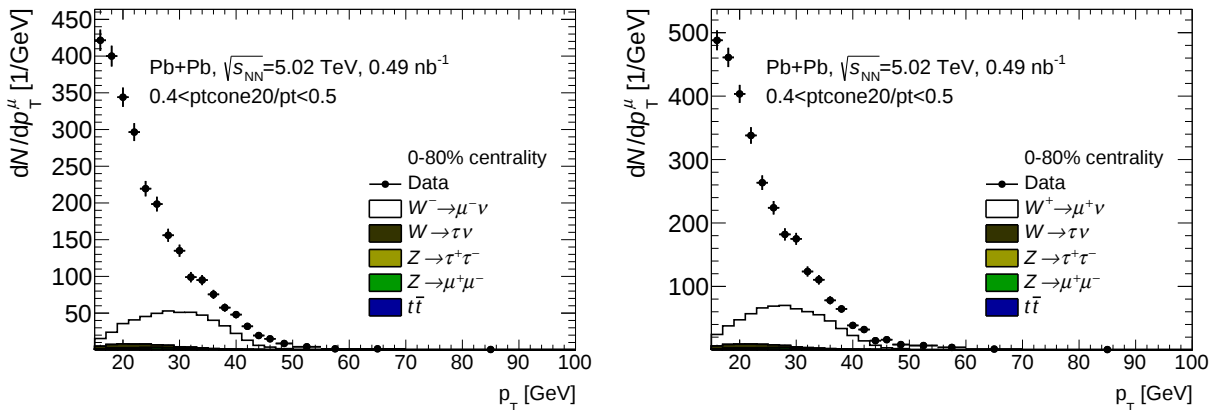


Figure 62: Distributions of p_T^μ for negative (left) and positive (right) muons in a selected isolation slice ($0.4 < pt_{\text{cone20}}/pt < 0.5$). The MC samples are normalized to the to their expected number of events in the data.

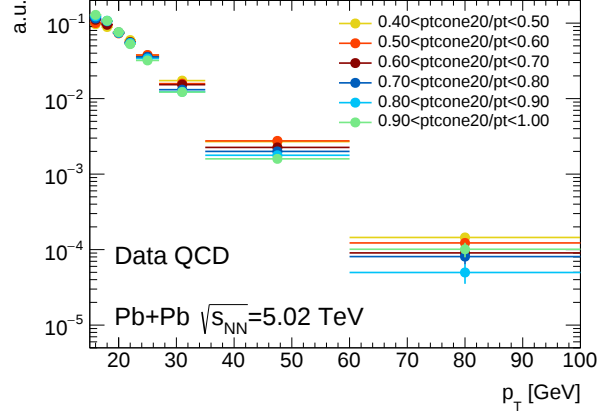


Figure 63: Shapes of p_T^μ distributions for muons coming from various isolation slices.

from EW and top-quark background processes. According to the general procedure, the residual contamination of signal and background processes is subtracted from CR.

Figure 63 presents the p_T^μ distributions for muons falling into different isolation slices in the 0–80% centrality class. The distributions are normalized to unity, so that the evolution of their shape between subsequent slices can be studied. It can be noticed that there is some variation of the p_T^μ shapes with the $ptcone20/pt$ requirement. This evolution of shapes is summarized in Figure 64 which shows ratios of normalized p_T^μ distributions for slices which have centres separated by 0.3 units in $ptcone20/pt$. The choice of the distance is made such that the evolution is more pronounced than for adjacent slices (with distance 0.1), but allows to use three ratios to derive an average shape correction with a satisfying statistical precision as shown in Figure 64. This average ratio is then used as the weight w (described in Section 9.1.1) to correct shapes of the p_T^μ distribution in the raw MJ background templates with the distance D set to 0.3.

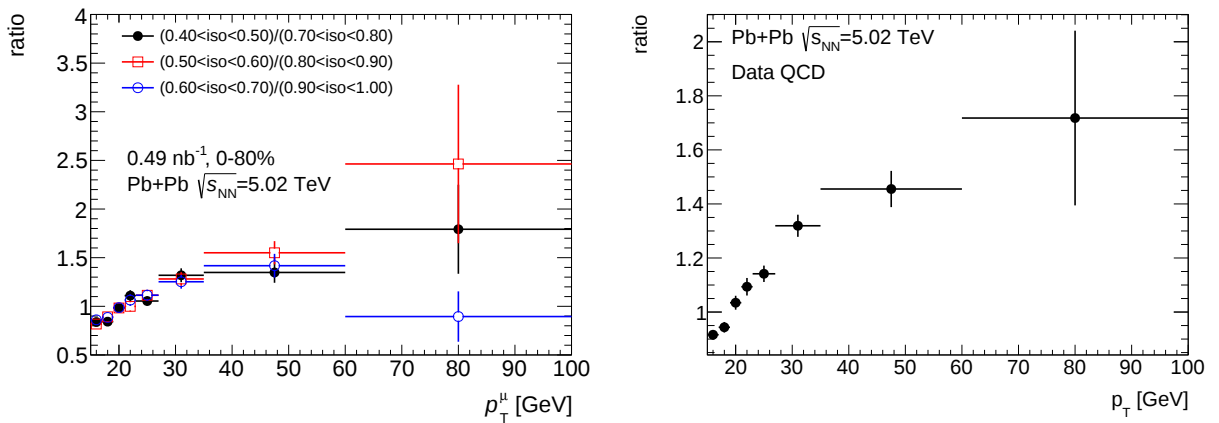


Figure 64: (Left) Ratios of the p_T^μ distribution shape for muons coming from various isolation slices separated by a distance of 0.3 units between their centres. (Right) Average ratio of the p_T^μ distribution shape for muons coming from isolation slices separated by a distance of 0.3 units between their centres.

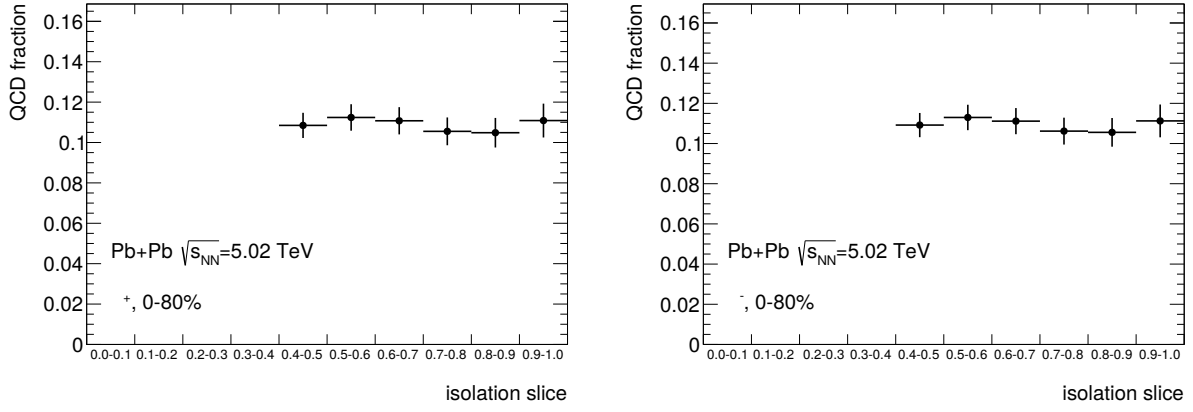


Figure 65: Multi-jet background fraction in SR obtained from template fits to the p_T^μ distribution in the scan over isolation slices. The template fit results are presented for $W^+ \rightarrow \mu^+ \nu$ (left) and $W^- \rightarrow \mu^- \nu$ (right) candidates in the 0–80% centrality class. The error bars represent the statistical uncertainty.

9.1.3 Isolation scan

In each of the isolation slices, the estimation of the MJ background yield is done using the p_T^μ distribution. All template fits performed for both the $W^+ \rightarrow \mu^+ \nu$ and $W^- \rightarrow \mu^- \nu$ candidates and using templates from the different isolation slices are summarized in Appendix A. Figure 65 shows the results of this isolation scan quantified by the fraction of MJ background in SR. An overall good agreement is observed between fractions obtained using templates from different isolation slices. The result of the fit in the first isolation slice ($0.4 < p_{T\text{cone20}}/p_T < 0.5$) is taken as the central value of the estimated MJ background fraction in SR. Figure 66 shows the isolation scan performed without reweighting the MJ template shape. In this case, the estimated MJ background fraction is falling while moving with the isolation interval towards less isolated

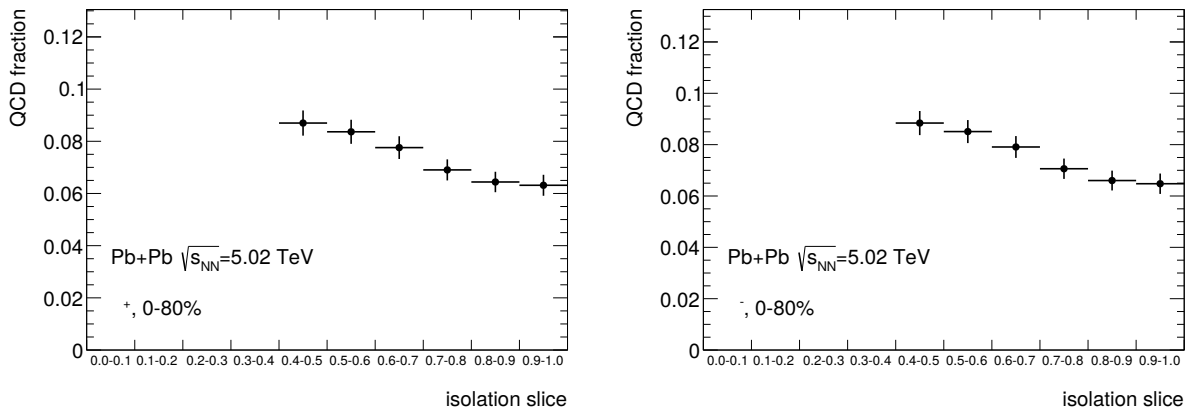


Figure 66: Multi-jet background fraction in SR obtained from template fits to the p_T^μ distribution in the scan over isolation slices without reweighting the MJ background template shape. The template fit results are presented for $W^+ \rightarrow \mu^+ \nu$ (left) and $W^- \rightarrow \mu^- \nu$ (right) candidates in the 0–80% centrality class. The error bars represent the statistical uncertainty.

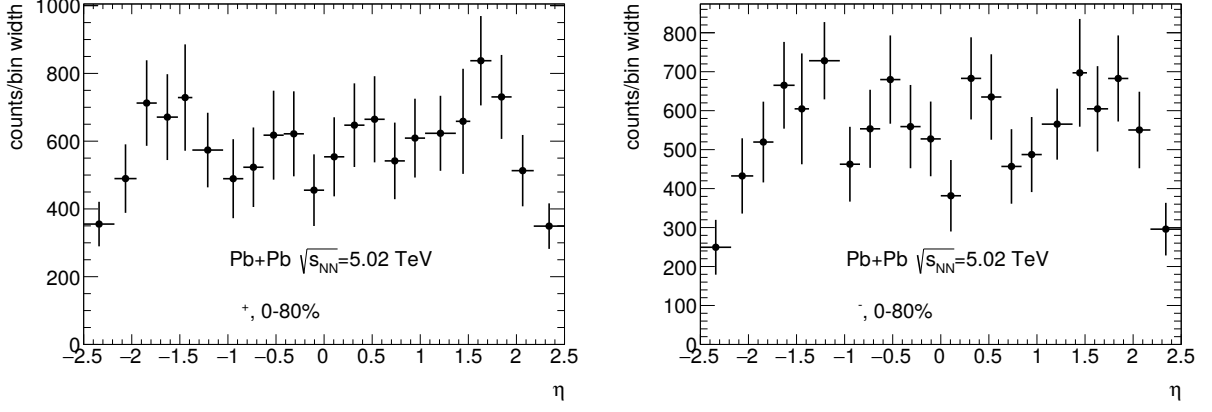


Figure 67: Estimated number of MJ background events in SR as a function of η divided by the η bin width. Results are presented for $W^+ \rightarrow \mu^+\nu$ (left) and $W^- \rightarrow \mu^-\nu$ (right) boson candidates in the 0–80% centrality class. The error bars represent the statistical uncertainty.

muons. This effect is caused by changes in the MJ template shape, which are partially related to the isolation variable definition (high- p_T muons tend to have a lower value of $ptcone20/pt$ than low- p_T muons). This clearly shows the benefit of the reweighting which allows to extract the MJ background fraction independently of the isolation slice used to define the MJ background template.

As a systematic check, the reweighting procedure of the MJ background template is varied. By default the distance d is defined from the centre of the isolation slice to the mean value of the signal isolation (taken from the signal MC sample). However, the width of the signal isolation region is non-negligible and therefore the distance d is also calculated to the boundaries of this region defined by the analysis cuts, namely 0 and 0.446. The impact of this check on results varies from 1 to 2% as shown in Section 12.

In order to estimate the MJ background yield differentially in η , the template fits are per-

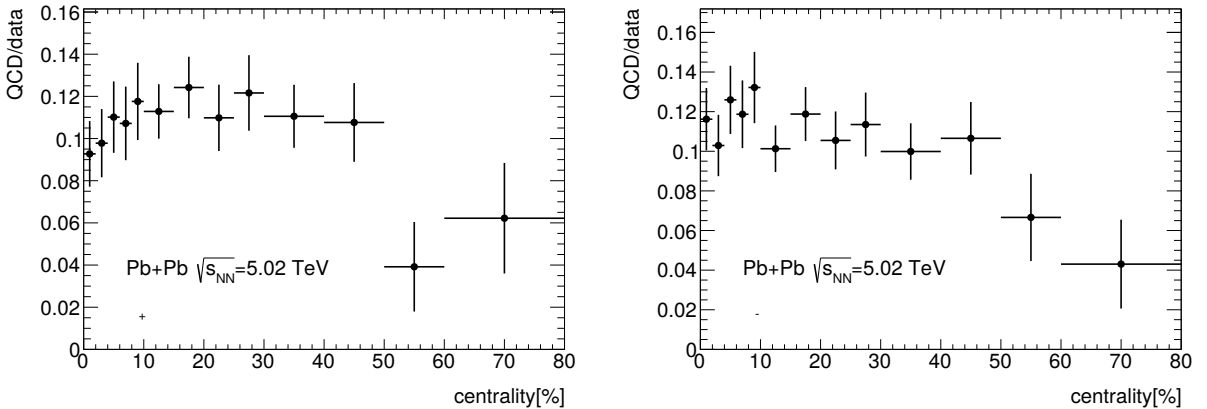


Figure 68: Estimated MJ background fraction in SR as a function of the centrality class. Results are presented for $W^+ \rightarrow \mu^+\nu$ (left) and $W^- \rightarrow \mu^-\nu$ (right) boson candidates. The error bars represent the statistical uncertainty.

formed separately for each η bin. Due to statistical limitations the same MJ background template is used in each of the fits. All template fits performed for both the $W^+ \rightarrow \mu^+ \nu$ and $W^- \rightarrow \mu^- \nu$ candidates are summarized in Appendix B. Figure 67 shows the estimated number of MJ background events in SR as a function of η divided by the η bin width.

The dependence of the MJ background fraction on centrality is also studied. Figure 68 presents the estimated MJ background fraction in SR as a function of the centrality class. The small MJ background fraction in the most peripheral bin is related to the better performance of isolation and p_T^{miss} reconstruction in events with a low underlying event activity.

9.1.4 Dependence of QCD multi-jet background template from η

Due to statistical limitations of the available sample the MJ template is constructed using muons from the entire η region. In order to test correctness of this assumption shape of templates obtained from distinct η regions were compared. Figure 69 present MJ templates constructed from muons falling into barrel ($|\eta| < 1.05$) and endcap ($1.05 < |\eta| < 2.4$) region compared to the nominal template. One can notice that difference between presented pseudorapidity regions is statistically significant. To cover given effect a systematic uncertainty is assigned where for QCD MJ background estimation is used template from the barrel and the endcap region. Details are given in the Section 12.6.

9.2 Weak-boson production

The production of Z bosons with subsequent decays to muon pairs, as well as W and Z bosons in the tauonic channel with subsequent decays to muons, are significant background processes to the W boson measurement in the muon channel. These background processes are simulated using POWHEG+PYTHIA8 in an NLO QCD approximation and then normalized to the integrated luminosity of the data according to Eq. 27. The nominal selection criteria are imposed

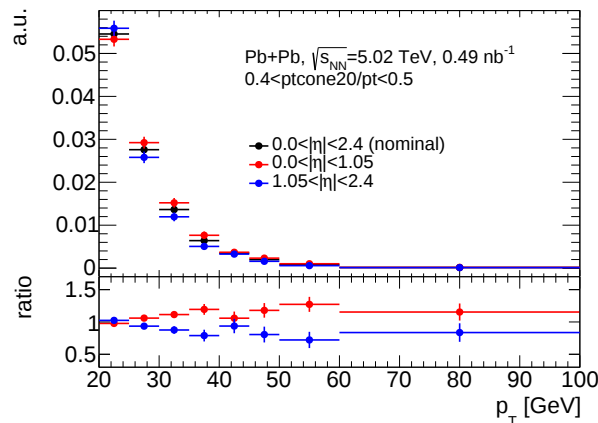


Figure 69: QCD MJ background template normalized to unity obtained in three η regions: barrel (red markers), endcap (blue markers) and whole muon acceptance (black markers). Bottom panel show ratio of barrel and endcap to the whole acceptance. Statistical uncertainties are calculated taking into account correlations between numerator and denominator.

Centrality class	$Z \rightarrow \mu^+ \mu^-$	$Z \rightarrow \tau^+ \tau^-$	$W^+ \rightarrow \tau^+ \nu$	$W^+ \rightarrow \mu^+ \nu$
0–2%	73.3 ± 1.2	5.54 ± 0.75	36.29 ± 0.99	1764 ± 12
2–4%	69.2 ± 1.1	5.78 ± 0.73	38.33 ± 0.99	1786 ± 12
4–6%	67.0 ± 1.1	6.48 ± 0.76	37.69 ± 0.94	1738 ± 11
6–8%	60.54 ± 0.94	4.96 ± 0.61	33.99 ± 0.84	1558 ± 10
8–10%	59.49 ± 0.91	5.12 ± 0.61	33.63 ± 0.82	1539.3 ± 9.9
10–15%	125.6 ± 1.2	10.53 ± 0.81	69.5 ± 1.1	3239 ± 13
15–20%	98.7 ± 1.1	7.34 ± 0.70	55.1 ± 1.0	2566 ± 12
20–25%	76.2 ± 1.1	5.11 ± 0.63	42.54 ± 0.96	1983 ± 12
25–30%	62.21 ± 0.86	4.98 ± 0.57	37.39 ± 0.79	1677.8 ± 9.5
30–40%	77.54 ± 0.79	5.72 ± 0.49	45.22 ± 0.72	2108.2 ± 8.7
40–50%	45.68 ± 0.65	4.29 ± 0.46	28.96 ± 0.62	1290.6 ± 7.3
50–60%	20.48 ± 0.31	1.71 ± 0.21	13.57 ± 0.30	590.7 ± 3.6
60–80%	14.61 ± 0.18	1.29 ± 0.13	9.92 ± 0.18	435.5 ± 2.1

Table 13: Estimated number of Z and W background events which contribute to the $W^+ \rightarrow \mu^+ \nu$ candidate sample selected in data. The last column gives the estimated number of signal events. All numbers are MC predictions and the uncertainties are statistical only.

on each MC sample. The predicted numbers of events coming from these background processes are summarised in Tables 13 and 14 for positive and negative W boson candidates, respectively. For comparison, the number of signal events estimated from the $W \rightarrow \mu \nu$ MC samples is also given. It is found that the $Z \rightarrow \mu^+ \mu^-$ and $W \rightarrow \tau \nu$ backgrounds are the most dominant ones. Compared to the total number of $W \rightarrow \mu \nu$ candidates selected in data, they amount to 3.0% and 1.9%, respectively, for negative muons, while for positive muons these fractions are 3.1% and 1.8%, respectively. The contributions from diboson production are considered to be negligible, since in the measurement of W boson production in pp collisions at $\sqrt{s} = 5.02$ TeV this background was estimated at the level of 0.1% [74].

9.3 Top-quark production

The contribution from $t\bar{t}$ production is also evaluated using the simulation. After applying all W boson selection requirements, 89 $t\bar{t}$ events are found, which corresponds to 0.17% of W boson candidates selected in data. With the current statistical precision this contribution is negligible. The contributions from single-top production are also considered to be negligible, since in the measurement of W boson production in pp collisions at $\sqrt{s} = 5.02$ TeV this background was estimated at the level of 0.1–0.2% [74].

9.4 Signal-like muons in data overlay

A background which is unique to MC simulation produced in the data overlay mode, is a potential contribution of signal-like muons from the MinBiasOverlay stream. Such a background could bias muon distributions in the simulation and affect the C_W corrections defined in Section 11.

Centrality class	$Z \rightarrow \mu^+ \mu^-$	$Z \rightarrow \tau^+ \tau^-$	$W^- \rightarrow \tau^- \nu$	$W^- \rightarrow \mu^- \nu$
0–2%	64.3 ± 1.1	5.13 ± 0.71	39.20 ± 0.98	1666 ± 13
2–4%	63.2 ± 1.1	5.54 ± 0.70	35.76 ± 0.90	1644 ± 12
4–6%	59.03 ± 0.99	5.02 ± 0.65	39.95 ± 0.93	1601 ± 12
6–8%	52.05 ± 0.87	4.15 ± 0.56	33.17 ± 0.79	1444 ± 10
8–10%	53.08 ± 0.86	3.82 ± 0.52	34.07 ± 0.78	1429.1 ± 9.9
10–15%	112.0 ± 1.2	8.48 ± 0.72	70.5 ± 1.0	3018 ± 13
15–20%	85.9 ± 1.1	7.34 ± 0.70	55.96 ± 0.95	2388 ± 12
20–25%	66.5 ± 1.0	6.56 ± 0.72	42.32 ± 0.91	1854 ± 12
25–30%	54.03 ± 0.80	4.85 ± 0.55	37.67 ± 0.76	1586.9 ± 9.6
30–40%	68.25 ± 0.74	6.12 ± 0.51	45.14 ± 0.68	1965.9 ± 8.8
40–50%	40.12 ± 0.61	2.78 ± 0.36	28.62 ± 0.58	1179.5 ± 7.3
50–60%	18.00 ± 0.29	1.35 ± 0.18	12.55 ± 0.28	545.3 ± 3.6
60–80%	12.71 ± 0.17	1.12 ± 0.11	9.57 ± 0.17	399.7 ± 2.1

Table 14: Estimated number of Z and W background events which contribute to the $W^- \rightarrow \mu^- \nu$ candidate sample selected in data. The last column gives the estimated number of signal events. All numbers are MC predictions and the uncertainties are statistical only.

Therefore, to study a potential contribution of signal-like muons from the underlying event to the MC samples, the analysis is performed on the MinBiasOverlay stream of one run (287866) which consists of more than 1.5M events corresponding to 6.5% of the total number of events in the MinBiasOverlay stream. Then the nominal selection of the W boson analysis is imposed on the given events. A total of 49 events passes all selection criteria which constitutes 0.003% of the total input sample. Therefore, this background is considered negligible in the analysis.

10 Backgrounds in the electron channel

10.1 Multi-jet production

In the case of the electron channel, the MJ background has contributions from semi-leptonic heavy-quark decays, material conversions or light hadrons faking electrons. The general idea of estimating the MJ background contribution to the signal region is described in Section 9.1.1, however a slight modification to this procedure is necessary in the electron channel. In the muon channel, the muon selection in CR is defined by the default identification requirement (Section 8) with a relaxed p_T^μ cut. The analysis of the electron channel shows that the number of events in CR is quite limited, and therefore the identification requirement for electrons in CR is modified from *MediumLH* to *LooseLH* in order to increase the available statistics.

The isolation selection for electrons is defined by rectangular cuts on two isolation variables: $pt2cone20/pt$ and $etcone20/pt$. Therefore, one of these isolation variables has to be chosen to perform the isolation scan. It is found that using the tracking isolation variable for the scan gives more counts in CR. In parallel, the cut on $etcone20/pt$ is removed while performing the isolation scan in order to further increase the number of available anti-isolated electrons.

10.1.1 Isolation slices

The isolation scan is performed in slices of $pt2cone20/pt$ with a width of 0.1 units, starting from 0.2. Figure 70 presents the p_T^e distribution for electrons which fall into a selected isolation slice ($0.2 < pt2cone20/pt < 0.3$). The MC samples are normalized to the to their expected number of events in the data according to Eq. (27). The drop just below 18 GeV is related to the electron trigger turn-on. It can be noticed that a small fraction of events in CR comes from the signal process with much smaller contributions from EW and top-quark background processes.

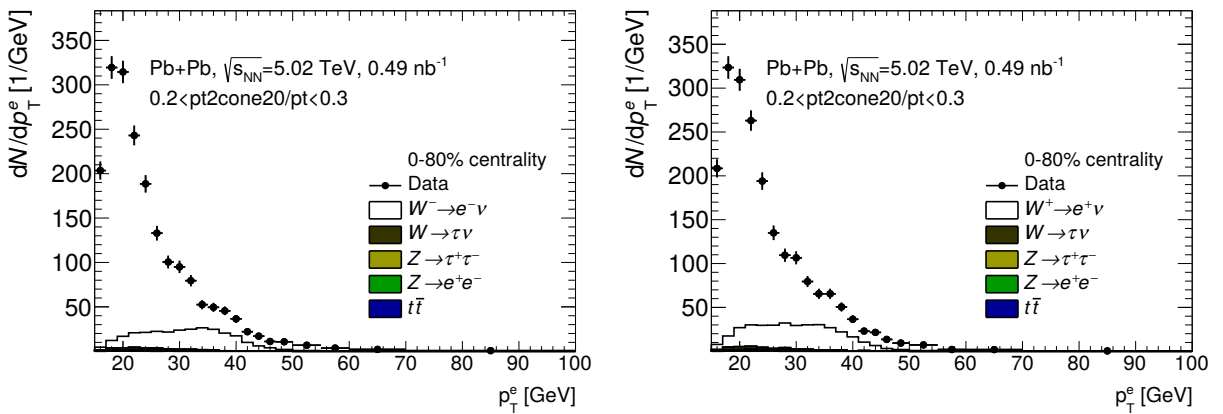


Figure 70: Distributions of p_T^e for negative (left) and positive (right) electrons in a selected isolation slice ($0.2 < pt2cone20/pt < 0.3$). No requirement on the calorimetric isolation variable $etcone20/pt$ is applied. The MC samples are normalized to the to their expected number of events in the data.

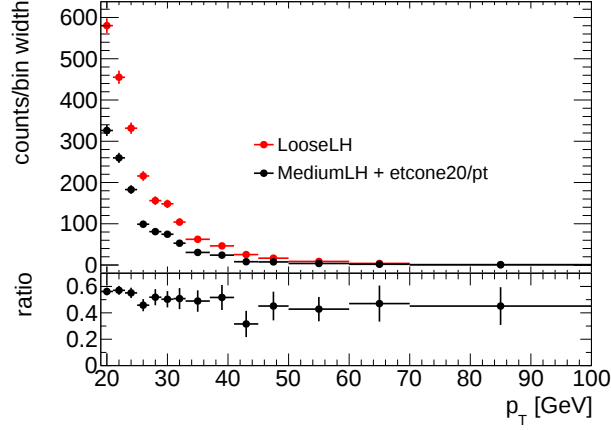


Figure 71: Comparison of p_T^e distributions for anti-isolated electrons in a selected isolation slice ($0.2 < pt2cone20/pt < 0.3$) with nominal (black markers) and relaxed (red markers) requirements on identification and $etcone20/pt$. The signal and background MC contributions are subtracted from the distributions.

According to the general procedure, the residual contamination of signal and background processes is subtracted from CR.

Figure 71 presents a comparison of multi-jet background templates obtained from a selected isolation slice ($0.2 < pt2cone20/pt < 0.3$) before and after relaxing the electron identification and isolation requirements. The signal and background MC contributions are subtracted from the templates. The ratio of the two templates is almost constant with p_T^e , indicating a good agreement of the template shapes. Deviations from a constant ratio are smaller than the systematic effects of varying the template shape as described in Section 12.6. Since the final multi-jet background normalization is obtained from template fits, there is no need to introduce a scaling factor to correct for the differences between the nominal electron selection and the one used for the template.

Figure 72 presents the p_T^e distributions for electrons falling into different isolation slices in the 0–80% centrality class. The distributions are normalized to unity, so that the evolution of

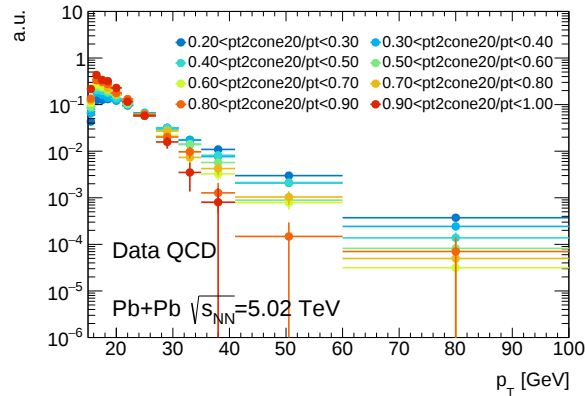


Figure 72: Shapes of p_T^e distributions for electrons coming from various isolation slices.

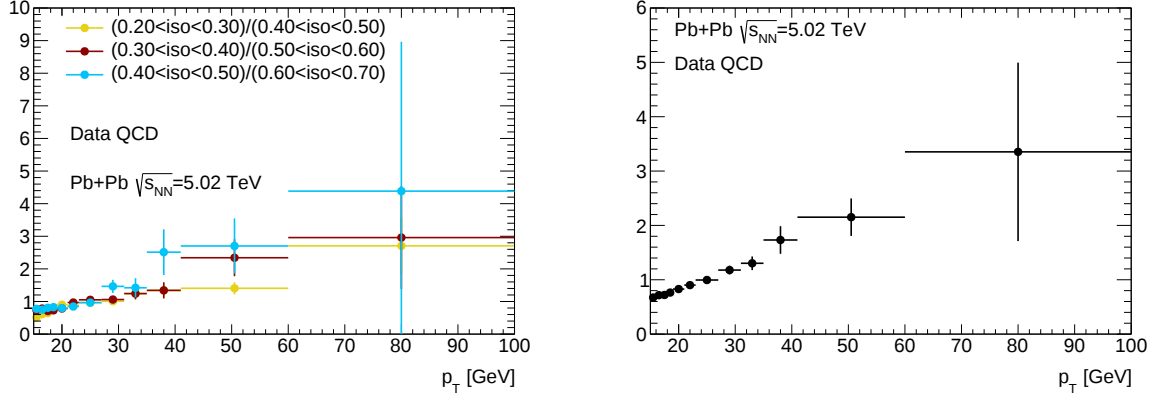


Figure 73: (Left) Ratios of the p_T^e distribution shape for electrons coming from various isolation slices separated by a distance of 0.2 units between their centres. (Right) Average ratio of the p_T^e distribution shape for electrons coming from isolation slices separated by a distance of 0.2 units between their centres.

their shape between subsequent slices can be studied. It can be noticed that the p_T^e shapes tend to change with the $pt2cone20/pt$ requirement even stronger than for the muons. This evolution of shapes is summarized in Figure 73 which shows ratios of normalized p_T^e distributions in slices which have centres separated by 0.2 units in $pt2cone20/pt$. The choice of the distance is made such that the evolution is more pronounced than for adjacent slices (with distance 0.1), but allows to use three ratios to derive an average shape correction with a satisfying statistical precision as shown in Figure 73. This average ratio is then used as the weight w (described in Section 9.1.1) to correct shapes of the p_T^e distribution in the raw multi-jet background templates with the distance D set to 0.2.

10.1.2 Isolation scan

Like in the muon channel, the estimation of the multi-jet background yield in each of the isolation slices is done using p_T^e distribution. All template fits performed for both the $W^+ \rightarrow e^+ \nu$ and $W^- \rightarrow e^- \nu$ candidates and using templates from the different isolation slices are summarized in Appendix C. Figure 74 shows the results of this isolation scan quantified by the fraction of MJ background in SR. An overall good agreement is observed between fractions obtained using templates from different isolation slices. The estimated MJ background fraction in SR is roughly 20% which is almost twice as large as in the muon channel ($\sim 11\%$). Differences in MJ background levels between channels were also observed in W boson measurements in Pb+Pb collisions at 2.76 TeV [67] and in pp collisions at 5.02 TeV [74]. The result of the fit in the first isolation slice ($0.2 < pt2cone20/pt < 0.3$) is taken as the central value of the estimated MJ background fraction in SR.

The systematic uncertainty related to the MJ background evaluation procedure is estimated in the same manner as in the muon channel. By default the distance d is defined from the centre of the isolation slice to the mean value of the signal isolation (taken from the signal MC sample). However, the width of the signal isolation region is non-negligible and therefore the distance d

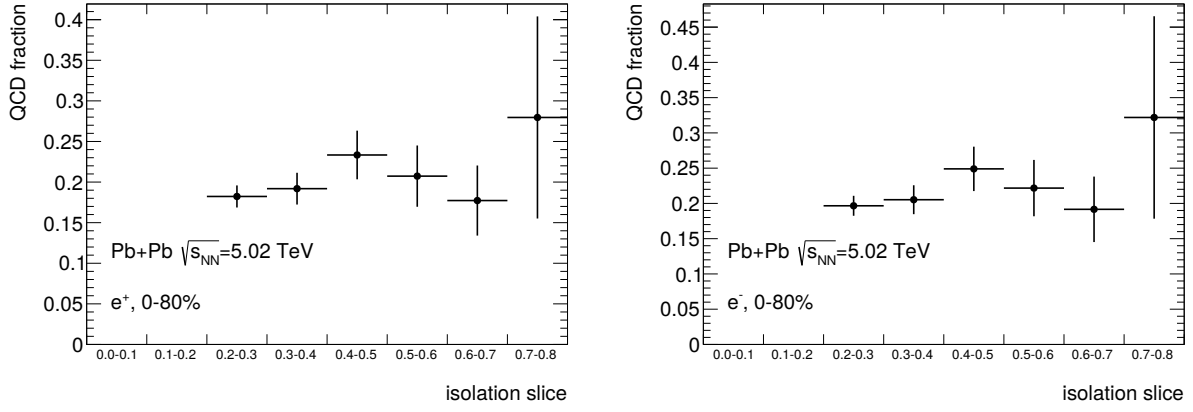


Figure 74: Multi-jet background fraction in SR obtained from template fits to the p_T^e distribution in the scan over isolation slices. The template fit results are presented for $W^+ \rightarrow e^+ \nu$ (left) and $W^- \rightarrow e^- \nu$ (right) candidates in the 0–80% centrality class. The error bars represent the statistical uncertainty.

also calculated to the boundaries of this region defined by the analysis cuts, namely 0 and 0.1. The impact of this check on results varies from 2 to 10% as shown in Section 12.

In order to estimate the multi-jet background yield differentially in η , the template fits are performed separately for each η bin. Due to statistical limitations the same MJ template is used in each of the fits. All template fits performed for both the $W^+ \rightarrow e^+ \nu$ and $W^- \rightarrow e^- \nu$ candidates are summarized in Appendix D. Figure 75 shows the estimated number of multi-jet background events in SR as a function of η divided by the η bin width.

The dependence of the multi-jet background fraction on centrality is also studied. Figure 76 presents the estimated MJ background fraction in SR as a function of the centrality class. The small MJ background fraction in the most peripheral bin is related to the better performance of isolation and p_T^{miss} reconstruction in events with a low underlying event activity.

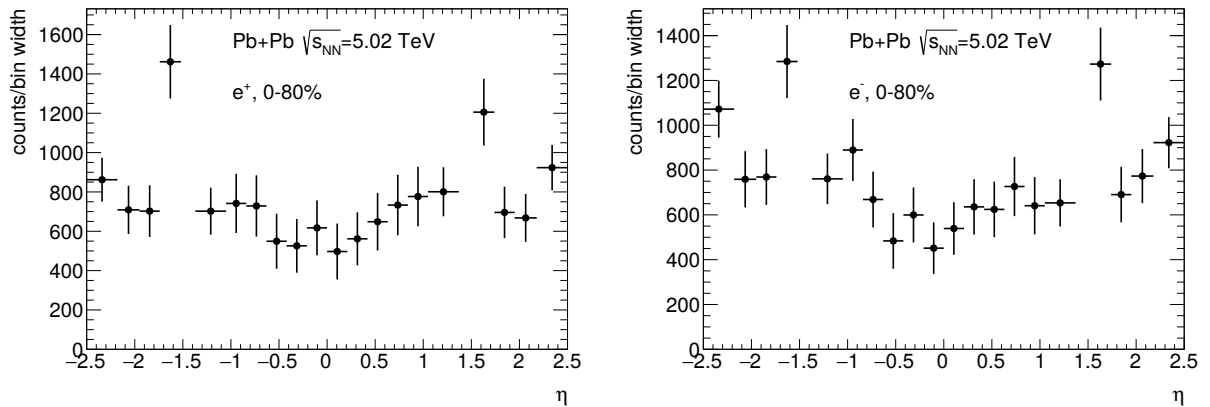


Figure 75: Estimated number of multi-jet background events in SR as a function of η divided by the η bin width. Results are presented for $W^+ \rightarrow e^+ \nu$ (left) and $W^- \rightarrow e^- \nu$ (right) boson candidates in the 0–80% centrality class. The error bars represent the statistical uncertainty.

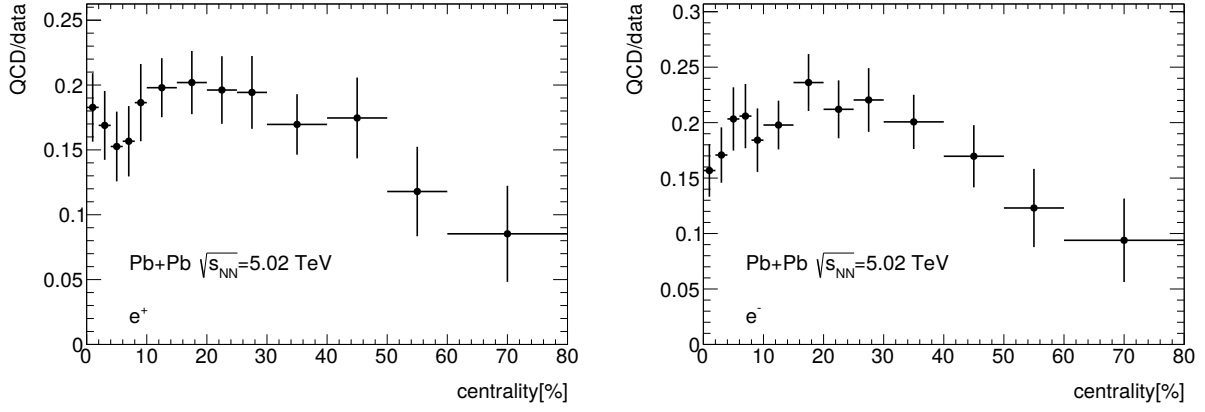


Figure 76: Estimated multi-jet background fraction in SR as a function of the centrality class. Results are presented for $W^+ \rightarrow e^+ \nu$ (left) and $W^- \rightarrow e^- \nu$ (right) boson candidates. The error bars represent the statistical uncertainty.

10.1.3 Dependence of QCD multi-jet background template from η

With similar manner to the muon channel dependence of the MJ template from η was tested (see Section 9.1.4). Figure 77 presents MJ templates constructed from electrons falling into barrel ($|\eta| < 1.37$) and endcap ($1.52 < |\eta| < 2.47$) region compared to the nominal template. One can notice that difference between presented pseudorapidity regions is statistically significant. To cover given effect a systematic uncertainty is assigned where for QCD MJ background estimation is used template from the barrel and the endcap region. Details are given in the Section 12.6.

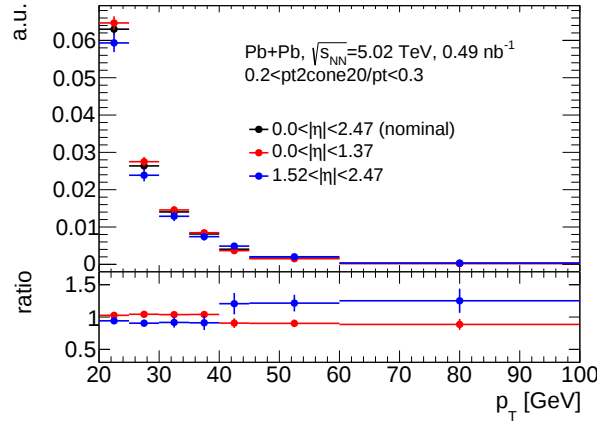


Figure 77: QCD MJ background template normalized to unity obtained in three η regions: barrel (red markers), endcap (blue markers) and whole electron acceptance (black markers). Bottom panel show ratio of barrel and endcap distributions to the whole acceptance distribution. Statistical uncertainties are calculated taking into account correlations between numerator and denominator.

Centrality class	$Z \rightarrow e^+e^-$	$Z \rightarrow \tau^+\tau^-$	$W^+ \rightarrow \tau^+\nu$	$W^+ \rightarrow e^+\nu$
0–2%	73.8 ± 2.6	2.6 ± 1.2	26.89 ± 0.79	1286.1 ± 8.1
2–4%	69.4 ± 2.5	3.6 ± 1.3	24.93 ± 0.73	1227.1 ± 7.6
4–6%	61.9 ± 2.2	5.3 ± 1.5	22.41 ± 0.66	1133.8 ± 7.0
6–8%	60.7 ± 2.1	4.6 ± 1.3	21.75 ± 0.62	1080.9 ± 6.6
8–10%	53.7 ± 2.0	1.18 ± 0.68	21.90 ± 0.60	1013.7 ± 6.7
10–15%	124.7 ± 2.6	5.5 ± 1.3	45.04 ± 0.79	2192.3 ± 8.2
15–20%	100.2 ± 2.5	5.5 ± 1.4	35.31 ± 0.73	1764.8 ± 7.7
20–25%	82.0 ± 2.5	3.8 ± 1.2	28.91 ± 0.72	1438.7 ± 7.6
25–30%	62.8 ± 1.9	2.79 ± 0.89	22.89 ± 0.56	1130.7 ± 5.9
30–40%	86.3 ± 1.8	4.74 ± 0.96	29.16 ± 0.52	1503.9 ± 5.5
40–50%	45.8 ± 1.4	2.03 ± 0.66	15.97 ± 0.40	800.3 ± 4.3
50–60%	20.5 ± 0.63	0.58 ± 0.27	7.07 ± 0.19	362.9 ± 2.0
60–80%	14.1 ± 0.35	0.26 ± 0.10	4.39 ± 0.10	228.8 ± 1.0

Table 15: Estimated number of Z and W background events which contribute to the $W^+ \rightarrow e^+\nu$ candidate sample selected in data. The last column gives the estimated number of signal events. All numbers are MC predictions and the uncertainties are statistical only.

10.2 Weak-boson production

The contributions from electroweak background processes are estimated in the same way as for the muon channel. The predicted numbers of events coming from these background processes are summarised in Tables 15 and 16 for positive and negative W boson candidates, respectively. For comparison, the number of signal events estimated from the $W \rightarrow e\nu$ MC samples is also given. It is found that the $Z \rightarrow e^+e^-$ and $W \rightarrow \tau\nu$ backgrounds are the most dominant ones. Compared to the total number of $W \rightarrow e\nu$ candidates selected in data, they amount to 5.5% and

Centrality class	$Z \rightarrow e^+e^-$	$Z \rightarrow \tau^+\tau^-$	$W^- \rightarrow \tau^-\nu$	$W^- \rightarrow e^-\nu$
0–2%	67.6 ± 2.5	0.99 ± 0.70	25.69 ± 0.74	1226.4 ± 8.4
2–4%	64.8 ± 2.4	2.9 ± 1.2	24.17 ± 0.69	1154.1 ± 7.8
4–6%	58.8 ± 2.2	2.06 ± 0.92	22.08 ± 0.62	1079.0 ± 7.3
6–8%	53.7 ± 2.0	1.18 ± 0.68	21.90 ± 0.60	1013.7 ± 6.7
8–10%	51.9 ± 1.9	3.1 ± 1.1	19.55 ± 0.54	936.7 ± 6.2
10–15%	111.3 ± 2.5	6.5 ± 1.4	43.87 ± 0.74	2050.1 ± 8.4
15–20%	91.3 ± 2.4	6.2 ± 1.4	35.57 ± 0.70	1650.1 ± 7.9
20–25%	75.0 ± 2.4	3.7 ± 1.2	28.42 ± 0.68	1339.9 ± 7.8
25–30%	60.6 ± 1.8	2.33 ± 0.83	21.29 ± 0.52	1058.0 ± 6.0
30–40%	77.9 ± 1.7	2.89 ± 0.75	29.18 ± 0.49	1401.7 ± 5.7
40–50%	43.6 ± 1.3	1.34 ± 0.55	16.10 ± 0.39	750.5 ± 4.4
50–60%	18.26 ± 0.60	0.71 ± 0.29	6.97 ± 0.18	341.5 ± 2.0
60–80%	12.02 ± 0.32	0.46 ± 0.14	4.40 ± 0.09	210.4 ± 1.1

Table 16: Estimated number of Z and W background events which contribute to the $W^- \rightarrow e^-\nu$ candidate sample selected in data. The last column gives the estimated number of signal events. All numbers are MC predictions and the uncertainties are statistical only.

2.1%, respectively, for negative electrons, while for positive electrons these fractions are 5.7% and 2.0%, respectively.

10.3 $t\bar{t}$ production

The contribution from $t\bar{t}$ production is also evaluated using the simulation. After applying all W boson selection requirements, 48 $t\bar{t}$ events are found, which corresponds to 0.13% of W boson candidates selected in data. With the current statistical precision this contribution is negligible.

11 Measurement procedure

11.1 Bin-by-bin correction

The $W \rightarrow \mu\nu$ ($W \rightarrow e\nu$) event yields are measured within a kinematic fiducial region defined by the requirements on the muon (electron) p_T and η , neutrino p_T or p_T^{miss} , and transverse mass m_T . Efficiency correction factors C_W are calculated from the signal $W \rightarrow \mu\nu$ ($W \rightarrow e\nu$) MC samples. They are defined as ratios of signal events passing the W boson selection criteria at the reconstruction level from Section 8, to the signal events that pass the muon (electron) p_T and η , neutrino p_T , and m_T requirements at the generator level i.e.:

$$C_W(\eta^{\text{reco}}, \text{centrality}, \text{charge}) = \frac{N_{\text{sel,pass}}^W(\eta^{\text{reco}}, \text{centrality}, \text{charge})}{N_{\text{sel,gen}}^W(\eta^{\text{true}}, \text{centrality})}. \quad (49)$$

The C_W factors correct for inefficiencies in the lepton reconstruction, identification, isolation and trigger, effects due to lepton momentum resolution, and by construction they can exceed unity. The C_W corrections also account for inefficiency due to the Z -veto requirement and for the extrapolation from the $|\eta^{\text{reco},\mu}| < 2.4$ ($|\eta^{\text{reco},e}| < 2.47$) phase-space region to the $|\eta^{\text{true}}| < 2.5$ phase-space region, which affects the most forward η^μ (η^e) bins. All efficiency scale factors used in the analysis are applied to the numerator of C_W .

Figure 78 shows C_W correction factors evaluated as a function of muon (electron) η for both charges in events from the 0–80% centrality class. Also η distributions for positive and negative muons (electrons) after imposing the kinematic requirements at the generator and reconstruction level are presented. The C_W correction varies with η . The asymmetric shape is due to forward-backward differences in the performance of various systems. It is true that by design ATLAS detector is forward-backward symmetric but it is not possible to fabricate exactly the same modules. Moreover, with an operation more and more dead modules appear which also contribute to the asymmetry in the C_W correction factor. The statistical errors of SFs are not propagated to the C_W factors, since they are treated as a contribution to systematic uncertainties as described in Section 12.

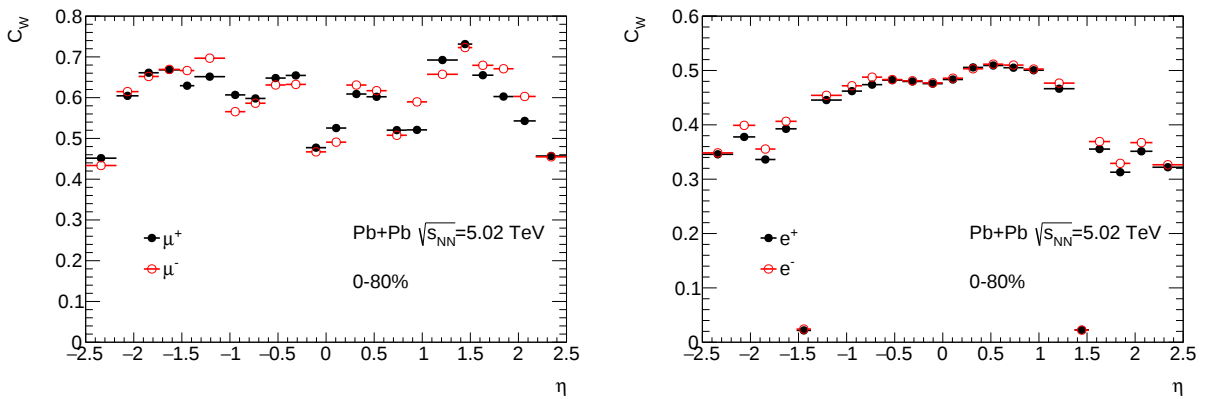


Figure 78: Correction factor C_W as a function of lepton η for both charges for muons (left) and electrons (right).

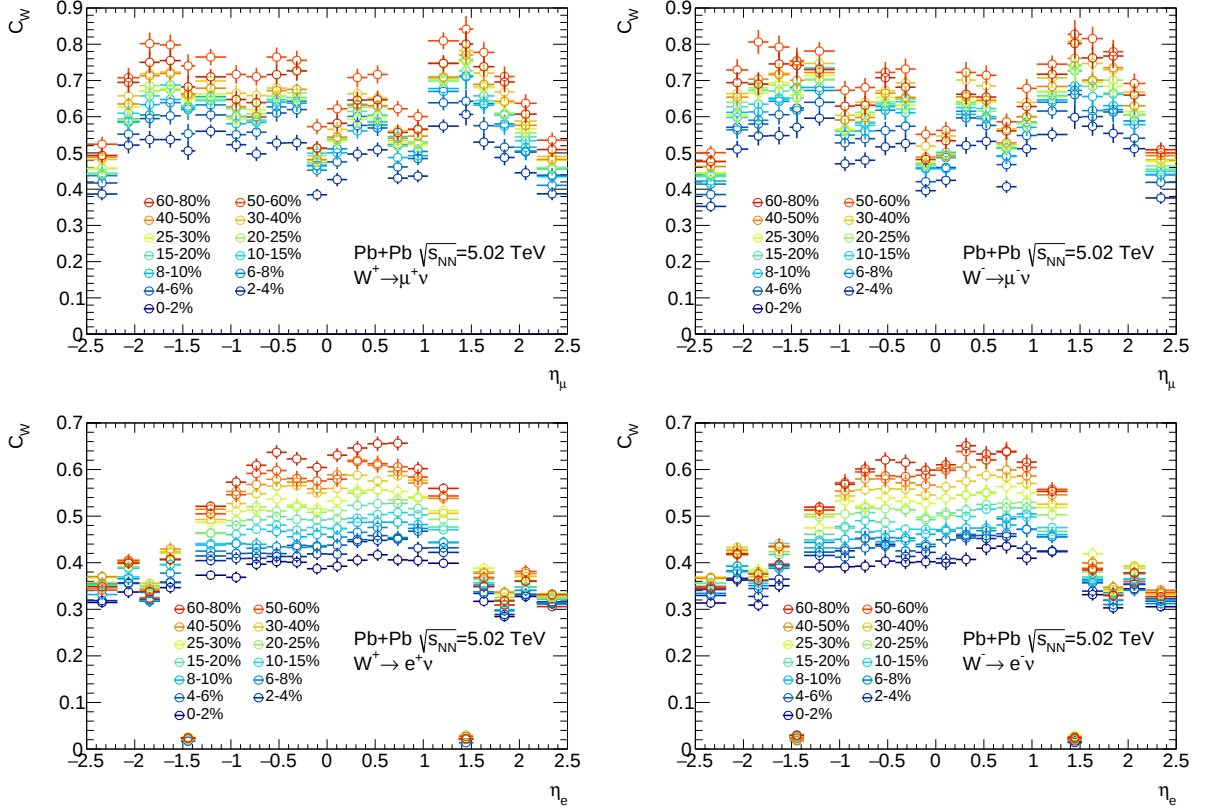


Figure 79: Correction factor C_W as a function of lepton η for positive (left) and negative (right) muons (top) and electrons (bottom) evaluated in different centrality classes.

Figure 79 shows C_W correction factors evaluated as a function of muon (electron) η for positive and negative muons (electrons) in all centrality classes.

11.2 Measurement methodology

Event yields for $W \rightarrow \ell\nu$ production in $|\eta^\ell| < 2.5$, $N^{W \rightarrow \ell\nu}$, are measured using the formula:

$$N^{W \rightarrow \ell\nu} = \frac{N^{\text{obs}} - N^{\text{bkg}}}{C_W}, \quad (50)$$

where N^{obs} and N^{bkg} are numbers of reconstructed W boson candidates and background events in the data, respectively, and C_W is the efficiency correction factor. This formula is used to obtain the corrected yields in each bin of η^ℓ separately, while the integrated production yields are calculated by summing the contributions from all η^ℓ bins.

The lepton charge asymmetry measures the difference between the event yields of the $W^+ \rightarrow \ell^+\nu$ and $W^- \rightarrow \ell^-\nu$ processes and it is defined as:

$$A_\ell = \frac{N_{W^+ \rightarrow \ell^+\nu} - N_{W^- \rightarrow \ell^-\nu}}{N_{W^+ \rightarrow \ell^+\nu} + N_{W^- \rightarrow \ell^-\nu}}, \quad (51)$$

where $N_{W^+ \rightarrow \ell^+\nu}$ ($N_{W^- \rightarrow \ell^-\nu}$) is the estimated number of produced W^+ (W^-) bosons.

11.3 Closure test of the trigger efficiency correction

In order to check whether the lack of trigger simulation in muon MC samples does not introduce a bias or systematic error in the measurement, a trigger closure test is performed. For this purpose $Z \rightarrow \mu^+\mu^-$ and $W \rightarrow \mu\nu$ MC samples have been produced in the HIJING [75] overlay mode, which allows to include trigger information. A disadvantage of this type of samples is that HIJING does not properly simulate the underlying event, which results in slightly lower track multiplicities in comparison to the data. The trigger efficiency used in the closure test is extracted from $Z \rightarrow \mu^+\mu^-$ events, while the closure test is performed on the $W \rightarrow \mu\nu$ signal samples.

Figure 80 shows results of the trigger efficiency closure test done on the uncorrected η distribution of reconstructed muons. Firstly, the $Z \rightarrow \mu^+\mu^-$ sample is used to extract the single muon trigger efficiency with the TP method explained in Section 6.2. Then, the W boson analysis criteria are imposed on the $W \rightarrow \mu\nu$ signal samples with and without trigger matching. The η distribution obtained with trigger matching is corrected using the extracted trigger efficiency and compared with the distribution obtained without trigger matching. This closure test is performed in the 0–80% centrality class. From the ratio plots presented in the bottom panels of Figure 80 one can notice that the two η distributions agree within statistical uncertainties which are at the level of 2–3%. One caveat of using the HIJING overlay samples is that they have a MB

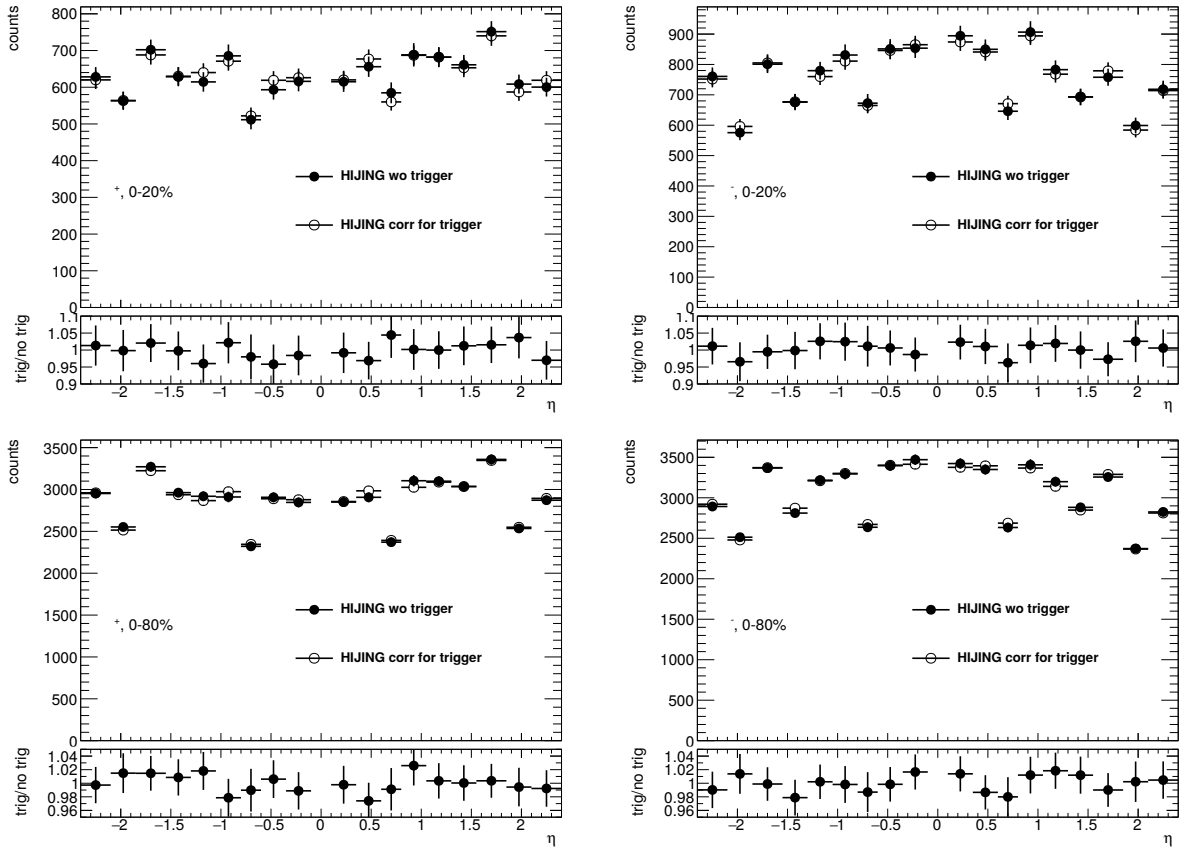


Figure 80: Closure tests for the trigger efficiency correction for positive (left) and negative (right) muons falling into the 0–20% (top) and 0–80% (bottom) centrality class.

centrality distribution while data is biased towards more central events (see Figure 15). Thus, the closure test is repeated in the 0–20% centrality class and its results are presented in Figure 80. The statistical precision is worse as four times less events fall into this centrality class. Nevertheless, again a reasonable agreement between the two η distributions is observed within statistical uncertainties. The conclusion from this closure test is that the trigger efficiency correction, which is based on the efficiency measured in data and applied to MC samples, does not introduce any bias to the measurement. Therefore, no systematic uncertainty is assigned due to the trigger non-closure.

12 Systematic uncertainties

In this analysis, various sources of systematic uncertainties are considered, as described in the following.

12.1 Muon performance

The following points describe systematic uncertainties on C_W factors in the $W \rightarrow \mu\nu$ analysis which arise due to the muon selection. All these uncertainties are added in quadrature and their impact on the measurements is presented in Figure 81. By construction these uncertainties are up and down symmetric.

Muon trigger efficiency

As described in Section 6.2, the single-muon trigger efficiency is studied in the data using the TP method. The extracted efficiency is used to reweight MC samples but it is known with a limited statistical precision due to the number of Z candidate events observed in data.

The measured trigger efficiency is obtained in η bins which are defined by η coverage of the TGC and RPC modules. Especially, these bins are not the same as analysis bins which were chosen to allow comparison with the previous ATLAS measurements. In order to propagate the statistical uncertainties correctly to measured observables, a toy MC method is used. In this method the new set of trigger efficiency is defined as:

$$\epsilon_i^t = \epsilon^t + r_i(\epsilon^t, \sigma(\epsilon^t)), \quad (52)$$

where $r_i^t(\epsilon^t, \sigma(\epsilon^t))$ is a random number from a Gaussian distribution with a mean equal to the efficiency value and a standard deviation equal to the efficiency statistical uncertainty. An index t correspond to the subsequent η bins in which the efficiency is extracted and i is the i -th iteration of produced modified efficiencies. Then an n sets of the efficiencies are produced and measurement of a given observable is repeated n times using modified efficiency. As an uncertainty on the measured observable is taken standard error calculated from the produced n iterations. It was found that $n = 50$ is sufficient to have a good estimate of the propagated uncertainty.

After imposing toy MC method the impact on the η yields varies between 3% and 4% and is one of the dominant contributions to the systematic uncertainties. Due to the fact that the trigger efficiency uncertainties are uncorrelated between η bins, the impact on integrated yields as a function of centrality is around 0.7%. The results of the toy MC study are also used while propagating the trigger efficiency uncertainty to the measured charge asymmetry.

Muon reconstruction and identification

The Medium muon reconstruction and identification efficiency is measured with the TP method in both the data and the $Z \rightarrow \mu^+\mu^-$ MC sample to derive efficiency scale factors (see Section 6.1). The statistical uncertainty of the scale factors is propagated via a toy MC to the

C_W factors and gives an uncertainty of about 1% which is mostly constant in η . The impact on integrated yields as a function of centrality is around 0.3%.

Muon isolation

The efficiency of the muon isolation selection is measured with the TP method in both the data and the $Z \rightarrow \mu^+\mu^-$ MC sample to derive efficiency scale factors (see Section 6.3). The statistical uncertainty of the scale factors is propagated via a toy MC to the C_W factors and gives an uncertainty between 0.5% and 1%. The impact on integrated yields as a function of centrality is around 0.2%.

Muon momentum scale and resolution

In order to account for the differences in the muon momentum scale and resolution in data and simulation, muons in the MC samples require a correction of their reconstructed momentum. The systematic uncertainties associated with this correction are evaluated using variations of the correction parameters defined by ATLAS collaboration. The variations applied in this analysis are related to the smearing of muon ID track momentum, muon ME track momentum and the ID and MS scale correction parameters. After applying these systematic variations, the C_W correction is re-evaluated. All of the effects related to the muon p_T scale and resolution are found to be below 0.1% and as such they are considered to be negligible in the analysis.

12.2 Electron performance

The correction factors C_W in the $W \rightarrow e\nu$ analysis are affected by systematic effects arising from the electron selection. Detailed studies of electron reconstruction, identification, isolation and trigger efficiencies are described in Section 6.4. The results of these studies are a set of scale factors which are applied to the electron MC samples. Each of the scale factors has associated statistical and systematic uncertainties. A toy MC study is used to propagate the statistical uncertainties. The systematic uncertainties are propagated by varying a given scale factor up and down by its uncertainty. It is done in a fully correlated way between η bins and uncorrelated between types of scale factors. The total effect of the systematic variations of scale factors is below 1% and it is subdominant. The total impact of statistical uncertainties on the η yields is more significant and varies between 4 and 6%. Due to the fact that statistical uncertainties are uncorrelated between η bins, the impact on integrated yields as a function of centrality is around 2.5%. All these uncertainties are added in quadrature and their impact on the measurements is presented in Figure 82.

Electron energy scale and resolution

In order to account for the differences in the electron energy scale and resolution in data and simulation, electrons in the MC samples require a correction of their reconstructed momentum. The systematic uncertainties associated with this correction are evaluated using variations of the

correction parameters defined by the ATLAS collaboration. The systematic effects are found to be below 0.1% and as such they are considered to be negligible in the analysis.

12.3 ID misalignment

The issue with ID alignment and its impact on the muon momentum measurement is described in Section 4.2.2. Figure 17 shows a 2% charge-dependent shift in the muon momentum scale. To minimize the bias on the analysis, the ME muon kinematics are used. The electron momentum measurement is not sensitive to this issue as it is mostly reconstructed from the EM calorimeter. However, a non-zero impact on the measured observables is still expected due to the definition of p_T^{miss} . This variable is calculated using either ID tracks or combined muons which are affected by the ID misalignment. This could be fixed only with a reprocessing of the data or with additional changes to the algorithms evaluating missing transverse momentum. At the time of writing this thesis, both solutions are not feasible, and thus an additional systematic uncertainty has to be considered. A conservative approach is to vary p_T^{miss} by 2% in data only. In some η bins both systematic variations go in the same direction (e.g. increase of W boson yields), thus the mean variation is taken as systematic uncertainty and symmetrized. For consistency this procedure is applied in all η bins. The impact on the η yields is around 1% for both the electron and muon channels.

12.4 p_T^{miss} uncertainty

As discussed in Section 7 the resolution of p_T^{miss} reconstruction is quite poor in Pb+Pb collisions. Therefore, a systematic uncertainty is estimated by varying the p_T^{min} requirement on tracks which are used for the p_T^{miss} calculation. The nominal analysis reconstructs p_T^{miss} using a $p_T^{\text{min}} = 4$ GeV requirement, and two variations are considered with $p_T^{\text{min}} = 3$ GeV (looser) and $p_T^{\text{min}} = 5$ GeV (tighter). The average departure from the nominal measurement for η yields is at the level of 1–2% for the muon channel and 2–4% for the electron channel. In some η bins both systematic variations go in the same direction (e.g. increase of W boson yields), thus the mean variation is taken as systematic uncertainty and symmetrized. For consistency this procedure is applied in all η bins.

It was found that even after scaling p_T^{miss} in data by 2% (see Section 12.3) excess visible in $p_T^{\text{miss}} > 60$ GeV region in Figures 85 and 90 is still present. The most probable explanation is underestimated background contribution. For that systematic uncertainty is assigned which sets upper cut $p_T^{\text{miss}} < 60$ GeV. The impact on results was found to be at the level 1-2% and is mostly present in central events.

12.5 EW and $t\bar{t}$ backgrounds

As a systematic uncertainty in estimating EW backgrounds, a theoretical uncertainty of $\pm 5\%$ on the W and Z boson production cross sections is considered [76]. For the theoretical uncertainty on the $t\bar{t}$ production, a $\pm 6\%$ variation in the cross section is taken [76]. The uncertainties

in the normalization of W and Z processes are conservatively treated as fully correlated. The impact of the variations of EW process cross sections on the measured yields is less than 0.2% and is similar for both the electron and muon channels. The systematic uncertainty related to the $t\bar{t}$ production cross section is found to be less than 0.1%.

12.6 QCD multi-jet background

The QCD multi-jet background contribution is evaluated using the template fits described in Section 9.1. By default the shape of the QCD multi-jet background template is reweighted to the mean of the signal isolation region. As a systematic check, the template is reweighted to the boundaries of the signal isolation region. The effect is around 2% for the muon channel and is slightly asymmetric between the upper and lower variations. In case of the electron channel, the impact is between 2 and 5% in the barrel region, while in the endcap region it is between 5 and 11%. This sizeable difference between detector regions is related to the significant QCD multi-jet background contamination in the forward region. Therefore, any change in the number of estimated background events is more pronounced.

Due to statistical limitations of the available sample the MJ template is constructed using leptons from the entire η region. In Sections 9.1.4 and 10.1.3 was shown that there is an η dependence of the shape of the QCD multi-jet background template. As a systematic check, the templates constructed from the leptons falling into detector barrel and endcap region were used to evaluate the background. The effect is between 1-2% for the muon channel and is slightly asymmetric between the upper and lower variations. In case of the electron channel, the impact is around 1% in the barrel region, while in the endcap region it is between 2 and 5%.

Both above effects were added in quadrature assuming no correlations between them.

12.7 T_{AA} uncertainty

The nuclear thickness function T_{AA} is used to normalize the W boson production yields. The uncertainties of the average T_{AA} values for all considered centrality classes are given in Table 5. They amount to up to 1.5% for 0–20% centralities and increase to almost 7% for the 50–80% centrality class. This uncertainty is propagated to the final results by varying the data normalization factors up and down by this value. The impact on the W boson yields in η is around 1.5% constant over the entire η range. It is reported as an independent normalization uncertainty.

12.8 Charge misidentification

The cross sections for W boson production can be sensitive to the lepton charge misidentification rates. It was found in Run 1 studies that the probability of wrongly associating the charge to a reconstructed electron in MC is lower by 5-20% than in data [63]. This mismodelling depends mainly on the imposed electron selection and η region. The limited statistics of $Z \rightarrow e^+e^-$ events in Pb+Pb data do not allow to extract a meaningful rate of electron charge

misidentification. Therefore, a conservative approach is chosen, in which the charge misidentification rate in MC simulation is varied by 20%. The impact on C_W corrections is found to be around 0.1% in the most forward η bin and below 0.01% in the central η region. In case of the charge asymmetry measurement, the uncertainty due to charge misidentification is roughly 40 times less than the statistical uncertainty. Therefore, this systematic uncertainty is neglected when considering the total uncertainty for the W boson production yields, as well as for the charge asymmetry. For muons, the effect of charge misidentification is entirely negligible.

12.9 Summary of systematic uncertainties

For each individual systematic check, upward and downward deviations from the nominal measurement are evaluated. Since a method used to combination of decay channels (see Section 13.3) is designed for combining Gaussian uncertainties, all systematic uncertainties are symmetrized by taking average of up and down values. The total systematic uncertainty is a sum in quadrature of all individual contributions. The summary of considered systematic effects on measured yields is given in Figure 81 for the muon channel and in Figure 82 for the electron

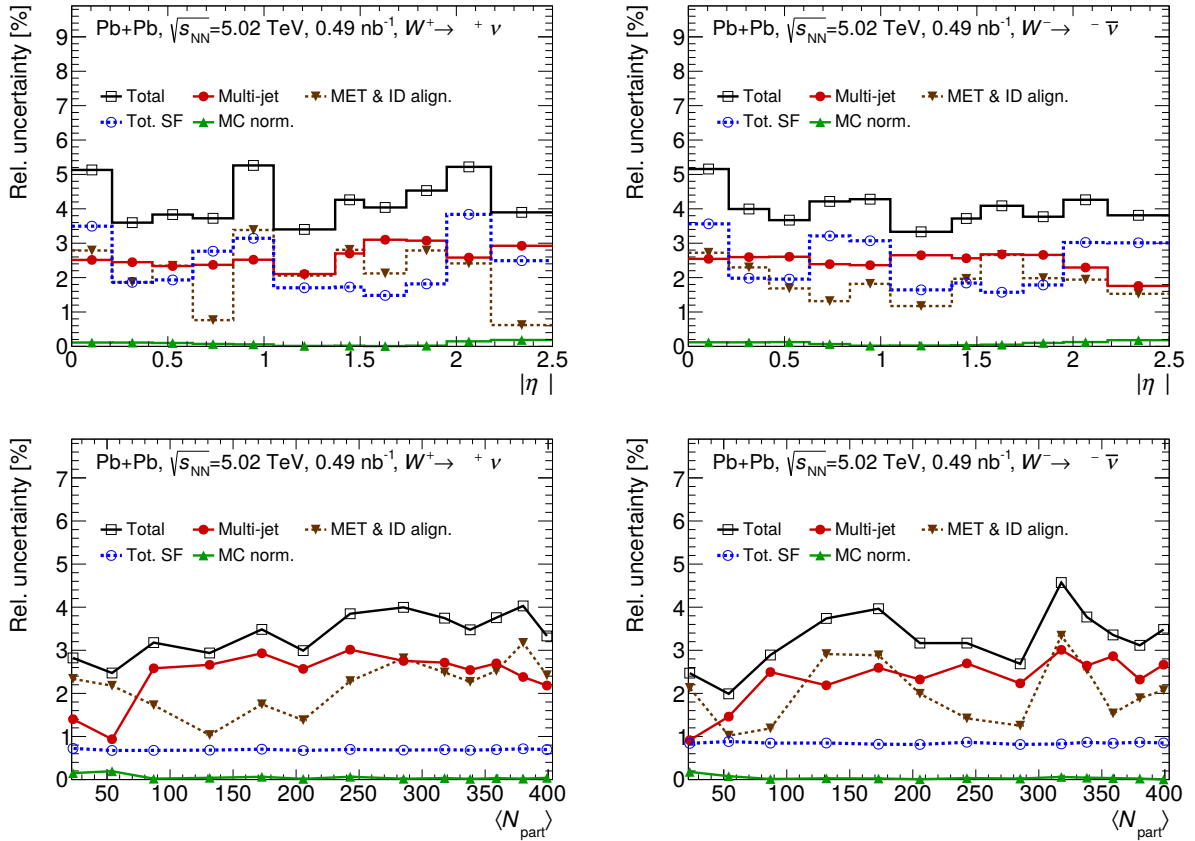


Figure 81: Relative systematic uncertainties on W boson yields measured as a function of muon $|\eta|$ (top) and centrality (bottom) for positive (left) and negative (right) muons. The total systematic uncertainty is represented by the black open squares, while other lines represent individual contributions. The muon performance related uncertainties ("Tot. SF"), as well as the p_T^{miss} resolution and ID misalignment uncertainties ("MET and ID align."), are added in quadrature.

channel. Figure 83 present systematic effects on measured charge asymmetry. In these plots, the following systematic uncertainties were grouped together by adding them in quadrature:

- lepton performance related uncertainties ("Tot. SF"),
- p_T^{miss} uncertainty and ID misalignment ("MET and ID align.").

The total systematic uncertainty on the W boson yields measured in the muon channel varies between 3 and 6% as a function of η , and is largely independent of centrality at about 3%. In the electron channel, the precision of the measurement in the barrel region is comparable to the precision of the muon channel measurement in the same region. However, systematic uncertainties in the endcap region are much larger reaching up to 13%, which is caused by the significant QCD multi-jet background contamination and lower statistical precision of efficiency SFs. The systematic uncertainty is also independent of centrality at about 5%. For the lepton charge asymmetry, absolute systematic uncertainties are presented, as this observable is close to 0 in some bins and therefore relative errors tend to be large.

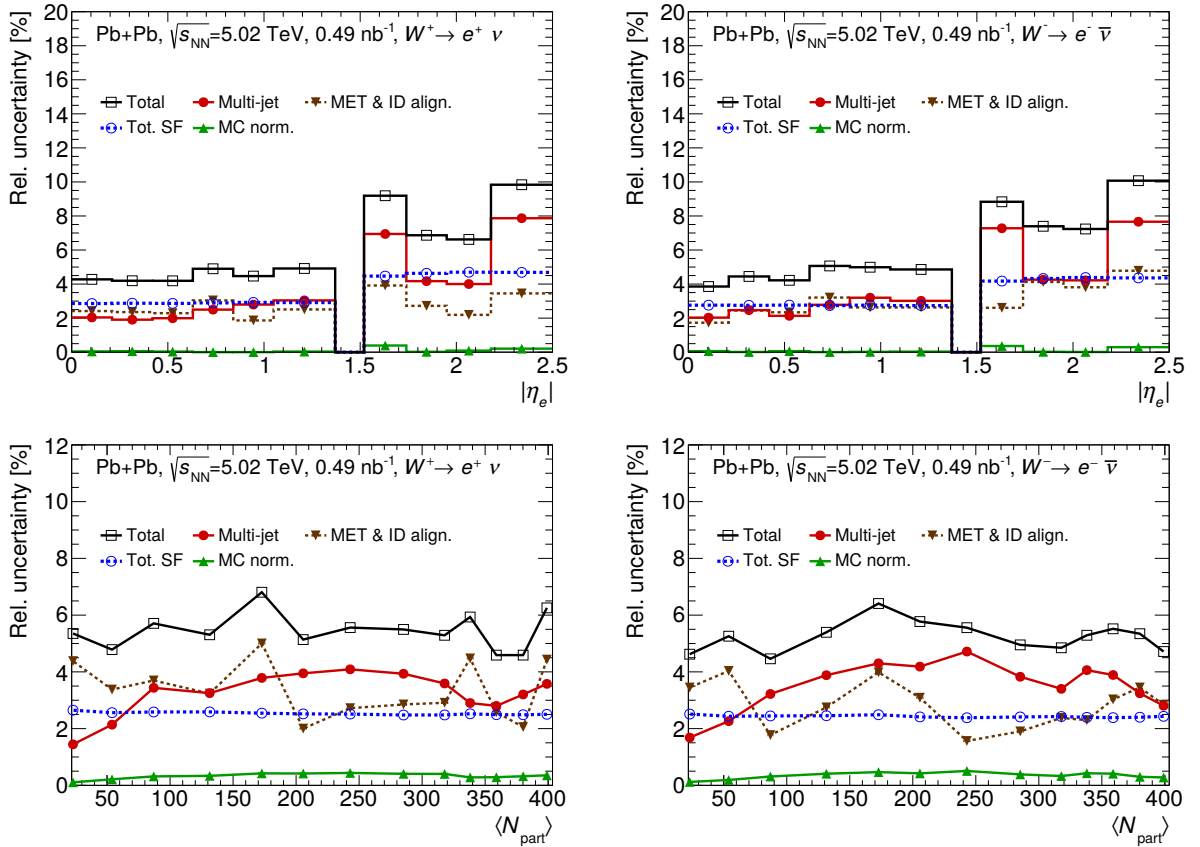


Figure 82: Relative systematic uncertainties on W boson yields measured as a function of electron $|\eta|$ (top) and centrality (bottom) for positive (left) and negative (right) electrons. The total systematic uncertainty is represented by the black open squares, while other lines represent individual contributions. The electron performance related uncertainties ("Tot. SF"), as well as the p_T^{miss} resolution and ID misalignment uncertainties ("MET and ID align."), are added in quadrature.

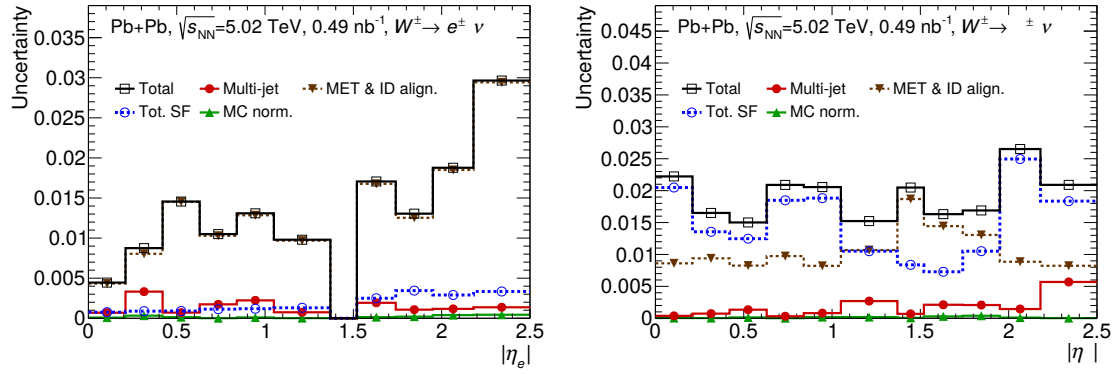


Figure 83: Absolute systematic uncertainties on the lepton charge asymmetry measured as a function of electron (left) and muon (right) η . The total systematic uncertainty is represented by the black open squares, while other lines represent individual contributions. The electron performance related uncertainties ("Tot. SF"), as well as the p_T^{miss} resolution and ID misalignment uncertainties ("MET and ID align."), are added in quadrature.

13 Results

In this section main results obtained in the analysis are presented and discussed.

13.1 Results in the muon channel

Control plots

Figure 84 show detector-level distributions of muons η and p_T in $W \rightarrow \mu\nu$ candidate events before background subtraction and application of the C_W correction factors. The histograms present contributions from the signal MC simulation as well as from various background sources. The signal MC samples are normalized using Eq. 27, while background contributions are normalized according to the description in Section 9, and efficiency SFs are applied to the MC predictions. There is a fairly good agreement in the shapes of the measured distributions shown as full points and the sum of signal and background contributions, as well as in the overall normalization.

For completeness, distributions of p_T^{miss} and m_T are also shown in Figure 85. An impact of the ID misalignment (see Section 4.2.2) on the p_T^{miss} performance can be noticed. Events with positive

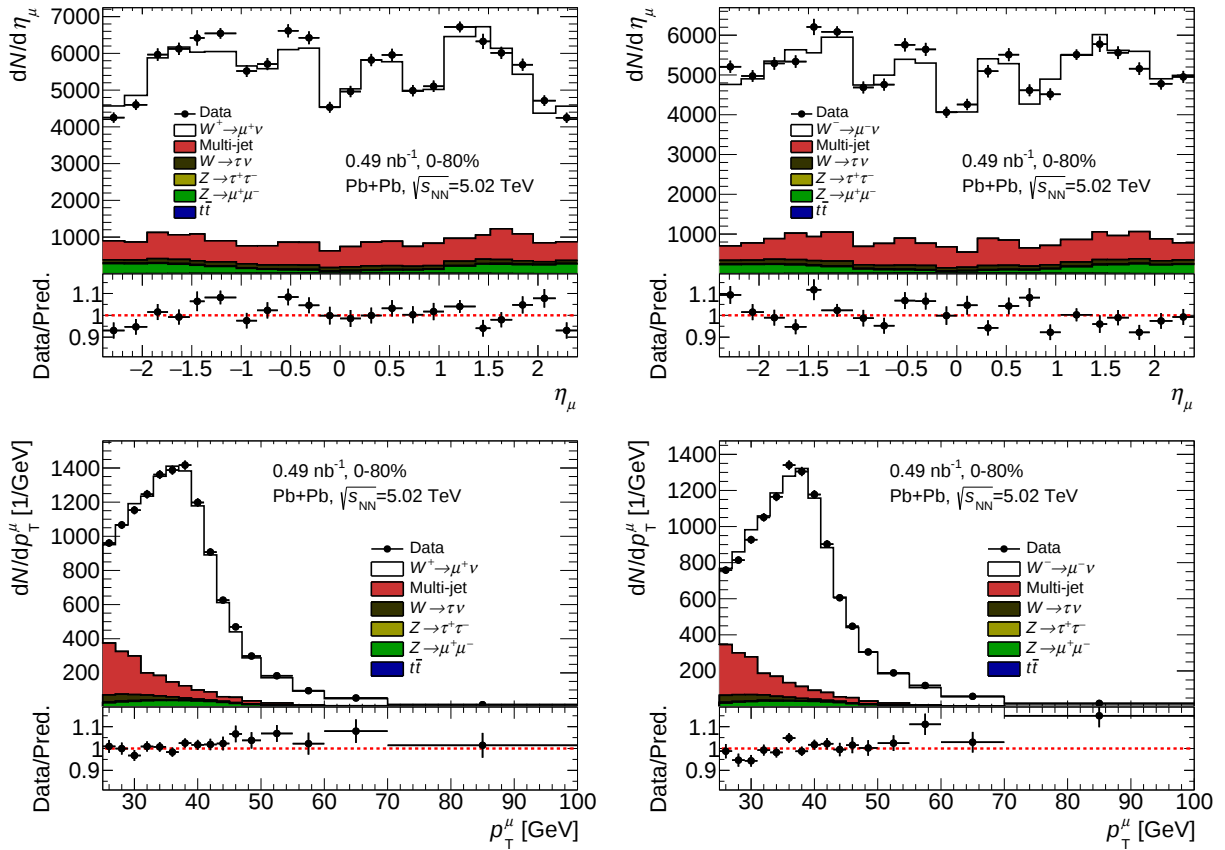


Figure 84: Detector-level η (top) and p_T (bottom) distributions of muons from W^+ (left) and W^- (right) candidate events with the full $W \rightarrow \mu\nu$ selection applied. The contributions of QCD multi-jet and EW background events are normalized according to their expected number of events. Distributions are presented for the 0–80% centrality class. Data are shown as full points with statistical errors marked as vertical bars.

muons are more biased towards higher p_T^{miss} , while those with negative muons are biased in the opposite direction. Detailed studies of the region $p_T^{\text{miss}} > 60$ GeV showed that misalignment issue is not able to fully explain differences between data and MC simulation. Therefore additional systematic uncertainty is assigned setting an upper cut $p_T^{\text{miss}} < 60$ GeV. The impact on results was found to be at the level $\sim 1\%$ and is mostly present in central events. It is also reported in Section 12.4. Since the m_T is built from p_T^{miss} therefore observed discrepancy in p_T^{miss} projects on the observed discrepancy in the m_T .

T_{AA} scaling

The absence of suppression in W boson yields as a function of collision centrality is expected due to only weak interaction of EW bosons and their decay products with the QGP medium produced in Pb+Pb collisions. To compare the number of W bosons produced in each centrality class Eq. 50 is used and $N^{W \rightarrow \mu\nu}$ is divided by the average nuclear thickness function $\langle T_{\text{AA}} \rangle$ listed in Table 5. The resulting number is normalized to the total number of MB events (N_{evt}) which have been probed in the corresponding centrality class.

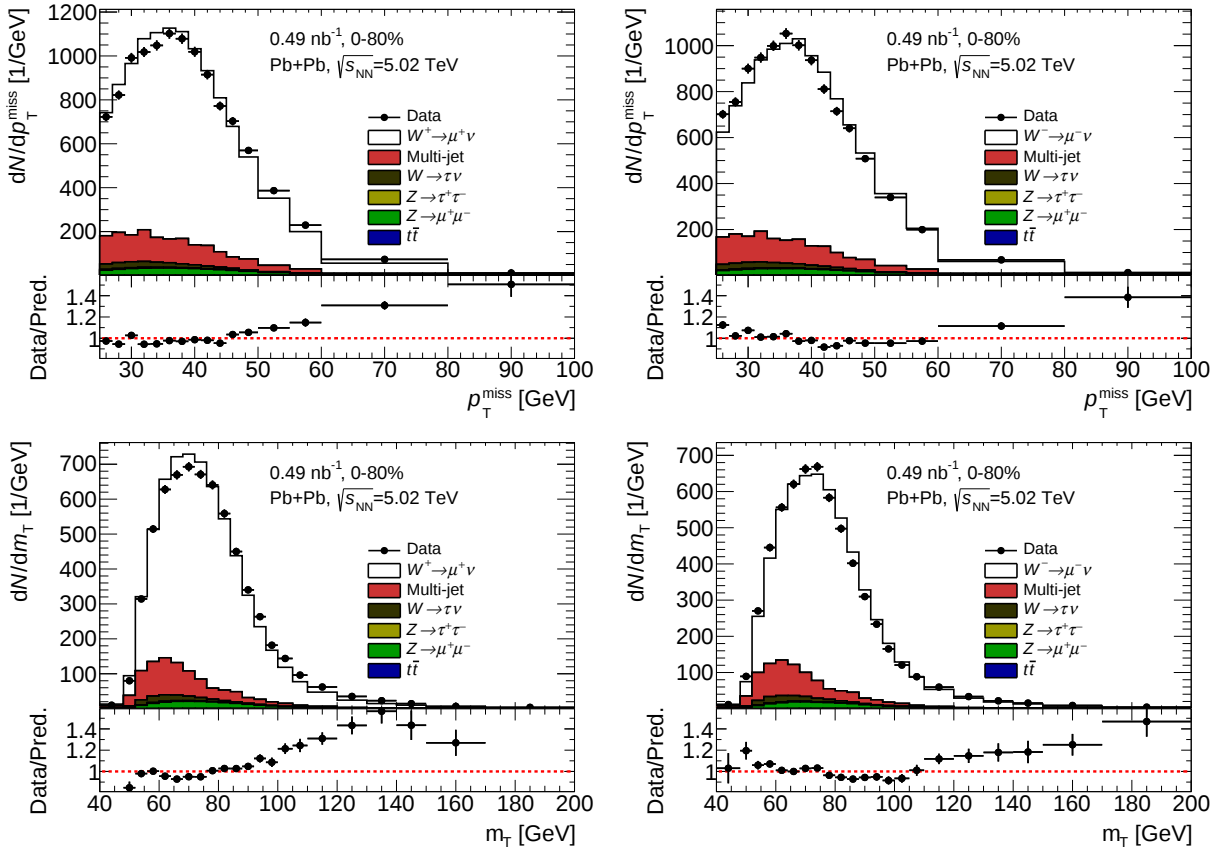


Figure 85: Detector-level p_T^{miss} (top) and m_T (bottom) distributions in W^+ (left) and W^- (right) candidate events with the full $W \rightarrow \mu\nu$ selection applied. The contributions of QCD multi-jet and EW background events are normalized according to their expected number of events. Distributions are presented for the 0–80% centrality class. Data are shown as full points with statistical errors marked as vertical bars.

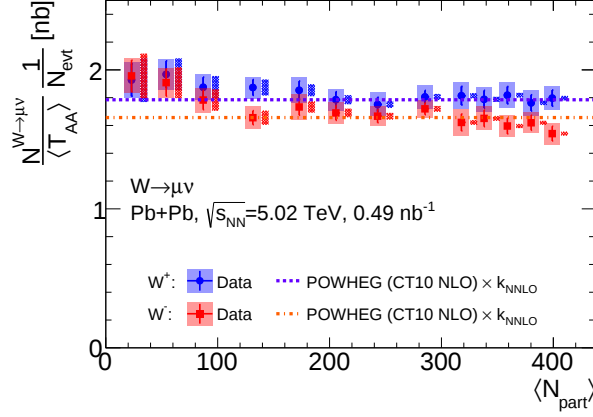


Figure 86: Fiducial W boson production yields scaled by the mean nuclear thickness function $\langle T_{AA} \rangle$ measured in the muon decay channel as a function of the mean number of participants $\langle N_{part} \rangle$ for W^+ and W^- . Error bars show statistical uncertainties, whereas systematic and statistical uncertainties added in quadrature are shown as the filled boxes around data points. The normalization uncertainty related to $\langle T_{AA} \rangle$ is represented by the hatched area shifted horizontally for better visibility. The dotted lines represent predictions obtained using the POWHEG+PYTHIA8 with CT10 PDFs, which are scaled with a k -factor.

Figure 86 shows the W boson yields in the fiducial region scaled by $\langle T_{AA} \rangle$ as a function of $\langle N_{part} \rangle$ for W^+ and W^- bosons. The yields in each centrality class are obtained by integrating the η differential yields within that centrality class after background subtraction and efficiency correction. The systematic and statistical uncertainties of the measurement are also shown, whereas the systematic uncertainty related to $\langle T_{AA} \rangle$ is presented separately as a normalization uncertainty. The production yields scaled by $\langle T_{AA} \rangle$ are largely independent of collision centrality. Only the yields measured in the most peripheral class deviate from a constant value, however the uncertainty on $\langle T_{AA} \rangle$ is also large in this class (at the level of 8%).

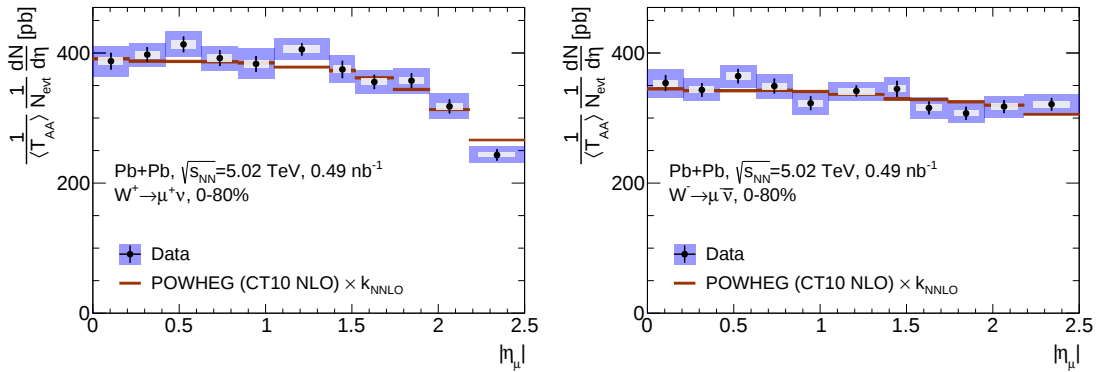


Figure 87: Differential production yields scaled by $\langle T_{AA} \rangle$ and integrated over 0–80% centralities for W^+ (left) and W^- (right) bosons as a function of absolute pseudorapidity of the muon. Data are compared to the prediction obtained using the POWHEG+PYTHIA8 with CT10 PDFs scaled to an NNLO QCD calculation. Error bars show statistical uncertainties, whereas systematic and statistical uncertainties added in quadrature are shown as the filled boxes. The normalization uncertainty related to $\langle T_{AA} \rangle$ is represented by the grey boxes.

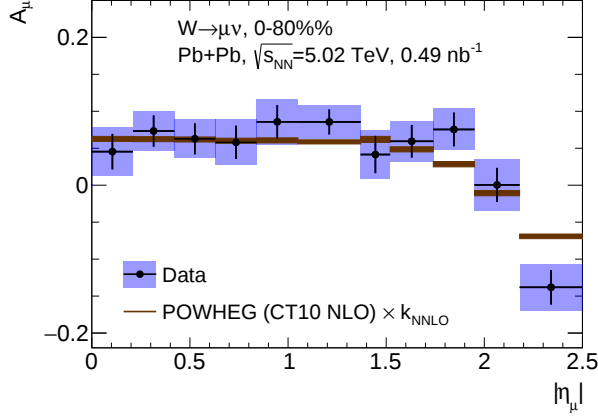


Figure 88: Muon charge asymmetry integrated over 0–80% centralities as a function of absolute pseudorapidity of the muon. Error bars represent statistical uncertainties, whereas total systematic uncertainties are shown as the filled boxes. The measured distributions are compared to the prediction obtained using the POWHEG+PYTHIA8 with CT10 PDFs scaled to an NNLO QCD calculation.

$W \rightarrow \mu\nu$ absolute pseudorapidity dependence

Figure 87 shows differential $W^+ \rightarrow \mu^+\nu$ and $W^- \rightarrow \mu^-\nu$ production yields integrated over 0–80% centrality classes as a function of absolute muon pseudorapidity. Both the statistical and systematic uncertainties are shown, whereas the systematic uncertainty related to $\langle T_{AA} \rangle$ is presented separately. Also included in the figures are predictions from POWHEG+PYTHIA8 using the CT10 PDFs scaled to NNLO predictions. Only central values are plotted. For $W \rightarrow \mu\nu$ production, shapes of the data and prediction tend to be consistent.

$W \rightarrow \mu\nu$ charge asymmetry

Measured muon charge asymmetry as a function of absolute pseudorapidity of the muon is presented in Figure 88 alongside with the asymmetry predicted by POWHEG+PYTHIA8 with CT10 PDFs scaled to an NNLO QCD calculation.

13.2 Results in the electron channel

Control plots

Figure 89 shows detector-level distributions of electron η and p_T in $W \rightarrow e\nu$ candidate events before background subtraction and application of the C_W correction factors. The histograms present contributions from the signal MC as well as from various background sources. The signal MC samples are normalized using Eq. 27, while background contributions are normalized according to the description in Section 10, and efficiency SFs are applied to the MC predictions. There is a fairly good agreement in the shapes of the measured distributions shown as full points and the sum of signal and background contributions, as well as in the overall normalization.

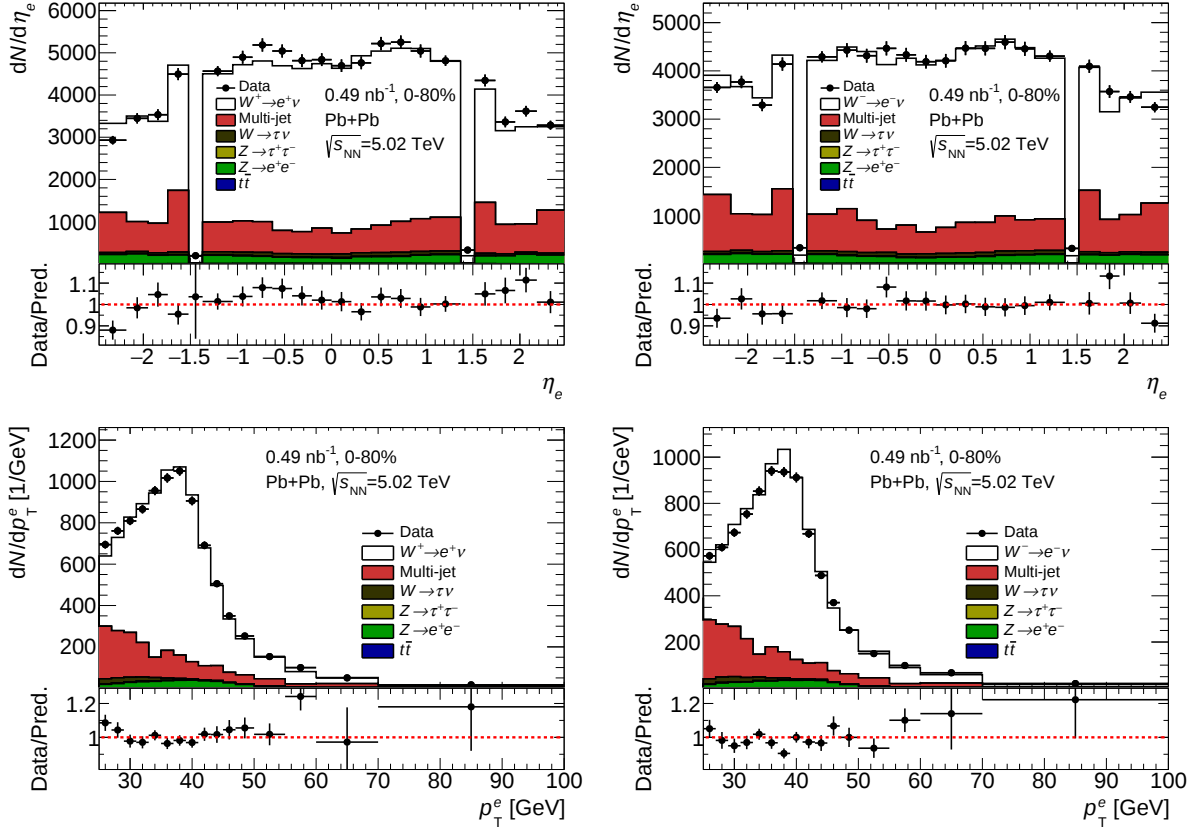


Figure 89: Detector-level η (top) and p_T (bottom) distributions of electrons from W^+ (left) and W^- (right) candidate events with the full $W \rightarrow e\nu$ selection applied. The contributions of QCD multi-jet and EW background events are normalized according to their expected number of events. Distributions are presented for the 0–80% centrality class. Data are shown as full points with statistical errors marked as vertical bars.

For completeness, distributions of p_T^{miss} and m_T are also shown in Figure 90. An impact of the ID misalignment (see Section 4.2.2) on the p_T^{miss} performance can be noticed. Events with positive electrons are more biased towards higher p_T^{miss} while those with negative electrons are more biased in the opposite direction. As in the muon channel studies of region $p_T^{\text{miss}} > 60$ GeV showed that misalignment issue is not able to fully explain differences between data and MC simulation. Therefore additional systematic uncertainty is assigned setting and upper cut $p_T^{\text{miss}} < 60$ GeV.

T_{AA} scaling

Figure 91 shows the W boson yields in the fiducial region scaled by $\langle T_{AA} \rangle$ as a function of $\langle N_{\text{part}} \rangle$ for W^+ and W^- bosons. The yields in each centrality class are obtained by integrating the η differential yields within that centrality class after background subtraction and efficiency correction. The systematic and statistical uncertainties of the measurement are also shown, whereas the systematic uncertainty related to $\langle T_{AA} \rangle$ is presented separately as a normalization uncertainty. The production yields scaled by $\langle T_{AA} \rangle$ are largely independent of collision centrality.

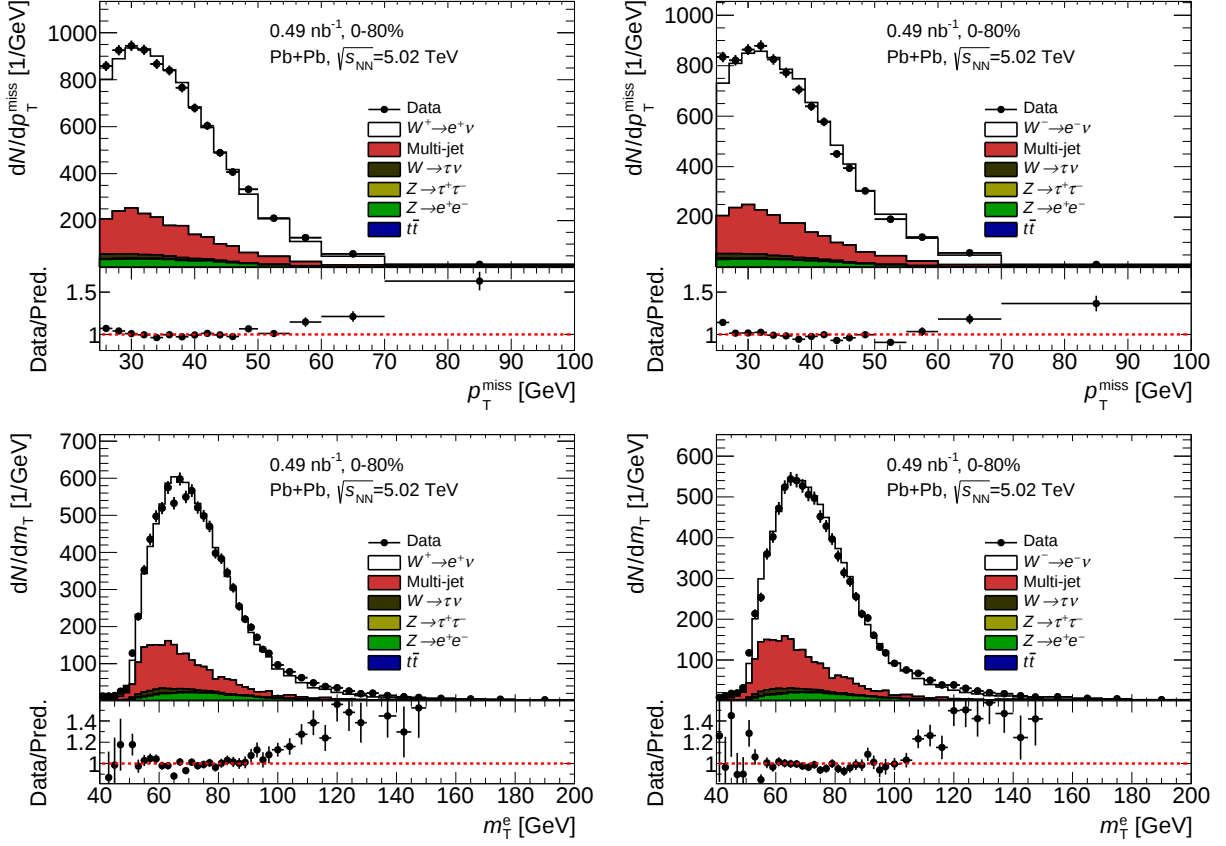


Figure 90: Detector-level p_T^{miss} (top) and m_T (bottom) distributions in W^+ (left) and W^- (right) candidate events with the full $W \rightarrow e\nu$ selection applied. The contributions of QCD multi-jet and EW background events are normalized according to their expected number of events. Distributions are presented for the 0–80% centrality class. Data are shown as full points with statistical errors marked as vertical bars.

$W \rightarrow e\nu$ absolute pseudorapidity dependence

Figure 92 shows differential $W^+ \rightarrow e^+\nu$ and $W^- \rightarrow e^-\nu$ production yields integrated over 0–80% centrality classes as a function of absolute electron pseudorapidity. Both the statistical and systematic uncertainties are shown, whereas the systematic uncertainty related to $\langle T_{AA} \rangle$ is presented separately. Also included in the figures are predictions from POWHEG+PYTHIA8 using the CT10 PDFs scaled to NNLO predictions. Only central values are plotted. For $W \rightarrow e\nu$ production, shapes of the data and prediction tends to be consistent.

$W \rightarrow e\nu$ charge asymmetry

Measured electron charge asymmetry as a function of absolute pseudorapidity of the electron is presented in Figure 93 alongside with the asymmetry predicted by POWHEG+PYTHIA8 with CT10 PDFs scaled to an NNLO QCD calculation.

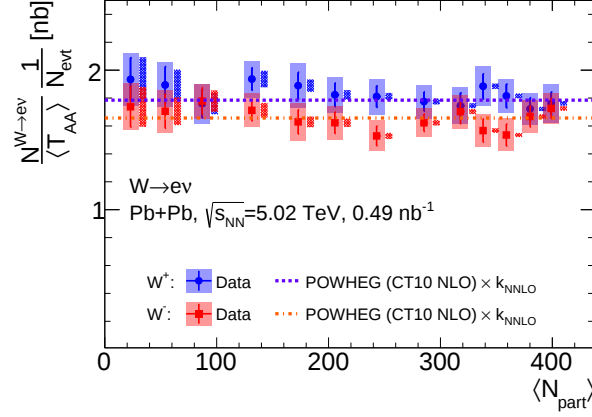


Figure 91: Fiducial W boson production yields scaled by the mean nuclear thickness function $\langle T_{AA} \rangle$ measured in the electron decay channel as a function of the mean number of participants $\langle N_{\text{part}} \rangle$ for W^+ and W^- . Error bars show statistical uncertainties, whereas systematic and statistical uncertainties added in quadrature are shown as the filled boxes around data points. The normalization uncertainty related to $\langle T_{AA} \rangle$ is represented by the hatched area shifted horizontally for better visibility. The dotted lines represent predictions obtained using POWHEG+PYTHIA8 with CT10 PDFs, which are scaled with a k -factor to an NNLO QCD calculation and account for the different isospin combinations.

13.3 Combination of electron and muon decay channels

The measurements in the electron and muon decay channels are combined using the Best Linear Unbiased Estimate (BLUE) method [77, 78], which implements an analytical χ^2 minimization accounting separately for statistical and systematic uncertainties. The input to the method is the full uncertainty covariance matrix including correlations between channels and measurement bins, which is constructed from the sum of separate covariance matrices for each uncertainty

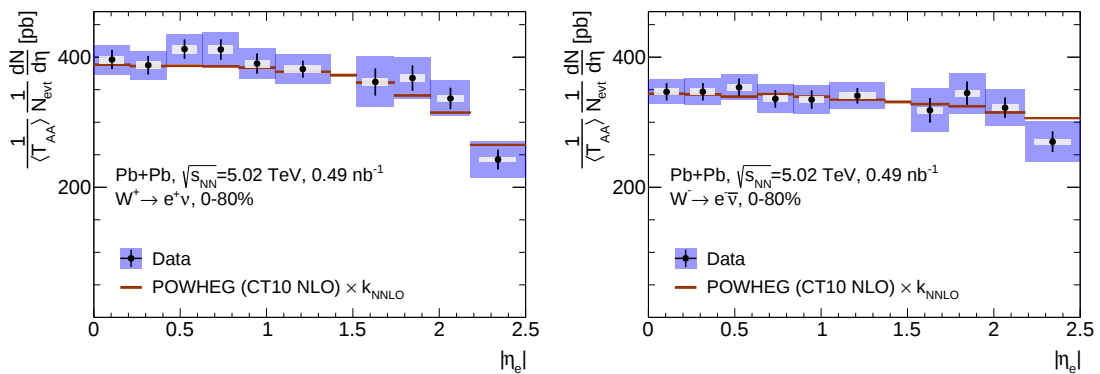


Figure 92: Differential production yields scaled by $\langle T_{AA} \rangle$ and integrated over all centralities for W^+ (left) and W^- (right) bosons decaying into electrons as a function of absolute pseudorapidity of the electron. The measured distributions are compared to the prediction obtained using the POWHEG+PYTHIA8 generator with CT10 PDFs scaled to an NNLO QCD calculation. Error bars show statistical uncertainties, whereas systematic and statistical uncertainties added in quadrature are shown as the filled boxes. The normalization uncertainty related to $\langle T_{AA} \rangle$ is represented by the grey boxes.

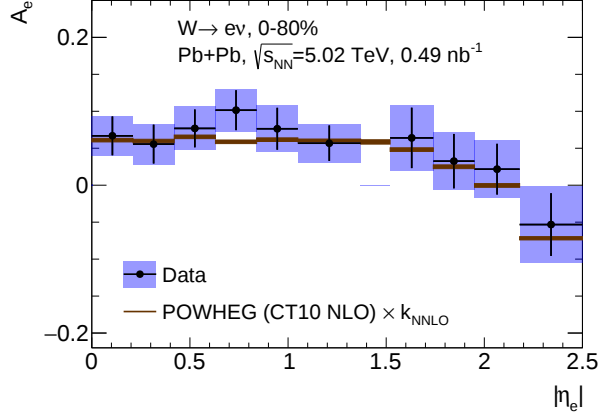


Figure 93: Electron charge asymmetry integrated over 0–80% centralities as a function of absolute pseudorapidity of the electron. Error bars represent statistical uncertainties, whereas total systematic uncertainties are shown as the filled boxes. The measurement for $1.37 < |\eta_e| < 1.52$ is missing because of the rejection of electrons falling in the calorimeter crack region. The measured distributions are compared to the prediction obtained using the POWHEG+PYTHIA8 with CT10 PDFs scaled to an NNLO QCD calculation.

source. Some uncertainties, like the statistical component of uncertainties in the lepton efficiency scale factors, are uncorrelated between bins, which do not necessarily corresponds to the analysis bins. These uncertainties are propagated using the toy MC method as described in Section 12. Using this information, correlation and covariance matrices can be built in the binning of the measurement and synchronised across the relevant channels. However, other systematic checks do not provide directly a covariance matrix, and therefore some assumptions about correlations between bins and channels need to be made. The T_{AA} uncertainty and theoretical uncertainty in production cross sections for simulated processes is taken to be fully correlated between analysis bins and channels. This approach is justified as these are normalization factors which are common for both channels and across all analysis bins. The uncertainty in the QCD multi-jet

Systematic uncertainty	η bins	centrality classes	decay channels
e SFs (stat.)	x	✓	x
e SFs (sys.)	✓	✓	x
e QCD	✓	✓	x
μ SFs (stat.)	x	✓	x
μ QCD	✓	✓	x
p_T^{miss}	✓	✓	✓
ID align.	✓	✓	✓
MC norm.	✓	✓	✓
T_{AA}	✓	✓	✓

Table 17: Summary of assumed correlations of systematic uncertainties across analysis channels and bins. The uncertainties are assumed to be either fully correlated (✓) or uncorrelated (x) between η bins, centrality classes or decay channels (electron and muon channels).

Observable	χ^2	d.o.f.
W^+ - η yield	4.6	10
W^- - η yield	11.4	10
W^+ - centrality yield	3.4	13
W^- - centrality yield	12.7	13
charge asymmetry	7.0	10

Table 18: Value of χ^2 resulting from the electron and muon channel combination for a given observable. The number of degrees of freedom is given in the last column.

background estimation is taken to be correlated between analysis bins and uncorrelated between channels. Finally, the uncertainties related to the ID misalignment and p_T^{miss} resolution are taken to be correlated between analysis bins and channels. The summary of these assumptions is given in Table 17.

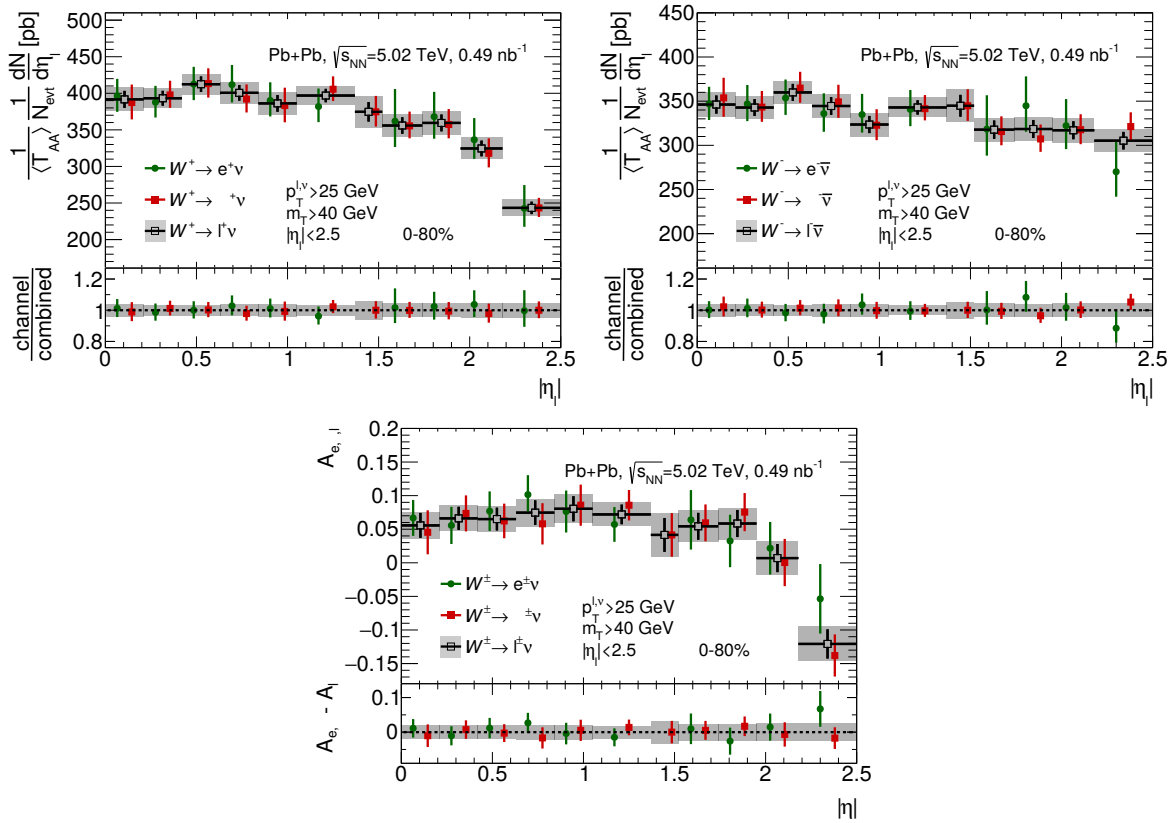


Figure 94: Differential fiducial W^+ (top left) and W^- (top right) boson production yields scaled by $\langle T_{AA} \rangle$ and lepton charge asymmetry (bottom) as a function of absolute pseudorapidity of the charged lepton shown separately for electron and muon decay channels as well as for their combination. Statistical and total (statistical and systematic uncertainties added in quadrature) uncertainties of the combined yields are shown as bars and shaded boxes, respectively. For the individual channels, only the total uncertainties are shown as error bars. The lower panels show the ratios of channels to combined yields in each bin with error bars and the shaded boxes representing the total uncertainties on the channels and combined yields, respectively. The points for individual channels are shifted horizontally for better visibility.

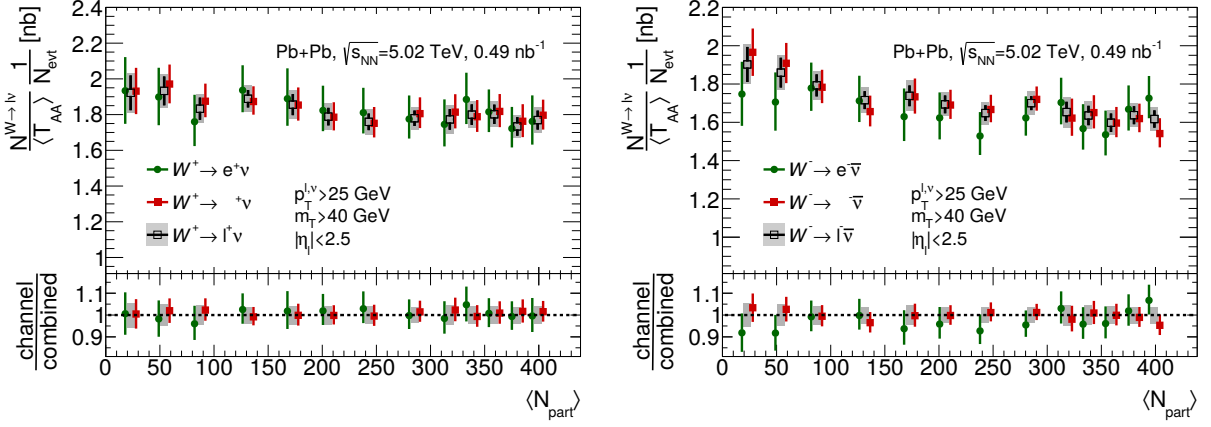


Figure 95: Fiducial W^+ (left) and W^- (right) boson production yields scaled by $\langle T_{AA} \rangle$ as a function of $\langle N_{part} \rangle$ shown separately for electron and muon decay channels as well as for their combination. Statistical and total (statistical and systematic uncertainties added in quadrature) uncertainties of the combined yields are shown as bars and shaded boxes, respectively. For the individual channels, only the total uncertainties are shown as error bars. The lower panels show the ratios of channels to combined yields in each bin with error bars and the shaded boxes representing the total uncertainties on the channels and combined yields, respectively. The points for individual channels are shifted horizontally for better visibility.

The combination of results is performed separately for the W^+ and W^- boson production yields measured as a function of lepton η and centrality, as well as for the lepton charge asymmetry. The resulting χ^2 values, which indicate the compatibility between measurements from the two channels, are given in Table 18.

The combined results are shown in Figures 94 and 95 as a function of absolute lepton pseudorapidity and $\langle N_{part} \rangle$ respectively. A good agreement is observed between the channels. The muon channel results tend to have a slightly higher weight in the combination procedure due to better statistical and systematic precision of the measurement.

13.4 Theoretical predictions

The fiducial inclusive production yields of W bosons are measured in the phase space defined as:

$$p_T^\ell > 25 \text{ GeV}, \quad |\eta_\ell| < 2.5, \quad p_T^{\nu} > 25 \text{ GeV}, \quad m_T > 40 \text{ GeV}$$

where p_T^ℓ is the decay lepton transverse momentum, η_ℓ is the lepton pseudorapidity, m_T is the lepton-neutrino transverse mass, and p_T^ν is the neutrino transverse momentum. The predictions are calculated using the MCFM code [79] at NLO accuracy in QCD. The yields are calculated for W boson decays into leptons at the Born level to match the definition of the measured yields in the data. The MCFM predictions are calculated using the proton PDF set CT14NLO [80] and two nuclear PDF (nPDF) sets: NCTEQ15 [81] and EPPS16 [82]. Predictions calculated with CT14NLO include all isospin combinations weighted according to their expected collision rates introduced in Section 3.2. The uncertainties in theoretical predictions are dominated by the limited knowledge of PDFs or nPDFs. The theoretical uncertainties come from the following sources:

- The uncertainties related to PDFs (nPDFs) are evaluated from the variations of NLO PDF (nPDF) sets [83] provided by the authors. The PDF uncertainties for all considered sets are rescaled from 90% CL to 68% CL.
- Scale uncertainties are determined by varying the renormalisation scale μ_R and the factorisation scale μ_F simultaneously up and down by a factor of 2. The envelope of yields obtained from these variations is taken as the uncertainty.
- The uncertainty due to α_S is estimated following the prescription given by authors of the CT14NLO PDF set. It corresponds to varying α_S by ± 0.001 (68% CL) around the central value of $\alpha_S(m_Z) = 0.118$. These variations are implemented by using the PDF sets CT14NLO_AS_0117 and CT14NLO_AS_0119. The uncertainty due to α_S is not included for predictions obtained with nCTEQ15 and EPPS16 nPDFs. For these sets the authors did not provide separate sets with a varied value of α_S , however its contribution to the total uncertainty is expected to be small compared to nPDF variations.

13.5 Comparison to theory

Figure 96 shows differential $W^+ \rightarrow \ell^+ \nu$ and $W^- \rightarrow \ell^- \nu$ production yields scaled by $\langle T_{AA} \rangle$ integrated over 0–80% centrality class as a function of pseudorapidity. Both the statistical and systematic uncertainties are shown, while the systematic uncertainty related to the normalization factor $\langle T_{AA} \rangle$ is not shown. Also included in the plots are predictions from MCFM calculations using the CT14NLO PDF set and the EPPS16 and nCTEQ15 nPDF sets. In the case of predictions obtained with CT14NLO, the isospin effects are taken into account. For both $W^+ \rightarrow \ell^+ \nu$ and $W^- \rightarrow \ell^- \nu$ production, shapes of the data and predictions tend to be consistent. One can notice that nPDFs underestimate the measured yields by 10–20%.

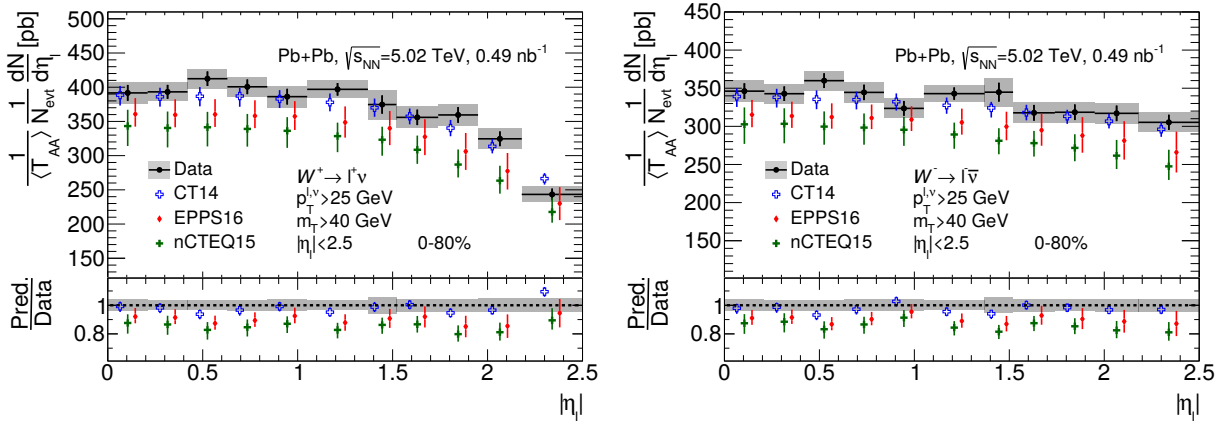


Figure 96: Differential W boson production yields measured as a function of absolute lepton η for W^+ (left) and W^- (right) bosons. Error bars show statistical uncertainties, whereas systematic and statistical uncertainties added in quadrature are shown as the filled boxes, while the systematic uncertainty related to $\langle T_{AA} \rangle$ is not shown. The measured distributions are compared to predictions obtained with the CT14NLO PDF set and the EPPS16 and nCTEQ15 nPDF sets.

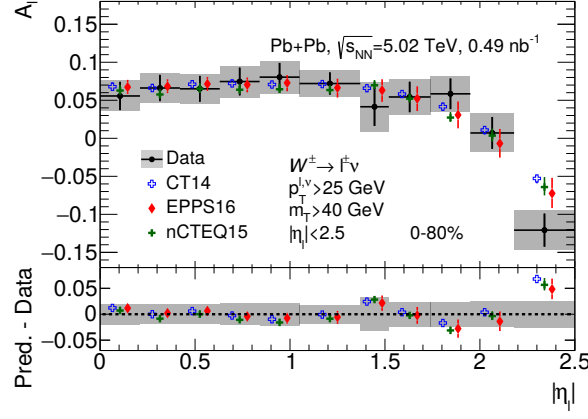


Figure 97: Lepton charge asymmetry measured as a function of absolute lepton η for W bosons. Error bars show statistical uncertainties, whereas systematic and statistical uncertainties added in quadrature are shown as the filled boxes. The T_{AA} -related uncertainty cancels out in the charge asymmetry. The measured distributions are compared to predictions obtained with the CT14NLO PDF set and the EPPS16 and nCTEQ15 nPDF sets.

The lepton charge asymmetry is presented in Figure 97 alongside with the asymmetry predicted from the EPPS16 and nCTEQ15 nPDF sets and CT14nlo PDF sets.

In order to compare the number of W bosons produced in different centrality classes, the yields are divided by the average value of the thickness function $\langle T_{AA} \rangle$ listed in Table 5 (following Eq. 50). Then, they are normalized using the total number of MB events (N_{evt}) which have been probed in the corresponding centrality class.

Figure 98 shows the centrality scaling in the fiducial region as a function of $\langle N_{\text{part}} \rangle$ for W^+ and W^- bosons. The systematic and statistical uncertainties are also shown, whereas the systematic

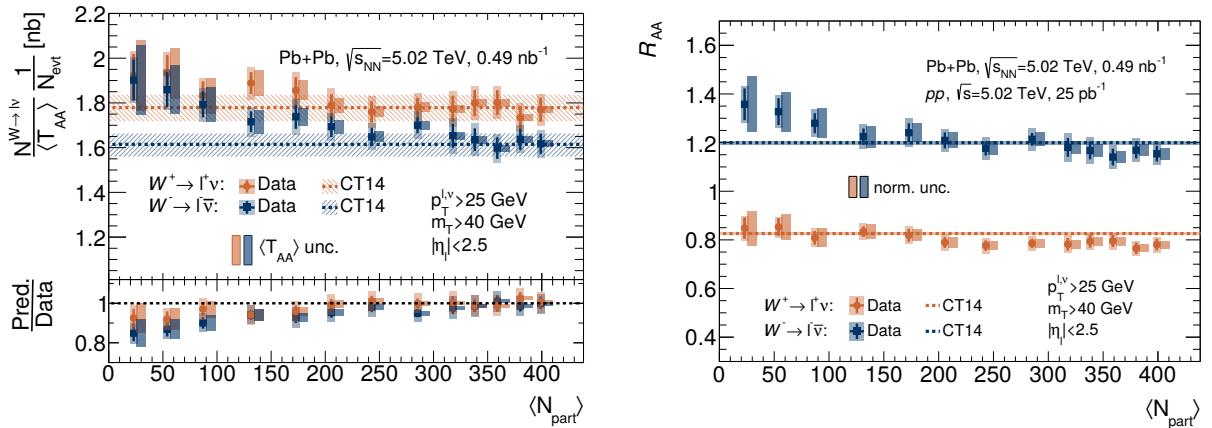


Figure 98: Fiducial yields scaled by the average nuclear thickness function (left) and R_{AA} (right) measured as a function of $\langle N_{\text{part}} \rangle$ for W^+ and W^- bosons decaying into leptons. Error bars show statistical uncertainties, whereas systematic and statistical uncertainties added in quadrature are shown as the filled boxes, while systematic uncertainties related to $\langle T_{AA} \rangle$ are represented by shaded boxes shifted along the x axis for better visibility. Predictions calculated using the CT14NLO PDF set are shown as the horizontal bands. In the lower panel the ratios of the predictions to the measured yields are displayed.

uncertainties related to $\langle T_{AA} \rangle$ are represented by shaded boxes shifted along the x axis for better visibility. The normalised production yields for W^+ bosons are about 10% higher comparing to the yields for W^- bosons. The data points are also compared to theoretical predictions based on the CT14NLO PDF set, which include the isospin effect. The normalised production yields for $W^\pm$ bosons are independent of centrality, and are in good agreement with the predictions for mid-central and central collisions represented by $\langle N_{\text{part}} \rangle$ values above 200. For mid-peripheral and peripheral collisions corresponding to $\langle N_{\text{part}} \rangle < 200$, a slight excess of the $W^\pm$ bosons in the data is observed in comparison to the theory predictions. The effect grows as $\langle N_{\text{part}} \rangle$ decreases. It is largest in the most peripheral bin and amounts to 1.73 (0.76) standard deviations for W^- (W^+) boson production. After combining four bins with the lowest $\langle N_{\text{part}} \rangle$ values, the excess in measured normalised production yields over the theory predictions is 1.33 (0.83) standard deviations for W^- (W^+) bosons. It was checked whether the events from the lowest $\langle N_{\text{part}} \rangle$ bin could be contaminated by a contribution from photo-nuclear background. Such events characterize signal in only one side of ZDC, however no significant enhancement of events with asymmetric signals in ZDC in either side of ATLAS was seen.

In Figure 98 the nuclear modification factor R_{AA} , defined in Eq. 21, is also presented. The values of W boson production cross sections in pp collisions at $\sqrt{s} = 5.02$ TeV are taken from Ref. [74]. All uncertainties are assumed to be fully uncorrelated between the pp and Pb+Pb measurements, therefore they are added in quadrature.

13.6 Neutron skin effect and comparison to the update Glauber model

For consistency with other heavy-ion measurements from the ATLAS Collaboration, this analysis uses the binning in FCal ΣE_T and geometric parameters determined from the Glauber models v2.4 as default. Recently, an updated version of the MCGlauber code, v3.2, has become available with several improvements in the geometric modelling. These improvements are described in Ref. [84], and include a lower value of $\sigma_{\text{inel}}^{\text{NN}}$ with a smaller uncertainty (67.6 ± 0.5 mb), separate radial distributions for protons and neutrons in the nucleus, and other improvements in the determination of nucleon positions within the nucleus. To re-assess the scaling of boson yields within this improved model of the Pb+Pb collision geometry, the centrality determination is performed following the same procedure described in Ref. [45] but using an alternate set of Pb+Pb events generated with MCGlauber v3.2. The estimated value of $\langle T_{AA} \rangle$ in the centrality classes is lower by 1% in the most central events, but higher by 6–7% in the most peripheral class, consistent with the change in $\langle T_{AA} \rangle$ found in Ref. [84]. The systematic uncertainties of $\langle T_{AA} \rangle$ are determined following procedures identical to the Glauber v2.4 case [45], but with a smaller $\sigma_{\text{inel}}^{\text{NN}}$ variation of ± 0.5 mb.

The measurement of normalised production yields for W^+ and W^- bosons is repeated using the alternative FCal ΣE_T ranges to define centrality classes, N_{evt} and $\langle T_{AA} \rangle$ values, extracted from the Glauber v3.2 model. The comparison of normalised production yields as a function of $\langle N_{\text{part}} \rangle$ for geometric parameters obtained with the Glauber model v2.4 and v3.2 is shown in Figure 99. For both the W^+ and W^- bosons, the normalised production yields extracted with

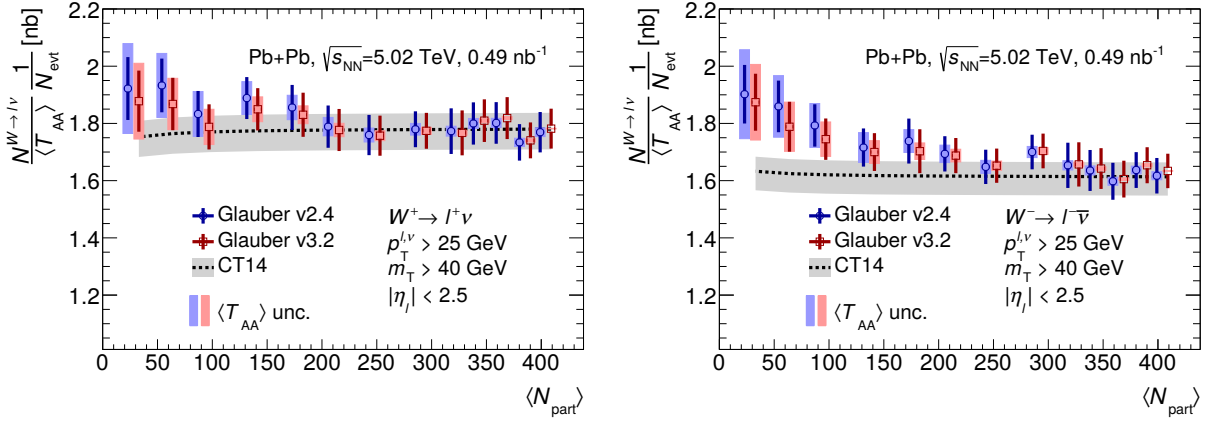


Figure 99: Comparison of normalised production yields for W^+ (left) and W^- (right) bosons as a function of $\langle N_{\text{part}} \rangle$ using geometric parameters obtained with the Glauber models v2.4 and v3.2. The dashed lines show predictions calculated using the CT14NLO PDF set which incorporate the neutron-skin effect evaluated using the separate radial distributions for protons and neutrons provided by the Glauber model v3.2. Uncertainties related to the determination of radial distributions for nucleons are not included. Error bars show statistical and systematic uncertainties added in quadrature, whereas systematic uncertainties due to $\langle T_{\text{AA}} \rangle$ are shown as shaded boxes around the data points. The points for Glauber model v3.2 are shifted horizontally for better visibility.

geometric parameters from the Glauber model v3.2 are slightly closer to the constant yields expected from a scaling with the nuclear thickness. This improvement is more pronounced in peripheral events, but the Glauber model v3.2 results still do not fully follow a constant scaling. In addition, differences between the yields obtained using the Glauber model v2.4 and v3.2 are smaller than the experimental uncertainties. Theoretical predictions shown in Figure 99 are calculated using the CT14NLO PDF set and incorporate the neutron-skin effect [85] evaluated using the separate radial distributions for protons and neutrons provided by the Glauber model v3.2. The difference in radial distributions results in an evolution of the effective proton-to-neutron ratio with centrality. The impact of the neutron skin on normalised $W^\pm$ boson production yields is largest in the most peripheral collisions, where the predictions differ by -1.4% (1%) for W^+ (W^-) bosons with respect to predictions calculated using a constant proton-to-neutron ratio.

14 Conclusions

In this thesis measurement of inclusive production of $W^\pm \rightarrow \ell^\pm \nu$ in the electron and muon channels in Pb+Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV is presented. The measurements are based on the data collected in 2015 using the ATLAS detector at the LHC and corresponding to an integrated luminosity of 0.49 nb^{-1} .

The fiducial production yields scaled by the average thickness function, $\langle T_{\text{AA}} \rangle$, and the total number of minimum-bias Pb+Pb events, N_{evt} , are measured in the phase space region defined by the charged lepton transverse momentum $p_{\text{T}}^\ell > 25$ GeV and pseudorapidity $|\eta_\ell| < 2.5$, the transverse momentum of the (anti)neutrino $p_{\text{T}}^\nu > 25$ GeV and the transverse mass of the charged lepton–(anti)neutrino system $m_{\text{T}} > 40$ GeV.

The dominant background contribution comes from the multi-jet production. It is evaluated using a data-driven method and amounts to up to 20% in the electron and about 13% in the muon decay channels. Other, smaller, background contributions come from EW boson decays ($Z \rightarrow \mu^+ \mu^- (\tau^+ \tau^-)$ and $W \rightarrow \tau \nu$) and $t\bar{t}$ production. They are estimated by normalising MC simulations to the integrated luminosity of the data sample.

The normalised production yields, corrected for background and efficiency, are presented as a function of the absolute pseudorapidity of the charged lepton $|\eta_\ell|$ and the average number of nucleons participating in the collision $\langle N_{\text{part}} \rangle$, the later being a measure of the collision centrality.

The normalised production yields for $W^\pm$ bosons are consistent between the two leptonic decay channels which are combined in this analysis. The combined normalised production yields are consistent with theoretical predictions based on the CT14NLO PDF set, while predictions obtained with the EPPS16 and nCTEQ15 nPDF sets underestimate the measured yields by 10–20%. The measured yields for $W^\pm$ bosons are also used to obtain the lepton charge asymmetry, which is well described by the above mentioned theoretical predictions. The lepton charge asymmetry changes sign and becomes negative for $|\eta_\ell| > 2$, which is an indication of the isospin effect yielding a larger fraction of $W^- \rightarrow \ell^- \nu$ events in Pb+Pb compared to pp collisions. Normalised production yields for $W^\pm$ bosons are in agreement with the expected scaling with $\langle T_{\text{AA}} \rangle$ for mid-central and central events. In the range $\langle N_{\text{part}} \rangle < 200$, a systematic excess of the normalised production yields of $W^\pm$ bosons is observed in the data in comparison to the theory predictions with the isospin effect included. The effect is largest in the most peripheral bin for W^- bosons where the excess amounts to 1.73 standard deviations. A comparison of normalised production yields for geometric parameters obtained with two versions of the Glauber model v2.4 and v3.2 shows that the Glauber v3.2 results are somewhat closer to the constant yields expected from the scaling with the nuclear thickness. However, the difference between the two results is smaller than the measurement uncertainties after the uncertainty on $\langle T_{\text{AA}} \rangle$ is excluded. Impact of the neutron-skin effect [85] evaluated using the separate radial distributions for protons and neutrons provided by the Glauber model v3.2 was found to be at the level -1.4% (1%) for W^+ (W^-) bosons with respect to predictions calculated using a constant proton-to-neutron ratio. Given current measurement precision data are not sensitive enough to confirm the neutron-skin effect.

Nuclear modification factors, R_{AA} , for $W^\pm$ boson production are calculated using cross-

sections measured in pp collisions at the same centre-of-mass energy. The R_{AA} factors also do not depend significantly on $\langle N_{\text{part}} \rangle$.

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Appendices

A Muon channel multi-jet background template fits

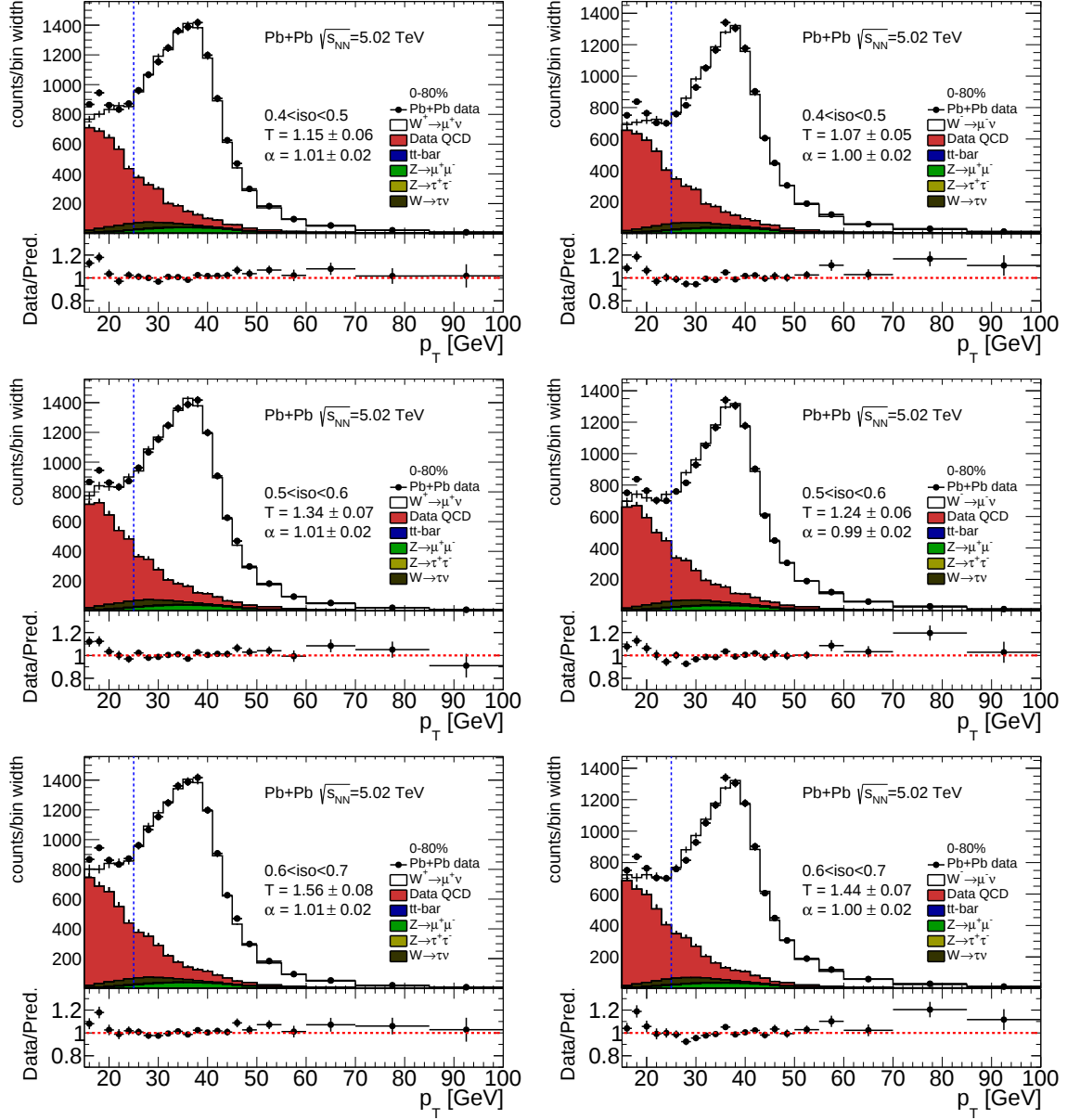


Figure 100: Multi-jet background template fits performed using the muon p_T distribution with the MJ template obtained from selected isolation slices (see labels). The fits are presented for positive (left) and negative (right) muons. Distributions are presented for the 0–80% centrality class.

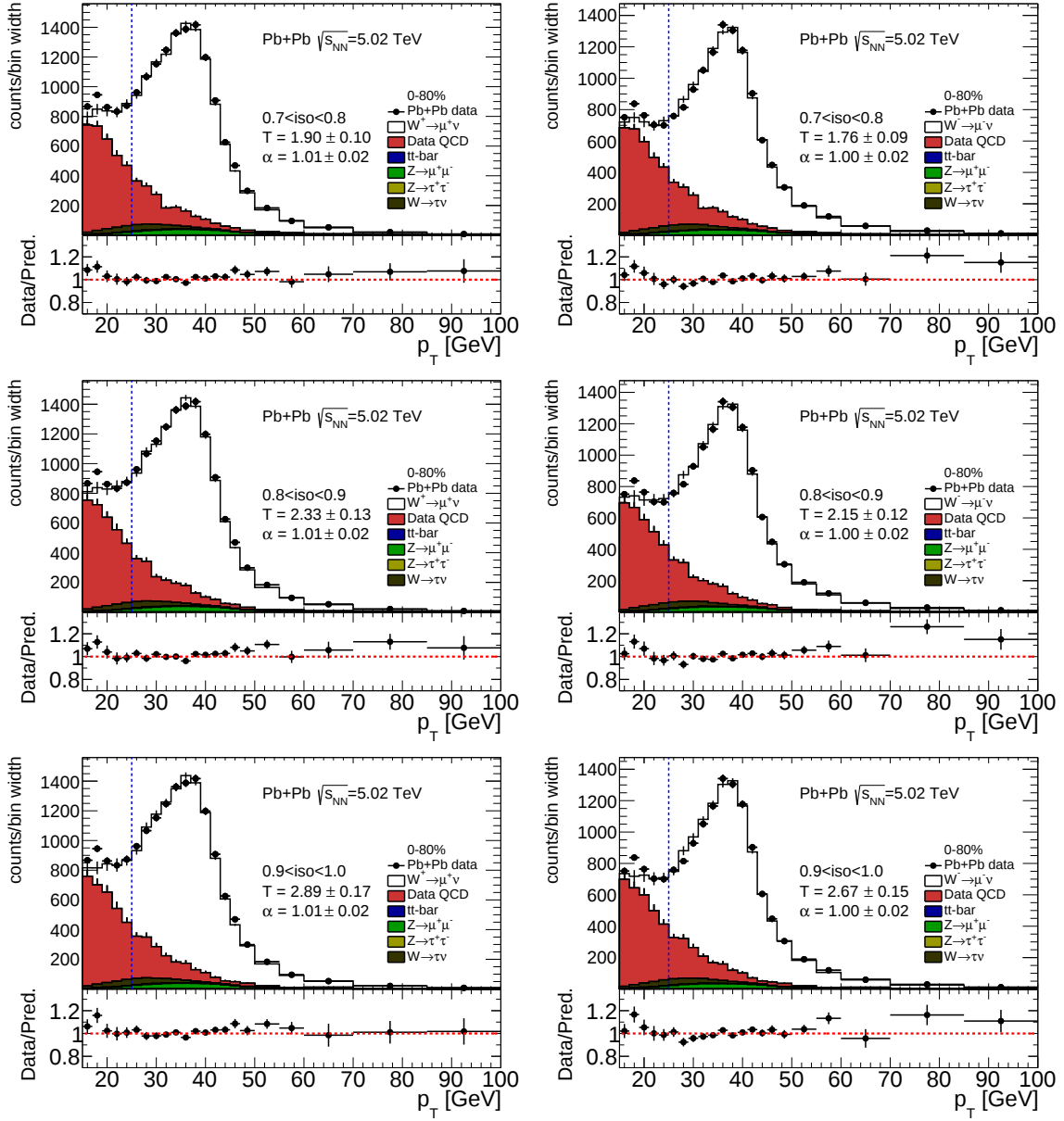


Figure 101: Multi-jet background template fits performed using the muon p_T distribution with the MJ template obtained from selected isolation slices (see labels). The fits are presented for positive (left) and negative (right) muons. Distributions are presented for the 0–80% centrality class.

B Muon channel multi-jet background template fits - η bins

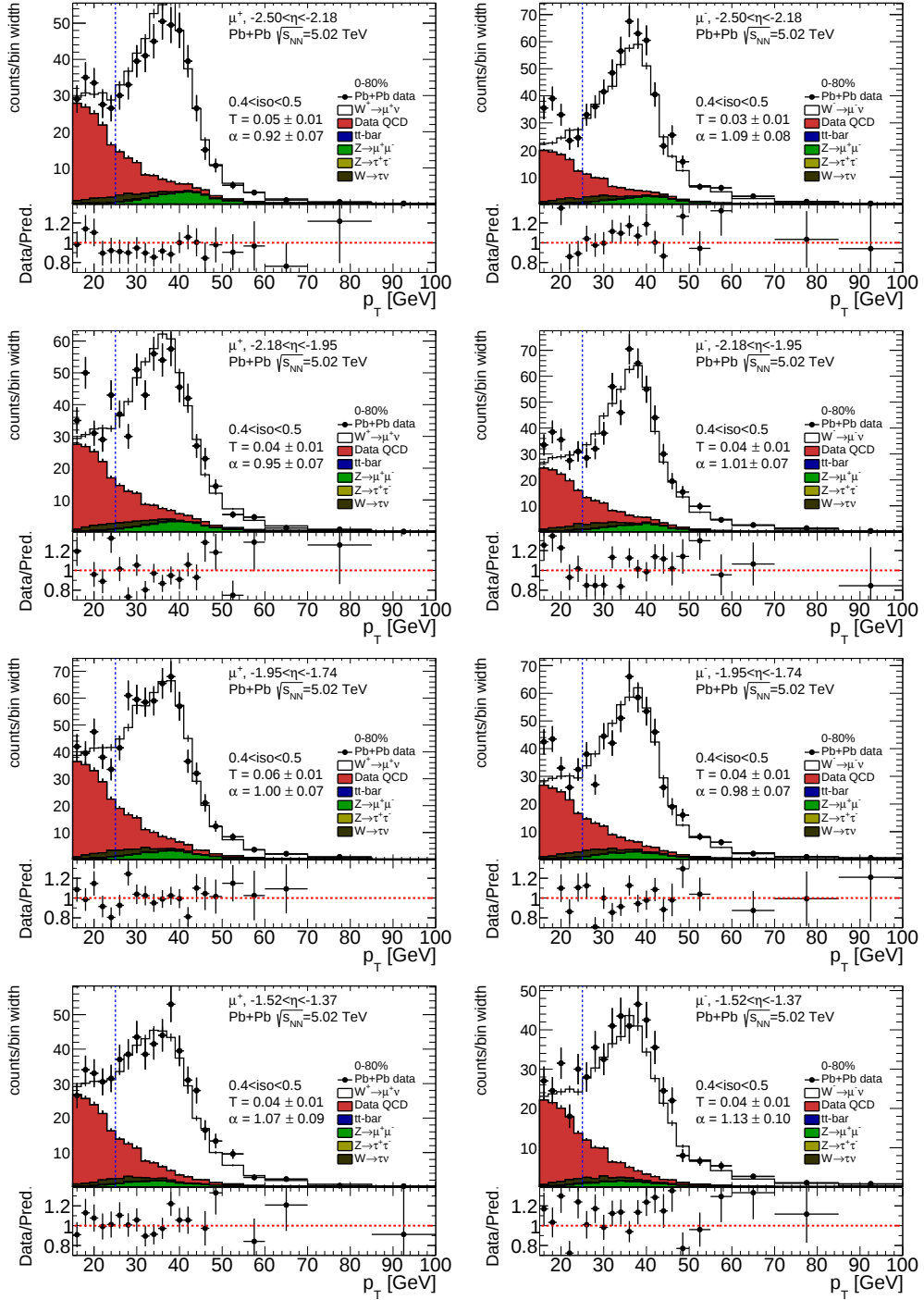


Figure 102: Multi-jet background template fits performed using the muon p_T distribution with the MJ template obtained from selected isolation slices (see labels). The fits are presented for positive (left) and negative (right) muons from different η bins (different rows). Distributions are presented for the 0–80% centrality class.

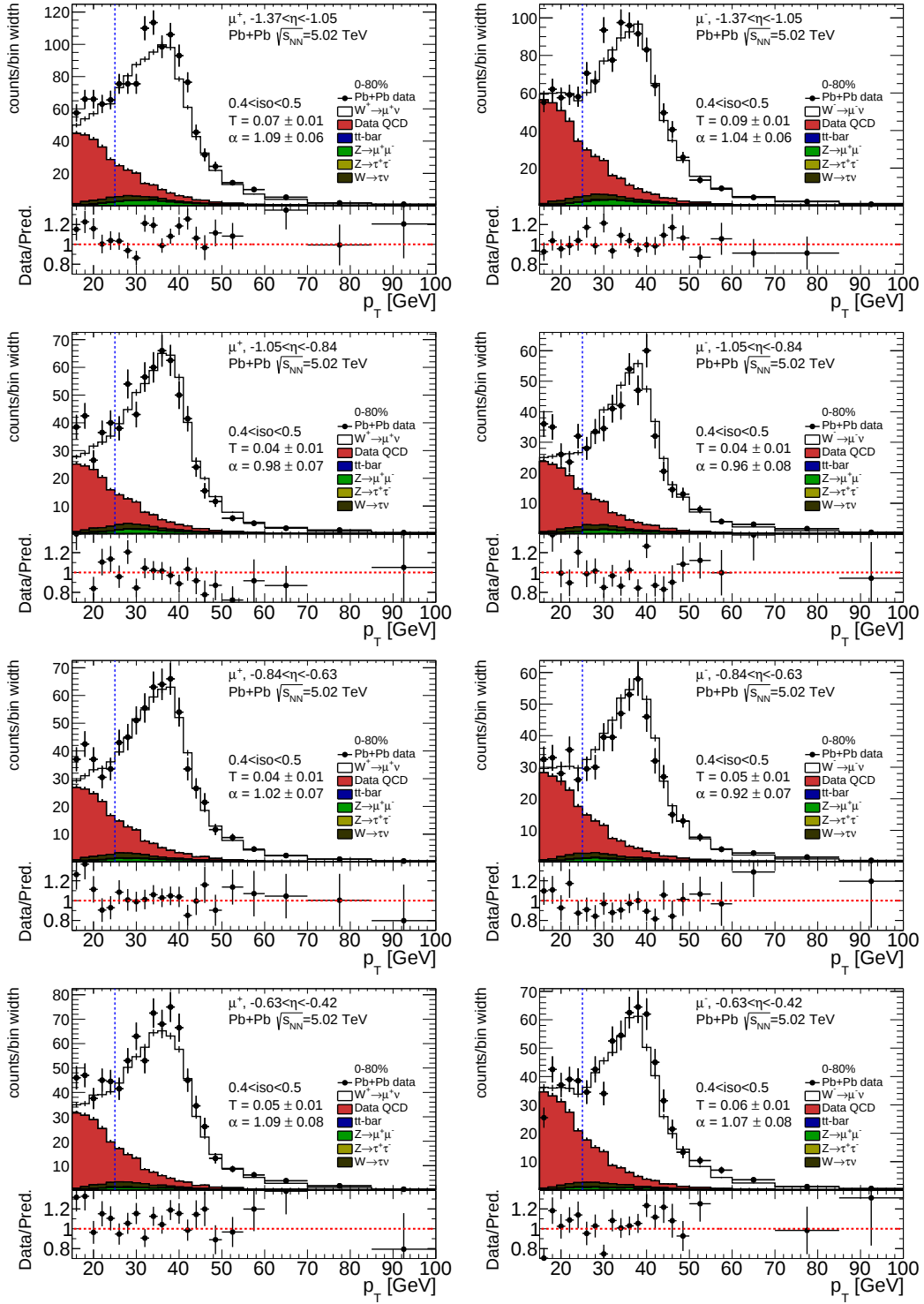


Figure 103: Multi-jet background template fits performed using the muon p_T distribution with the MJ template obtained from selected isolation slices (see labels). The fits are presented for positive (left) and negative (right) muons from different η bins (different rows). Distributions are presented for the 0–80% centrality class.

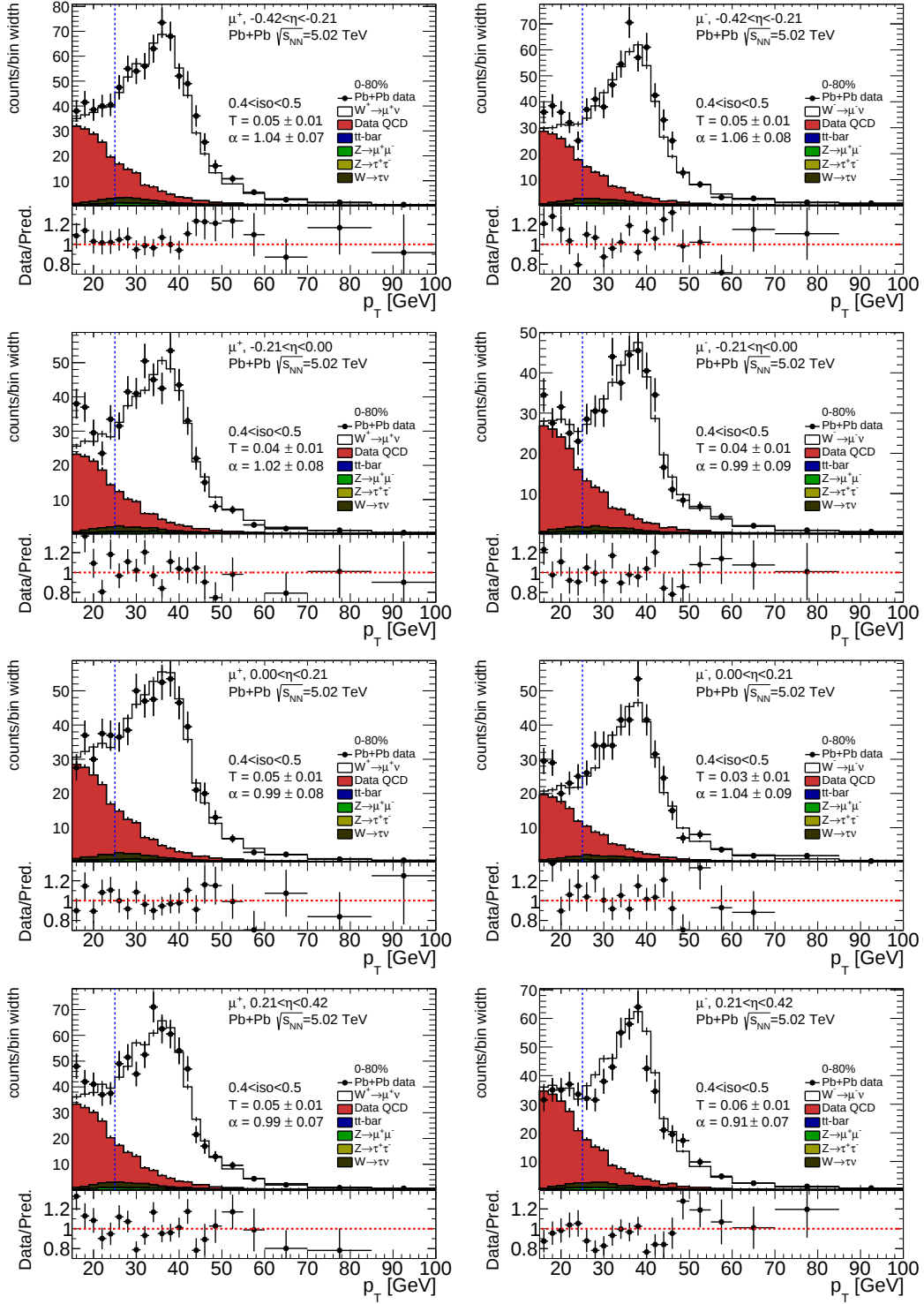


Figure 104: Multi-jet background template fits performed using the muon p_T distribution with the MJ template obtained from selected isolation slices (see labels). The fits are presented for positive (left) and negative (right) muons from different η bins (different rows). Distributions are presented for the 0–80% centrality class.

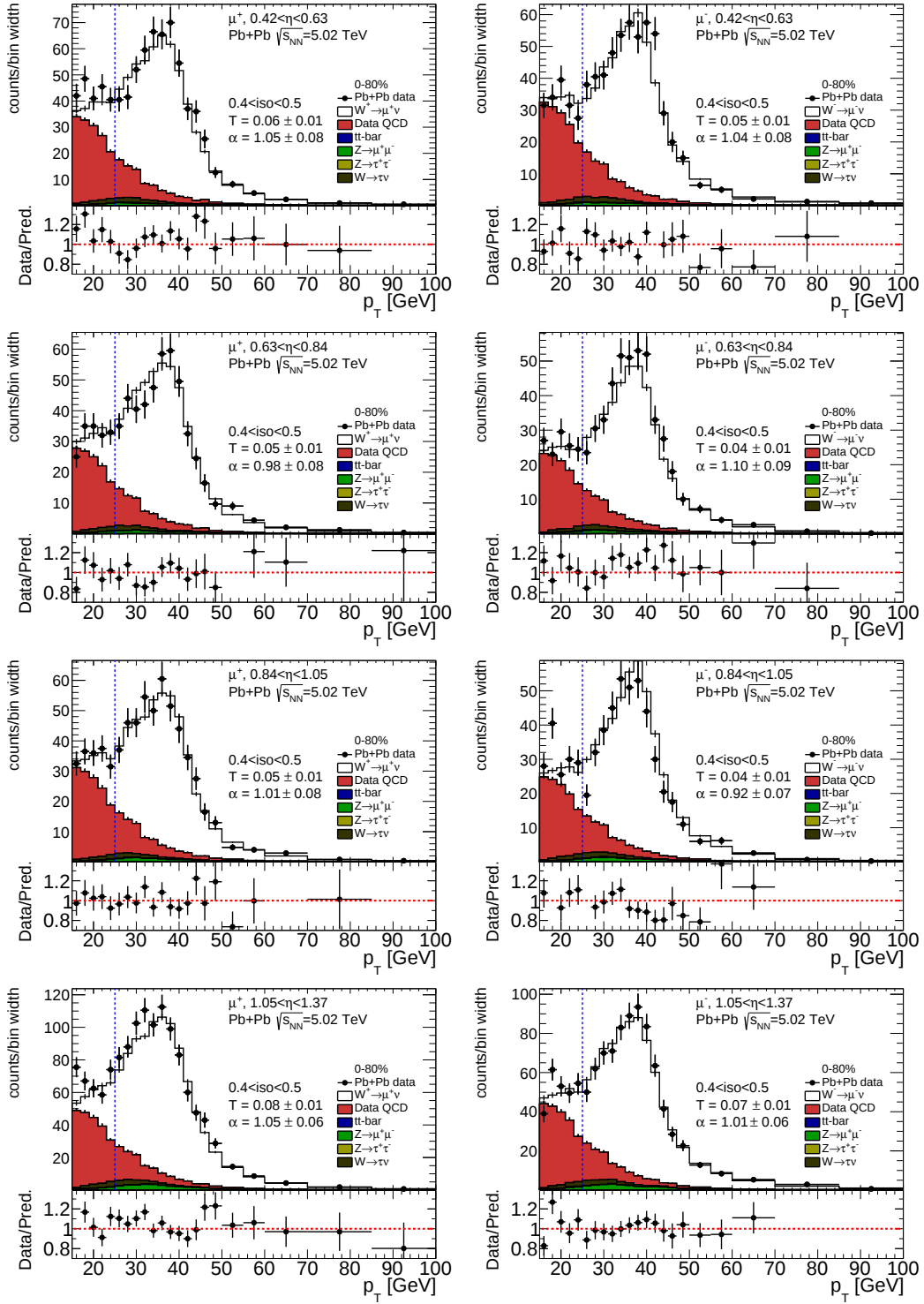


Figure 105: Multi-jet background template fits performed using the muon p_T distribution with the MJ template obtained from selected isolation slices (see labels). The fits are presented for positive (left) and negative (right) muons from different η bins (different rows). Distributions are presented for the 0–80% centrality class.

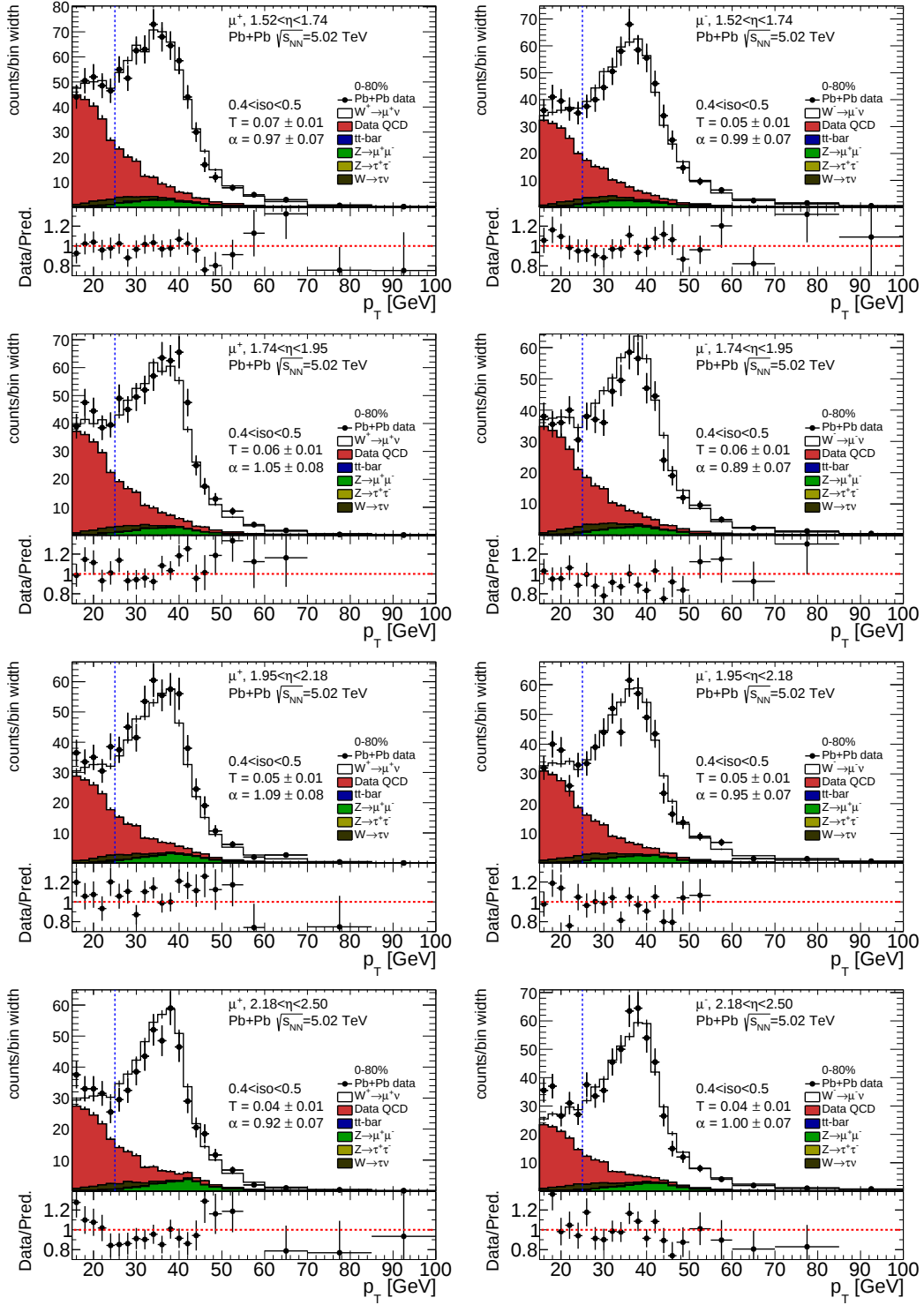


Figure 106: Multi-jet background template fits performed using the muon p_T distribution with the MJ template obtained from selected isolation slices (see labels). The fits are presented for positive (left) and negative (right) muons from different η bins (different rows). Distributions are presented for the 0–80% centrality class.

C Electron channel multi-jet background template fits

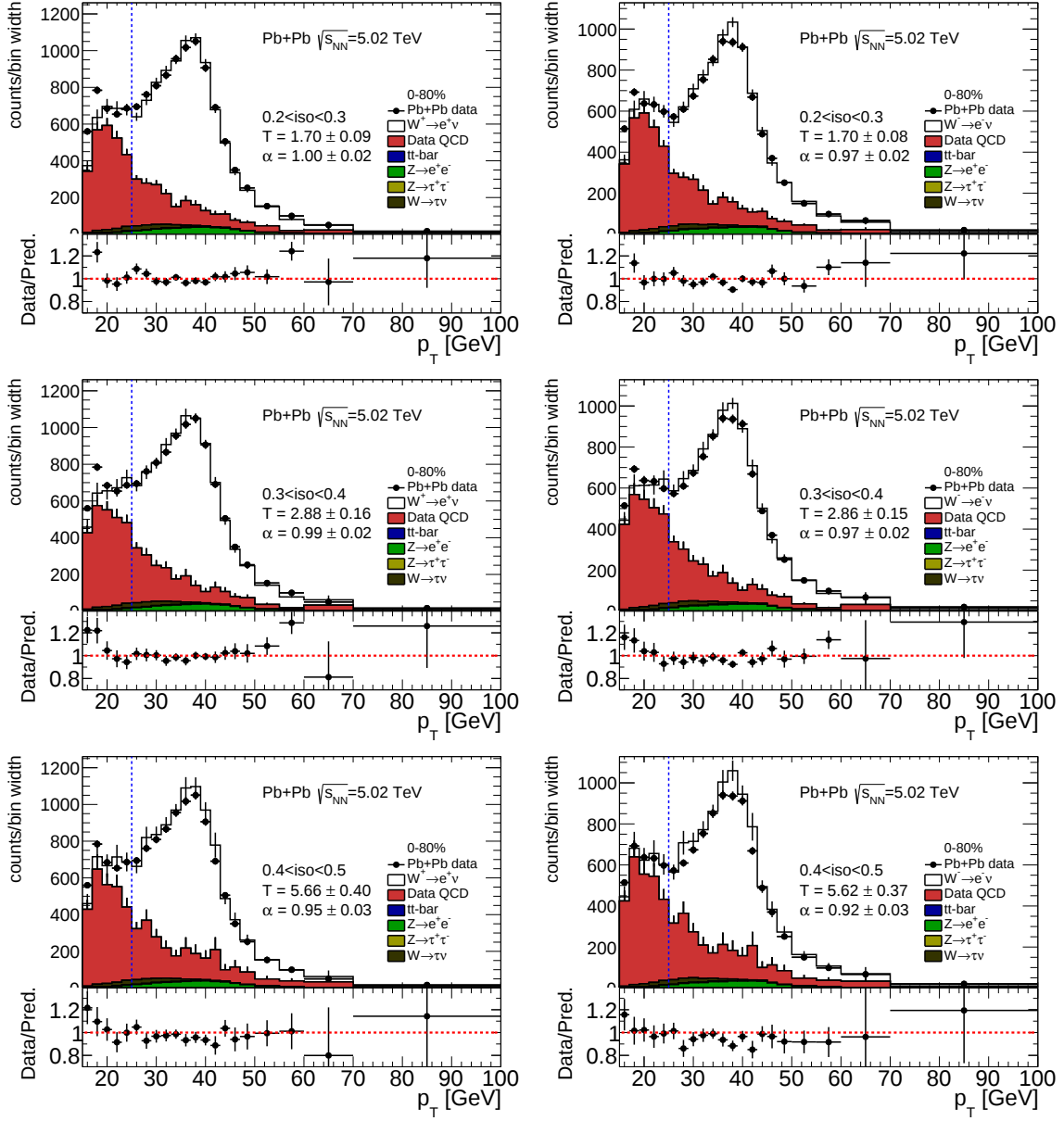


Figure 107: Multi-jet background template fits performed using the electron p_T distribution with the MJ template obtained from selected isolation slices (see labels). The fits are presented for positive (left) and negative (right) electrons. Distributions are presented for the 0–80% centrality class.

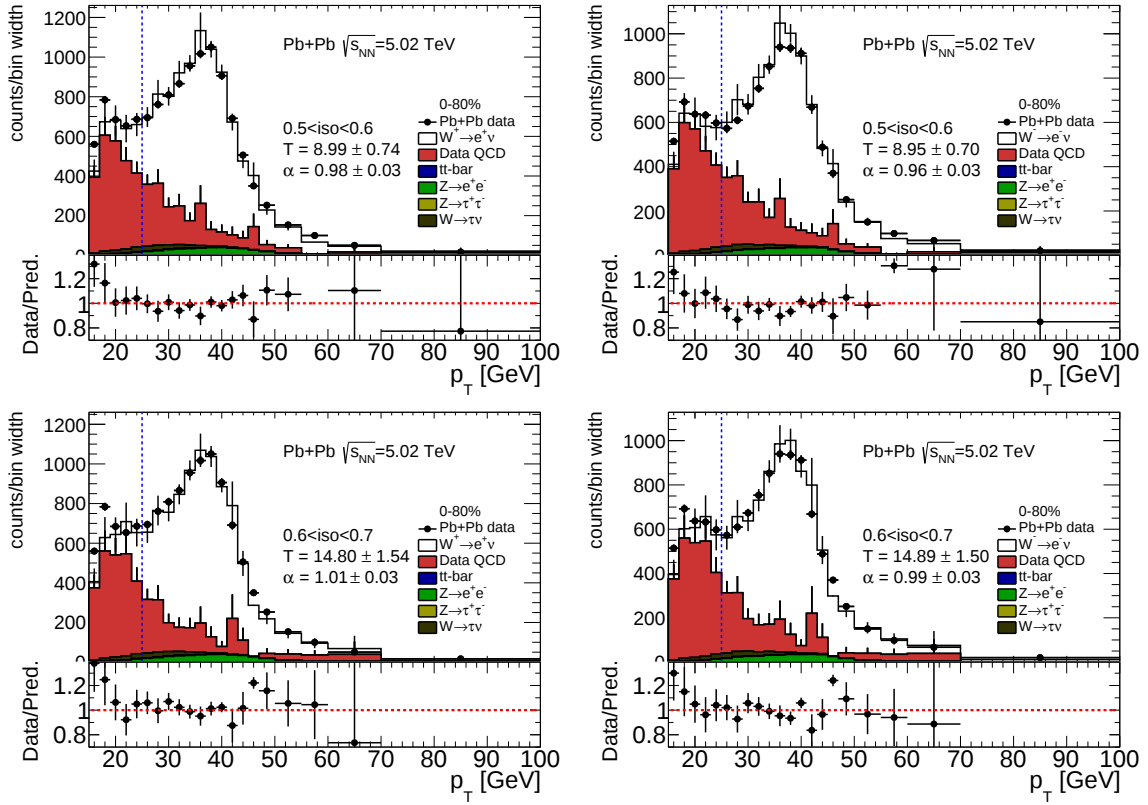


Figure 108: Multi-jet background template fits performed using the electron p_T distribution with the MJ template obtained from selected isolation slices (see labels). The fits are presented for positive (left) and negative (right) electrons. Distributions are presented for the 0–80% centrality class.

D Electron channel multi-jet background template fits - η bins

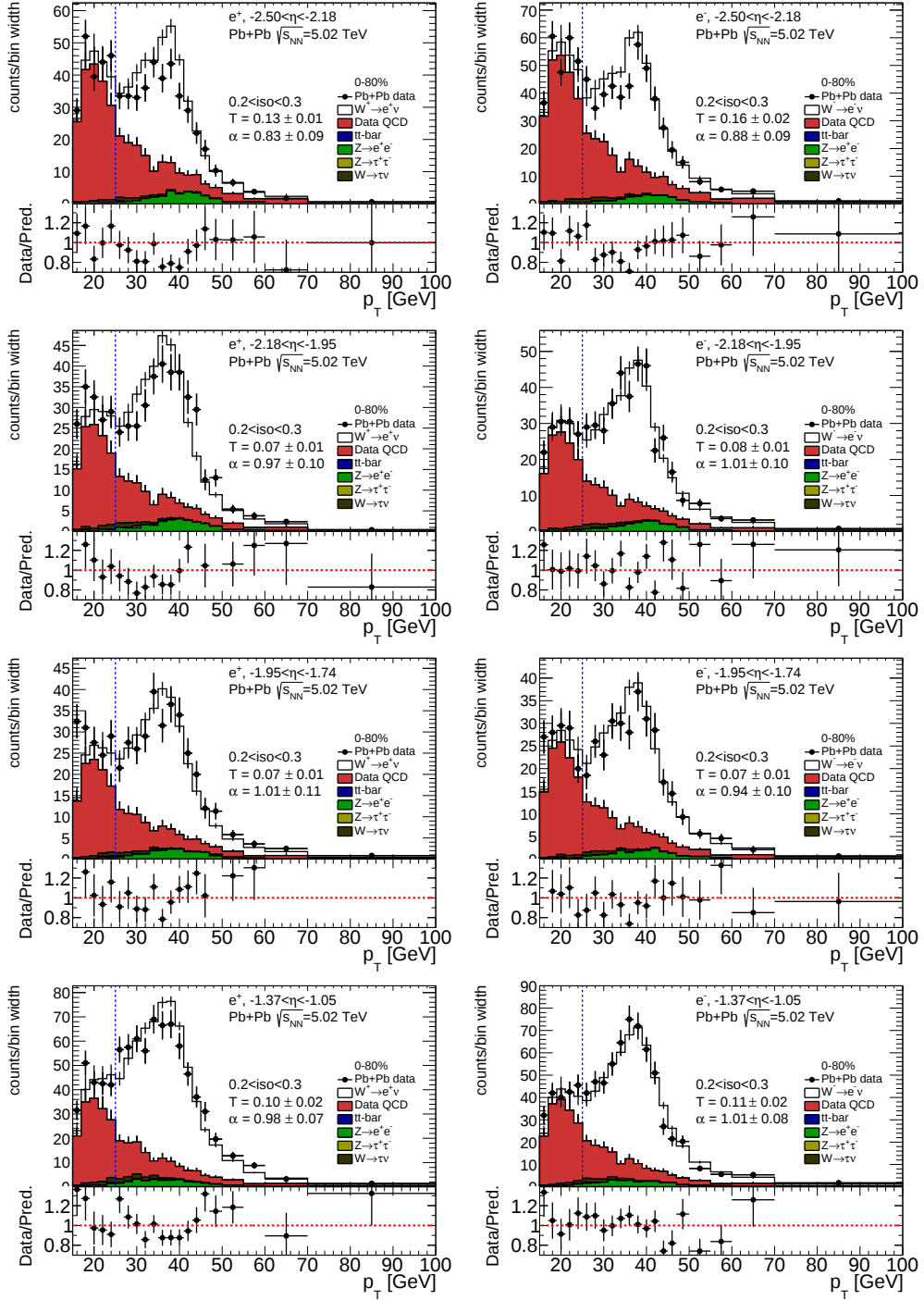


Figure 109: Multi-jet background template fits performed using the electron p_T distribution with the MJ template obtained from selected isolation slices (see labels). The fits are presented for positive (left) and negative (right) electrons from different η bins (different rows). Distributions are presented for the 0–80% centrality class.

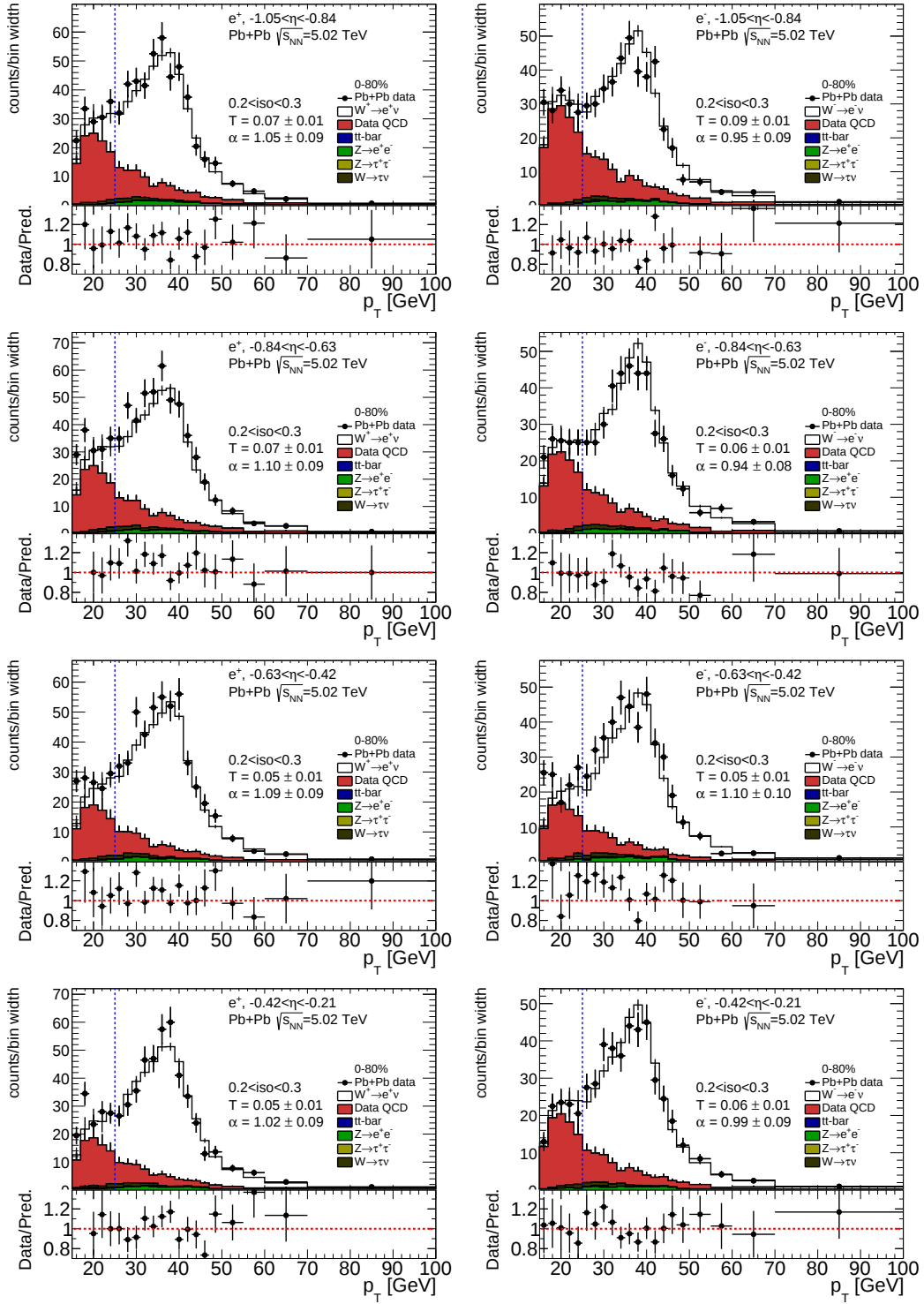


Figure 110: Multi-jet background template fits performed using the electron p_T distribution with the MJ template obtained from selected isolation slices (see labels). The fits are presented for positive (left) and negative (right) electrons from different η bins (different rows). Distributions are presented for the 0–80% centrality class.

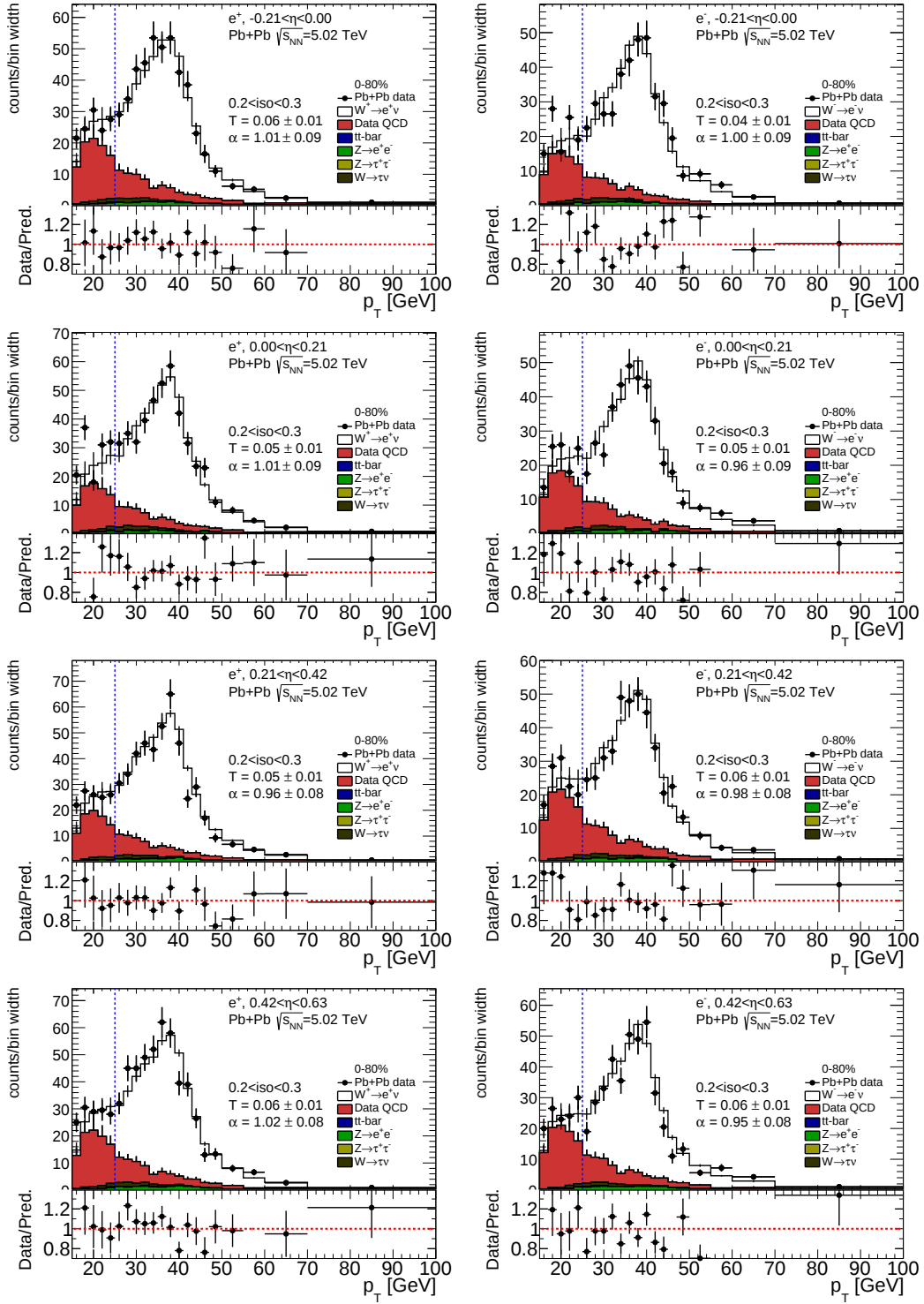


Figure 111: Multi-jet background template fits performed using the electron p_T distribution with the MJ template obtained from selected isolation slices (see labels). The fits are presented for positive (left) and negative (right) electrons from different η bins (different rows). Distributions are presented for the 0–80% centrality class.

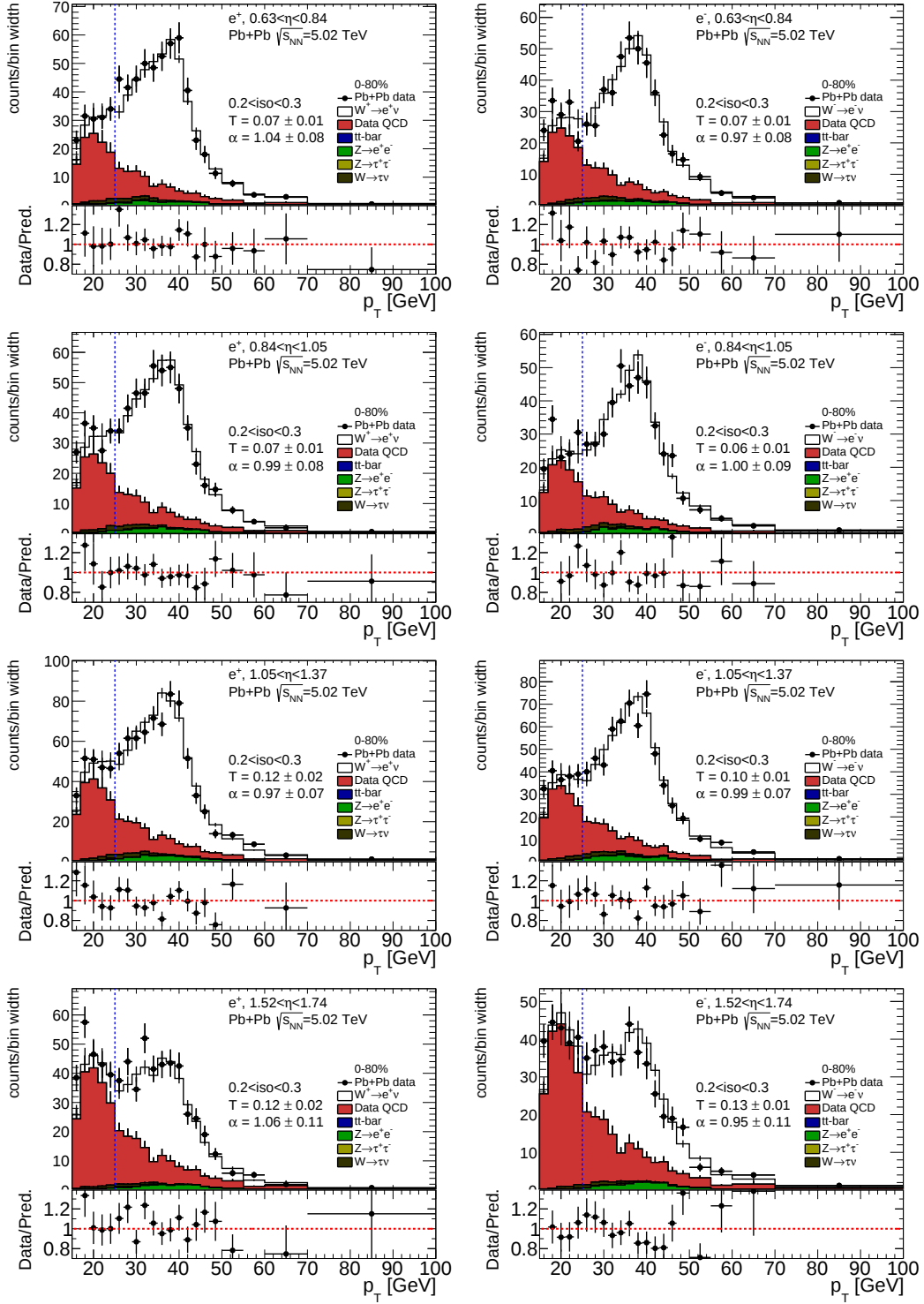


Figure 112: Multi-jet background template fits performed using the electron p_T distribution with the MJ template obtained from selected isolation slices (see labels). The fits are presented for positive (left) and negative (right) electrons from different η bins (different rows). Distributions are presented for the 0–80% centrality class.

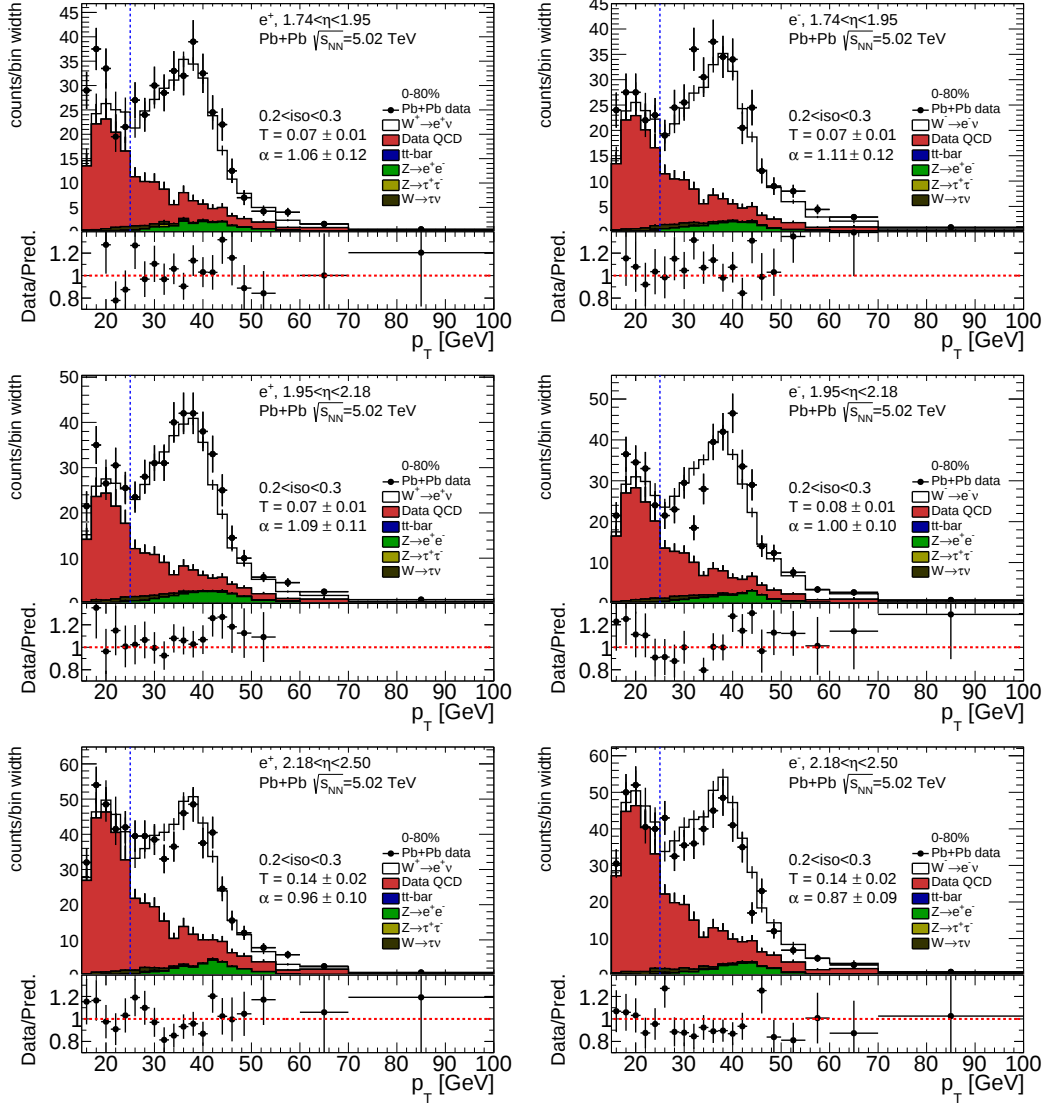


Figure 113: Multi-jet background template fits performed using the electron p_T distribution with the MJ template obtained from selected isolation slices (see labels). The fits are presented for positive (left) and negative (right) electrons from different η bins (different rows). Distributions are presented for the 0–80% centrality class.