

Measurement of Z boson production in heavy-ion collisions with the CMS detector at the LHC

Ph.D. thesis

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1 Introduction

Particle physics tries to answer some of the fundamental questions of our Universe: what are the basic building blocks of matter and what is the nature of the forces acting between them? The current theory of elementary particles and interactions is the Standard Model that combines three out of the four fundamental interactions. The unified quantum theory of electromagnetism, weak and strong interactions provides a surprisingly good description of the observed phenomena in various particle physics experiments performed in the last hundred years. Additionally, particle physics helps to understand the processes transpired in the early Universe before the atoms could form.

The Standard Model consists of elementary particles characterized by their intrinsic angular momentum, spin. The matter particles are fermions with spin one-half and are divided into three generations of leptons and quarks. Ordinary matter is made up from particles of the first generation: the up and the down quarks building up the protons and neutrons inside the nucleus of every atom that is surrounded by the electrons. The interactions between the elementary particles are mediated by integer spin bosons. These are the massless photon, the massive W and Z bosons and the gluons of the strong interaction carrying charge themselves. The picture in fig. 1.1 became complete with the discovery of the Higgs boson in 2012 that is important for understanding of the origin of the mass of the elementary particles.

In the experiments particles are accelerated to high energies and collided with each other in order to achieve high energy transfers providing access to interactions acting at very small distances. The measured quantities are inclusive and differential cross sections of different processes identified in the complex detector systems of the experiments. The cross section is an effective area that quantifies the probability of an interaction to occur between the beam and the target particles. It can be generalized to the probability of specific types of events and compared to the cross sections calculated in the theoretical framework of the Standard Model.

High-energy particle and nuclear physics experiments are performed at large laboratories like the European Organization for Nuclear Research (CERN), Fermi National Accelerator Laboratory (Fermilab) and Brookhaven National Laboratory (BNL) where the largest accelerators can reach the highest collision energies at

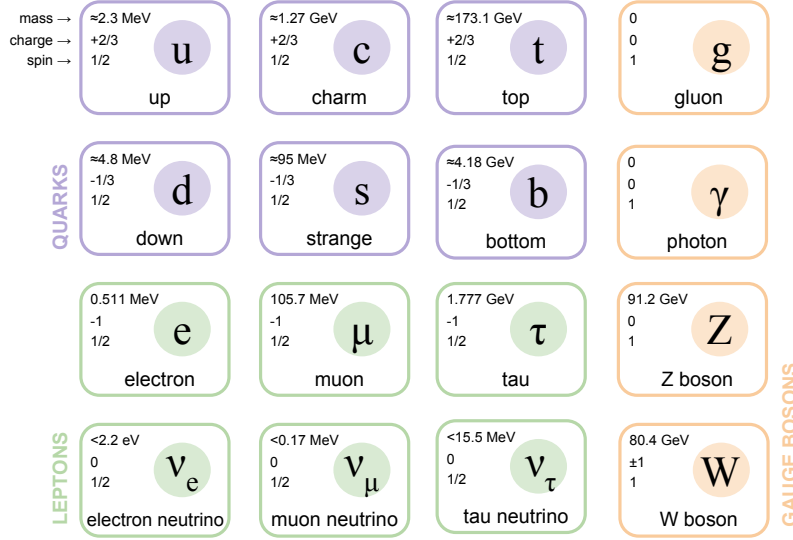


Figure 1.1: The Standard Model of elementary particles with the three generations of matter, gauge bosons in the fourth column, and the Higgs boson in the fifth.

present. In this thesis, I present studies of collisions of protons and lead nuclei at the Large Hadron Collider (LHC) at CERN recorded by the Compact Muon Solenoid (CMS) experiment. Studies of lead-lead (Pb-Pb) and proton-lead (p-Pb) collisions and their comparisons to proton-proton (p-p) collisions provide a unique opportunity to study the properties of the strong interactions and nuclear matter at extreme conditions.

This thesis is organized in the following way: in Chapter 2 and 3 the theoretical introduction for heavy-ion collisions and Z bosons is presented and the measurements are motivated. Chapter 4 introduces the detector system of the CMS experiment. Chapter 5 summarizes the datasets used in the analyses of centrality and Z bosons presented in Chapters 6 and 7. Finally, results are detailed in Chapter 8 and a summary is given in Chapter 9. In each chapter, I cite the relevant publications where the presented results appeared and also the corresponding internal documents and conference proceedings that demonstrate my contribution to and recognition by the CMS collaboration.

2 Heavy-ion collisions in a nutshell

The study of heavy-ion collisions provides a unique opportunity to study the nature of the strong interaction in the domain of extreme temperatures and densities, that has been present in the early universe $\sim 10^{-6}$ s after the big bang. The theory of strong interaction, quantum chromodynamics (QCD), provides the framework for the study of heavy-ion collisions. QCD is a non-abelian quantum field theory that describes the interaction between quarks mediated by gluons through the color charge. A peculiar property of QCD is confinement which means that quarks are always bound into color-neutral objects called hadrons. When one tries to separate a quark from a hadron, energy builds up between the quarks with the growing distance and when it reaches a critical level, a quark-antiquark pair is created and a new hadron is formed. The other special property of QCD is asymptotic freedom meaning that the interaction strength becomes smaller at very high energies or very small distances. This leads to the idea of the quark-gluon plasma where the energy density is high enough for deconfinement of hadrons to free quarks and gluons. The Relativistic Heavy Ion Collider (RHIC) experiments at BNL have found that the behaviour of the medium produced in gold-gold (Au-Au) collisions is consistent with a strongly interacting almost perfect liquid of quarks and gluons [1, 2, 3, 4]. In this chapter a brief insight to the studies of the properties of heavy-ion collisions and the produced hot and dense medium is presented.

2.1 Glauber model and particle production

An important property of each collision is its initial geometry determined by the impact parameter, b , the distance between the centers of the two colliding nuclei. The impact parameter can not be measured experimentally, instead the multiplicity of produced particles in the event is used to assign each event to a centrality class that is expressed in percentage of the total inelastic cross section. One can safely assume that the particle multiplicity is a monotonic function of the impact parameter. Collisions with small impact parameter or large overlap area between the nuclei are called central events with a large number of produced particles. Collisions with a larger impact parameter are called peripheral events with a lower particle multi-

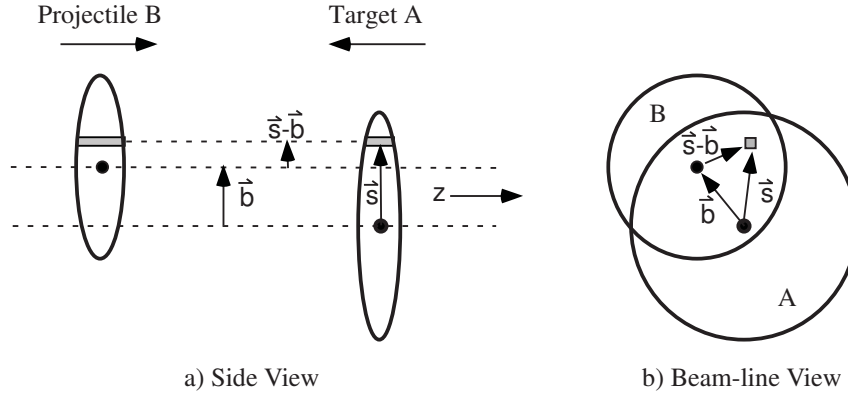


Figure 2.1: Schematic representation of the optical Glauber model geometry in the transverse and longitudinal views [7].

plicity. Instead of impact parameter, centrality is often expressed in terms of the number of participating nucleons, N_{part} , the nucleons that undergo at least one inelastic collision or in terms of the number of elementary nucleon-nucleon collisions, N_{coll} . These measures have a one-to-one relationship with the impact parameter and can be calculated in a Glauber model [5, 6, 7].

The Glauber model views nucleus-nucleus (A-B) collisions in terms of individual interactions of the constituent nucleons. Assuming independent linear trajectories of nucleons, it is possible to obtain simple analytical expressions for the nuclear cross section, N_{coll} and N_{part} . The density distribution of nuclei is parametrized using a Woods-Saxon distribution:

$$\rho(r) = \rho_0 \frac{1 + w(r/R)^2}{1 + \exp\left(\frac{r-R}{a}\right)}, \quad (2.1)$$

where ρ_0 is the nucleon density, R is the radius, a is the skin thickness and w measures the deviation from a spherical shape. These parameters for the different nuclei are determined from low-energy electron scattering experiments.

Interpreting $\rho(r)$ as the probability to find a nucleon at a given position in nucleus A, one can define the nuclear thickness function as

$$T_A(\mathbf{s}) = \int dz \rho(\mathbf{s}, z). \quad (2.2)$$

Similarly defining T_B for nucleus B, one can define the nuclear overlap function for A-B collisions at a given impact parameter by

$$T_{AB}(\mathbf{b}) = \int d^2s T_A(\mathbf{s}) T_B(\mathbf{s} - \mathbf{b}) \quad (2.3)$$

that has a unit of inverse area. A schematic picture of the geometry of A-B collisions is shown in fig. 2.1. Taking the nucleon-nucleon inelastic cross section, $\sigma_{\text{inel}}^{\text{NN}}$, one

finds that the probability of an inelastic interaction to happen between A and B is $\sigma_{\text{inel}}^{\text{NN}} T_{\text{AB}}(\mathbf{b})$. From combinatoric considerations the total probability of an interaction between A and B nucleus can be calculated and its integral gives the total inelastic cross section as

$$\sigma_{\text{inel}}^{\text{AB}} = \int d^2b \left[1 - \exp \left(-\sigma_{\text{inel}}^{\text{NN}} T_{\text{AB}}(\mathbf{b}) \right) \right]. \quad (2.4)$$

The number of binary nucleon-nucleon collisions for a given b also follows from this probability as

$$N_{\text{coll}}(b) = \sigma_{\text{inel}}^{\text{NN}} T_{\text{AB}}(b). \quad (2.5)$$

Finally, the number of participating nucleons or wounded nucleons can be calculated in this simple combinatoric approach as

$$N_{\text{part}}(b) = A \int d^2s T_A \left(1 - \left[1 - \sigma_{\text{inel}}^{\text{NN}} T_B(b-s) \right]^B \right) + B \int d^2s T_B \left(1 - \left[1 - \sigma_{\text{inel}}^{\text{NN}} T_A(s) \right]^A \right), \quad (2.6)$$

where A and B are the number of nucleons in A and B nuclei, respectively. These quantities in the Glauber-model calculation have a dependence on the center-of-mass energy per nucleon pair, $\sqrt{s_{\text{NN}}}$, through the inelastic nucleon-nucleon cross section.

In the experimental measurements, Monte Carlo (MC) programs are used for the Glauber-model estimation of the centrality related quantities in each event class [7]. In a Glauber MC model, the individual nucleons are stochastically distributed event-by-event and the collision properties are calculated averaging over many events. These models give very close results to the above introduced optical or eikonal Glauber model. Details of the treatment of centrality in the CMS experiment are presented in Section 6.

The quantities N_{part} and N_{coll} and their centrality dependence is important in the description of particle production in heavy-ion collisions. According to the wounded nucleon model [8], the number of produced particles in the collision scales with the number of participating nucleons based on a few simple considerations. First of all, the particle multiplicity is dominated by soft particles that are produced from the excitations of the individual nucleons. Assuming that soft interactions between nucleons only produce excitations and then the excited nucleons decay after leaving the interaction region, the number of produced particles only depends on the number of participating nucleons. This model gives an approximate description of the measurements at different energies but other effects have to be taken into account for a more precise model of particle production. At higher energies, the hard processes become more important in the modeling of particle multiplicities. Because of their small cross section, the hard processes and their contribution to particle

production scale with the number of binary collisions. The measured centrality dependence of particle multiplicity from RHIC and LHC can be fitted with the two components scaling with N_{part} and N_{coll} that gives an impression on the role of hard processes and its increase with collision energy.

2.2 Space-time evolution of the collisions

A simple picture of the space-time evolution of heavy-ion collisions separates the different characteristic stages that follow each other in time. The two incoming nuclei are affected by Lorentz contraction and seen as two disks in the laboratory frame. In the overlapping region of the two nuclei the nucleons collide near simultaneously with a chance of large momentum transfer between two partons (quarks and gluons) called the hard scattering. The inelastic collisions of nucleons create a large number of free partons that can thermalize through additional scatterings and form a nuclear matter with high temperature and density that starts to expand and cool down rapidly. When the system reaches a critical temperature, hadrons form out of the soup of quarks and gluons known as the chemical freeze-out. The chemical freeze-out marks the end of inelastic interactions when the number of final state particles gets set. This hadronic gas further expands and cools down until the elastic interaction rate becomes so small that thermalization is no longer possible. This is the kinetic freeze-out of the system, when the momentum of the final state hadrons is set and they fly freely to the detectors.

In the detector, the momentum distribution of the particles is measured. Its Fourier decomposition reads

$$E \frac{d^3N}{d^3p} = \frac{1}{2\pi} \frac{d^2N}{p_T dp_T dy} \left(1 + 2 \sum_{n=1}^{\infty} v_n \cos [n(\phi - \Psi_R)] \right), \quad (2.7)$$

where E is the particle energy, p_T the transverse momentum, ϕ the azimuthal angle, Ψ_R the reaction plane and y denotes the rapidity of the observed particle. The rapidity is defined as

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}. \quad (2.8)$$

In the measurements, the pseudorapidity of the particles is usually used because it does not require the knowledge of the particle species. It is defined with the polar angle, θ , measured from the beam axis, z , as $\eta = -\ln \tan(\theta/2)$ that is equivalent to rapidity for massless particles. A schematic picture of the transverse plane of the collisions is shown in fig. 2.2. The Fourier coefficients v_n are also called flow coefficients with v_1 being the directed flow, v_2 the elliptic flow, v_3 the triangular flow, etc. Extensive studies of these flow harmonics have been performed by the

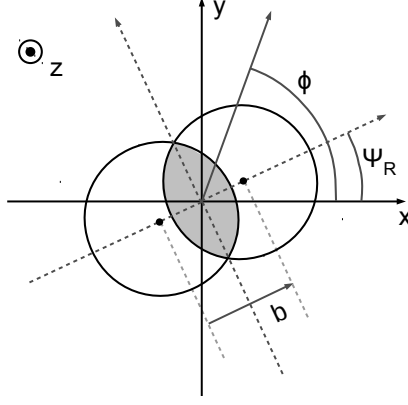


Figure 2.2: Schematic representation of the collision coordinate system in the transverse plane [10].

experiments at RHIC [1, 2, 3, 4] and LHC [9, 10, 11].

The flow coefficients measure the azimuthal anisotropy of the emitted particles in the final state. The observed non-zero v_n coefficients are considered as a signature of collective behaviour of the system produced in the collisions. The measurements can be successfully described by relativistic hydrodynamics calculations using different initial conditions [12]. Ideal hydrodynamics without viscous effects does a surprisingly good job in reproducing experimental data. The applicability of hydrodynamics demands a short mean free path with respect to the system size, that leads to the conclusion that the created medium is strongly interacting and behaves like a nearly perfect fluid. The agreement with the different v_n measurements is improved using viscous hydrodynamic simulations and can be used to extract the shear viscosity to entropy density ratio, which is very low [13].

2.3 Hard probes of the hot and dense medium

The hard interaction of partons happens in the first instants of the reaction process before a medium can be formed, thus the produced particles constitute direct probes of the partonic phases of the collision. Their yield is expected to scale with the number of binary nucleon-nucleon collisions from simple geometric considerations. Electroweak probes do not participate in the strong interaction that makes them ideal probes of the initial state of the collisions. Details on how the Z boson is used to constrain the distribution of partons in the nucleus are presented in Chapter 3. Photons and weak bosons can also be used to verify the geometrical scaling properties of hard processes.

Photons directly coming from the interaction can provide information about several stages of the collisions, although their measurement is challenging due to the large amount of background photons from hadron decays. The so-called prompt photons created in the hard scattering provide information on the initial state of the

collision and can be calculated with perturbative QCD methods. Photons are also created in the fragmentation of hard scattered partons described by the fragmentation functions. Pre-equilibrium and thermal photons are emitted from the QCD medium and hadronic matter before and in local thermal equilibrium. These type of photons are hard to distinguish. Thermal photons are important for obtaining information from the temperature of the hot and dense QCD medium [2].

Partons produced in the hard scattering are highly virtual and reduce their virtuality by radiating gluons or by splitting into quark-antiquark pairs. Finally, the partons fragment into hadrons and this collimated spray of hadrons is called a jet. Jets are important observables in high-energy collisions and the modification of their properties in heavy-ion collisions can provide detailed information about the medium. The produced hard parton interacts with the hot and dense medium through its color charge and loses part of its energy. This phenomenon is called jet quenching that is observed with the suppression of high- p_T hadrons in nucleus-nucleus collisions compared to proton-proton collisions or with the modification of the two-particle correlation function.

In the dominant hard scattering processes, two partons are produced back-to-back in azimuthal angle with similar transverse momentum. These dijet events are well identified in p-p collisions experimentally and well described by theoretical calculations. When produced in the initial phase of heavy-ion collisions, both jets have to propagate through the strongly interacting medium before their fragments are measured by the detectors. Depending on the position of their production, the two partons have to pass through different amount of matter where they lose part of their energy that results in a large transverse momentum asymmetry of dijet events. This asymmetry is shown in fig. 2.3 as observed at RHIC in 200 GeV Au-Au collisions with the two-particle correlation function [4]. The charged particles form a jet peak in the $\Delta\phi = \phi_1 - \phi_2$ distribution at $\Delta\phi = 0$ but the so-called away-side peak around $\Delta\phi = 2\pi$ is suppressed in central Au-Au collisions compared to p-p collisions. At the LHC in 2.76 TeV lead-lead (Pb-Pb) collisions, the jets are directly reconstructed and the asymmetric dijet events can be observed event-by-event as shown in fig. 2.3. It is also found that the average asymmetry increases with centrality as expected, because of the larger volume of the strongly interacting matter [14, 15].

Although dijet production offers an abundant probe of the medium, the information about the kinematics before the medium interaction is lost. Studying the correlation of electroweak bosons and jets provides further information on the energy loss of partons in the medium. At leading order, photons or weak bosons are produced back-to-back with an associated parton having close to the same transverse momentum. In this manner, the asymmetry between bosons and jets is a clean probe

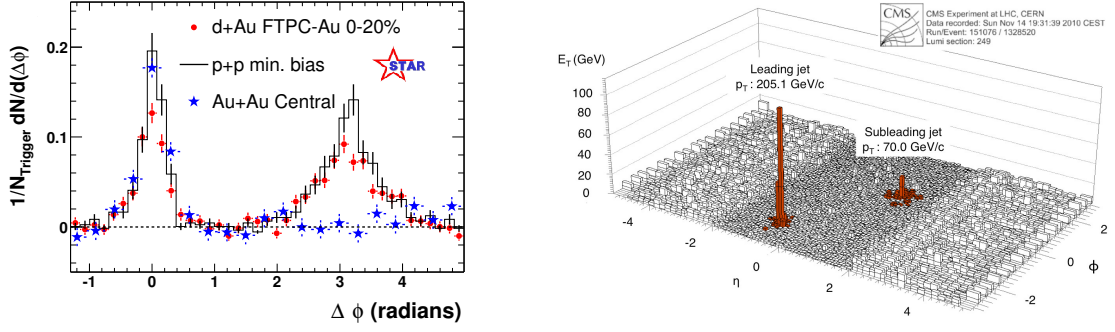


Figure 2.3: *Left:* Dihadron azimuthal correlations from STAR experiment [4]. *Right:* Dijet event with a quenched subleading jet recorded by the CMS experiment [15].

of jet quenching and requires precise measurements of photons and weak bosons.

In addition to correlations, the commonly used observable for quantifying jet quenching and other medium effects is the nuclear modification factor

$$R_{AA} = \frac{d^2 N^{AA}/dydp_T}{T_{AA} d^2 \sigma^{pp}/dydp_T}, \quad (2.9)$$

where N^{AA} is the invariant yield of a given particle in A-A collisions, σ^{pp} the cross section of the particle in p-p collisions and T_{AA} is the nuclear overlap function as described in Section 2.1. The R_{AA} quantifies the suppression of high- p_T hadrons or jets in A-A collisions as a function of their transverse momentum or event centrality. The nuclear modification factor for electroweak bosons is expected to be one that is consistent with no modification.

An independent signal of the formation of a strongly interacting medium is the suppression of quarkonia in heavy-ion collisions compared to p-p collisions. Debye screening of color charges and the attraction between heavy quarks (charm or bottom) and their antiquarks in a hot and dense QCD medium is expected to suppress the formation of quarkonium bound states. As the temperature of the medium rises, various quarkonium states are expected to melt one by one in the sequence of their increasing binding energies. The sequential melting of heavy quarkonia thus serves as a thermometer for the medium. However, a reliable theoretical estimation of quarkonium rates needs to take into account several other competing effects: shadowing and saturation effects in the initial state, initial and final state radiation, parton energy loss, quarkonium production via color-singlet and color-octet channels, feed-down from the excited states, recombination and coalescence of independently produced heavy quarks and antiquarks, etc. A systematic study of the suppression patterns of J/ψ and Υ families, together with baseline proton-nucleus measurements help to disentangle these hot and cold nuclear matter effects.

2.4 Proton-nucleus collisions

The purpose of proton-nucleus (p-A) collisions in the experimental heavy-ion programs is two-fold [16, 17]. On the one hand, cold nuclear matter effects can be measured directly without the presence of a hot and dense medium. Especially relevant for these studies are the nuclear parton distribution functions presented in detail in Section 3.2. On the other hand, new physics domains of QCD, characterized by large gluon densities in the hadron wave function, are expected to be more easily accessible by increasing the atomic number of the colliding objects.

Proton-nucleus collisions were studied in fixed target experiments at CERN SPS and at Fermilab. At RHIC deuterons (d) instead of protons were accelerated due to technical reasons and collided with Au nuclei. An example reference measurement of the two-particle correlation function in d-Au collisions is shown in fig. 2.3. It proved that in Au-Au collisions the suppression of the away-side jet peak is due to final state medium effects that are not present in d-Au collisions [4]. Such reference measurements of hadron production and quarkonia serve as benchmarking of the initial state or cold nuclear matter effects in nucleus-nucleus collisions both at RHIC and at the LHC.

At low values of the longitudinal parton momentum fraction, Bjorken x , where the gluon density inside protons and nuclei is large, parton saturation is expected to occur. It means that the linear regime in the evolution equations of the parton distributions should cease to be valid at the saturation scale. This new domain can be described by an effective theory derived from QCD, called the color glass condensate, see [18, 19] for a review. The presence of a scale, which for large enough nuclei or small enough x could be in the perturbative region, allows to perform calculations of quantities usually considered to belong to the soft physics in nuclear collisions, e.g. total multiplicities. The study of p-A collisions offers the best experimental conditions for benchmarking of the initial stages of the collisions, that are important for precise determination of quantities such as the shear viscosity of the produced medium.

3 Introduction to Z bosons

The Z boson has a long history in experimental high-energy physics since its discovery in 1983 by the UA1 and UA2 experiments in proton-antiproton collisions at the SPS at CERN [20, 21]. Precise studies of its properties were performed in electron-positron collisions at the SLC and LEP colliders at center-of-mass energies close to the Z boson mass peak of about $91 \text{ GeV}/c^2$ [22]. The precise mass, the partial and total width of the Z boson and its couplings to fermions [23] are important parameters of the Standard Model (SM). The number of generations with light neutrino, the effective electroweak mixing angle for leptons and other constraints on SM particles have also been determined that are used as input for the hadron collider experiments at the Tevatron and the LHC.

The Z boson production is an important benchmark process in proton-antiproton collisions at the Tevatron experiments CDF [24] and D0 [25] just like it is in proton-proton collisions at the LHC experiments ATLAS [26], CMS [27, 28] and LHCb [29]. It provides information on the background in searches for new physics beyond the SM, hence its precise knowledge is crucial for future discoveries at the LHC. The well-known Z boson peak is also used in the calibration of the energy scale of electron and muon detectors and in the alignment of the charged particle tracking system of the experiments. The Z boson cross section can be used as a luminosity monitor in order to improve the precision of other experimental cross sections.

The production cross section of Z bosons can be determined by theoretical calculations at next-to-next-to-leading order (NNLO) in perturbative QCD (pQCD) with a precision of a few percent [30, 31]. At the LHC, a similar experimental precision can be reached by studying the Z boson decays to muon and electron pairs, providing stringent tests of the theory. The dominant uncertainties in the calculations stem from the uncertainties of the momentum distributions of partons (PDFs) in the colliding protons. Measurements of the differential cross section of lepton pairs [32, 33, 34, 35] are also used to constrain the PDFs in the high Q^2 region and in a wide range of Bjorken x that is accessible by the LHC experiments.

In the following, the expectations for the Z boson production in heavy-ion collisions are reviewed with emphasis on the modification of parton distributions in nuclei.

3.1 Z bosons in heavy-ion collisions

The high center-of-mass energy and the high luminosity of the LHC allow the study of Z bosons in heavy-ion collisions for the first time. The mass and the total width of the Z boson are $M_Z = 91.187 \pm 0.002 \text{ GeV}/c^2$ and $\Gamma_{\text{vacuum}} = 2.495 \pm 0.002 \text{ GeV}/c^2$, respectively [23] that could be in principle modified by the hot and dense QCD medium produced in heavy-ion collisions. By the uncertainty principle, the Z boson is created approximately $1/M_Z = 0.002 \text{ fm}/c$ after nuclear contact before a medium of quarks and gluons can form, and it decays with a lifetime of $1/\Gamma_{\text{vacuum}} = 0.08 \text{ fm}/c$. In a simple approach considering immediate thermalization of quarks and gluons, the Z boson would decay in the high temperature medium. Some estimates indicate that in this scenario the width could be modified by only $\Delta\Gamma = 1.5 \text{ MeV}/c^2$ in a $T = 1 \text{ GeV}$ medium [36], which is experimentally not measurable.

On the other hand, in the most accepted picture of the evolution of heavy-ion collisions, the Z boson is produced and decays before a medium is formed. In this case, the medium influence on its decay products has to be examined [37]. Its decay to electron or muon pairs with a branching ratio of 3.4% is of particular interest because the leptons do not carry color charge, hence they can pass through the medium without strong interaction. However, the leptons can interact electromagnetically with the charges of the medium and suffer elastic scattering with radiating a photon afterwards. Theoretical calculations suggest that the mean free path of electrons in a $T = 1 \text{ GeV}$ medium is of the order of 10 fm, that would result on average only in one elastic collision while traversing through the medium. Thus the energy loss due to electromagnetic interaction or radiation can be neglected experimentally.

As Z bosons are produced in the initial hard parton scattering and they are insensitive to the QCD medium, they can be used to validate the scaling of hard processes with the number of elementary nucleon-nucleon collisions. They can serve as reference to processes that are modified by the medium for example inclusive jet and heavy quarkonium production. At leading order in pQCD, the jets are always produced in back-to-back pairs with equal p_T and it is also possible that a Z boson is produced associated with an opposite side jet that balances its high transverse momentum. The study of Z-jet correlations are ideal for understanding the energy loss of jets in the medium and modifications to the jet fragmentation functions [38].

However, Z boson production can be affected by the initial state of heavy-ion collisions, called cold nuclear matter effects. The production yield in pA or AA collisions compared to the binary collision scaled p-p yield can be modified by the fact that the ratio of u and d quarks in the Pb nucleus is different from that in the proton, called isospin effect. Another example of cold nuclear matter affecting the Z boson yield is shadowing that is often described by multiple scattering of the initial

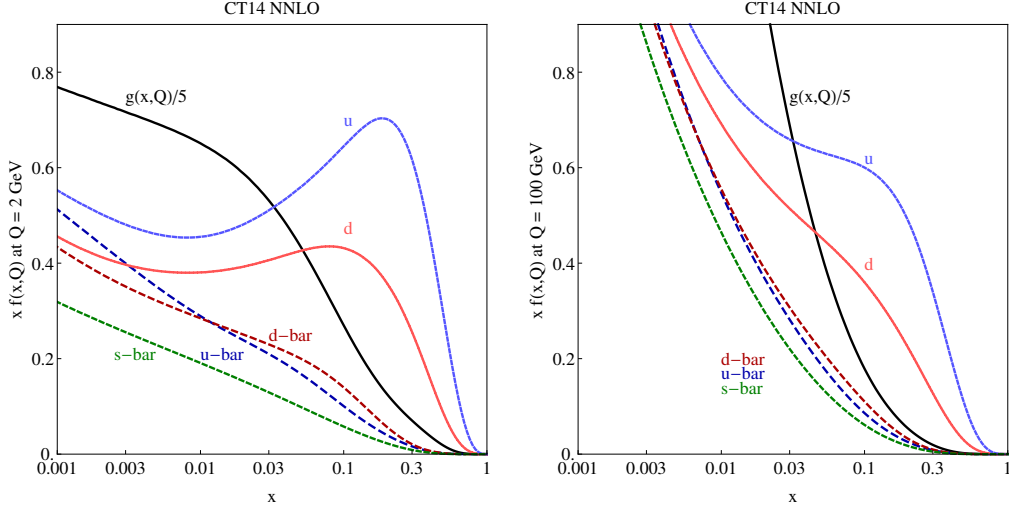


Figure 3.1: Parton distribution functions from CT14 [42] at two different energy scales.

parton [39, 40]. Phenomenological calculations are also available on the energy loss of the initial parton traversing through the nucleus before the hard collision [41]. A more global picture of initial state effects is provided by nuclear parton distribution functions (nPDFs) that parametrize the modification of the momentum distribution of the initial partons in the nucleus. A detailed descriptions of nPDFs is given in Section 3.2 and their relevance and predictions for Z boson measurements in p-Pb and Pb-Pb collisions at the LHC are summarized in Section 3.3.

3.2 Nuclear parton distribution functions

Processes in high-energy collisions are calculated in pQCD in terms of interactions between the partons inside the proton. Parton distribution functions provide a non-perturbative input to these calculations in order to describe the probability of finding a parton with a specific flavor carrying fraction x of the proton momentum. Fig. 3.1 shows an example of such distributions from CT14 [42] at two different energy scales, Q , that characterizes the momentum transfer in a specific process. At parton momenta third of the proton momentum ($x \approx 0.3$) a peaking structure is visible for the u and d quarks that is equivalent with the statement that the proton is made up of one d and two u quarks. Other important features of PDFs are that gluons are dominating in the low x region and at higher energy scales the antiquarks become more important.

Since the discovery that quarks and gluons in bound nucleons show different momentum distributions to those measured in free or loosely bound nucleons [43], more precise measurements were performed to study the partonic structure of nuclei, and on the theory side different groups developed more and more precise determination of nuclear parton distribution functions [44, 45, 46, 47, 48]. On one hand, precise

knowledge of nPDFs is required for understanding the mechanisms associated with nuclear binding from a QCD improved parton model perspective. On the other hand, nPDFs are important input for heavy-ion collisions performed at RHIC and LHC and for neutrino experiments.

Nuclear parton distribution functions, f_i^A , are usually defined for each parton flavor, i , as the free proton PDF, f_i^p , and a multiplicative correction factor, R_i^A , at a given initial energy scale, Q_0^2 :

$$f_i^A(x, Q_0^2) = R_i^A(x, Q_0^2) f_i^p(x, Q_0^2) , \quad (3.1)$$

where x is the longitudinal momentum fraction of the parton in the nucleon. In principle, it is defined in the range of $0 < x < A$, which reflects the fact that a parton in a nucleus may carry more than the average nucleon momentum. However, the free proton PDFs are restricted to the range $0 < x < 1$, thus the nPDFs defined through eq. (3.1) are also constrained to $x < 1$.

The nuclear modification factors are calculated by performing a global fit of different experimental datasets to determine the best set of nPDFs that describe all the data. The possible datasets included in the global fits are structure function ratios of charged lepton deep inelastic scattering (DIS) off nuclei, cross section ratios of Drell-Yan (DY) lepton pair production in proton-nucleus or deuteron-nucleus collisions, inclusive hadron production in d-Au collisions and structure functions from neutrino DIS off nuclei. The different processes constrain the nPDF fits in different regions of x as it is explained later.

The different processes are calculated in pQCD in the collinear factorization approach folding the PDFs with perturbatively calculable parton level cross sections $\hat{\sigma}$:

$$\sigma_{\text{DIS}}^{l+A \rightarrow l+X} = \sum_{i=q,\bar{q},g} f_i^A(Q^2) \otimes \hat{\sigma}^{l+i \rightarrow l+X}(Q^2) \quad (3.2)$$

$$\sigma_{\text{DY}}^{p+A \rightarrow l^+l^-+X} = \sum_{i,j=q,\bar{q},g} f_i^p(Q^2) \otimes f_j^A(Q^2) \otimes \hat{\sigma}^{i+j \rightarrow l^+l^-+X}(Q^2) \quad (3.3)$$

$$\sigma^{A+B \rightarrow \pi+X} = \sum_{i,j,k=q,\bar{q},g} f_i^A(Q^2) \otimes f_j^B(Q^2) \otimes \hat{\sigma}^{i+j \rightarrow k+X}(Q^2) \otimes D^{k \rightarrow \pi}(Q^2) \quad (3.4)$$

where $D^{k \rightarrow \pi}$ is the fragmentation function and the dependence on α_s and the collision kinematics is not shown. The factorization, renormalization and fragmentation scales are usually set to equal and fixed to the characteristic scale, Q , in the process. The characteristic scale is set for DIS to $Q^2 = -q^2$, where q is the virtual photon momentum, for DY production to the invariant mass, M^2 , of the lepton pair and for inclusive pion production to the transverse momentum, p_T^2 , of the pion. The parton level cross sections are calculated at NLO in pQCD using the modified minimal

subtraction ($\overline{MS}$) renormalization scheme.

The nPDFs are the non-perturbative inputs to pQCD and their process independence is an assumption, not coming from first principles but it is a rigorous and testable theory. The Q^2 evolution of PDFs is calculated by Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) equations that can be applied only in the perturbative region, hence the initial scale is set usually to $Q_0^2 = 1 \text{ GeV}^2$ and only data above $Q^2 > 1 \text{ GeV}^2$ is used in the analyses. The free proton PDFs used as reference in the different nPDF analyses vary depending on the group: nDS [45] uses GRV98 [49] free proton PDF set, HKN [46] uses MRST [50], EPS09 [47] uses CTEQ6.1M [51] and DSSZ [48] uses MSTW [52], just to mention a few of the recent NLO analyses of nPDFs. Some of them performed checks on the dependence on the different free proton PDFs and found no significant changes in the results but in principle, nPDFs should be coupled with the same reference PDF set that was used for their global fit.

The nuclear modification factor, $R_i^A(x, Q^2)$, for each i parton flavor is parametrized by a functional form that is flexible enough to describe all features of the different measurements as a function of x , Q^2 and A . Some of the parameters can be fixed by charge, baryon number and momentum conservation but there is not enough data to constrain each parton flavor separately, thus different assumptions are needed to limit the number of free parameters in the global fit. Such an assumption is the isospin symmetry, where the d and u quark modification is set to be equal for both valence and sea quarks. In most global nPDF analyses there are three nuclear modification factors: for valence quarks, R_v , for sea quarks and antiquarks, R_s , and for gluons, R_g . The strange and heavy quarks and antiquarks can be taken into account in the DGLAP evolution in a general mass variable flavor number scheme (contributing at scales that exceed their mass) or in some cases they are simply neglected as the data is not sensitive enough to their contributions.

The nPDFs are determined by a set of parameters that give the best fit of the data points used in each analysis. The best parameter set is found by a χ^2 minimization approach with the χ^2 defined as

$$\chi^2 = \sum_i \omega_i \frac{(\sigma_i^{\text{exp}} - \sigma_i^{\text{th}})^2}{\Delta_i^2}, \quad (3.5)$$

where σ_i^{exp} are the measured cross sections, σ_i^{th} are the calculated cross sections with a given set of parameters and ω_i are weights assigned to each dataset. Weights are assigned to datasets e.g. in EPS09 analysis in an iterative way to increase the impact of some of the data points to better constrain the gluon distributions. Other analyses do not apply any weights to the datasets ($\omega_i = 1$). The number of free parameters in the global fit varies between different analyses but it is in the order

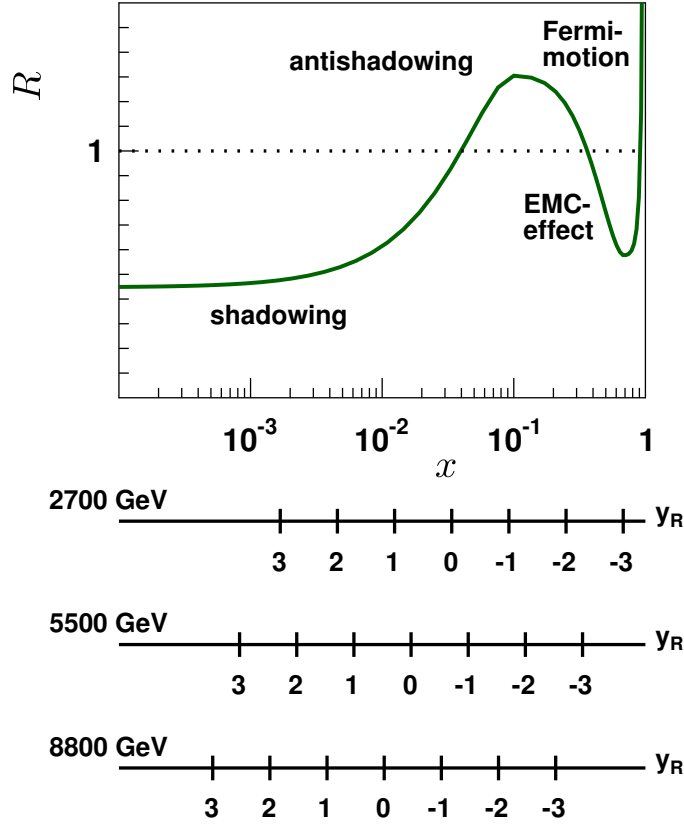


Figure 3.2: The typical shape of the nuclear modifications as a function of x , and the kinematical reach for Z boson production at three different center-of-mass energies where y_R is the Z boson rapidity [54].

of 15–25. The amount of data points used in the global fits is growing with time as more measurements have been performed. Lately, in DSSZ where all four types of datasets are used, the number of data points included in the global fit reached 1579.

A typical nuclear modification factor as a function of x has four different regions called shadowing, antishadowing, EMC effect and Fermi motion as demonstrated in fig. 3.2. The depletion in the parton distributions for $x < 0.1$ is called shadowing and it can be explained by partons interacting between neighboring nucleons or by multiple scattering of the incident parton, see [40] for a review. The transition region of $0.1 < x < 0.3$ with structure function ratios above 1 is called antishadowing region and it is usually discussed as coming from the application of sum rules for momentum, baryon number and charge conservation. The EMC region (where EMC stands for the European Muon Collaboration [43]) corresponds to $0.3 < x < 0.8$ and a nuclear modification below unity, that has several theoretical explanations like nuclear binding or pion exchange, see [53] for a review. The rise in the structure function ratios for $0.8 < x$ is related to the Fermi motion of the nucleons within the nucleus at rest.

Charged lepton DIS data is analyzed in the form of structure function ratios from

the EMC [55], NMC [56, 57, 58, 59] and SLAC E-139 [60] experiments. The F_2^A structure function of heavy nuclei compared to the deuteron structure function, F_2^d , as a function of x shows directly the different regions of the nuclear modification as described above. These data have an excellent constraining power for quark distributions in the whole range, $0.01 < x < 1$, spanned by the measurements. At large x they are mainly sensitive to the valence quarks and at small x to the sea quarks. At moderate x , close to the antishadowing peak, such separation of the sea and valence quark contributions is not possible on the basis of this type of data alone. The main gluon constraints provided by DIS comes from the Q^2 dependence of the ratios and the scale evolution of sea quarks that is driven by gluons.

Drell-Yan dilepton production in pA collisions from the E772 [61] and E866 [62] experiments is presented as cross section ratios with different nuclear targets as a function of x and M . The momentum fractions of the target and projectile nucleons is related to the measured rapidity of the dilepton pair in the following way: $x_{1,2} = \sqrt{M^2/s} e^{\pm y}$. The DY data together with the DIS can discriminate between valence and sea quarks around $x = 0.1$ and has some sensitivity to constrain sea quarks in the region $0.01 < x < 0.2$. The relatively large scale of the data, given by $M^2 > Q_0^2$ provides handle on evolution effects that constrain the gluons as well.

Pion production in d-Au collisions presented by the PHENIX [63] and STAR [64, 65, 66] experiments adds a direct constraint for the gluon distributions. The measured cross section at midrapidity is normalized to the corresponding yield in p-p collisions and presented as a function of the pion p_T . In general, hadron production results are less straightforward to interpret than DIS data, because each value of p_T samples different fractions of the contributing hard scattering processes integrated over a large range of x , and since p_T sets the factorization scale in eq. (3.4), the cross section ratios also reflect the energy dependence of the nuclear modifications. An additional complication is that cross sections are also sensitive to the modeling of the hadronization process and its medium induced modifications that would modify the fragmentation functions, $D^{k \rightarrow \pi}$, in eq. (3.4). In EPS09 analysis, only neutral pion production is included from the PHENIX experiment with a large $\omega_{\pi^0} = 20$ weight that produces a large antishadowing and EMC effect for gluons. The analysis of DSSZ includes both neutral and charged pion data in the global fit without additional weights and taking into account possible medium modification of fragmentation functions. This results in a smaller nuclear modification of gluon PDFs in DSSZ than in EPS09.

Neutrino DIS data from the NuTeV [67], CDHSW [68] and CHORUS [69] experiments are presented as absolute structure functions as a function of x and Q^2 . This type of data are only included in the global analysis of DSSZ but their compatibility was discussed with other global analyses as well [70]. Neutrino induced DIS

off nuclei provides charged current interaction measurements that are sensitive to different combination of valence and sea quarks compared to the neutral current DIS measured with charged leptons. These new data improve the valence and sea quark separation significantly in the entire x range covered by the available measurements.

The common approach to estimate the uncertainties of PDFs obtained from global χ^2 optimizations is using the Hessian method, that explores the uncertainties associated with the fit through a Taylor expansion around the global minimum. The latest nPDFs are available with the number of free parameters times two different error sets that make the propagation of nPDF uncertainties to any hard process observable possible. The functional form of the nuclear modification of PDFs allows extrapolation to regions of low x that are not constrained by data so far but the uncertainties may not cover possible biases due to the choice of the functional form. When calculating hard processes with absolute cross sections instead of cross section ratios, the uncertainties of the free proton PDF set have to be combined with the uncertainties of the nPDF set for a conservative estimate. It is usually recommended to combine the different nuclear PDFs with the same free proton PDFs that were used in their global fit.

In summary, the extraction of nPDFs from different datasets has an established method with increasing precision by including more data in the global fit. However, the kinematic range covered by previous experiments is small compared to the kinematic range accessible at the LHC [16, 17] as shown in fig. 3.3. It has to be noted that other parametrizations for shadowing exist that use different theory input to calculate modifications of parton distributions in nuclei [40, 71]. Here, the nuclear PDF phenomenology that is used frequently in experimental comparisons was reviewed.

3.3 Z bosons as a probe of nuclear parton distribution functions

The LHC will require a good knowledge of nPDFs in a kinematical region never explored before by DIS or other experiments as shown in fig. 3.3, in order to separate hot and cold nuclear matter effects in AA collisions. Weak boson production at the LHC can serve as powerful tool for testing the pQCD factorization assumption and for constraining nPDFs in the high Q^2 and low x region of the phase space. In this section, some predictions for Z boson production in p-Pb and Pb-Pb collisions at the LHC are introduced.

The shape of the rapidity distribution of the Z bosons is sensitive to the nuclear modification of the PDFs [54, 72]. As shown in fig. 3.2, the rapidity is closely related

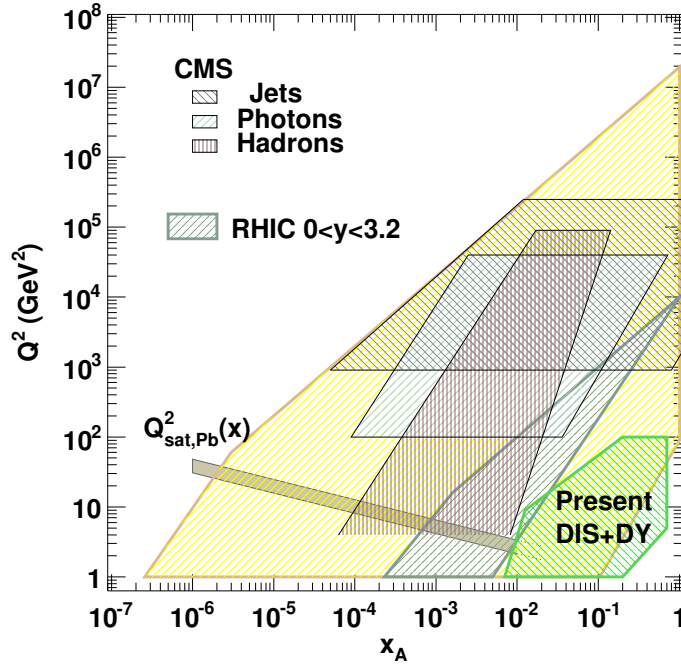


Figure 3.3: Total kinematical reach of p-Pb collisions at $\sqrt{s_{NN}} = 8.8$ TeV at the LHC. Also shown is the reach with an integrated luminosity of 0.1 pb^{-1} for some of the hard probes for CMS [16].

to the parton momentum fraction at the different center-of-mass energies accessible by the LHC. In Pb-Pb collisions, the rapidity distribution is symmetric and the nuclear modification of the colliding partons affect the cross section simultaneously. However, in p-Pb collisions the Z boson rapidity can be translated directly to parton x values in the nucleus, and differences from p-p collisions are direct observations of nuclear effects.

Fig. 3.4 shows some example predictions of the rapidity dependence of Z boson production in Pb-Pb and p-Pb collisions from [54]. On the left-hand side, the nuclear modification factor, R_{AA} , is shown as a function of the absolute value of the rapidity. The R_{AA} has the advantage that the uncertainties from the free proton PDFs cancel in the ratio. On the right-hand side, the p-Pb cross section for positive (forward) rapidity is divided by the one for negative (backward) rapidity, called forward-backward asymmetry. The asymmetry is a more sensitive observable to nuclear effects than the cross section because the uncertainties related to the normalization cancel in the ratio.

The measurement of the transverse momentum distribution provides further tests of QCD factorization because of the two energy scales present in the process with the mass and the p_T of the Z boson. At low p_T non-perturbative effects have to be taken into account in calculations with resummation of large logarithms. At high p_T the perturbation theory can be used up to high orders in QCD. The shape of

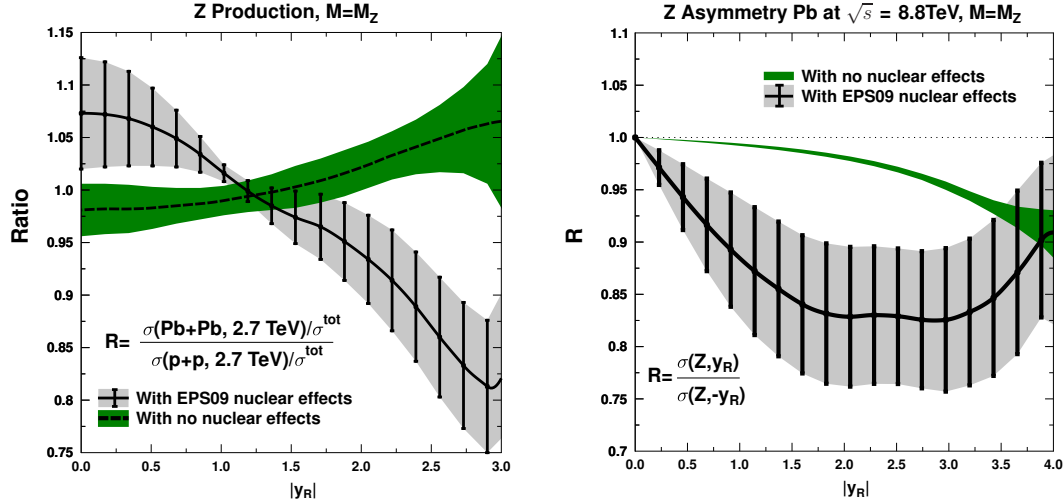


Figure 3.4: *Left:* The predicted ratio between the normalized Z boson cross sections in Pb-Pb and p-p collisions at $\sqrt{s_{\text{NN}}} = 2.7$ TeV. *Right:* The predicted ratio between forward and backward yields of Z bosons in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 8.8$ TeV. The green solid bands represent the predictions calculated with CTEQ6.6 without nuclear effects, and the solid black barred lines with gray shade are the predictions computed by CTEQ6.6 applying the nuclear effects from EPS09 [54].

the p_T distribution is sensitive to nuclear modification of PDFs [72, 73]. Above 20 GeV/c gluon initiated processes become dominant providing direct access to the gluon nuclear PDF that is not well constrained by data so far.

Fig. 3.5 shows the spectrum of Z bosons in p-Pb collisions in a wide range of p_T with and without nuclear effects from EPS09 and their ratio as calculated in [73]. The depletion at low p_T can be explained by shadowing of the quarks in the nucleus that is present in most nPDF parametrizations. The excess at high p_T is due to gluon antishadowing present in EPS09 that is not present for example in nDS, thus precise measurement of the p_T spectrum could differentiate between different nPDFs.

To demonstrate the constraining power of p-Pb collisions at the LHC, a Bayesian reweighting technique of nPDFs was developed in [74]. This method allows to study the compatibility of new data with those used in the original nPDF fits quantitatively and to determine the impact of new data on the central values and uncertainties of the nPDFs. It was shown that p-Pb collisions have the potential to constrain sea quark and gluon nuclear PDFs in the small x region in order to improve theoretical predictions for Pb-Pb collisions.

In summary, the goal of the measurements presented in this thesis is to test the binary scaling of hard probes in heavy-ion collisions and to constrain nuclear modification of PDFs in a new kinematic region. The more precise knowledge of nPDFs is necessary in the study of hard processes in order to disentangle effects of the initial state cold nuclear matter from those of the hot and dense QCD medium produced in nucleus-nucleus collisions.

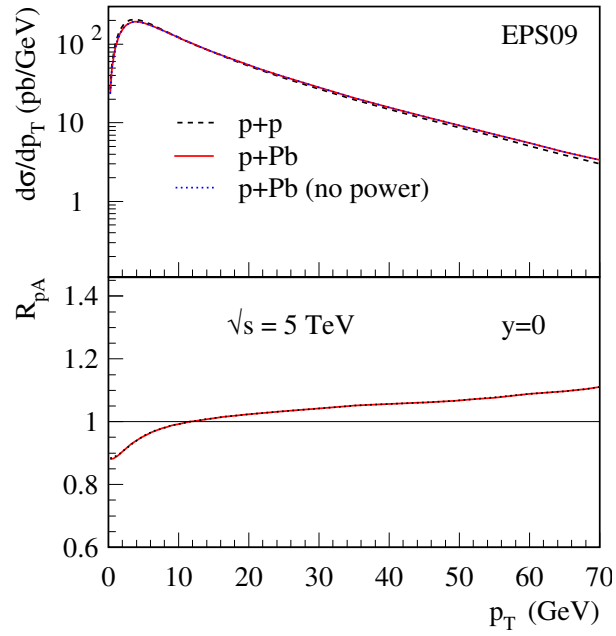


Figure 3.5: The Z boson production cross section per nucleon as a function of p_T at $\sqrt{s_{NN}} = 5$ TeV for p-p and p-Pb collisions and their ratio using the EPS09 nuclear modification of PDFs [73].

4 The CMS experiment

The Compact Muon Solenoid is one of the two general-purpose detectors at the LHC facility at CERN. The full description of the detector design is documented in detail in [75], while here only the subdetectors used in the study of collision centrality and of Z bosons are briefly introduced.

The overall layout of CMS is shown in fig. 4.1. At the heart of CMS is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T that bends charged particles for a precise momentum measurement. Within the solenoid volume are the silicon tracking detectors, the lead tungstate crystal electromagnetic calorimeter (ECAL) and the brass/scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors.

CMS uses a right-handed coordinate system, with the origin at the nominal interaction point, the x axis pointing to the center of the LHC, the y axis pointing up (perpendicular to the LHC plane), and the z axis along the anticlockwise-beam direction. The polar angle θ is measured from the positive z axis and the azimuthal angle ϕ is measured in the x - y plane. The pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$. The transverse momentum, p_T , and the transverse energy, E_T , are computed from the x and y components.

4.1 The silicon tracking detectors

The CMS inner tracking system consists of two main parts: the silicon pixel and the silicon strip detectors that are closest to the interaction point. They measure charged particle trajectories including muons and electrons in the pseudorapidity region of $|\eta| < 2.5$.

The silicon pixel detector has three barrel layers and two endcap disks per side covering the region from 4 cm to 15 cm in radius and within 49 cm on either side of the collision point along the LHC beam axis. The pixels have an area of $100 \times 150 \mu\text{m}^2$ on a sensitive silicon layer of $250 \mu\text{m}$ thickness. The modules are oriented in

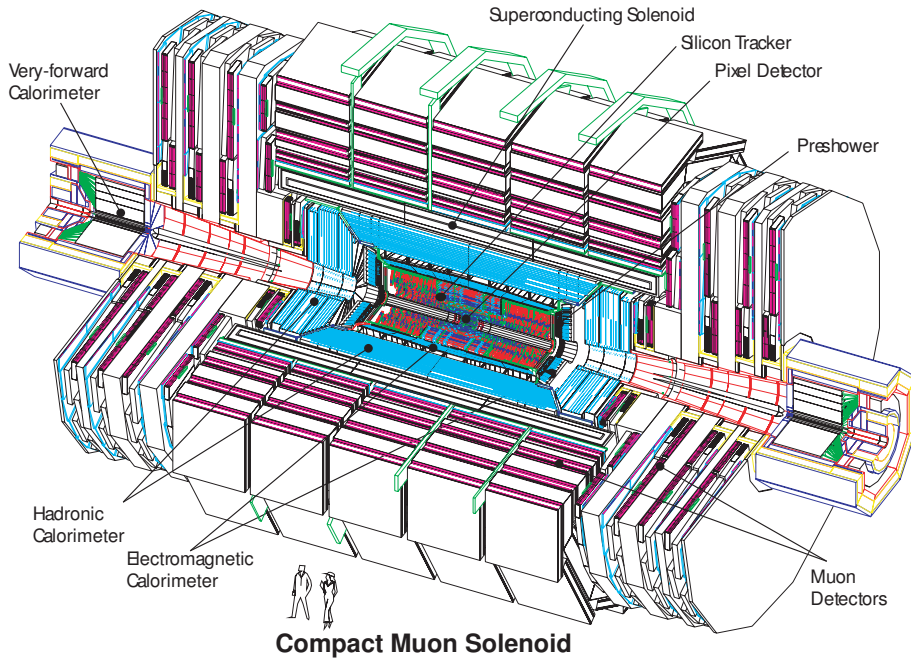


Figure 4.1: A perspective view of the CMS detector.

a way to optimize the charge share between pixels due to Lorentz angle, which results in a position resolution of $10\ \mu\text{m}$ and $15\ \mu\text{m}$ in azimuthal and longitudinal directions, respectively. There are in total 66 million pixels, which can handle the highest multiplicity events in central heavy-ion collisions or in high pile-up p-p collisions.

The silicon strip tracker consists of four inner barrel (TIB) layers, six outer barrel (TOB) layers, three inner disks (TID) and nine endcap disks (TEC) covering the region up to 116 cm in radius and 282 cm in both directions along the z axis. The individual components are modules with 512 or 768 strips arranged in layers in the barrel region and in rings centered on the beam line in the disks. The typical strip size is $10\ \text{cm} \times 80\ \mu\text{m}$ with a thickness of $320\ \mu\text{m}$ in the inner modules and $500\ \mu\text{m}$ in the outer modules. The first two layers of the TIB and TOB, the first two rings of the TID and the inner-most two rings and the fifth ring of the TEC have so-called stereo modules. The stereo modules are made of two single modules mounted back-to-back with the second module rotated by $100\ \text{mrad}$ with respect to the first module, which allows a measurement in the orthogonal direction. There are in total 9.3 million active elements with an effective area reaching $198\ \text{m}^2$.

4.2 The muon system

The goal of the muon system is to provide muon identification and momentum measurement as well as triggering signals. The muon chambers are the outermost subdetectors of CMS embedded in the steel flux-return yoke. Three technologies are used for muon identification: drift tube (DT) chambers, cathode strip cham-

bers (CSC) and resistive plate chambers (RPC).

The DTs are located in the barrel region where the muon rate is expected to be low and the local magnetic field has a relatively low intensity. They are organized in 5 stations along the z axis and each station is made up of 4 concentric rings along the radial direction. The DTs are used as tracking detectors with a single point resolution of about $200\ \mu\text{m}$ covering the pseudorapidity range up to $|\eta| < 1.2$.

The CSCs are located in the endcap region extending the muon coverage to $0.9 < |\eta| < 2.4$. They are arranged in four disks on each side of the CMS barrel with full ϕ coverage. Each disk consists of concentric rings comprised of 18 or 26 stations. The CSCs are multiwire proportional chambers that provide fast signals and good intrinsic spacial resolution operating in the non-uniform magnetic field.

In addition, RPCs are located in both the barrel and endcap regions in-between the DTs and CSCs covering $|\eta| < 2.4$. They are gaseous parallel-plate detectors that combine adequate spatial resolution with a very good time resolution of about 3 ns. Therefore, a fast dedicated muon trigger can unambiguously identify the relevant bunch crossings up to the design collision rate of the LHC.

4.3 The calorimeters

The two main calorimeter systems are the HCAL and the ECAL designed to measure the energy deposit of particles and to absorb them. The full calorimeter system is used for reconstructing jets and missing transverse energy in the collision events.

The ECAL is a hermetic, homogeneous calorimeter comprising 61200 lead tungstate (PbWO_4) crystals mounted in the central barrel part, closed by 7324 crystals in each of the 2 endcaps. The primary goal of the ECAL is to reconstruct photons and electrons. The lead tungstate scintillating crystals were chosen to have a short radiation length (χ_0) and to be fast and radiation hard.

The ECAL barrel (EB) covers a pseudorapidity interval of $0 < |\eta| < 1.48$. Each crystal has a front face cross section of about $22 \times 22\ \text{mm}^2$, which covers 0.0174 in $\Delta\phi$ and $\Delta\eta$, and a length of 230 mm, corresponding to $25.8\chi_0$. The ECAL endcaps (EE) are at a distance of 315 cm from the center of CMS and cover the pseudorapidity range of $1.48 < |\eta| < 3.0$. The endcap crystals are all identical and have a front face cross section of $29 \times 29\ \text{mm}^2$ and a length of 220 mm, corresponding to $24.7\chi_0$.

The HCAL is a brass/scintillator sampling calorimeter located outside of the ECAL. The HCAL consists of the barrel (HB) and the endcap (HE) hadron calorimeters surrounded by the superconducting magnet, the outer (HO) hadron calorimeters located outside of the magnet. The hadronic forward (HF) calorimeters, complementing the pseudorapidity coverage at high η , are made of a steel absorber and embedded quartz fibers that provide a fast collection of Cherenkov light.

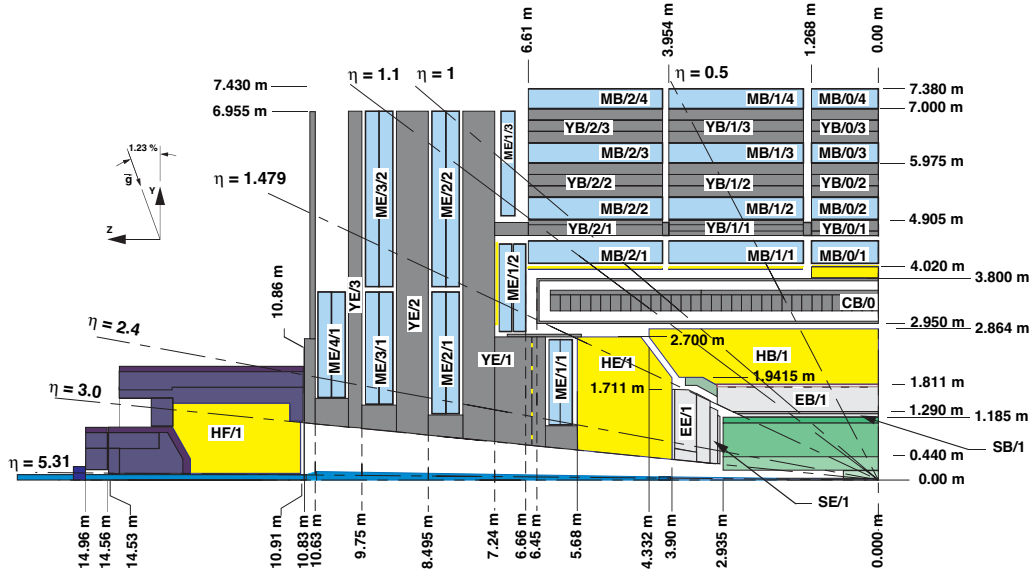


Figure 4.2: A schematic view of one quarter of the CMS detector.

The HB consists of two half barrels divided in the z direction covering the pseudorapidity range of $|\eta| < 1.3$. Its segmentation in $\Delta\eta$ and $\Delta\phi$ is 0.087×0.087 . The HO covers a similar pseudorapidity range as the HB outside the solenoid. It ensures the sampling of the energy of penetrating hadron showers. The HE covers the pseudorapidity region $1.3 < |\eta| < 3.0$. For the 5 outermost towers at smaller η , the ϕ segmentation is 5 degrees and the η segmentation is 0.087. For the 8 innermost towers the ϕ segmentation is 10 degrees, while the η segmentation varies from 0.09 to 0.35 at the highest η .

The HF detectors are located 11.2 m from the interaction point on both sides. They cover the range of $2.9 < |\eta| < 5.2$ with a granularity of $\Delta\eta \times \Delta\phi = 0.175 \times 0.175$. The HF detectors play an important role in the study of heavy-ion collisions as they are used for selecting inelastic collision events and for determining the centrality class of an event. Fig. 4.2 shows the schematic longitudinal view of the CMS detector.

In addition to the muon detectors and calorimeters, dedicated trigger detectors provide information on the collisions happening at the CMS interaction point. The Beam Pick-up Timing for the eXperiments (BPTX) detectors are located around the beam pipe at a distance of 175 m from the interaction point, and are designed to provide precise information on the LHC bunch structure and timing of the incoming beams. The Beam Scintillator Counters (BSC) mounted on the HF calorimeters provide high efficiency particle detection with a 3 ns time resolution. The BSC played an important role in the first p-p collisions and also in the Pb-Pb running periods described hereafter.

5 Datasets and simulations

In this chapter, a short overview is given about the data workflow in CMS with the emphasis on the elements utilized in the Z boson analysis. The LHC delivers p-p, p-Pb or Pb-Pb collisions to the experiments and these collisions are triggered by the CMS trigger system. Then the detector is read out and an event is built from the different subsystem signals. The event goes through the event reconstruction in the central computing facilities of CERN and finally, it is stored in computing centers all over the globe. Depending on which type of trigger fired the event, it is assigned to a primary dataset (e.g. muon dataset). In the data analysis, the reconstructed data in a given primary dataset is accessed remotely for further processing. For calculating corrections, Monte Carlo (MC) simulations are used that are also described at the end of this chapter.

5.1 Heavy-ion data taking periods at the LHC

The first lead-lead collisions at the LHC happened in November 2010. The Pb ions collided with a center-of-mass energy of $\sqrt{s_{NN}} = 2.76$ TeV per nucleon pair that corresponds to the same LHC magnet settings as for $\sqrt{s} = 7$ TeV p-p collisions: $7 \text{ TeV} \cdot Z/A = 2.76 \text{ TeV}$, where $Z = 82$ and $A = 208$. The CMS experiment collected 55×10^6 minimum bias collision events corresponding to an integrated luminosity of about $7.2 \mu\text{b}^{-1}$. In this data sample 39 Z boson candidates were found in the dimuon decay channel by CMS [76]. The selection of minimum bias events is detailed in Chapter 6. The LHC delivered reference p-p data at the same center-of-mass energy and with comparable statistics in March 2011 that was used for example in the study of W bosons in p-p and Pb-Pb collisions [77]. These first results confirmed the scaling of weak boson yields with the number of binary nucleon-nucleon collisions but with a limited statistical precision.

At the second Pb-Pb run in November 2011, the LHC delivered 20 times more data corresponding to an integrated luminosity of about $160 \mu\text{b}^{-1}$ and more than 10^9 minimum bias events. The ATLAS collaboration published Z boson results based on this data sample [78] showing no modification of Z boson yields within the uncertainties of the measurement compared to NLO p-p theoretical predictions

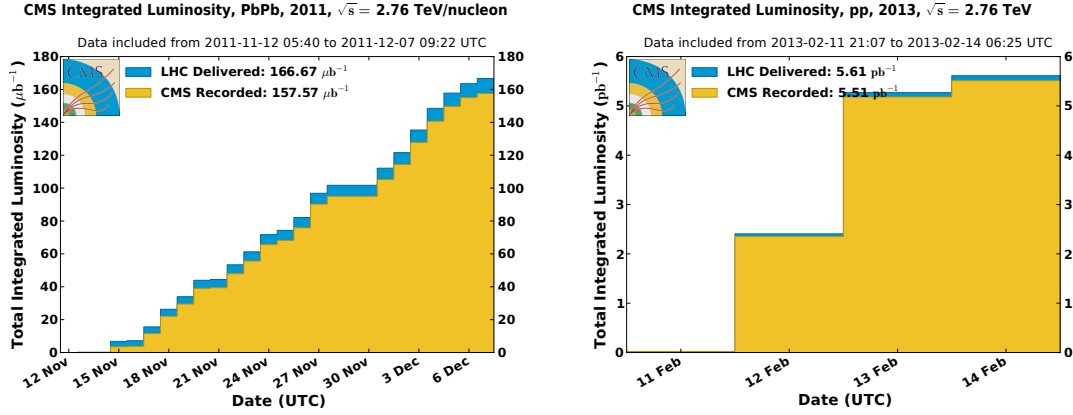


Figure 5.1: Cumulative luminosity versus day delivered to, and recorded by CMS during stable beams of lead-lead collisions in 2011 (*right*) and of proton-proton collisions in 2013 (*left*) at a center-of-mass energy per nucleon pair of 2.76 TeV.

scaled by number of elementary nucleon-nucleon collisions. Reference p-p data at $\sqrt{s} = 2.76$ TeV with high statistics was recorded in February 2013 by the LHC experiments. Fig. 5.1 shows the delivered and the recorded integrated luminosity as a function of time for the p-p and the Pb-Pb data at 2.76 TeV studied in this thesis.

The first proton-lead collisions at the LHC happened in September 2012 with a short pilot run. The p-Pb data taking took place in January 2013 where CMS recorded 34.6 nb^{-1} integrated luminosity corresponding to about 7×10^{10} sampled minimum bias events. Fig. 5.2 shows the delivered and recorded integrated luminosity as a function of time for the p-Pb data studied in this thesis. Due to the LHC magnet system the beam energies were 4 TeV for protons and 1.58 TeV per nucleon for lead nuclei, resulting in a center-of-mass energy per nucleon pair of $\sqrt{s_{\text{NN}}} = 5.02$ TeV. As a result of the energy difference between the colliding beams, the nucleon-nucleon center-of-mass frame is not at rest with respect to the laboratory frame. Particles emitted at a given rapidity y in the nucleon-nucleon center-of-mass frame are detected at $y + \Delta y$ in the laboratory frame where $\Delta y = -0.465$ for clockwise proton beam and $\Delta y = +0.465$ for counter-clockwise proton beam. The direction of the higher energy proton beam was initially set up to be clockwise, and was then reversed splitting the data in two parts with comparable sizes.

The data taking in CMS is organized into runs that correspond to a few hours of stable conditions of the detector. The data certification is also organized in terms of run numbers where the detector and software calibration performance is verified. Finally, the physics analysis is performed on a given range of certified data. As mentioned previously, the analysis of the 2011 Pb-Pb, the 2013 p-p and p-Pb data is described in this thesis.

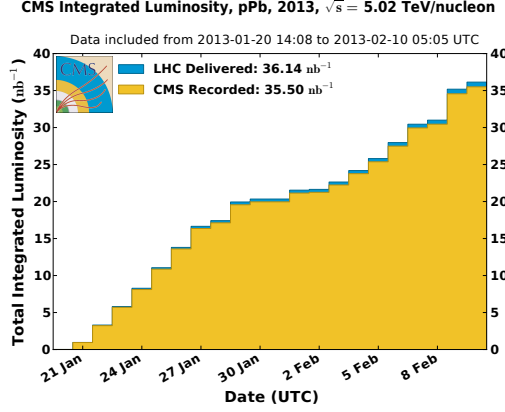


Figure 5.2: Cumulative luminosity versus day delivered to, and recorded by CMS during stable beams of proton-lead collisions in 2013.

5.2 Triggering of events

CMS has a two level trigger system. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select the most interesting events. The high-level trigger (HLT) processor farm further decreases the event rate in order to have a small enough amount of output data that can be stored.

Bunch crossings are identified by a coincidence of the BPTX signals on both sides of the experiment called the zerobias trigger. The average collision probability within a bunch crossing during the Pb-Pb data taking was approximately 1% therefore a so-called minimum bias trigger was necessary to select hadronic interactions. The minimum bias trigger required at least one signal above noise on each side of the interaction point in either the BSC or the HF detectors. In 2013, the BSC detectors could not be used due to radiation damage. The minimum bias trigger was defined by a BPTX coincidence and by requiring one charged particle track with $p_T > 0.4$ GeV/ c reconstructed in the pixel detector at HLT.

Due to storage size limitations only a fraction of all hadronic events can be stored therefore rare events have to be selected by dedicated triggers. Z bosons are produced in such rare events and dedicated muon and electron triggers were employed during data taking to store them. Muons are reconstructed at L1 using information only from the muon detectors. Events that have at least one L1 muon with p_T above a certain threshold are reconstructed at HLT using also information from the inner tracking detectors in order to achieve a good momentum resolution. Electromagnetic energy deposits are reconstructed at L1 through the sum of the transverse energy deposited in two neighboring groups of 5×5 ECAL crystals. Events with at least one such reconstructed deposit with E_T above 5 GeV are selected by the system. Photon and electron candidates are reconstructed at HLT using an

ECAL clustering algorithm that assigns a calibrated energy to each cluster.

5.3 Muon and electron reconstruction

Muon reconstruction in CMS [79] starts with reconstructing tracks independently in the inner tracker (tracker track) and in the muon system (standalone-muon track). Based on these objects, two reconstruction approaches are used: outside-in (global muon) and inside-out (tracker muon) algorithms. In the global muon reconstruction for each standalone-muon track, a matching tracker track is found by comparing parameters of the two tracks propagated onto a common surface. A global-muon track is fitted combining hits from the tracker track and standalone-muon track, using the Kalman-filter technique [80]. In the tracker muon reconstruction all tracker tracks with $p_T > 0.5$ GeV/ c and total momentum $p > 2.5$ GeV/ c are considered as possible muon candidates and are extrapolated to the muon system taking into account the magnetic field, the average expected energy losses, and multiple Coulomb scattering in the detector material. If at least one muon segment matches the extrapolated track, the corresponding tracker track qualifies as a tracker muon.

Excellent muon reconstruction performance is achieved by CMS [81] with a precision of better than 0.2% for the transverse momentum assignment of muon with $p_T < 100$ GeV/ c . The relative p_T resolution is between 1.3% and 2.0% for muons in the barrel and better than 6% in the endcaps, in good agreement with simulation. Owing to the high efficiency of the tracker track reconstruction [82] and the very high efficiency of reconstructing segments in the muon system, about 99% of muons produced in p-p collisions within the geometrical acceptance of the muon system and having sufficiently high momentum are reconstructed either as a global muon or a tracker muon, and very often as both.

Electron reconstruction in CMS uses information from the ECAL as well as from the silicon tracking detectors. Electrons are identified as clusters of ECAL energy deposits matched to reconstructed tracks in the tracker. The ECAL clustering algorithm is designed to collect the largest fraction of the energy of the original electron, including energy radiated along its trajectory spread in the azimuthal direction. Electron tracks are reconstructed using an algorithm that accounts for the energy loss due to bremsstrahlung in the tracker layers [83]. The electron momentum is estimated by combining the energy measurement in the ECAL with the momentum measurement in the tracker. The energy of an electron candidate with $E_T > 20$ GeV is essentially determined by the ECAL cluster energy, while its momentum direction is determined by that of the associated track. The overall momentum scale is calibrated in p-p collisions with an uncertainty smaller than 0.3% in the p_T range from 7 to 70 GeV/ c [84]. For electrons from Z boson decays, the effective momentum

Colliding system	Dataset name	Run range
Pb-Pb 2.76 TeV	/HIDiMuon/HIRun2011-25Oct2012-v1/RECO	181530-183126
p-Pb 5.02 TeV	/PAMuon/HIRun2013-28Sep2013-v1/RECO	210498-210658
p-Pb 5.02 TeV	/PAMuon/HIRun2013-PromptReco-v1/RECO	210676-211256
Pb-p 5.02 TeV	/PAMuon/HIRun2013-PromptReco-v1/RECO	211313-211631
p-p 2.76 TeV	/PPMuon/Run2013A-PromptReco-v1/RECO	211739-211831

Table 5.1: Dataset names and corresponding run ranges used in the muon analyses

resolution varies from 1.7% in the barrel to 4.5% in the endcaps.

5.4 Datasets for the Z boson analyses

The primary datasets and run ranges used in each muon analysis of the different colliding systems are summarized in table 5.1. In the case of the p-p and most of the p-Pb dataset, the initial reconstruction was used however, the first few runs of the p-Pb data were reprocessed with an updated calibration of the detector alignment that was already applied in the later runs. The final Pb-Pb analysis was performed on a dataset that was produced with an improved muon reconstruction software. The initial muon reconstruction used the tracker tracks from the dedicated heavy-ion track reconstruction algorithm that has a reduced efficiency compared to p-p collisions in order to cope with the increased multiplicity of particles in Pb-Pb collisions. The improved muon reconstruction algorithm performs additional iterative pattern recognition steps to find tracks in the tracker in the geometrical proximity of the standalone-muon candidate. The improved reconstruction increased the efficiency for muons coming from Z bosons to the level of the standard algorithms in p-p (or p-Pb) collisions.

The above muon datasets contain all events triggered by any of the muon triggers however, each Z boson analysis is performed with a specific trigger path. The Pb-Pb and the p-Pb analyses use single muon triggers with a relatively high p_T threshold on the trigger muon that has a sufficiently low rate to store every event. The trigger paths are *HLT_HIL2Mu15* with a p_T threshold of 15 GeV/ c for the Pb-Pb analysis and *HLT_PAMu12* with $p_T > 12$ GeV/ c for the p-Pb analysis. The p-p analysis is performed on a dataset triggered by *HLT_PADoubleMuOpen* path, a double muon trigger with no specific p_T threshold that was found to be best described by the simulation. In order to further reduce the contribution of non-collision events or cosmic muons, all the muon triggers were required to be in coincidence with a signal from both sides of the HF calorimeters.

The analysis in the electron channel makes use of double photon triggers called *HLT_PAPhoton20_Photon15_NoCaloIdVL* and *HLT_HIPhoton15_Photon20* for p-p

	Dataset name	Run range
Pb-Pb	/HIHighPt/HIRun2011-PromptReco-v1/RECO	181530-183126
p-Pb	/PAHighPt/HIRun2013-28Sep2013-v1/RECO	210498-210658
p-Pb	/PAHighPt/HIRun2013-PromptReco-v1/RECO	210676-211256
Pb-p	/PAHighPt/HIRun2013-PromptReco-v1/RECO	211313-211631
p-p	/PPPPhoton/Run2013A-PromptReco-v1/RECO	211739-211831

Table 5.2: Dataset names and corresponding run ranges used in the electron analyses

and Pb-Pb collisions, respectively. The triggers require two energy deposits in the ECAL with $E_T > 20$ GeV and $E_T > 15$ GeV. The electron reconstruction was missing from the standard workflow for Pb-Pb collisions and had to be processed in the analysis. In the case of p-Pb collisions, a single photon trigger path with a 15 GeV threshold is used: *HLT_PAPhoton15_TightCaloIdVL*, where the *TightCaloId* means that there are additional selection criteria applied on the hadronic calorimeter energy deposit in the area of the cluster and on the shape of the electromagnetic shower in order to reject jets and photons from hadron decays. Similar selection criteria are applied in the analysis described in Section 7.9 for the selection of the electron candidates that are tighter than the ones applied at the trigger level. The primary datasets used in the electron analyses are summarized in table 5.2.

5.5 Monte Carlo simulations

High-energy collisions can be simulated by different event generators depending on the colliding system and the studied physics process. These generators usually provide the final state particles with their decay history for each event. In the following, the event generators used in the study of p-Pb and Pb-Pb collision data are briefly introduced. Finally, the MC samples including the simulation of the detector response are summarized that are used in the analysis for calculating correction factors.

5.5.1 The PYTHIA generator

The PYTHIA event generator is widely used in high-energy physics research. It combines calculations from pQCD to phenomenological models in order to provide a complete description of collisions between energetic particles such as electrons, protons, neutrons and their antiparticles in various combinations. It includes a wide range of hard scattering processes of partons with initial and final state radiation corrections. The branching of the outgoing partons is modeled with a parton shower approach and a string fragmentation model is used for the hadronization to final state particles. The PYTHIA generator can also describe what happens to the

partons that remain from the initial proton after the hard scattering, called the underlying event. The parameters of the underlying event and multiparton interactions are tuned to match experimental data on particle multiplicity and spectra, resulting in different tunes of the same PYTHIA version.

The PYTHIA version 6.4 [85] is used throughout this thesis for generating the hard scattering processes such as Z boson production in p-p collisions with various underlying event tunes. In the case of p-Pb and Pb-Pb collisions a slightly modified program is needed for simulating a combination of p-p, p-n and n-n collisions. This generator is also referred to as PYQUEN which is a modified version of PYTHIA 6.4 to include collisions between the different nucleons and to simulate parton energy loss in the medium (hence the name PYthia QUENched). In the study of Z boson production the proper mix of p-p, p-n and n-n collisions is simulated without the jet quenching.

5.5.2 Generators for heavy-ion collisions

Since PYTHIA can only generate collisions between nucleons, different generators are needed for the description of collisions involving nuclei. HYDJET [86] is an event generator simulating jet production, jet quenching and flow effects in AA collisions. Its name comes from hydrodynamics plus jets and it is specialized to describe the particle multiplicities and collective effects observed in AA collisions at RHIC and LHC. In the analysis of Pb-Pb data the HYDJET version 1.8 is used which includes results from the first LHC Pb-Pb run in the tuning of its parameters.

HIJING (Heavy-Ion Jet INTERaction Generator) [87] is a Monte Carlo model simulating p-p, pA and AA interactions. It models the interplay between soft and hard QCD processes with minijet production and takes into account the nuclear shadowing of nuclei and the jet energy loss in AA collisions. The HIJING version 1.383 [88] is used in the analysis of p-Pb data.

In the studies of centrality of Pb-Pb and p-Pb collisions, other generators were also applied. The AMPT (A Multi-Phase Transport) [89] model uses HIJING for generating the initial conditions, a parton cascade model for the partonic scatterings, and a relativistic transport model for treating hadronic scatterings. The EPOS [90] generator is based on Gribov-Regge theory developed originally for particle showers produced by cosmic-rays. The latest version called EPOS LHC [91] is tuned to describe available data from hadronic interactions in a wide energy range from a few GeV up to 7 TeV reached by the LHC.

5.5.3 Matrix element generators

POWHEG (Positive Weight Hardest Emission Generator) is a method for interfacing computations at fixed next-to-leading order in QCD with shower Monte Carlo programs that are only simulating the hard scattering processes at leading order. The fragmentation of partons, the final state radiation and the underlying event are simulated with PYTHIA as a parton shower MC generator. The production of Z and W bosons at NLO is one of the first processes implemented in the POWHEG framework [92].

MCFM is Monte Carlo program which gives NLO predictions for a wide range of rare processes at hadron colliders [93]. It provides parton-level predictions without the branching of partons or their final state radiation. The nuclear modification of PDFs could be implemented in MCFM and the predictions with different nPDFs are compared to our experimental results.

5.5.4 MC samples for the Z boson analyses

In order to analyze data from the LHC and to calculate correction factors, the response of the detectors is simulated with GEANT4 [94]. The simulated detector response of each generated event goes through a trigger emulation and the same reconstruction algorithm as the real data.

The Z boson production including high mass virtual photon production (Drell-Yan process) is simulated by the PYTHIA generator with the proper mix of p-p, p-n and n-n interactions for each collision system. In order to take into account the effect of high particle multiplicity in Pb-Pb collisions, each PYTHIA signal event is embedded into a HYDJET minimum bias background event. The embedding is done at the level of detector hits, and the signal and background events share the same generated vertex location. The embedded events are then processed through the trigger emulation and the reconstruction as one event.

In the case of p-Pb collisions due to the different beam energies, the boost of generated particles to the laboratory frame is taken into account before the detector simulation. The minimum bias background events for embedding are produced by the HIJING generator. The signal and the background events are generated with both beam direction configurations to take into account possible asymmetries in the detector performance.

The POWHEG generator is also used to produce Z bosons with the CT10 free proton PDF set [95]. The events are hadronized by the PYTHIA parton shower to take into account the final state radiation but they are not processed through the detector simulation and reconstruction. At 2.76 TeV the p_T spectrum of Z bosons predicted by POWHEG was used to reweight the events produced by PYTHIA in

order to better describe the data from p-p and Pb-Pb collisions. In the analysis of p-Pb collisions at 5.02 TeV, the POWHEG generator is used to calculate the acceptance correction.

Each of the above samples simulate Z bosons or high mass virtual photons decaying to opposite sign muon or electron pairs. Additionally, different processes producing high p_T leptons are simulated in order to estimate the background contributions to the Z boson signal. These include Z bosons decaying to $\tau^+\tau^-$, $t\bar{t}$ production where both W bosons from the top (anti)quark decay to muon or electron, and QCD jet production with a high momentum transfer. Since the probability of jets containing a high p_T lepton is small, the generated events are filtered for lepton pairs before proceeding to the detector simulation and reconstruction. Another possibility to estimate the background from jets is to simulate heavy flavor b or c quark jets. The details of the background estimation procedures are described in Section 7.2.

6 Event selection and centrality determination

In this chapter, the minimum bias event selection and the event centrality determination in p-Pb and Pb-Pb collisions is presented. Since 2012 I am one of the two coordinators of the group responsible for the centrality object in the event reconstruction software and for the related event selection and Glauber-model studies. The event selection and the centrality is used in most of the measurements performed by the CMS heavy-ion group. The overview given here is based on internal documentation of the work performed with p-Pb [96] and Pb-Pb [97] collision data. The figures from the studies of p-Pb collisions were made public in a detector note [98].

The goal of these studies is to determine centrality classes in percentages of the total hadronic inelastic cross section of p-Pb or Pb-Pb collisions and to calculate the average number of participating nucleons and other Glauber-model related quantities for each event class. The classification requires to select hadronic inelastic events with high efficiency while keeping the contamination from background events low. The event selection and its efficiency estimation is described in detail in Section 6.1. The Glauber-MC calculations corresponding to p-Pb collisions at 5.02 TeV and Pb-Pb collisions at 2.76 TeV are summarized in Section 6.2. The measurement of centrality classes in p-Pb collisions and the mapping procedures for Glauber-model related quantities are presented in Section 6.3 and results from Pb-Pb collisions summarized in Section 6.4.

6.1 Event selection and efficiency

A clean selection of hadronic collision events is essential for every analysis. The main sources of contamination to hadronic events are electromagnetic collisions, beam-gas collisions and beam-induced background events. Due to the large number of protons in the Pb nucleus, the strong electromagnetic field interacts with the incoming proton or a nucleon in the other nucleus that causes it to break up. These events represent a different type of physics and are to be removed from the sample

of hadronic collisions. The beam-gas collisions happen with various atoms present in the LHC beampipe because the vacuum is not perfect. The beam-induced background events are due to upstream interaction between the particles of the beam and some stationary remnants in the beampipe or with the beampipe itself. An example of such a signal are beam-halo muons that remain after the interaction with the beampipe and from the decay of the produced particles. These muons cross the detector parallel to the beam on one side but no other signal is reconstructed on the other side.

6.1.1 Event selection and efficiency in p-Pb collisions

Minimum bias p-Pb collision events are selected online with requiring a BPTX coincidence trigger signal at L1 and a reconstructed pixel track with $p_T > 0.4 \text{ GeV}/c$ at HLT. This trigger is called *HLT_PAZeroBiasPixel_SingleTrack*. The need for further offline event cleaning is demonstrated by studying the correlation between the sum of transverse energy deposited in the HF calorimeters and the number of pixel clusters in the pixel detector in fig. 6.1. The diagonal correlation band of real p-Pb collisions is clearly visible but there is an additional band due to background at low forward energy and large number of pixel hits.

The presence of beam-induced background events is known since the first paper written in CMS. They are characterized by large multiplicities observed in the tracker without any sign of a common origin of the tracks within the interaction region. In order to remove these large multiplicity events, a so-called beam scraping filter was developed for p-p analyses. The filter removes events where the number of reconstructed tracks is larger than a certain value but the fraction of good quality tracks is low. The default parameter values for the filter were used also in p-Pb collisions, which are the minimum number of tracks required to check the quality of the event is 10, the minimum fraction of good quality tracks in the event is required to be larger than 25%, and the good quality requirement on the tracks is the so-called *highPurity* flag.

Further suppression of non-collision events is achieved by requiring a primary interaction vertex in the event. The event is accepted if at least one vertex passes the following vertex selection criteria. The vertex is required to be within $\pm 25 \text{ cm}$ from the center of the detector in the longitudinal direction and not further than 2 cm from the beamline in the transverse direction. Finally, at least two tracks are required to be associated with the vertex. The beam scraping filter and the primary vertex requirement remove successfully the events with low transverse energy in the HF and high pixel cluster multiplicity.

As previously mentioned, electromagnetic collisions such as photodissociation

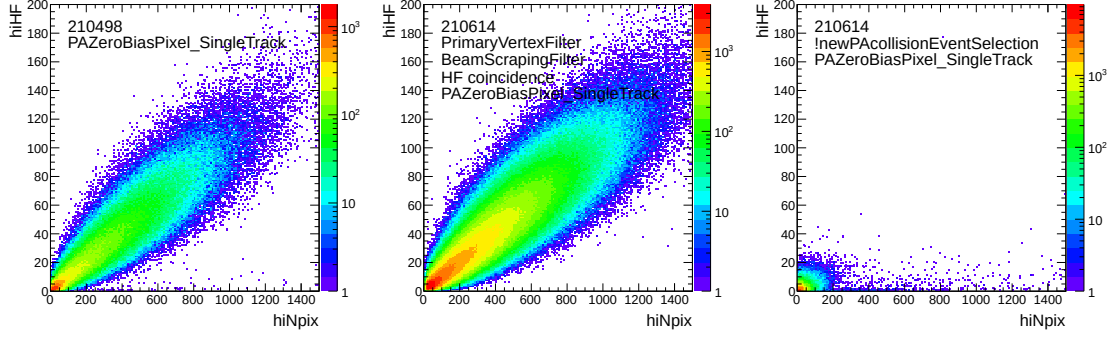


Figure 6.1: Correlation between the total transverse energy measured in HF and the number of pixel clusters in p-Pb collisions for all events selected by the minimum bias trigger (*left*), events selected by the offline event selection criteria (*middle*) and triggered events rejected by the offline selection (*right*).

of the proton are considered as background for the p-Pb analysis event selection. Since the electromagnetic events are mostly single sided producing activity only in one side of the CMS detector, a coincidence requirement on the HF calorimeters is imposed to remove them. At least one calorimeter tower with more than 3 GeV energy deposit is required on each side of the HF. The effect of this requirement is explicitly seen in fig. 6.1, where the events that failed the event selection are also shown on the left-hand side and they have very low HF E_T and low pixel multiplicity.

Because the centrality is determined from calorimeter information as described in Section 6.3, multiple collisions in the same bunch crossing can not be separated. For a well-defined centrality measurement these pileup events have to be removed. The approach to select clean single-vertex p-Pb collisions is to investigate the number of tracks assigned to each reconstructed vertex in the event and the distances of these vertices in the beam direction. Based on studies using low pileup p-Pb data and MC simulations, events with more than a certain number of tracks attached to the second vertex at a given distance from the first vertex (with highest track multiplicity) are identified as pileup events and removed from the minimum bias event sample. The threshold on the track multiplicity is higher for smaller distances to account for the fact that events with a smaller vertex separation and greater multiplicity have a higher probability of vertex splitting in the reconstruction algorithm. The residual pileup fraction was estimated to be less than 0.01% for minimum bias p-Pb events.

The event selection studies summarized here are also described in the analysis of two-particle correlations [99] and of dijet events [100, 101] in p-Pb collisions that are the first applications of this work.

In order to connect the variables related to the collision geometry from Glauber model with the measured quantities, the data has to be corrected to the total inelastic hadronic cross section. The offline event selection criteria described above remove some good collision events while rejecting the background, thus the efficiency

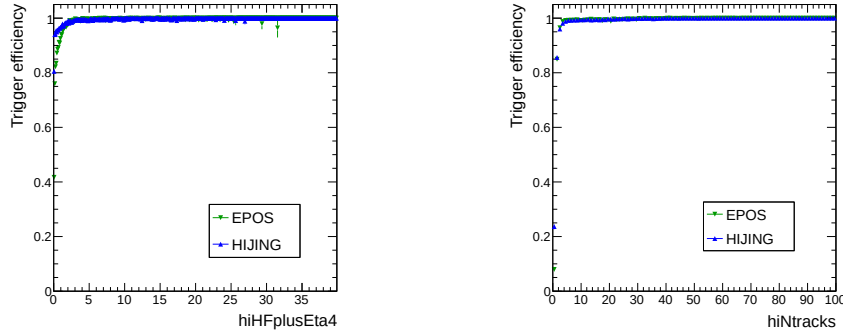


Figure 6.2: Minimum bias trigger efficiency as a function of the transverse energy deposited in HF on the Pb-going side (*left*) and as a function of the number of good quality tracks (*right*) from the EPOS and HIJING MC generators.

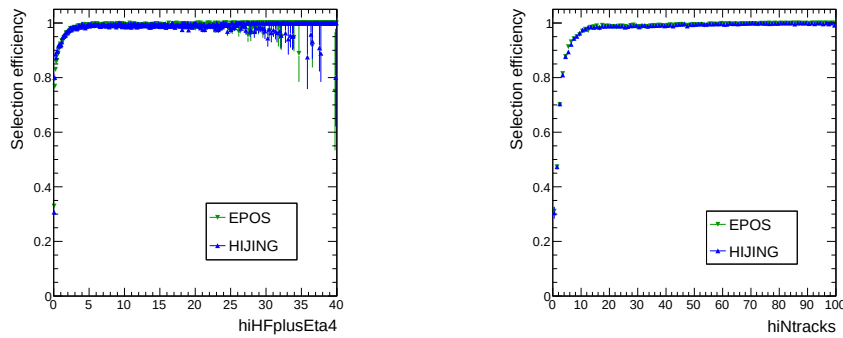


Figure 6.3: Event selection efficiency for triggered events as a function of the transverse energy deposited in HF on the Pb-going side (*left*) and as a function of the number of good quality tracks (*right*) from the EPOS and HIJING MC generators.

of the selection for hadronic inelastic events has to be estimated. The efficiency has two components: the trigger efficiency and the offline selection efficiency and both are determined from MC simulations of inelastic p-Pb collisions produced by the HIJING and EPOS generators.

The trigger efficiency is defined as the ratio of the number of events that fire the single pixel track trigger to the number of generated events. This is calculated in every multiplicity bin, where the multiplicity can be the number of good quality tracks reconstructed in the event or the sum of the transverse energy deposited in the HF detectors. Fig. 6.2 shows the trigger efficiency as a function of these variables from the two MC generators. The integrated value of the trigger efficiency is found to be 98.6% from HIJING and 94.6% from EPOS and the inefficiency occurs at low multiplicities.

The selection efficiency is defined as the ratio of selected inelastic events over all events triggered by the single pixel track trigger. Fig. 6.3 shows the selection efficiency from the two MC generators as a function of the HF E_T on the Pb-going side and the number of tracks. The integrated value for the selection efficiency is 96.3% according to the HIJING and 95.9% from the EPOS generator. The inefficiency oc-

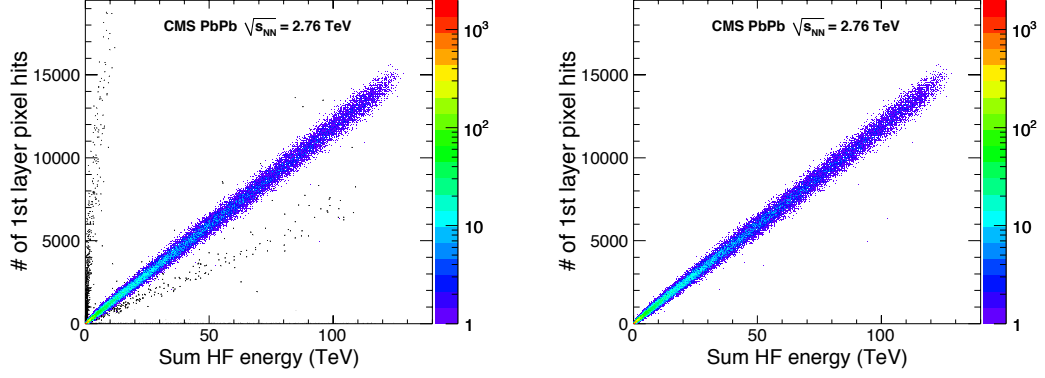


Figure 6.4: Correlation between the total transverse energy measured in HF and the number of pixel clusters in Pb-Pb collisions for all events selected by the minimum bias trigger (*left*) and events selected by the offline event selection criteria (*right*).

curs at low multiplicities similarly to the trigger efficiency because high multiplicity collisions are more likely to produce deposits in both HF calorimeters and a primary vertex. The pileup rejection and the beam scraping filter does not remove events from the simulation. The primary vertex filter removes 1.7% (1.4%), the HF coincidence requirement removes 3.0% (2.8%) of the triggered events and the overlap between them is about 0.6% (0.5%) according to EPOS (HIJING) generators.

Though the HF coincidence requirement is supposed to reject all electromagnetic events where the proton breaks up in the strong magnetic field of the Pb nucleus, the contamination of such events to the selected minimum bias collisions has been estimated. Electromagnetic events were generated by the STARlight [102] generator interfaced with PYTHIA. The cross section of electromagnetic events is estimated to be 195 mb according to this generator. The HF coincidence requirement removes 99.925% of these electromagnetic events and the remaining contamination amounts to a cross section of 0.15 mb. Compared to the measured 2061 ± 80 mb total hadronic inelastic p-Pb cross section [103], the electromagnetic events have a negligible contamination to the minimum bias event sample.

6.1.2 Event selection and efficiency in Pb-Pb collisions

Minimum bias Pb-Pb collisions were selected by a combination of the BSC and HF detectors firing on both sides of the interaction point. Similar to p-Pb collisions, the correlation between the sum of the E_T deposited in the HF calorimeters and the number of pixel hits is studied for offline event cleaning as shown in fig. 6.4. Beside the pronounced diagonal correlation band of real Pb-Pb collisions, there are additional bands due to background events. In order to select a clean sample of hadronic inelastic events, similar event selection requirements are applied to Pb-Pb data as to p-Pb data described above.

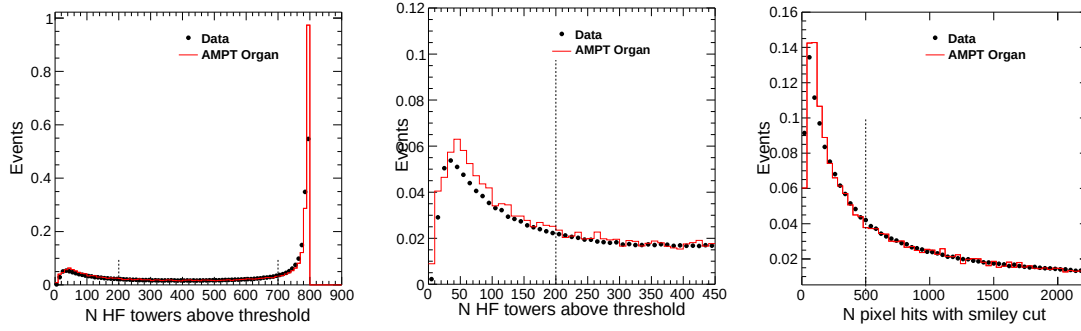


Figure 6.5: Number of HF towers above noise threshold (*left and middle*) and number of pixel hits (*right*) comparing selected event from data to all events from simulation in order to extract a selection efficiency. The dashed lines show the boundaries used for normalization of the simulation.

Beam halo muons are identified with the BSC detectors using the time difference between the signals on the two sides of the interaction point and then rejected from the minimum bias event sample. This removes part of the events with high number of pixel hits but small energy deposits in the HF calorimeters. The other part is rejected by a requirement of the pixel cluster-length compatibility with the reconstructed vertex. This also removes the band in fig. 6.4 below the sharp correlation of collision events with slightly larger HF activity for the same number of pixel hits. A requirement of a reconstructed vertex with at least two associated tracks is also imposed that removes beam-gas and electromagnetic collisions with low activity in the pixel detectors. Finally, a coincidence of three calorimeter towers with at least 3 GeV energy in both sides of HF is required in order to remove electromagnetic collisions.

The contamination from electromagnetic events is estimated with comparing the event rates as a function of the sum of E_T in the HF detectors with different selection criteria between data and HYDJET simulation that only includes hadronic inelastic events. The ratio of the rates with HF coincidence of two or three towers agrees well between data and simulation after applying the vertex requirement. This gives confidence that the contamination of electromagnetic events is negligible in the minimum bias event sample.

The minimum bias trigger and event selection efficiency is estimated using AMPT and HYDJET simulation compared to Pb-Pb collision data after event cleaning. The two quantities used for the efficiency estimation are the number of HF calorimeter towers with energy above noise and the number of pixel hits. The efficiency is calculated from simulation and is found to be lower than unity only for the most peripheral events with low multiplicity. In order to better constrain the uncertainties on this estimate from simulation, the number of HF towers and the number of pixel hits is compared between data and simulation in fig. 6.5. The simulation

is normalized to the data distribution in the region indicated by the dashed lines where the efficiency is 100%. In this way, the inefficiency of the event selection is visible by the difference between the two distributions. The uncertainty on the event selection efficiency is estimated by varying the parameters of the MC generators and the normalization ranges. Finally, the overall trigger and event selection efficiency for minimum bias Pb-Pb collisions is found to be $97 \pm 3\%$.

6.2 Glauber model calculations

As introduced in Section 2.1, the Glauber model is a multiple collision model that treats nucleus-nucleus collisions as an independent sequence of nucleon-nucleon collisions. The calculations implemented in CMS utilize the Glauber-MC program developed for the PHOBOS collaboration [104]. The nucleons are distributed in the initial state according to the Woods-Saxon distribution in eq. (2.1), where the radius for the ^{208}Pb nucleus is $R = 6.62$ fm, its skin depth is $a = 0.546$ fm, and its shape is spherical thus $w = 0$. An additional parameter of the Glauber-MC calculation is the inter-nucleon separation between the centers of the nucleons themselves that is set to $d_{\min} = 0.4$ fm. The model assumes that the nucleons travel on straight-line trajectories and interact through the inelastic nucleon-nucleon cross section as measured in p-p collisions. The nominal values are $\sigma_{\text{inel}}^{\text{NN}} = 70$ mb at $\sqrt{s_{\text{NN}}} = 5.02$ TeV used for p-Pb collisions and $\sigma_{\text{inel}}^{\text{NN}} = 64$ mb at $\sqrt{s_{\text{NN}}} = 2.76$ TeV used for Pb-Pb collisions. These values come from a fit to all available measurements of p-p and p- $\bar{\text{p}}$ collisions at lower energies. A nucleon-nucleon collision takes place in the simulations if the relative transverse distance between two nucleons is smaller than $\sqrt{\sigma_{\text{inel}}^{\text{NN}}/\pi}$.

The impact parameter, the number of participating nucleons and the number of binary collisions are calculated for one million events simulated by Glauber MC for both p-Pb and Pb-Pb collisions. The results for p-Pb collisions are shown in fig. 6.6 for b , N_{part} and their correlation. In p-Pb collisions $N_{\text{coll}} = N_{\text{part}} - 1$ by definition, thus it is not shown separately. Note that the correlation between b and N_{part} is quite broad in case of p-Pb collisions that makes it difficult to introduce impact parameter dependence in theoretical models based on experimental measurements expressed as a function of the number of participating nucleons that is closer related to measurable quantities. The total hadronic inelastic cross section of p-Pb collisions at 5.02 TeV is calculated to be 2.11 ± 0.09 b. The results of the Glauber-MC calculation for Pb-Pb collisions are shown in fig. 6.7 for b , N_{part} , N_{coll} and their correlations. The impact parameter and the number of participants show a stronger correlation than in p-Pb collisions. The calculated total hadronic inelastic cross section of Pb-Pb collisions at 2.76 TeV is 7.64 ± 0.42 b.

The uncertainties of the quantities derived from the Glauber model are estimated

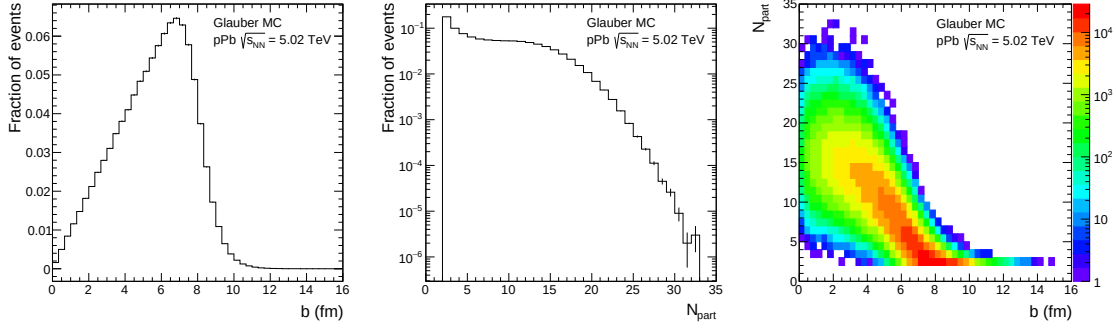


Figure 6.6: Results of the Glauber-MC calculation for the impact parameter, the number of participating nucleons and their correlation in p-Pb collisions at 5.02 TeV.

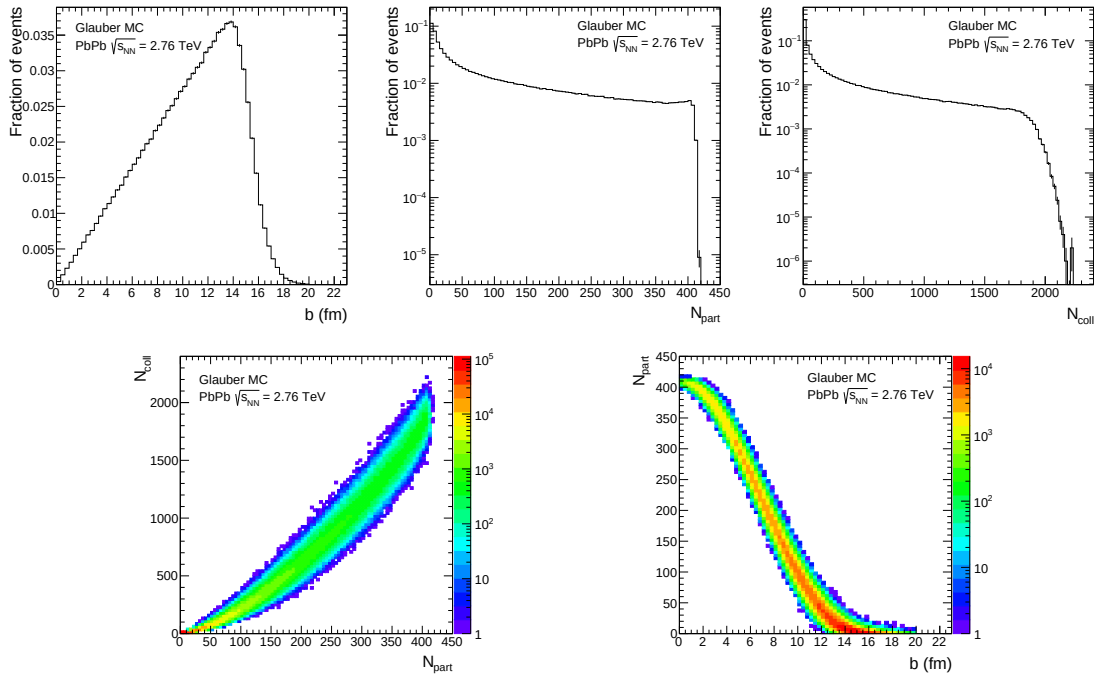


Figure 6.7: Results of the Glauber-MC calculation for the impact parameter, the number of participating nucleons, the number of binary collisions and their correlations in Pb-Pb collisions at 2.76 TeV.

by varying the parameters R , a , $\sigma_{\text{inel}}^{\text{NN}}$ and d_{min} within their uncertainties. The nuclear radius is varied by $\pm 2\%$, the skin depth by $\pm 10\%$, the intra-nuclear separation by $\pm 100\%$ and the nucleon-nucleon inelastic cross section is varied by ± 5 mb ($\pm 7.8\%$) for Pb-Pb and ± 4 mb ($\pm 5.7\%$) for p-Pb collisions as agreed between the LHC experiments.

6.3 Centrality reconstruction in p-Pb collisions

The impact parameter of the collisions can not be measured directly, thus simulations are used to connect the measured and the centrality related quantities.

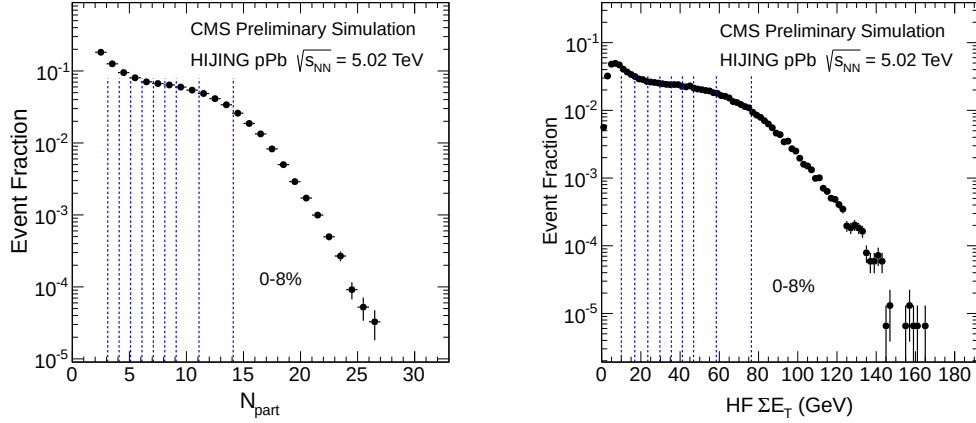


Figure 6.8: Example for assigning events into centrality classes using the number of participating nucleons (*left*) or the sum of the transverse energy deposited in the HF calorimeters (*right*) using simulated p-Pb collision from the HIJING generator.

6.3.1 Centrality measures

It is shown from simulations in Section 6.4 that in Pb-Pb collisions the total energy measured in the HF calorimeters is highly correlated with N_{part} . In p-Pb collisions however, due to the smaller number of participants and produced particles this correlation is much looser. Additionally, the asymmetry of the colliding system causes that the measured energies in the two sides of the detector carry different amount of information. Thus, a more sophisticated centrality measure is sought.

The goal is to find such a centrality measure that the charged particle $dN/d\eta$ distributions in the centrality classes defined by this measure and by N_{part} match well. The classification of events into centrality classes using N_{part} or the sum of the energy in the HF calorimeters is shown in fig. 6.8 for demonstration. The $dN/d\eta$ distributions for events in five centrality classes are shown in fig. 6.9, where the figures represent event classes derived using two different regions of the HF detectors symmetric around the interaction point. The difference between the $dN/d\eta$ distributions is clearly visible but using the inner rings of the HF ($4.0 < |\eta| < 5.2$) as centrality measure gives a reasonable agreement with the event classes using N_{part} .

The least biased centrality measure is found with an optimization procedure assigning weights to different η regions when calculating the total E_T in the HF calorimeters. The difference in the $dN/d\eta$ distributions in the $|\eta| < 2.4$ region between the HF and N_{part} event classes is used to calculate a χ^2 that is minimized by changing the weights assigned to the HF η regions. The result of the optimization is that the most backward regions of the HF are preferred. A simple choice is to use the inner rings $\eta < -4$ of the HF on the Pb-going side of the interaction. The $dN/d\eta$ distributions for these classes are compared with the N_{part} event classes in fig. 6.10. The ratio of the distributions in the five event classes shown in the right-hand side

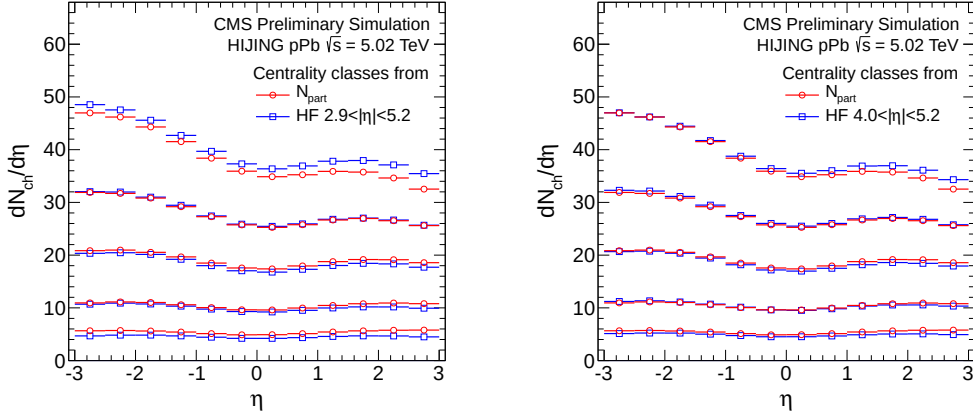


Figure 6.9: Particle multiplicity as a function of η in five different event classes using N_{part} and the sum of HF E_T in the $2.9 < |\eta| < 5.2$ (left) and in the $4.0 < |\eta| < 5.2$ (right) regions for classification.

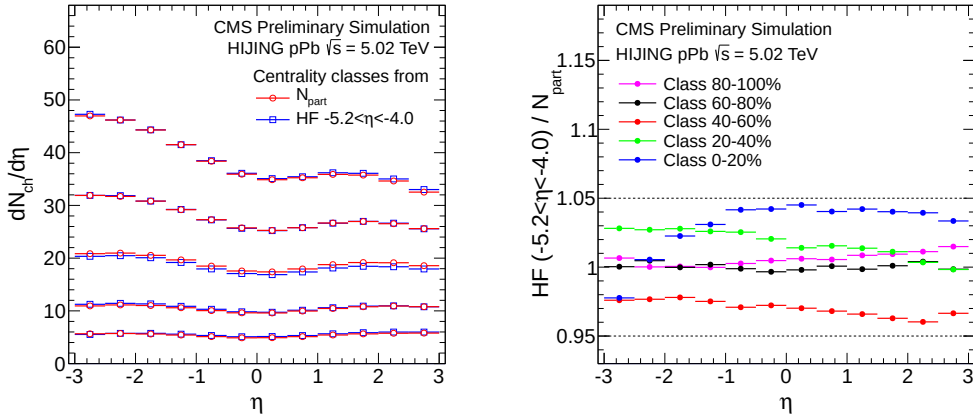


Figure 6.10: Particle multiplicity as a function of η in five different event classes using N_{part} and the sum of HF E_T in the $-5.2 < |\eta| < -4.0$ region for classification (left) and their ratio (right).

of the figure demonstrates that the agreement is better than 5%.

This optimization study only deals with the average $dN/d\eta$ of charged particles but for different type of observables other centrality measures might be necessary to perform a least biased measurement. In the analysis of dijet events in p-Pb collisions [100, 101], it was found that using a single sided centrality measure biases the jet measurement thus a symmetric variable, the inner rings of the HF calorimeters were used.

Finally, the stability of the HF detector response is checked during the p-Pb data taking. The distribution of the HF E_T on the Pb-going side is shown for different runs in fig. 6.11 separately for the two beam configurations. Only events after the hadronic inelastic event selection and pileup rejection are shown. The agreement of the distributions validates the pileup rejection and proves that only one calibration of the centrality bin boundaries is needed for each of the two beam configurations.

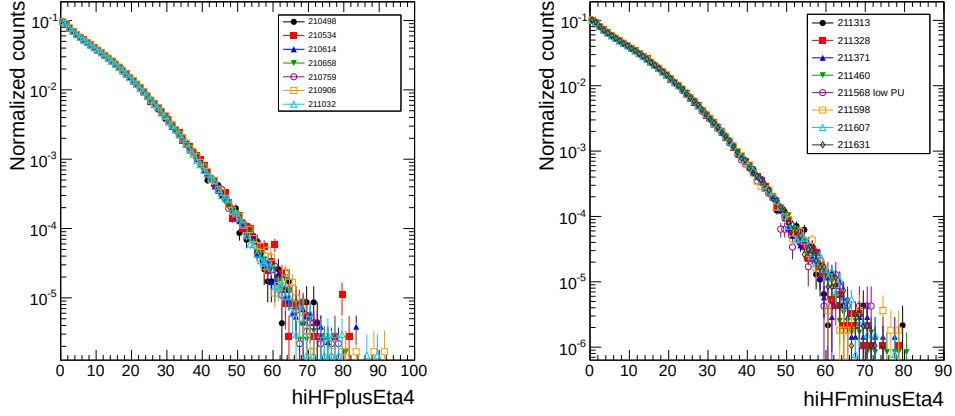


Figure 6.11: Distribution of the sum of HF E_T in the $\eta > 4$ region for different runs with the first (p-Pb) beam direction (*left*) and the sum of HF E_T in the $\eta < -4$ region for different runs with the second (Pb-p) beam direction (*right*).

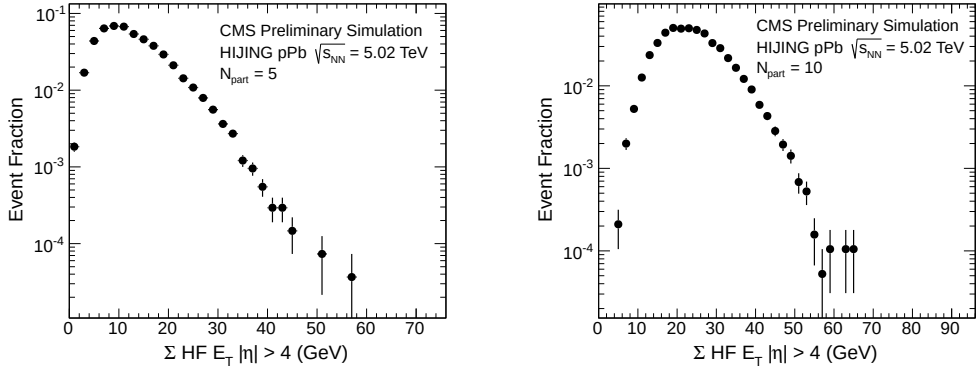


Figure 6.12: Distribution of the sum of HF E_T in $4 < |\eta| < 5.2$ region for events with $N_{\text{part}} = 5$ (*left*) and $N_{\text{part}} = 10$ (*right*) from HIJING p-Pb simulation.

6.3.2 Detector effects on Glauber calculation

This section summarizes the connection of the measured event classes to the Glauber-model related quantities like N_{part} . To first approximation the MC event generators that simulate the HF response can be used to calculate the average N_{part} in each event class. However, the Glauber-model implementation in the different generators is different, thus it is desirable to connect the measured quantities with the Glauber-model calculation described in Section 6.2.

The first method presented here is called the smearing method. The first step is to determine the HF E_T distribution for each value of N_{part} from MC simulations using the HIJING and the EPOS event generators. Fig. 6.12 shows the distribution for $N_{\text{part}} = 5$ and 10 from HIJING as an example. This step provides the simulation of the detector resolution and the event-by-event fluctuations of energy production in the HF region for each N_{part} . The second step is to generate a random HF E_T value for each of the one million Glauber-MC events according to the distributions

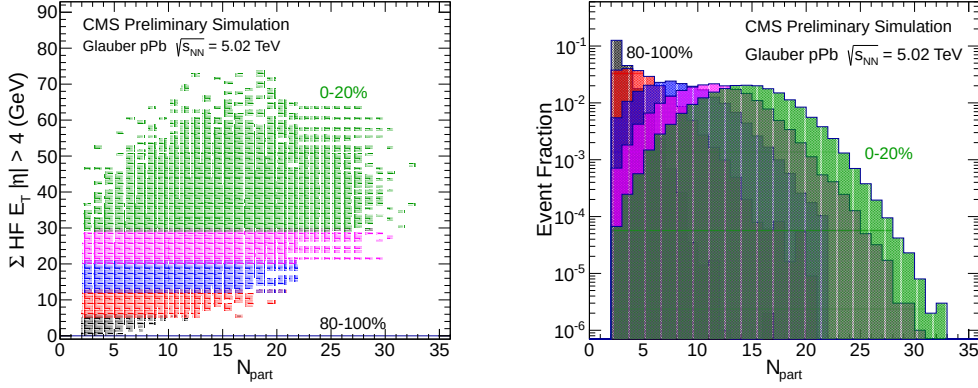


Figure 6.13: *Left:* Correlation of the number of participating nucleons and the sum of HF E_T in $4 < |\eta| < 5.2$ region divided into five event classes. *Right:* Distribution of the number of participating nucleons in the five event classes.

shown in fig. 6.12. The resulting HF E_T distribution of all events is divided into equal area centrality classes and the average N_{part} , N_{coll} and b are determined for them. This second step is demonstrated in fig. 6.13: The left-hand side shows the correlation of N_{part} and the centrality measure in HF showing 5 centrality classes of equal size. The right-hand side shows the N_{part} distribution of the same classes from where the average and the width of the N_{part} distribution for each class is calculated. Note that between the centrality measure in the HF and N_{part} there is a quite loose correlation that results in a large variance of the N_{part} distribution.

The described procedure is also used for calculating the average number of binary collisions and the average impact parameter for the centrality classes. The results for the average N_{coll} are shown in fig. 6.14 for ten centrality classes comparing the use of EPOS and HIJING generators for the smearing method. The results from the different generators agree quite well. The error bars represent the total systematic uncertainty from the combination of the uncertainties from the variation of the Glauber-model parameters and the variation of the trigger and event selection efficiency.

An alternative method to extract the number of binary collisions for each centrality class is based on fitting the measured HF E_T or track multiplicity distribution with negative binomial distribution (NBD) functions combined with the Glauber model. The NBD function,

$$P_{\mu,k}(n) = \frac{\Gamma(n+k)}{\Gamma(n+1)\Gamma(k)} \frac{(\mu/k)^n}{(\mu/k+1)^{n+k}}, \quad (6.1)$$

describes the multiplicity or HF E_T distribution for a single nucleon-nucleon collision with μ and k controlling the mean and the width of the distribution, respectively. The charged particle multiplicity distribution in p-p collisions is fitted well with NBD functions [105]. In heavy-ion collisions, it is assumed that the nucleon-nucleon

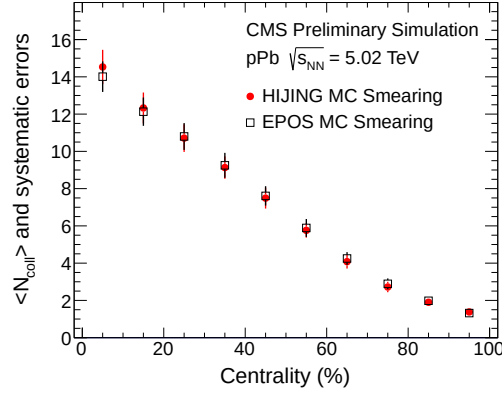


Figure 6.14: The average number of binary collisions in ten p-Pb event classes from the smearing method using two different event generators.

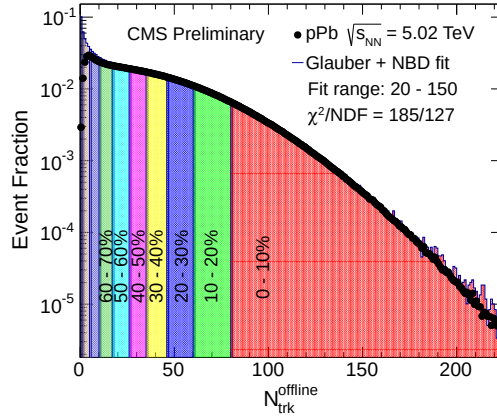


Figure 6.15: Distribution of the number of reconstructed tracks in p-Pb collisions and its fit by the sum of negative binomial distributions.

collisions independently produce such distributions. For every Glauber-MC event, the NBD is sampled N_{coll} times to obtain the averaged simulated multiplicity distribution for this event. The multiplicity distribution is simulated for an ensemble of events and for various values of the NBD parameters μ and k and a minimization procedure is applied to find the parameters which result in the smallest χ^2 . The results of such a fit of the distribution of the number of reconstructed tracks in p-Pb collisions is shown in fig. 6.15. The procedure applied here follows the one performed by the ALICE collaboration for Pb-Pb collisions [106].

The simulated multiplicity or HF E_T distribution with the Glauber model and the fitted NBD parameters is used to determine the average N_{coll} , N_{part} and b for the measured centrality classes shown by the different colors in fig. 6.15. The average N_{coll} for ten centrality classes is shown in fig. 6.16 comparing the fit results from different centrality measures and the smearing method using HIJING simulation. The different centrality measures show very little difference between the average values of N_{coll} . The error bars represent the systematic uncertainty from the variation of

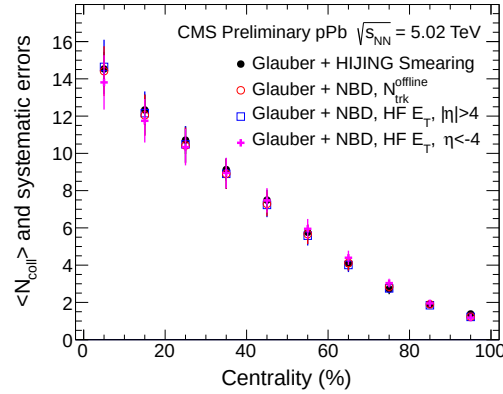


Figure 6.16: The average number of binary collisions in ten p-Pb event classes from the different centrality determination methods.

the Glauber-model parameters that are correlated between the different methods.

Studying the various procedures for calculating the Glauber-model related quantities of event classes defined by various measured distributions shows that the average values of the number of binary collisions are the same. However, very different type of events are selected by the centrality measures using the tracker in the midrapidity region or the HF calorimeters in the forward and backward rapidity regions. The measure of the event centrality in p-Pb collisions has to be chosen for each analysis after studying the biases of the experimental observable on the event classification variable. The analysis of the transverse energy flow in p-Pb collisions [107] presents studies as a function of centrality based on the work of the centrality group presented here.

6.4 Centrality reconstruction in Pb-Pb collisions

In Pb-Pb collisions at 2.76 TeV nucleon-nucleon center-of-mass energy, the centrality is determined by the sum of the transverse energy deposited in the HF calorimeters covering the $2.9 < |\eta| < 5.2$ region. The events are assigned to 40 centrality classes corresponding to 2.5% of the total hadronic inelastic cross section taking into account the inefficiency of the event selection in the most peripheral centrality class. The distribution of the HF energy and the fraction of events falling into each centrality bin is shown in fig. 6.17 for minimum bias and jet triggered events. It is visible that the centrality bin distribution of minimum bias events is flat by definition except the most peripheral bins. Events with a jet above 50 GeV/ c are more frequent in central events because the probability of hard processes is expected to be proportional to the number of nucleon-nucleon collisions.

The average number of participating nucleons and other Glauber-model related quantities are determined from the smearing method as described previously for p-

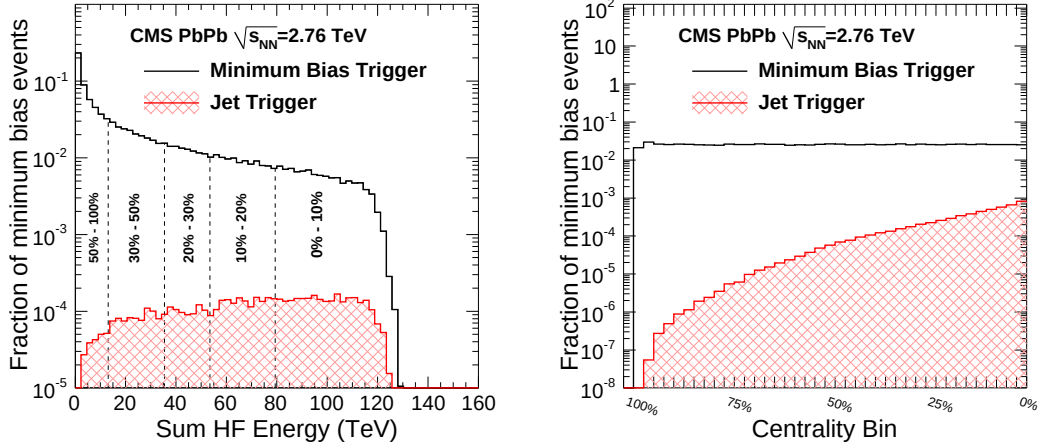


Figure 6.17: Distribution of the total HF E_T (*left*) and the fraction of events in the 40 centrality bins (*right*) for minimum bias Pb-Pb collisions (black open histograms) and for the subset of events passing the HLT jet trigger (red hatched histograms). [15]

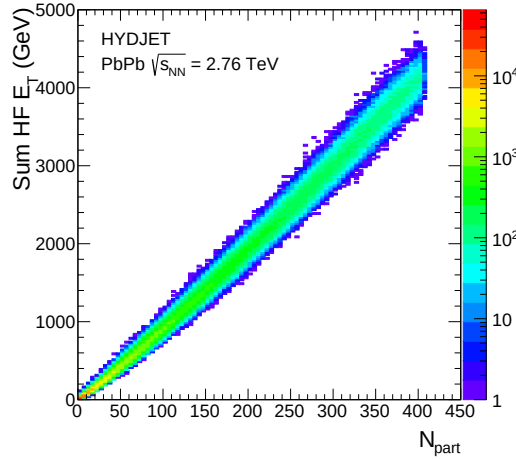


Figure 6.18: Correlation of the number of participating nucleons and the sum of HF E_T in Pb-Pb collisions from HYDJET simulation.

Pb collisions. The AMPT and HYDJET event generators are used to simulate the HF response for each value of N_{part} in order to estimate the detector effects on the Glauber model. The correlation between N_{part} and the centrality measure in HF is tighter in Pb-Pb collisions compared to p-Pb collisions as shown in fig. 6.18. Due to the very high number of produced particles, the biases on the event centrality introduced by selecting events with hard probes is negligible in Pb-Pb collisions.

Table 6.1 shows the results for the average values of N_{part} , N_{coll} and T_{AA} from the smearing method for the centrality classes used in the analysis of Z bosons in Pb-Pb collisions. The uncertainties represent the total systematic uncertainty combining the variations of the Glauber-model parameters and the event selection efficiency. As already mentioned in eq. (2.5), the nuclear overlap function is connected to the number of binary collisions through the inelastic nucleon-nucleon cross section:

Centrality	$\langle N_{\text{part}} \rangle$	$\langle N_{\text{coll}} \rangle$	$\langle T_{\text{AA}} \rangle$ (mb $^{-1}$)
[50, 100]%	22 ± 2	30 ± 5	0.47 ± 0.07
[40, 50]%	86 ± 4	176 ± 21	2.75 ± 0.30
[30, 40]%	130 ± 5	326 ± 34	5.09 ± 0.43
[20, 30]%	187 ± 4	563 ± 53	8.80 ± 0.58
[10, 20]%	261 ± 4	927 ± 81	14.5 ± 0.80
[0, 10]%	355 ± 3	1484 ± 120	23.2 ± 1.00
[0, 100]%	113 ± 3	363 ± 32	5.67 ± 0.32

Table 6.1: The average values for N_{part} , N_{coll} and the nuclear overlap function corresponding to the centrality ranges used in the Z boson analysis.

$T_{\text{AA}} = N_{\text{coll}}/\sigma_{\text{inel}}^{\text{NN}}$. The average T_{AA} for 0–100% centrality can also be expressed as $T_{\text{AA}} = A^2/\sigma_{\text{inel}}^{\text{PbPb}}$, where $A = 208$ is the number of nucleons in the Pb nucleus and $\sigma_{\text{inel}}^{\text{PbPb}} = 7.65 \pm 0.42$ b is the total inelastic hadronic cross section computed from the Glauber model.

In summary, I showed the details of centrality determination and event selection in PbPb collisions, that has been performed with the 2010 and 2011 data, and is utilized in the analysis of Z bosons in the next chapter. As the contact person for centrality, I performed similar event selection and centrality determination studies in pPb collisions recorded in 2013. I participated in the data taking and provided the event selection for several analyses. I performed studies of the biases introduced to the centrality classification due to the asymmetric collision system and I calibrated the event classes for the different variables. I showed that the average number of elementary nucleon-nucleon collisions is independent of the centrality measure, though different type of events are selected by the centrality classification.

7 The analysis of Z bosons

The analysis of p-p, p-Pb and Pb-Pb collision data is presented in this chapter that was the main part of my work. The details of the muon analysis are demonstrated by the p-Pb data analysis that was entirely performed by me, while on the Pb-Pb analysis we worked together with two colleagues. The differences between the p-p, p-Pb and Pb-Pb data are also summarized in each section. This chapter is based on internal documentation of the analysis work within the collaboration [108, 109, 110].

The goal of the analysis is to calculate the Z boson production cross section determined by the following formula

$$\sigma = \frac{S - B}{\epsilon \cdot \alpha \cdot \mathcal{L}_{\text{int}}} , \quad (7.1)$$

where S is the number of signal Z boson candidates, B the estimated background, ϵ the efficiency, α the acceptance and $\mathcal{L}_{\text{int}}$ the integrated luminosity. When the cross section is calculated as a function of rapidity or transverse momentum of the Z bosons, then all components are evaluated in bins of y or p_T and resolution effects are also taken into account.

This chapter is organized in the following way: The selection of muons and Z boson candidates is summarized in Section 7.1. The estimation of the background is described in Section 7.2. Before applying corrections based on simulations, in Section 7.3 the data and MC simulations are compared. The acceptance, efficiency and resolution corrections are described in Sections 7.4 – 7.6. The systematic uncertainties associated with each component of the analysis are presented in Section 7.8. Finally, the Z boson analysis in the electron channel is summarized in Section 7.9 in which I only assisted.

7.1 Signal extraction

As mentioned previously, Z bosons are identified through their dimuon decay channel. Thus muons that come from the primary collision vertex and have high transverse momentum have to be selected with high efficiency, while fake and cosmic muons and those that are produced in decays of hadrons have to be suppressed.

Fake muons can result from hadrons that pass through the calorimeters and leave a signal in the muon detectors or from accidental matching of muon segments and tracks. The muon identification is based on the "tight muon" requirements recommended by the Muon Physics Object Group within CMS. They are based on extensive studies of cosmic muon and p-p collision data. The quality requirements used in this analysis are the following:

- each muon has to be reconstructed with both the global muon and the tracker muon reconstruction algorithms as described in Section 5.3,
- the global track needs a $\chi^2/\text{ndf} < 10$ to ensure a reasonable fit quality,
- at least 1 valid muon hit associated with the global muon is required to make sure that the tracker and muon system informations are consistent,
- a similar requirement to the L1 muon trigger logic is imposed with at least two matching segments in different stations,
- the impact parameter with respect to the primary vertex has to be $|d_{xy}| < 0.2$ cm to ensure consistency of the muon track with the location of the vertex and to reduce cosmic background,
- the longitudinal distance with respect to the primary vertex is required to be $|d_z| < 0.5$ cm to further suppress cosmic muons and muons from decays in flight,
- only muons with a number of pixel hits ≥ 1 are selected to reject non-prompt muons,
- to guarantee a good p_T assignment some minimal number of measurement points in the tracker is needed thus the number of tracker layers ≥ 6 is required.

The effect of these requirements were also studied in heavy-ion collisions as shown in Section 7.3, and found to be consistent with simulations and p-p collision data at 7 and 8 TeV.

In order to suppress background from multijet events and other sources, the muons used in the analysis are required to have high transverse momentum. Thus the acceptance cuts for the muons considered are: $p_T^\mu > 20$ GeV/ c that is well above the trigger threshold and $|\eta^\mu| < 2.4$ to be within the geometrical acceptance of the muon detectors. All events with at least two muons fulfilling these quality and acceptance criteria are kept and the invariant mass of each muon pair is calculated from their (p_T, η, ϕ) coordinates and the known muon mass of 105.66 MeV/ c^2 [23].

The Z boson candidates are selected by looking at events triggered by a specific trigger in each dataset as described in Section 5.4. In order to make sure that one or both of the muons coming from the Z boson triggered the event, trigger matching requirements have to be fulfilled. In the case of p-Pb and Pb-Pb collisions a single muon trigger is used in the analysis and one of the muons from the Z boson are required to be matched to the trigger object. In the case of p-p collisions a double

muon trigger is used, thus both of the muons are required to be matched to the two legs of the trigger object. For the trigger matching a two-dimensional angular distance between the muon reconstructed in the HLT and in the event reconstruction is calculated: $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$, where $\Delta\phi$ and $\Delta\eta$ are the differences in the ϕ and η coordinates, respectively. The trigger matching requirement in the analysis is $\Delta R < 0.1$.

The raw yield of Z bosons is determined by simple counting of the oppositely-charged muon pairs in the 60–120 GeV/ c^2 invariant mass range that fulfil the acceptance, quality and trigger matching requirements. In the data samples studied, no events are found with more than one such pair. The Pb-Pb and p-p data analysis at 2.76 TeV is restricted to $|y| < 2$ in rapidity of the Z bosons in order to avoid large correction and associated uncertainties at the edge of the acceptance. The number of Z boson candidates found in the Pb-Pb data sample after the improved muon reconstruction algorithm is 1022, while the p-p data at the same center-of-mass energy contains 830 candidates. There is no rapidity restriction applied in p-Pb collisions because nuclear effects are expected at the most forward and backward rapidity values. Thanks to the higher center-of-mass energy, the p-Pb data sample has 2183 Z boson candidates.

Fig. 7.1 shows the invariant mass distribution of the selected muon pairs in the three collision systems compared to the corresponding simulations. The MC distributions are normalized to the number of opposite-charge pairs found in the 80–100 GeV/ c^2 mass range. The agreement between the data and simulation is good and the background under the Z boson peak is low. The small number of same-charge muon pairs shown in the figure also indicates the low level of background that is investigated in the next section.

7.2 Background estimation

Possible background contributions to the $Z \rightarrow \mu\mu$ production are $t\bar{t}$, $Z \rightarrow \tau\tau$, diboson (WW, WZ, ZZ) and W+jet production as well as QCD processes involving muons inside jets. In this section the contribution of these processes is estimated from theoretical and measured cross sections and from data-driven methods. The 7 TeV p-p results are used because there are very little p-p data available at 2.76 TeV and not any at 5.02 TeV. The 7 TeV cross sections can be used as an upper limit for the estimation of the background contamination or the scaling with the center-of-mass energy from theoretical models.

The largest contribution is expected to be the $t\bar{t}$ process where both W bosons from the top quarks decay to muons. The top pair production cross section is measured to be 168 pb in p-p collisions at 7 TeV corrected for acceptance, efficiencies

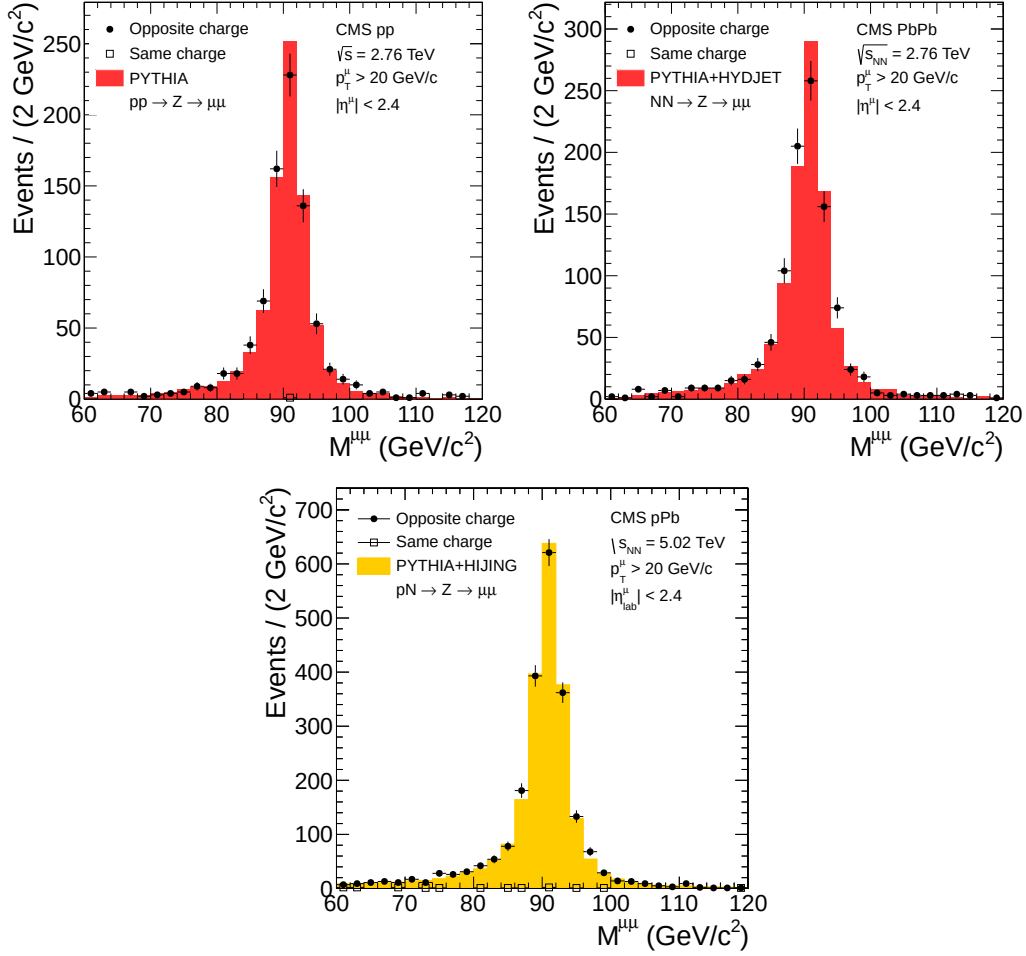


Figure 7.1: The invariant mass distribution of selected muon pairs from p-p, Pb-Pb and p-Pb collision data compared to simulations. The MC samples are normalized to the number of events in the data.

and branching fractions [111]. In the $t\bar{t}$ decay the probability for both W bosons to decay to leptons is about 10.5% that has to be divided by 9 for all the lepton combinations assuming lepton universality. This translates into about 2 pb cross section, that is compared to the $Z \rightarrow \mu\mu$ cross section of 968 pb at 7 TeV, giving about 0.2% $t\bar{t}$ contamination. If one assumes the same acceptance for muons in the two processes and the same ratio between cross sections at 5.02 TeV, the expected number of $t\bar{t}$ events is about 4.4 in the 2183 Z boson candidate events in p-Pb collisions. This is a conservative estimate because the cross section of $t\bar{t}$ production increases more with the center-of-mass energy than the Z boson production. In Pb-Pb collisions because of the smaller center-of-mass energy, 1–2 background events are expected for the 1022 signal events.

The $Z \rightarrow \tau\tau$ process has the same production cross section as the $Z \rightarrow \mu\mu$ but the probability for both τ leptons to decay to muons is $(17\%)^2 = 3\%$. However, the muons from the τ decays are softer than the ones directly coming from Z bosons, which makes the dimuon invariant mass lower for these events and only a few of

them will contribute in the 60–120 GeV/ c^2 mass region.

The diboson (WW, WZ, ZZ) production cross section is at least 3 orders of magnitude lower than the Z boson production cross section at 7 TeV [112, 113]. The smaller center-of-mass energy in p-Pb and Pb-Pb collisions makes this ratio even smaller, which means that only a few events would be produced and the probability of those events to produce two high p_T muons is negligible.

The W+jet production cross section with at least one jet with $p_T > 30$ GeV/ c is in the same order of magnitude as the Z boson production cross section as measured at 7 TeV [114]. However, the probability for a jet to contain a high p_T muon is quite small, which makes the W+jet contribution negligible. Looking at MC samples originally produced for jet studies with $p_T > 30$ GeV/ c jets confirms that the fraction of events containing at least one high p_T muon is of the order of 10^{-4} .

Finally, QCD processes producing multiple jets as well as c and b quarks decaying to high p_T muons have to be considered. The $p_T > 20$ GeV/ c cut on the muons removes most of the possible QCD background events that can be confirmed by looking at MC samples of c and b -jets. In the case of both Pb-Pb and p-Pb collisions the number of events fulfilling the Z boson selection requirements was less than one after taking into account the integrated luminosity of the datasets.

The background is treated differently in the analysis of the Pb-Pb and p-p data compared to the p-Pb data. In the case of Pb-Pb and p-p collisions, only the same-charge muon pairs are subtracted as background from the raw yield of Z bosons and other possible contributions are taken into account in the systematic uncertainties. In the case of p-Pb collisions because of the higher statistics, the background estimate has been improved by a data-driven method detailed hereafter and then subtracted from the raw yield.

All processes considered above can produce a high p_T electron instead of one of the muons, which can be estimated by the "e μ -method" as it was done in [35]. For $t\bar{t}$ -like processes, where leptons result from decays involving vector bosons, for every real opposite-charge dimuon event, from lepton universality one expects two electron-muon dilepton events. At first order the observed number of oppositely-charged electron-muon pairs in the Z boson mass range divided by 2 can be taken as the background to the $Z \rightarrow \mu\mu$ signal. This factor of 2 needs to be corrected for the difference in the efficiency of the electron and muon reconstruction and selection.

The p-Pb dataset is analyzed to determine the number of electron-muon pairs in the Z boson mass range. The events are selected with the *HLT-PAMu12* trigger to have one high p_T muon in the event. The muons are selected with the tight identification criteria detailed above and the electrons are selected by a cut based electron identification developed for p-p collisions [84]. The leptons are required to have $p_T^{e/\mu} > 20$ GeV/ c , $|\eta^{e/\mu}| < 2.4$ and opposite charge. The efficiency of the

selected electrons is about 76.8% determined from $Z \rightarrow ee$ simulation which has to be compared to the efficiency of the selected muons that fired the *HLT_PAMu12* trigger that is 88.4% from simulation. The number of background events is determined by dividing the number of selected electron-muon pairs with $2\epsilon^e/\epsilon^\mu = 1.74$.

The number of selected pairs in the Z boson mass range is 64 in the full p-Pb dataset. As discussed above, the number of background events to the $Z \rightarrow \mu\mu$ sample is $1/1.74$ times this number, namely 37 background events compared to the 2183 signal events. Comparing this number to the cross section estimations above, the number of background events seems to cover all possible contributions.

Additional check was done with the same-charge muon pairs in the Z boson mass range, to see if there are any p_T or y bins where the same-charge pairs are concentrated. The expected number of muon pairs in the Z boson selection from QCD multijet events is negligible but they could be produced in specific regions at low p_T and forward rapidities. QCD multijet processes are expected to produce similar number of same-charge and opposite-charge muon pairs. For this reason, the observed number of same-charge pairs in data are subtracted as background in the bins of p_T and y . The number of same-charge pairs is 16 in the full p-Pb data sample and they are distributed evenly between the bins of the analysis. No pairs are observed in the most forward/backward rapidity bin or in the highest p_T bins.

For better understanding the source of the background, isolation requirements are applied. The muon is considered isolated if the sum of the transverse energy of all other particles within a cone centered around the muon is small compared to its transverse momentum. With isolation cuts on the muons the QCD events are expected to get reduced significantly but not the $t\bar{t}$ and the electroweak processes. The isolation is calculated in a cone of $R = 0.4$ around the muon and the cut is applied at 20% of its p_T . Using this isolation cut, the number of Z boson candidates is reduced to 1921 and no same-charge pairs are found. The number of opposite-charge electron-muon pairs after isolating both the muon and the electron is reduced to 11 and no same-charge pairs are found. These results show that the main background contribution is coming from QCD multijet events that is removed by the $e\mu$ -method and same-charge muon pairs.

In order to perform the background subtraction in bins of y and p_T of the Z bosons, background MC samples for the $t\bar{t}$, $Z \rightarrow \tau\tau$ and QCD processes were produced to estimate the shape of the background distributions. The goal is to normalize the MC samples with a method based on data in order to calculate the background in each p_T and y bin. For this, the number of oppositely-charged muon (electron-muon) pairs in the 60–120 GeV/ c^2 mass range fulfilling all selection criteria are counted in both data and MC samples. To estimate the contribution of QCD events, the number of isolated muon (electron-muon) pairs are also counted.

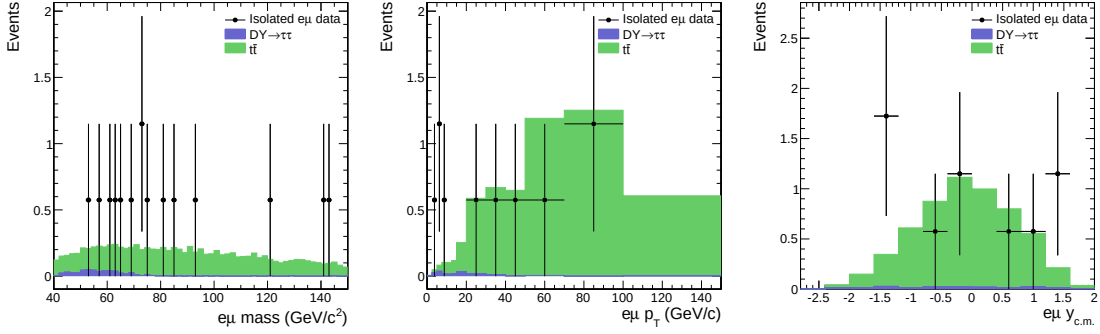


Figure 7.2: The invariant mass, p_T and y of isolated electron-muon pairs from data compared to isolated muon pairs in the background MC samples.

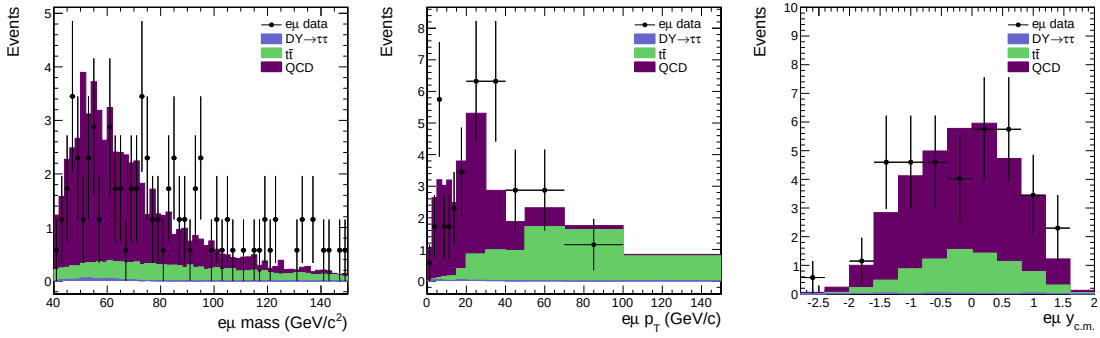


Figure 7.3: The invariant mass, p_T and $y_{c.m.}$ of electron-muon pairs from data compared to muon pairs in the background MC samples.

As discussed before, the isolation requirement removes the background events from QCD multijet processes that is also shown with the MC sample.

The $Z \rightarrow \tau\tau$ sample is normalized the same way as the $Z \rightarrow \mu\mu$ sample namely, to the number of oppositely-charged muon pairs in the 80–100 GeV/c^2 mass range and taking into account the branching ratio. In addition to the small 3% probability, the invariant mass of the muon pair in the event is smaller than the Z boson mass because of the momentum taken away by the neutrinos, thus the contribution of $Z \rightarrow \tau\tau$ events to the background is very small.

After fixing the normalization of the $Z \rightarrow \tau\tau$ sample, the $t\bar{t}$ sample is normalized with the isolated electron-muon pairs found in data. The mass, p_T and y of isolated electron-muon pairs in data are compared to the isolated muon pairs found in the $t\bar{t}$ and $Z \rightarrow \tau\tau$ MC samples in fig. 7.2. The 60–120 GeV/c^2 mass range is selected for the p_T and y figures as well as for the normalization, but in the left-hand side of the figure lower masses are also shown to demonstrate the good description of the background. Note that the $e\mu$ events are weighted by the ratio of electron and muon efficiencies as described previously.

The last step is to normalize the QCD sample to the non-isolated $e\mu$ data, taking into account the contributions from the other background sources. Fig. 7.3 shows

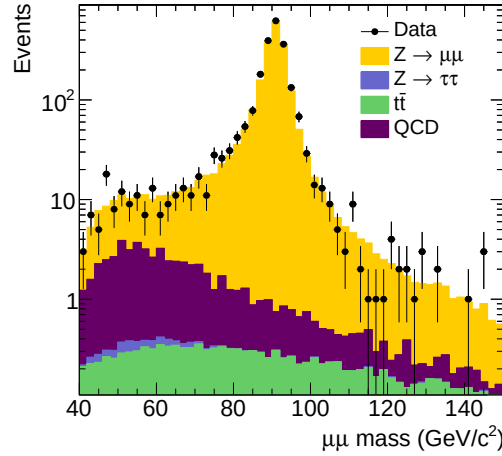


Figure 7.4: The invariant mass of muon pairs from p-Pb data compared to the signal plus background simulation.

the non-isolated $e\mu$ data compared with the background MC samples for the mass, p_T and y of the lepton pairs. The 60–120 GeV/c^2 mass range is selected for the p_T and y figures as well as for the normalization, but lower masses are also shown in the left-hand side of the figure to demonstrate the good description of the background.

Finally, the mass distribution of the oppositely-charged muon pairs in data is compared with the signal and background contributions from MC simulations in fig. 7.4. After normalization and taking into account the differences in electron and muon efficiencies, the number of background events is subtracted from the signal in each p_T and y bin together with the number of same-charge muon pairs.

7.3 Comparison of data and simulation

Before using the simulations to correct the data, one has to compare the basic reconstructed quantities between the simulation and the data to check the validity of the corrections. In the following, the p-Pb data is compared with PYTHIA+HIJING simulation that is the main MC sample used for the corrections. Similar conclusions were drawn from the comparisons in the case of Pb-Pb collision data and PYTHIA+HYDJET simulations [108].

The first quantity studied is the z position of the primary vertex, which is shown in fig. 7.5. Because the distributions show a large difference, the simulation needs to be reweighted according to the z position of the primary vertex. The weights are determined by fitting both the data and MC distributions with a single Gaussian as shown in fig. 7.5. In the following the events in the MC samples get a weight that corresponds to the ratio of the two functions.

Fig. 7.6 shows the centrality and HF E_T distributions in events where we require

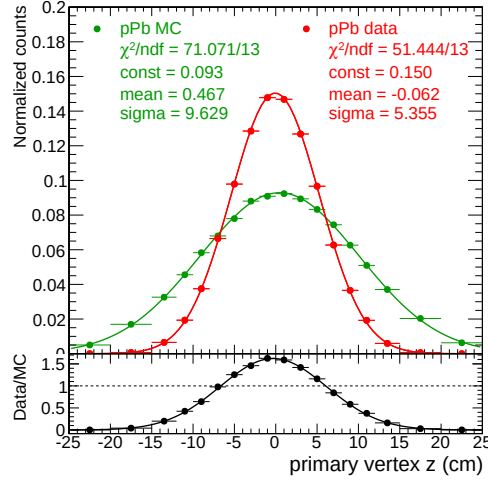


Figure 7.5: The z position of the primary vertex compared in data and simulation and the fitted functions used for the reweighting.

at least one good quality muon with $p_T > 15$ GeV/ c . The non-embedded signal sample is shown only for illustration, to demonstrate the effect of the p-Pb environment. The centrality distribution comes from slicing the HF E_T distribution in minimum bias events as described in Chapter 6. The centrality bin distribution for minimum bias events is flat by construction, however, the requirement of a high p_T muon biases this distribution because a hard scattering is more probable to happen in more central collisions. The centrality bin distribution is used for reweighting the embedded MC events to match the distribution in data. This procedure is used in order not to depend on the HF energy calibration, because the MC and data bin boundaries are determined separately from minimum bias data and MC samples. The effect of the centrality weighting is studied on the efficiencies but no difference is found with and without weighting. The centrality bin distribution and the vertex z position weights are assumed to be independent and the event weight is the product of the two.

After applying these event weights, the basic dimuon quantities can be studied. The dimuon invariant mass distribution from p-Pb data and simulation is compared already in fig. 7.4 and shows a good agreement. Fig. 7.7 shows the transverse momentum distribution of Z boson candidates from p-Pb data and simulation. The two beam directions are shown separately for data and MC together with their ratio. The data and simulation show a reasonable agreement in both the high and low p_T regions considering the limited statistics in the data sample. This agreement allows for using PYTHIA+HIJING simulation to correct for bin migration and resolution effects as well as for reconstruction efficiencies. In the case of Pb-Pb and p-p data at 2.76 TeV such an agreement is not observed because the Z+jet process was generated by PYTHIA not the simple Z boson production. In order to match the p_T distribution between data and simulation, the generated events were reweighted

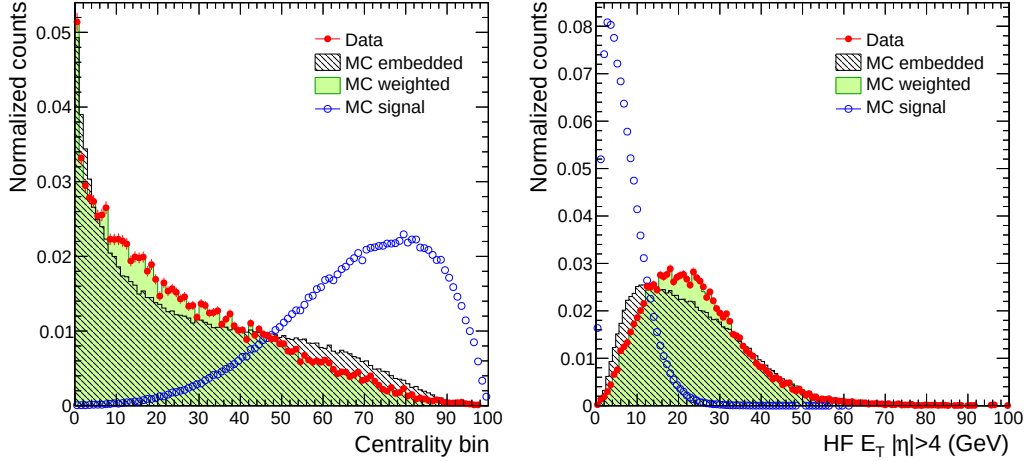


Figure 7.6: *Left:* Centrality distribution compared in data and the different MC simulations (events with at least one $p_T > 15$ GeV/c good quality muon). *Right:* HF transverse energy distribution used for the centrality binning compared in data and simulations. Also shown is the embedded MC simulation reweighted to match the data.

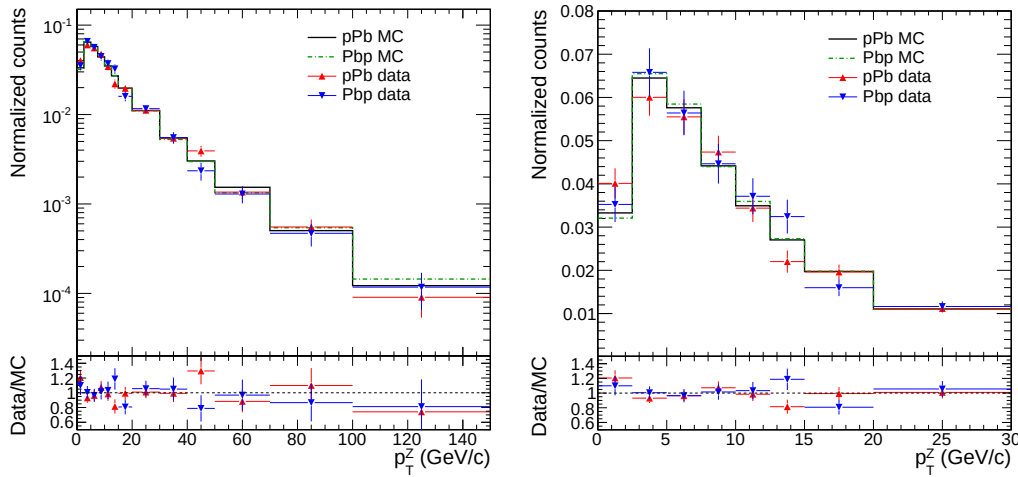


Figure 7.7: Transverse momentum distribution of Z bosons comparing PYTHIA+HIJING simulation and p-Pb data, separately for the two different beam directions.

according to the Z boson p_T distribution at 2.76 TeV predicted by POWHEG and then used for calculating the corrections for resolution and efficiencies.

Fig. 7.8 shows the rapidity (shifted to center-of-mass frame) and the azimuthal angle distributions of Z boson candidates from p-Pb data and simulation. The ϕ distribution agrees with the data within the statistical uncertainties and is not studied further. The rapidity distribution shows large statistical uncertainties and fluctuations between data and MC or between the different beam directions. Since the Z boson production as a function of rapidity is an important observable in this analysis, these differences have been studied further. No issues are found with specific regions of the detector and the differences between data and simulation are taken into account in the systematic uncertainties as described in Section 7.8. In

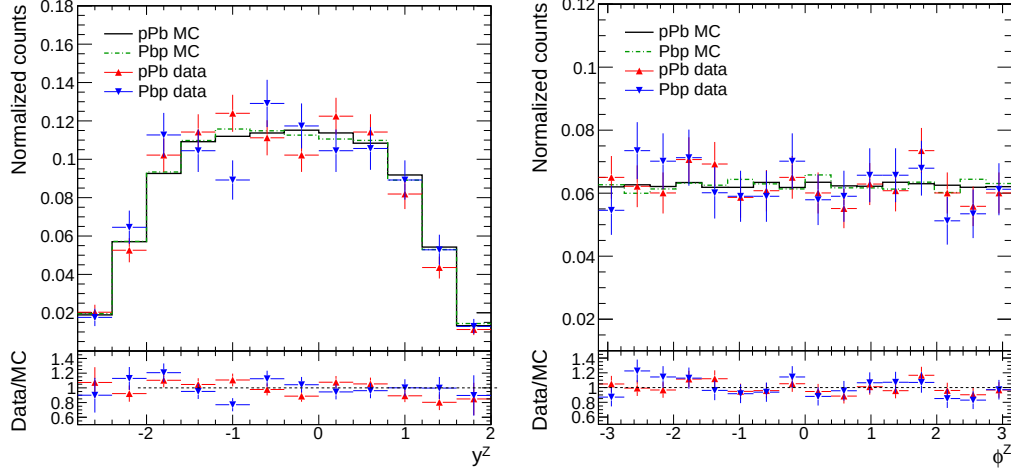


Figure 7.8: Rapidity (*left*) and azimuthal angle (*right*) distribution of Z bosons comparing PYTHIA+HIJING simulation and p-Pb data, separately for the two different beam directions.

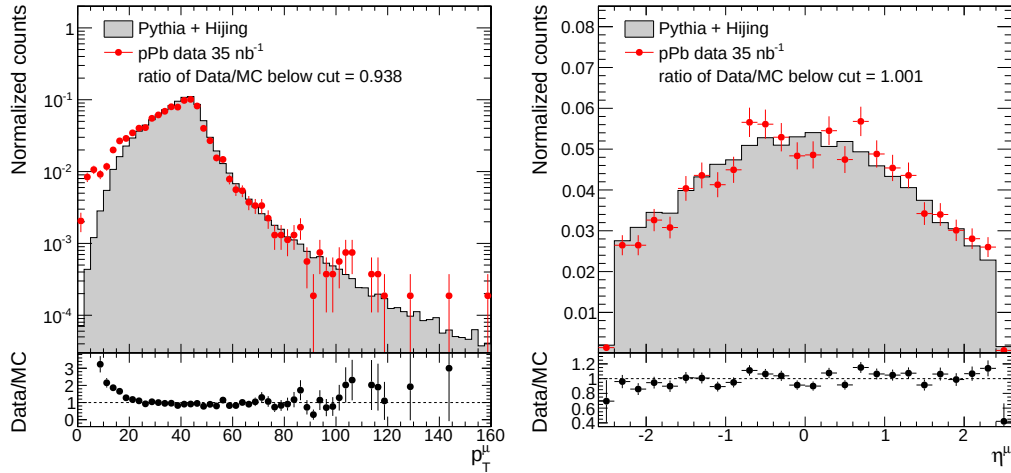


Figure 7.9: Single muon transverse momentum (*left*) and pseudorapidity (*right*) distribution of muons coming from Z bosons comparing PYTHIA+HIJING simulation and p-Pb data. All the quality and acceptance cuts are applied for the muons except the one on the variable shown.

summary, the basic kinematical distributions of the reconstructed dimuons agree between data and simulation within the statistical uncertainties.

To improve the statistical precision, the events from the two different beam direction are merged for the following single muon quantities. Fig. 7.9 shows the single muon transverse momentum and pseudorapidity distributions for muons coming from Z boson candidates. The quality cuts and the trigger matching is applied for the muons but no cut is applied for the variable plotted. The transverse momentum distribution shows an excess in the low p_T region from background muons which are removed by the $p_T > 20$ GeV/c acceptance cut. Above 20 GeV/c the data and simulation show a good agreement. The η of the muons in the second running period

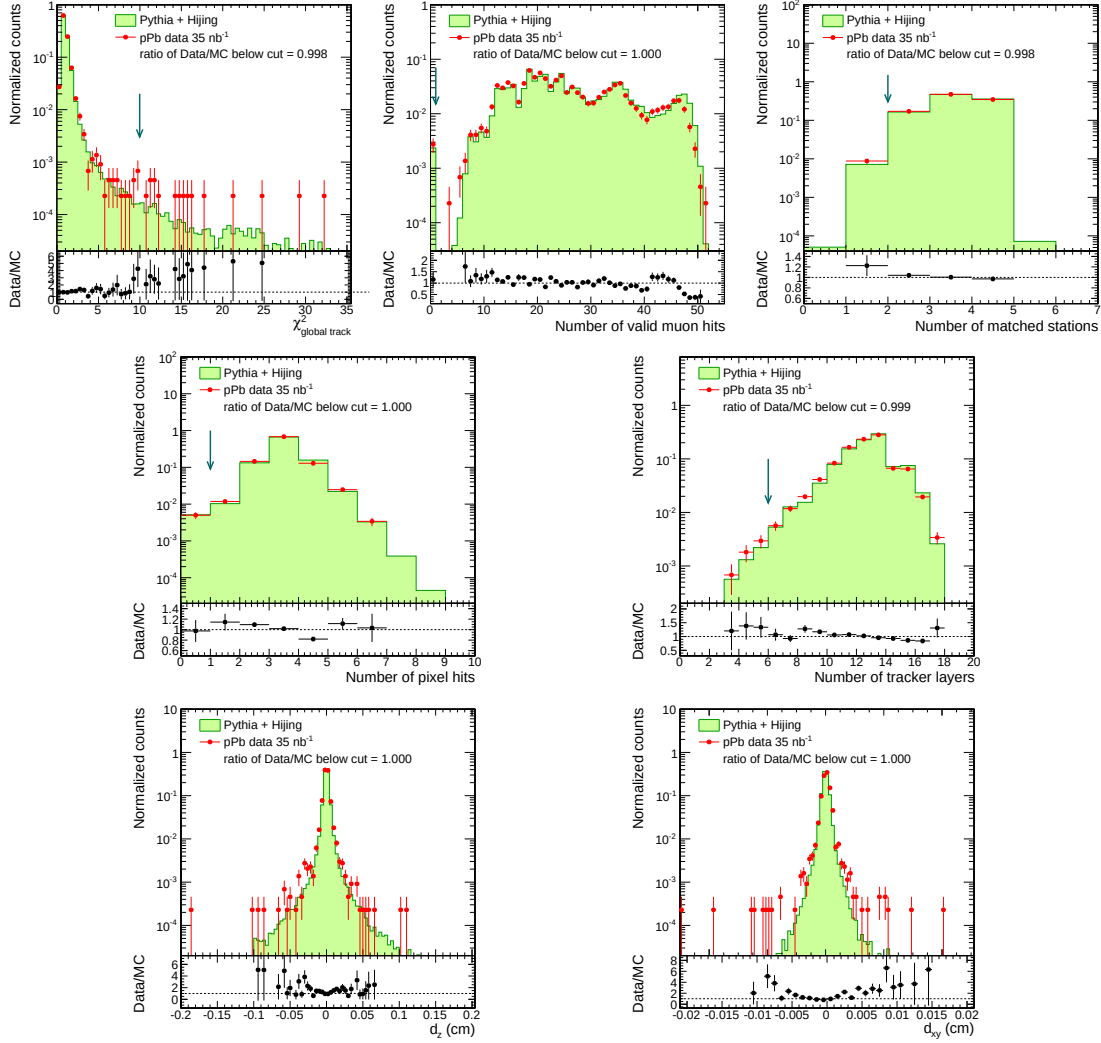


Figure 7.10: Muon quality variables of muons coming from Z candidates compared in MC and data. For every plot all the quality cuts are applied except the one under study.

was flipped because of the beam direction change. The η distribution of tight muons coming from Z boson candidates is in agreement between data and simulation.

Fig. 7.10 shows the variables used in the muon quality selection for muons coming from Z boson candidates in data and simulation. The acceptance cuts, the trigger matching and the quality cuts are applied for the muons except the cut on the variable studied. The cut values are shown in the figure with arrows to demonstrate that only a few muons fail the tight quality requirements. For the d_z and d_{xy} distributions the cut values are outside of the plotted range but there are no muons that fail only these quality cuts. The overall agreement between data and simulation is satisfactory and agrees with the more detailed muon performance studies from p-p collisions at 7 TeV [81].

7.4 Acceptance

The acceptance solely depends on the generator used for simulating the Z boson production. It provides an extrapolation factor to the full phase space from the region where Z boson identification is possible with the CMS detector. The acceptance is defined by the following equation

$$\alpha = \frac{N_{\text{gen}}^Z(|\eta^\mu| < 2.4, p_T^\mu > 20 \text{ GeV}/c)}{N_{\text{gen}}^Z}, \quad (7.2)$$

where N_{gen}^Z is the number of generated dimuons in the 60–120 GeV/ c^2 mass range. In the case of Pb-Pb and p-p collisions, the acceptance is calculated for Z bosons in the $|y| < 2$ range applying this selection in both the numerator and denominator of eq. (7.2).

The acceptance is calculated from PYQUEN+HYDJET simulation for Pb-Pb and from PYTHIA generator for p-p collisions at 2.76 TeV after applying the weights according to the primary vertex z position and the generated p_T of the Z bosons. The generated p_T distribution is reweighted to match the one given by the POWHEG generator because that gives a better description of the data than PYTHIA. The integrated acceptance in the $|y| < 2$ region is 0.707 at 2.76 TeV. In p-Pb collisions at 5.02 TeV the POWHEG simulation is used directly to evaluate the acceptance. The events are boosted to the laboratory frame due to the different beam energies and reweighted to match the primary vertex z distribution in data. The total acceptance is 0.516 for Z bosons in the 60–120 GeV/ c^2 mass range.

When calculating the acceptance as a function of transverse momentum and rapidity, the selection is applied in both the numerator and denominator of eq. (7.2). As an example, fig. 7.11 shows the acceptance calculated from POWHEG for boosted events at 5.02 TeV as a function of p_T and y in the center-of-mass frame. The asymmetry as a function of rapidity is due to the acceptance cut on the muon pseudorapidity being symmetric in the laboratory frame and not in the center-of-mass frame. This is not the case in Pb-Pb and p-p collisions where the system is symmetric around $y = 0$, therefore the quantities appearing in eq. (7.1) are evaluated as a function of $|y|$.

As visible also from eq. (7.2), the acceptance depends only on the generated distributions and the theoretical assumptions used in the simulation. There is no single event generator that gives the best calculation for both electroweak and QCD processes, not to mention the nuclear modification of these. For this reason, several effects are studied in order to estimate the systematic uncertainty associated with the acceptance correction.

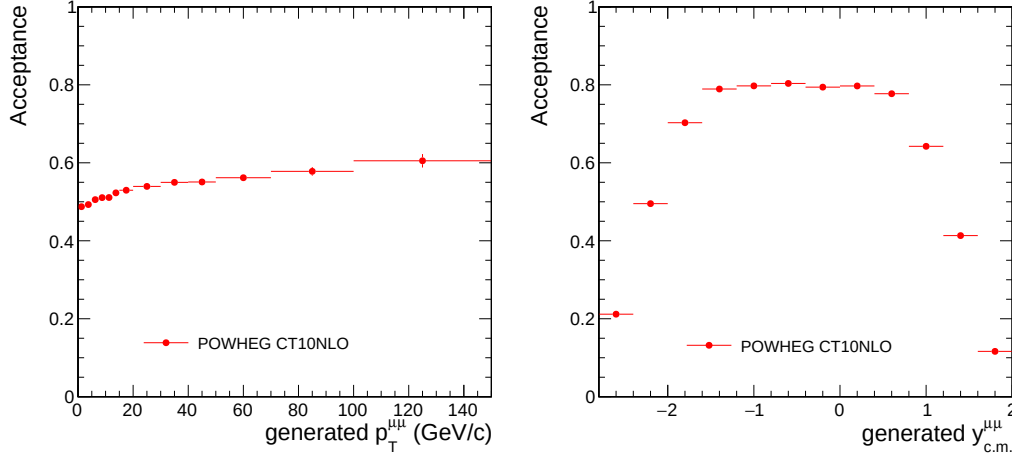


Figure 7.11: The acceptance for Z bosons in p-Pb collisions as a function of p_T (*left*) and y in the centre-of-mass frame (*right*) calculated from the POWHEG generator.

7.5 Efficiency

The efficiency expresses the fraction of Z bosons that get reconstructed and identified from the generated Z bosons in the fiducial region, where both muons fulfil the acceptance requirements. It is determined from MC samples using both the generator level information and the detector simulation. Because the data and simulation are not in perfect agreement, a data-based efficiency calculation is used to determine a correction factor to the efficiency from simulation. These scale factors are determined by applying the tag-and-probe method on both data and simulation in order to calculate single muon efficiencies. In the following, first the single muon efficiency calculation is presented and compared between data and the corresponding simulations, then the dimuon efficiency calculation from simulation is summarized.

7.5.1 Single muon efficiencies with tag-and-probe method

The tag-and-probe method is frequently used in CMS for estimating tracking and muon efficiencies in an almost unbiased way [81, 82]. It is based on decays of known resonances such as the $J/\psi \rightarrow \mu\mu$ or the $Z \rightarrow \mu\mu$ when the muons forming a peak verify that real muons are detected. Events are selected with strict selection requirements on one muon (the "tag" muon) and with a more relaxed selection on the other muon (the "probe" muon), such that the selection applied to the probe muon does not bias the efficiency that one wants to measure. The fraction of probe muons that pass the selection under study gives an estimate of its efficiency:

$$\epsilon_\mu = \frac{N_{\text{passing}}}{N_{\text{passing}} + N_{\text{failing}}} , \quad (7.3)$$

where N is the number of probe muons.

The single muon efficiencies are studied in data and simulation using the tag-and-probe method, in order to determine a correction for the detector simulation. The overall single muon efficiency is split into three parts:

$$\epsilon_{\mu} = \epsilon_{\text{tracking}} \cdot \epsilon_{\text{ID}} \cdot \epsilon_{\text{HLT}} , \quad (7.4)$$

where $\epsilon_{\text{tracking}}$ is the inner tracking efficiency, ϵ_{ID} is the tight muon identification efficiency and ϵ_{HLT} is the efficiency of the single muon trigger. The probes for each step should be defined to be the passing probes for the previous step to take into account the correlations between the different efficiencies. In the following, the details of the single muon efficiency calculation are presented for p-Pb collisions.

The tag muons for each efficiency are defined as global muons that pass the tight quality requirements, are matched to the *HLT_PAMu12* trigger and have $p_{\text{T}} > 15$ GeV/ c within the muon acceptance $|\eta| < 2.4$. In all cases the simulated events are reweighted according to the primary vertex z position and the centrality bin to match the distributions observed in data as described in Section 7.3.

Inner tracking efficiency

To measure the tracking efficiency in the silicon tracker, the probe muons are defined as standalone muons that have at least one valid hit in the muon stations. The momentum measurement of the standalone muon is forced to be taken from the muon stations alone, which gives a bad resolution for the Z boson mass peak. The passing probes are defined as standalone muons that are matched to a reconstructed track in the inner tracker. The association is done with a cut on the geometrical position, namely $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$. Each tag and probe pair is required to have an opposite charge and an invariant mass within the 40–140 GeV/ c^2 range. The wider mass range is necessary because of the poor momentum resolution of the standalone-muon reconstruction.

The efficiency is calculated by fitting separately (simultaneously) the invariant mass distribution from tags paired with passing and failing probes in MC (data). The Z boson signal is fitted with the sum of two Voigt functions (convolution of a Gaussian and a Lorentz function) and the non-resonant background is fitted with an exponential. An example for the mass fits in data and MC is shown in fig. 7.12.

The results of the fitted efficiencies are shown in fig. 7.13 as a function of muon η^{μ} , p_{T}^{μ} and event centrality. The overall efficiency quoted on the plot for data and MC is calculated for muons within $|\eta^{\mu}| < 2.4$ and $20 < p_{\text{T}}^{\mu} < 100$ GeV/ c . The tracking efficiency is higher than 99% for $p_{\text{T}} > 20$ GeV/ c muons both in data and simulation, which is consistent with previous results from p-p collisions at 7 and 8 TeV [82].

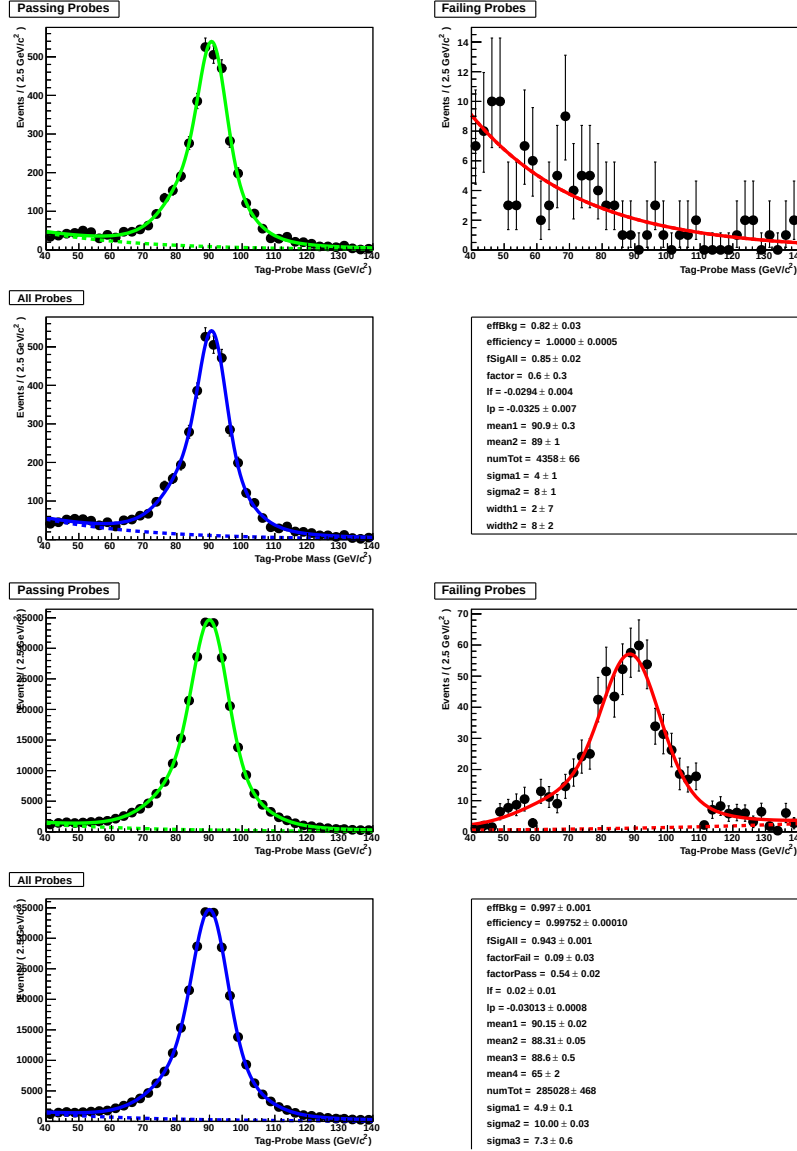


Figure 7.12: Tag-and-probe mass fit for inner tracking efficiency of single muons from data (*top*) and simulation (*bottom*) in the inclusive bin ($p_T^\mu > 20$ GeV/c, $|\eta^\mu| < 2.4$).

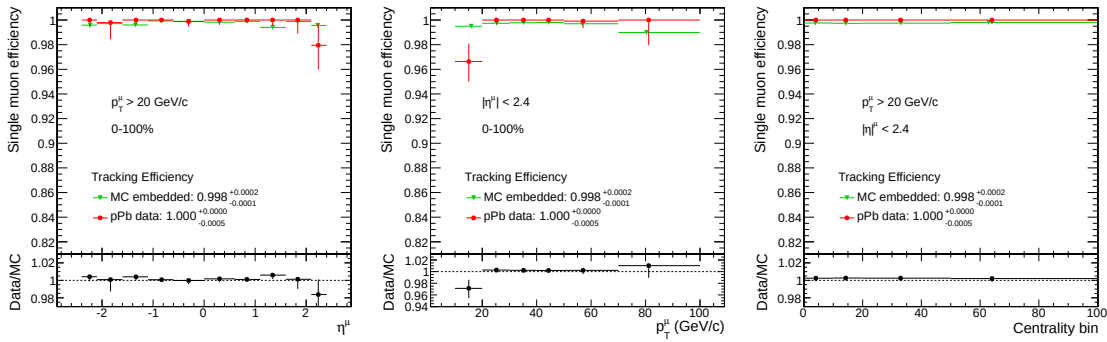


Figure 7.13: Inner tracking efficiency for single muons from data and simulation as a function of η^μ , p_T^μ and event centrality.

Muon identification efficiency

For the muon identification efficiency of the tight muon selection, the probes are all tracks reconstructed in the tracker. The passing probes are the muons that fulfil all the selection criteria defined by the tight identification cuts in Section 7.1. Note that this definition implicitly includes the efficiency for matching a track to the standalone muon. Each tag and probe pair is required to have an opposite charge and an invariant mass within the 60–120 GeV/ c^2 range.

The efficiency is calculated by a simultaneous fit to the invariant mass of the passing and failing probes paired with the tag muons. The Z boson signal is fitted with a Breit-Wigner function convoluted with a Crystal-Ball function and the background from non-muon tracks is fitted with an exponential. An example for the mass fits in data and MC is shown in fig. 7.14.

The results of the fitted efficiencies are shown in fig. 7.15 as a function of muon η^μ , p_T^μ and event centrality. The overall efficiency quoted on the plot for data and MC is calculated for muons within $|\eta^\mu| < 2.4$ and $20 < p_T^\mu < 100$ GeV/ c . The muon identification efficiency is about 96% for $p_T > 20$ GeV/ c muons both in data and simulation, which is consistent with previous results from p-p collisions at 7 and 8 TeV.

The identification efficiency is investigated further because the background is very high in the failing probe mass fits which results in high uncertainties. To reduce the uncertainties of the scale factors, the identification efficiency was redefined in a simple way. The probes were chosen to be tracker muons (where the inner track is already matched to muon segments) and the passing probes are the same tight id muons. The fitting is done in the same way and the results for the efficiency are shown in fig. 7.16 as a function of η^μ , p_T^μ and event centrality. As expected the statistical fluctuations of the efficiencies determined from data are reduced and the scale factors show little dependence on the kinematical variables.

Trigger efficiency

In order to measure the trigger efficiency of the single muon trigger *HLT_PAMu12*, the probes are muons that fulfil the tight identification criteria, and the passing probes are the ones also matched to the trigger. Each tag and probe pair is required to have an opposite charge and an invariant mass within the 60–120 GeV/ c^2 range.

The efficiency is calculated by a simultaneous fit to the invariant mass of the passing and failing probes paired with the tag muons. The Z boson signal is fitted with a Breit-Wigner function convoluted with a Crystal-Ball function and the background is fitted with an exponential. The mass distributions are very clean with negligible background as shown in fig. 7.17 that makes the results robust.

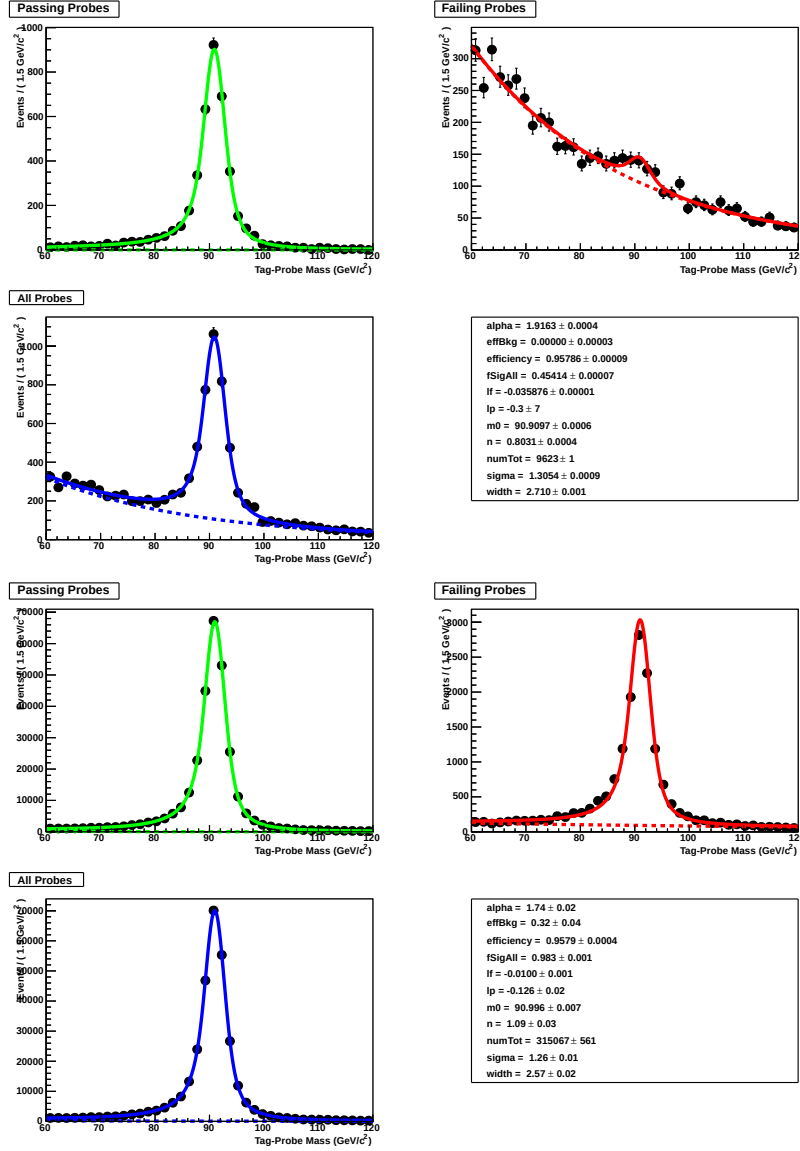


Figure 7.14: Tag-and-probe mass fit for tight muon identification efficiency from data (*top*) and simulation (*bottom*) in the inclusive bin ($p_T^\mu > 20 \text{ GeV}/c$, $|\eta^\mu| < 2.4$).

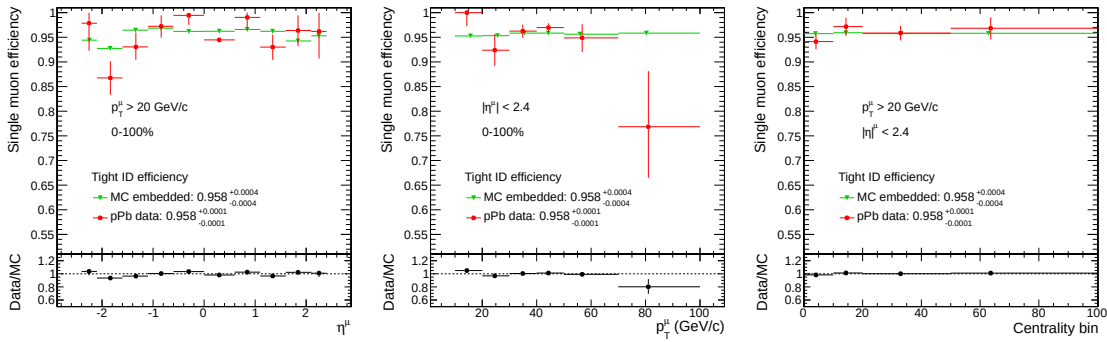


Figure 7.15: Muon identification efficiency for single muons from data and simulation as a function of η^μ , p_T^μ and event centrality.

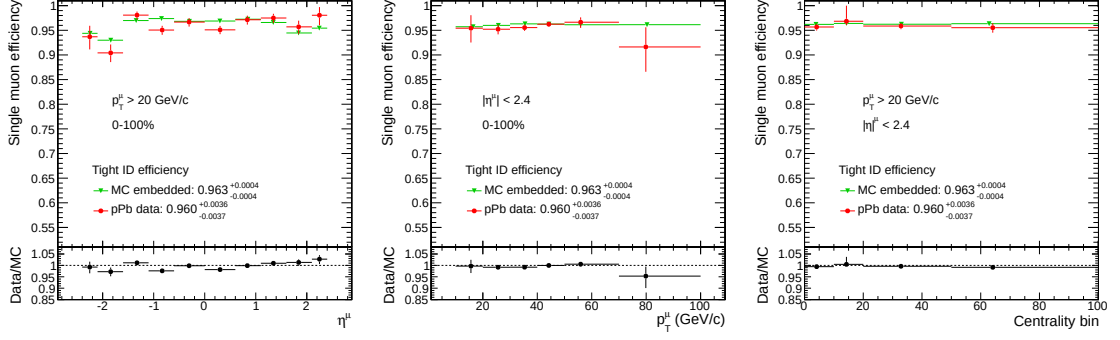


Figure 7.16: Muon identification efficiency (with tracker muon probes) for single muons from data and simulation as a function of η^μ , p_T^μ and event centrality.

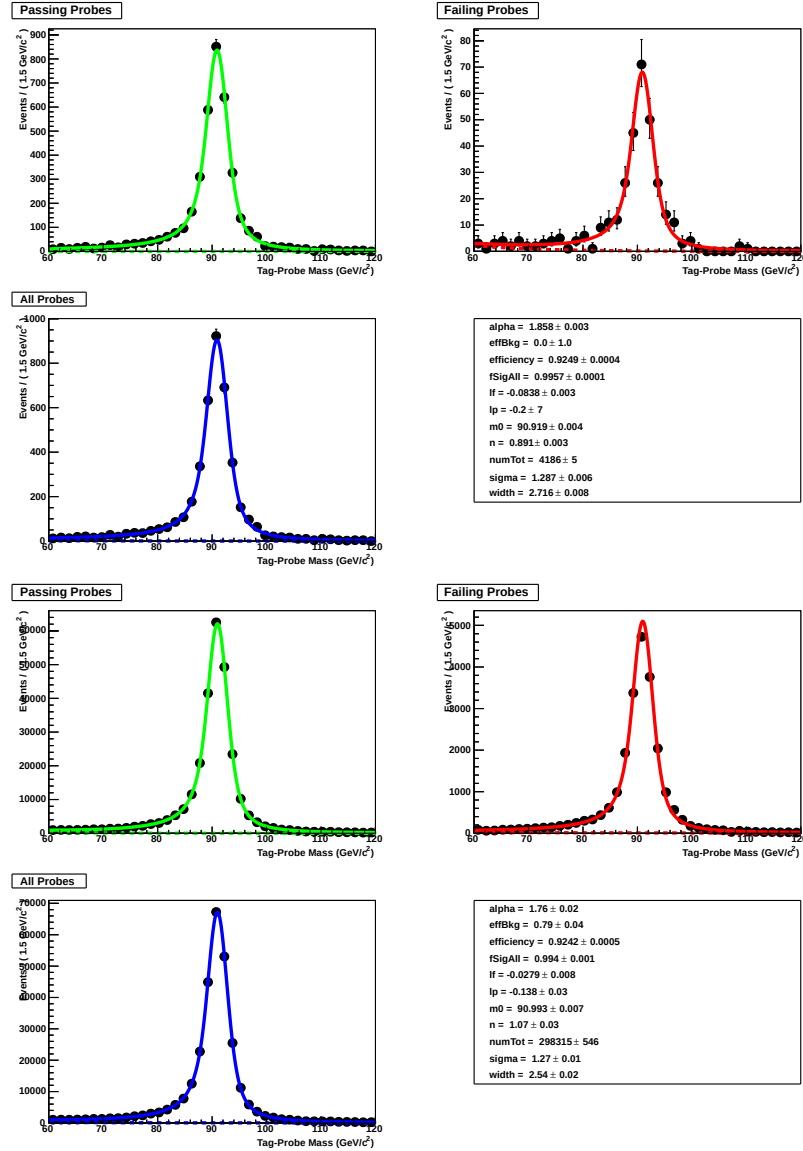


Figure 7.17: Tag-and-probe mass fit for single muon trigger efficiency from data (top) and simulation (bottom) in the inclusive bin ($p_T^\mu > 20$ GeV/c, $|\eta^\mu| < 2.4$).

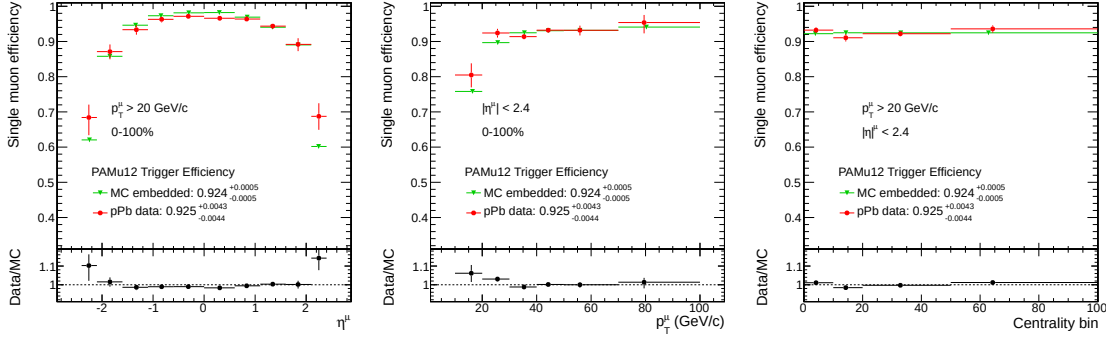


Figure 7.18: Efficiency of the *HLT_PAMu12* trigger from data and simulation as a function of η^μ , p_T^μ and event centrality.

The results of the fitted efficiencies are shown in fig. 7.18 as a function of muon η^μ , p_T^μ and event centrality. The overall efficiency quoted on the plot for data and MC is calculated for muons within $|\eta^\mu| < 2.4$ and $20 < p_T^\mu < 100$ GeV/c. The trigger efficiency is about 92.5% (92.4%) for $p_T > 20$ GeV/c muons in data (simulation), which translates into a very high efficiency for Z bosons if we take into account that only one of the muons is sufficient to trigger the event.

The trigger efficiency for Z bosons can be calculated by $1 - (1 - \epsilon_{\text{HLT}})^2$, which is 0.9944 from data and 0.9943 from simulation that translates into a scale factor for data–MC agreement of 1.0001. Because some η^μ dependence of the scale factors is visible, the effect of applying all scale factors on a muon-by-muon basis is investigated later.

Closure test

After calculating the components of the single muon efficiency by the tag-and-probe method, a closure test is performed to check if the single muon efficiency factorizes in these components. The single muon efficiency was calculated from simulation by taking the ratio of the number of reconstructed muons that fulfil the tight id cuts and the trigger matching over the number of generated muons in the acceptance. To compare with the tag-and-probe method, only events with at least one reconstructed tag muon were studied. The results of the two methods are compared in fig. 7.19 as a function of muon η^μ and p_T^μ .

The overall single muon efficiency is 88.3% from the tag-and-probe method and 88.4% from the generator level information. The difference is below 0.5% for every bin which is taken into account in the systematic uncertainty of the Z boson efficiency after applying the scale factors (see Section 7.8).

The identification efficiency was investigated with a different definition using tracker muon probes. In this case the factorization does not hold perfectly because of the missing efficiency of the stand-alone muon and track matching. The tag-and-

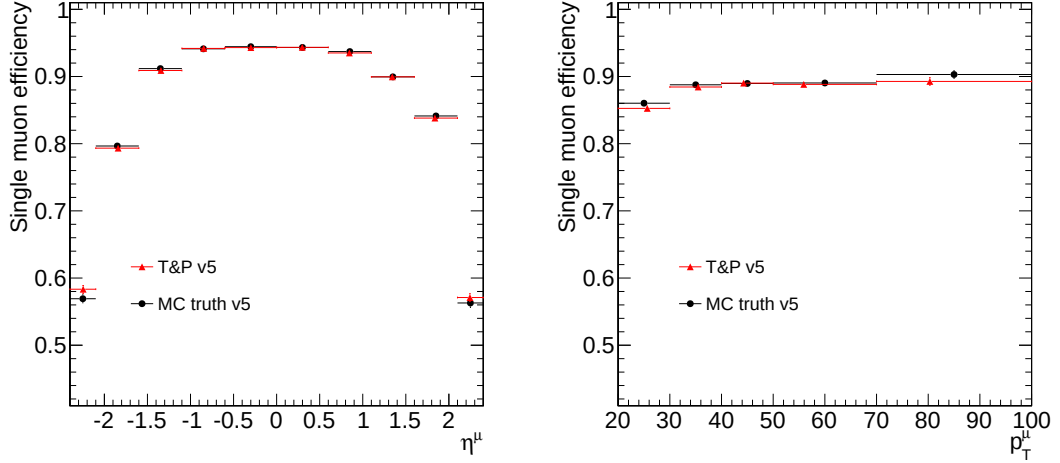


Figure 7.19: Single muon efficiency from the multiplication of the tag-and-probe efficiencies compared to the single muon efficiency using the generator level information from MC.

probe results are only used as data-simulation scale factors in the Z boson efficiency calculation. For this, one can assume that the tracker muon efficiency is described by the simulation and apply the scale factors calculated with the tracker muon probes. The uncertainty introduced by this assumption is also taken into account in the systematic uncertainties.

Additional check of the tag-and-probe results has been performed by comparing the two parts of the p-Pb dataset corresponding to the different beam directions. The difference between the resulting tag-and-probe efficiencies is within the statistical uncertainties in every bin.

Scale factors in Pb-Pb and p-p analyses

In the case of Pb-Pb and p-p collisions at 2.76 TeV, similar tag-and-probe efficiencies are calculated using data and simulation. The only difference is in the tracking efficiency that can not be probed with the simple geometrical matching criterion in the high multiplicity environment of Pb-Pb collisions. Thus it is calculated with stricter requirements on the passing probes and then compared between data and simulation. All three type of efficiencies agree between the Pb-Pb data and the PYTHIA+HYDJET simulation within a few percent. Because they show large statistical uncertainties when split into p_T^μ or η^μ bins, the integrated efficiencies are used to calculate an overall scale factor for the dimuon efficiency.

7.5.2 Efficiency from simulations

The efficiency is calculated from the embedded MC samples after applying the weighting for the primary vertex z position and for the centrality bin. The combined

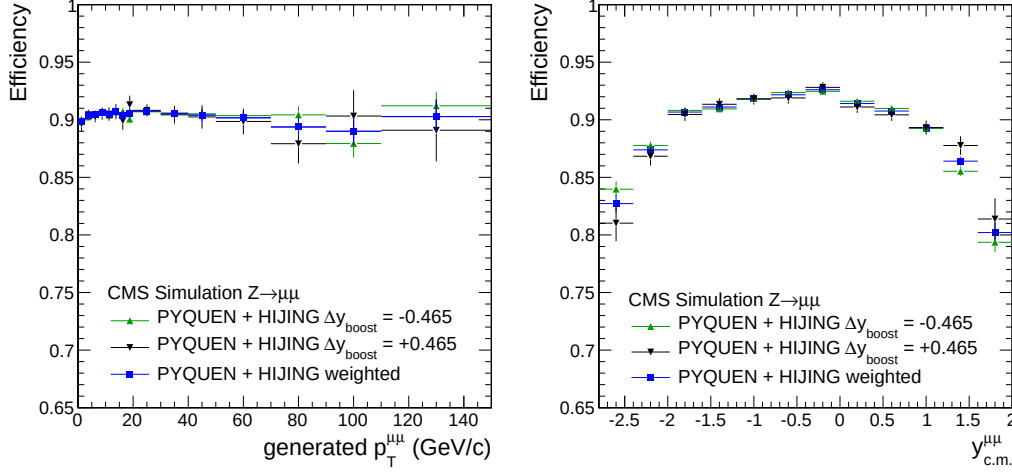


Figure 7.20: The combined reconstruction, muon identification and trigger efficiency for Z bosons as a function of transverse momentum and rapidity from PYTHIA+HIJING samples in the two beam directions and their weighted combination.

reconstruction, muon identification and trigger efficiency for Z bosons is defined as

$$\epsilon_{\text{MC}} = \frac{N_{\text{reco}}^Z(|\eta^\mu| < 2.4, p_T^\mu > 20 \text{ GeV}/c, \text{ selected})}{N_{\text{gen}}^Z(|\eta^\mu| < 2.4, p_T^\mu > 20 \text{ GeV}/c)}, \quad (7.5)$$

where the numerator is the number of selected Z boson candidates (reconstructed dimuon with mass in the 60–120 GeV/ c^2 range, where both muons fulfil the acceptance and quality requirements and one of them is matched to the trigger) and the denominator is equal to the numerator of eq. (7.2). In the case of Pb-Pb and p-p collisions the efficiency is calculated for Z bosons in the $|y| < 2$ range applying this selection in both the numerator and denominator of eq. (7.5).

It is important to note that in the numerator of eq. (7.5), reconstructed quantities are used for the values of the dimuon mass and rapidity and the single muon p_T and η , whereas in the denominator the generator level quantities are used. When binning in the Z boson transverse momentum both the reconstructed and generated Z boson events go into the generated p_T bin and the reconstructed p_T in data is unfolded before correcting for the efficiency. The details of these choices are given in Section 7.6 where the dimuon mass, rapidity and p_T resolution is studied.

Since the detector is not perfectly symmetric in the z direction, the two different beam configurations need to be taken into account when calculating the efficiency for p-Pb collisions. The PYTHIA+HIJING samples were produced with both beam direction settings, which can be used to determine the differences. For simplicity, the baseline efficiency is defined from a weighted combination of the two MC samples, where the amount of data in the two beam directions is taken into account. With the negative boost, the data collected correspond to 20.6 nb $^{-1}$, while with the positive boost they correspond to 14.0 nb $^{-1}$ integrated luminosity. The MC samples

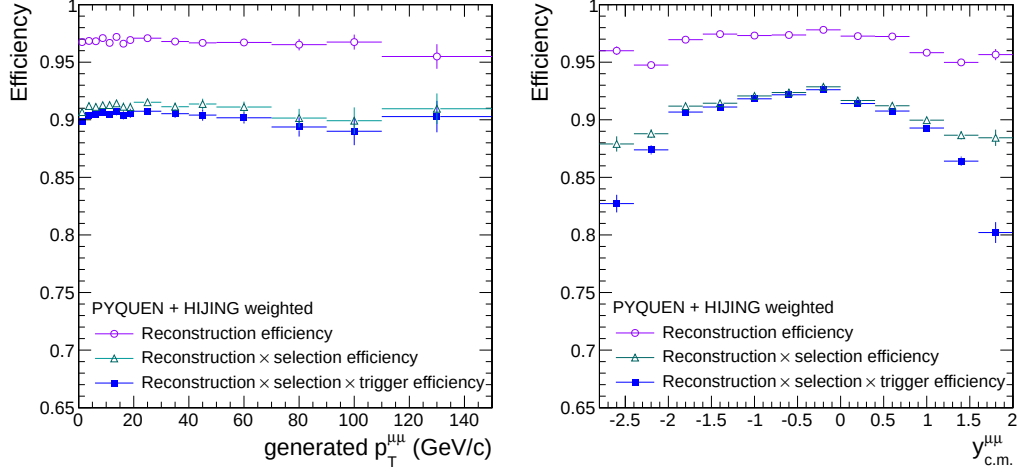


Figure 7.21: The combined reconstruction, muon identification and trigger efficiency for Z bosons as a function of transverse momentum and rapidity, applying the requirements after each other.

were weighted to correspond to an effective ratio of these values in the amount of generated events. Fig. 7.20 shows the efficiency as a function of the Z boson rapidity and transverse momentum from PYTHIA+HIJING samples in the two beam directions and their weighted combination.

The combined efficiency for reconstruction, identification and trigger matching is found to be 0.905 for Z bosons from PYTHIA+HIJING simulation. Fig. 7.21 shows the different components of the efficiency from simulation as a function of dimuon rapidity and transverse momentum. The different requirements are applied one after another: first a reconstructed dimuon is required in the Z boson mass range that fulfils the acceptance cuts, second the quality cuts are applied on the muons on top of the first, and at last the requirement of the trigger matching for one of the muons is applied. The transverse momentum dependence of the efficiency is found to be reasonably flat in the full range. The rapidity dependence shows a small drop of the efficiency from the midrapidity region to the forward/backward region from about 0.92 to 0.81.

Finally, the efficiency is corrected for the differences between data and simulation determined from the tag-and-probe method. The scale factors (ratio of efficiency from data and simulation) as a function of muon pseudorapidity are applied as weights to the reconstructed Z bosons muon-by-muon, which translates into the following:

$$\epsilon = \epsilon_{MC} \cdot SF(\eta_1^\mu) \cdot SF(\eta_2^\mu) , \quad (7.6)$$

where $SF(\eta^\mu)$ is the scale factor from either the tracking or the identification efficiency as shown in figs. 7.13 and 7.16. The scale factors as a function of p_T and centrality are taken to be flat that is a good approximation.

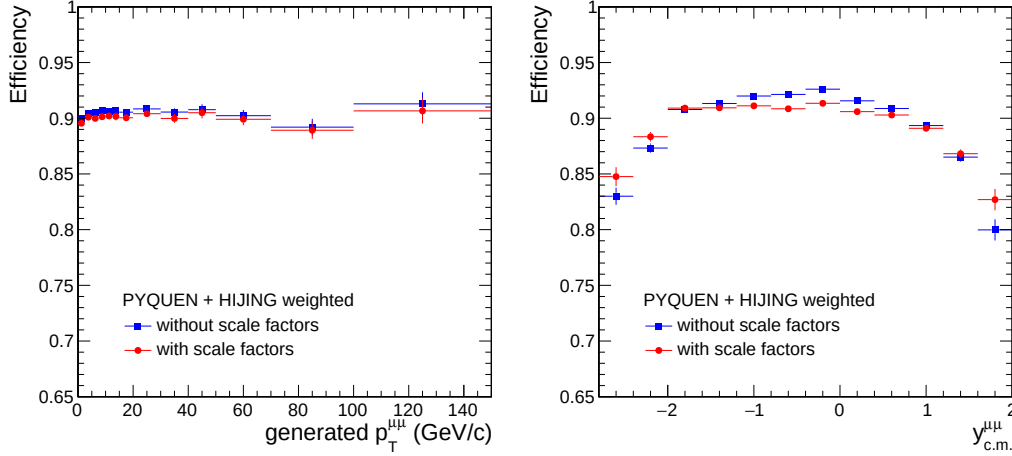


Figure 7.22: The combined reconstruction, muon identification and trigger efficiency for Z bosons in p-Pb collisions as a function of transverse momentum and rapidity before and after applying the scale factors from the tag-and-probe method.

The effect of scale factors from the tracking efficiency is small because they are very close to unity as shown in fig. 7.13. For muon identification efficiency, the scale factors using the tracker muon probes are used as shown in fig. 7.16 because they show less statistical fluctuation than the ones with all the tracks as probes in fig. 7.15. The overall change in the dimuon efficiency with both type of muon identification scale factors is similar, however the rapidity dependence gets distorted with the first definition thus the second one is used in the final results.

Applying the trigger efficiency scale factors needs further considerations because the trigger matching requirement is applied only on one muon leg of the Z boson candidate. The trigger efficiency for Z bosons was determined by the trigger simulation in the MC samples. The same can be calculated using the trigger efficiency for single muons determined from the tag-and-probe method applied on the MC simulation. Then the simulated trigger response is exchanged by resimulating the trigger efficiency by applying a weight to the reconstructed Z bosons as

$$weight = 1 - (1 - \epsilon_{\text{HLT}}(\eta_1^\mu)) \cdot (1 - \epsilon_{\text{HLT}}(\eta_2^\mu)). \quad (7.7)$$

The two methods are found to be in agreement, which gives confidence in the method of resimulating the trigger efficiency. In eq. (7.7) the single muon efficiency can be corrected with the scale factor from the tag-and-probe method in p-Pb data and simulation. When comparing the dimuon efficiency with and without scale factors, a difference appears in the most forward/backward rapidity bins, as expected from the tag-and-probe results on the single muon efficiency.

In summary, the efficiency for correcting the number of Z boson candidates in p-Pb data is calculated from the PYTHIA+HIJING simulation after applying scale

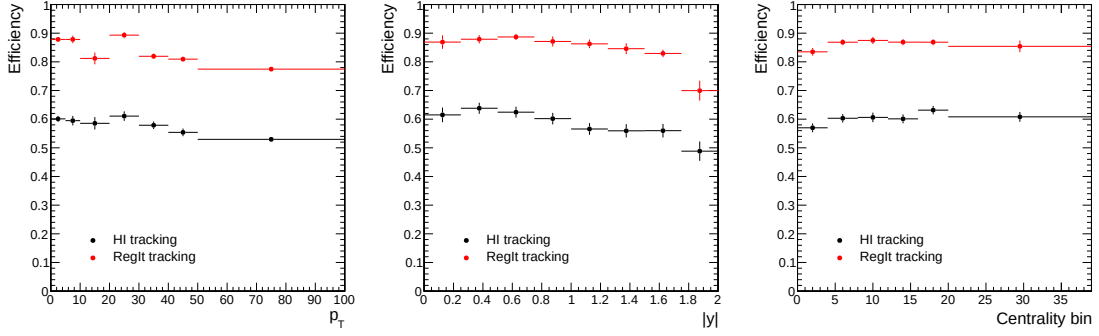


Figure 7.23: The efficiency for Z bosons in Pb-Pb collisions from PYTHIA+HYDJET simulation as a function of transverse momentum, rapidity and event centrality comparing the two muon reconstruction algorithms.

factors on each muon for the trigger, tracking and muon identification efficiencies determined from data. The final efficiency is shown in fig. 7.22 as a function of p_T and y compared to the one without scale factors. The integrated efficiency for Z bosons is 0.901 after applying the scale factors.

In the case of Pb-Pb collisions, PYTHIA+HYDJET embedded samples are used to evaluate the efficiency for identifying Z bosons. The integrated efficiency in the $|y| < 2$ region corrected with the scale factors from tag-and-probe is found to be 0.845 after applying the weights for the generated p_T , the vertex z position and the centrality distribution. Fig. 7.23 shows the efficiency from PYTHIA+HYDJET as a function of p_T , $|y|$ and event centrality for the two different muon reconstruction algorithms. As mentioned in Section 5.3, the final results are derived using the improved reconstruction algorithm called regional iterative (regit) tracking method that provides a large increase in the efficiency as demonstrated in the figure. In the case of p-p collisions, the efficiency is evaluated from PYTHIA simulation and found to be 0.885 for Z bosons in the $|y| < 2$ region.

7.6 Resolution effects and unfolding

The precision of the muon p_T assignment is limited by the finite precision of the particle position measurement in the detector. In the following, the effect of the muon p_T resolution on the reconstructed dimuon quantities is studied.

7.6.1 Mass resolution

The dimuon mass resolution can be studied by comparing the generated and the reconstructed dimuon mass. In the right-hand side of fig. 7.24 the $(M^{\text{gen}} - M^{\text{reco}})/M^{\text{gen}}$ distributions are shown in different Z boson p_T bins. The distributions in each bin are fitted with a Gaussian function, and the width of the Gaussian is plotted in the

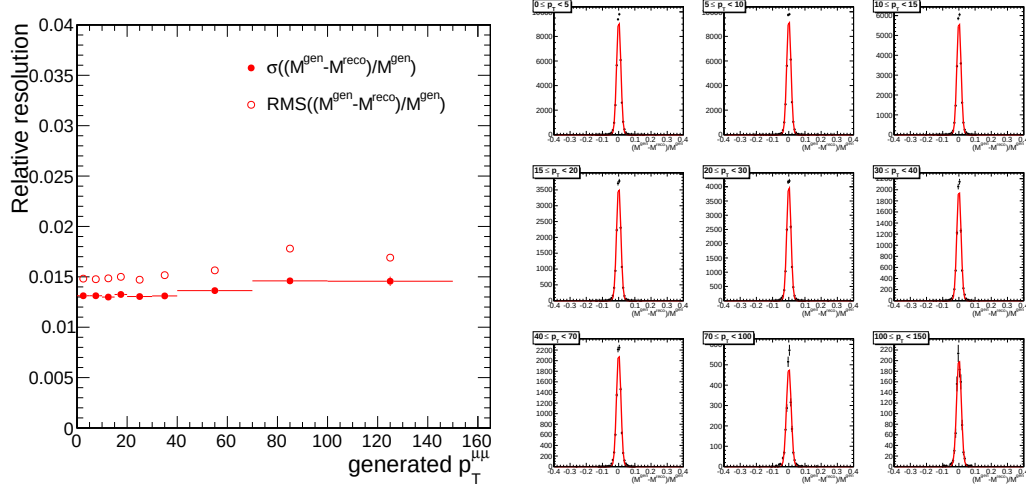


Figure 7.24: Mass resolution of Z boson reconstruction from PYTHIA+HIJING simulation as a function of transverse momentum (*left*) and the corresponding fits in the different bins (*right*).

left-hand side of fig. 7.24. Since the distribution is not necessarily described by a single Gaussian, the standard deviation (RMS) of the resolution distribution is also plotted in bins of the dimuon p_T .

The dimuon mass resolution of reconstructing Z bosons is of the order of 1.5% according to PYTHIA+HIJING simulation and does not show dependence on the dimuon transverse momentum. This value is small enough to take into account the mass resolution only in the efficiency corrections without additional unfolding. This is done by using the reconstructed mass in the nominator and the generated mass in the denominator of eq. (7.5).

7.6.2 Dimuon rapidity resolution

The dimuon rapidity resolution was studied the same way as the mass resolution. The rapidity resolution is not well described by a single Gaussian, which causes the RMS and the width of the fitted Gaussian function (σ) to be different, thus both the RMS and σ values are shown in the left-hand side of fig. 7.25 as a function of the dimuon p_T . The rapidity resolution is about 2% and does not depend on p_T . In the right-hand side of fig. 7.25 the absolute rapidity resolution is shown in bins of rapidity. There are some variations as a function of rapidity but the absolute resolution is below 0.008 for every bin, which is small compared to the bin size 0.4 of the analysis. The results are consistent between the two figures and confirm that it is enough to take into account the rapidity resolution effects in the efficiency calculation.

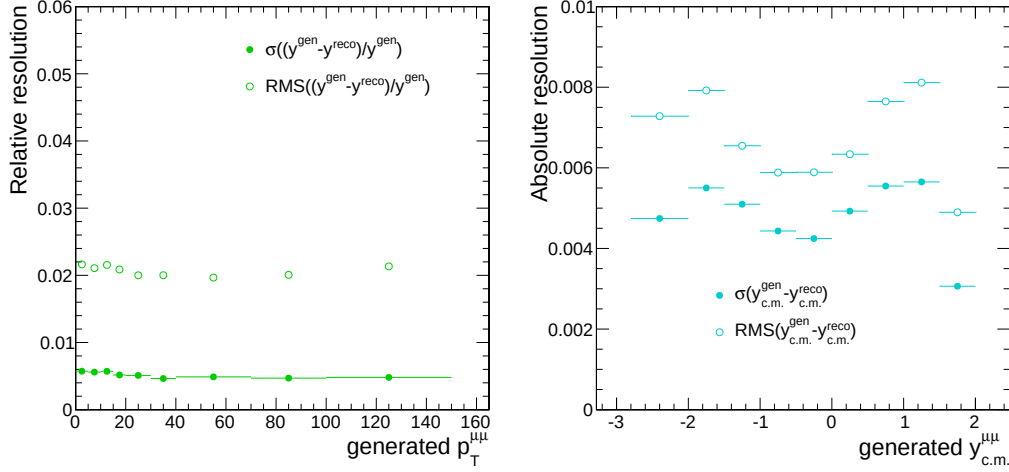


Figure 7.25: Dimuon rapidity resolution from PYTHIA+HIJING simulation: the relative resolution as a function of p_T (left) and the absolute resolution as function of y (right).

7.6.3 Dimuon transverse momentum resolution

Applying the same method for the dimuon p_T resolution as for the mass and rapidity, the resulting distributions in the different p_T bins already show that the dimuon p_T is highly affected by the finite detector resolution. The distribution of $(p_T^{\text{gen}} - p_T^{\text{reco}})/p_T^{\text{gen}}$ is not well described by a single Gaussian in the lower p_T bins thus the width of the fitted Gaussian and the RMS of the distribution in the different bins is shown in left-hand side of fig. 7.26. The p_T resolution for the lowest p_T bins is of the order of 30%, which means that the p_T spectrum has to be unfolded for resolution effects. Additionally, the absolute resolution of the dimuon p_T is calculated from the PYTHIA+HIJING simulation and shown in the right-hand side fig. 7.26 as a function of the dimuon p_T . The width of the fitted Gaussian gives an absolute dimuon p_T resolution of 0.6–1.6 GeV/c increasing with the dimuon p_T . The next section presents the details of the matrix inversion method used for unfolding the reconstructed Z boson p_T spectrum before applying the efficiency corrections.

7.6.4 Unfolding of the transverse momentum spectrum

As shown above, the muon p_T resolution directly affects the p_T of the Z boson, and as a result, some events from bin i of the "true" p_T spectrum end up in a different bin j of the measured one. The effect becomes particularly important in the low p_T portion of the spectrum, with bin sizes that are comparable to the resolution.

The dimuon p_T spectrum is unfolded with a simple matrix inversion technique, where the response matrix, $\underline{R}$, is constructed which describes the probability of an event to move from bin i (generated p_T) to bin j (reconstructed p_T). The unfolding

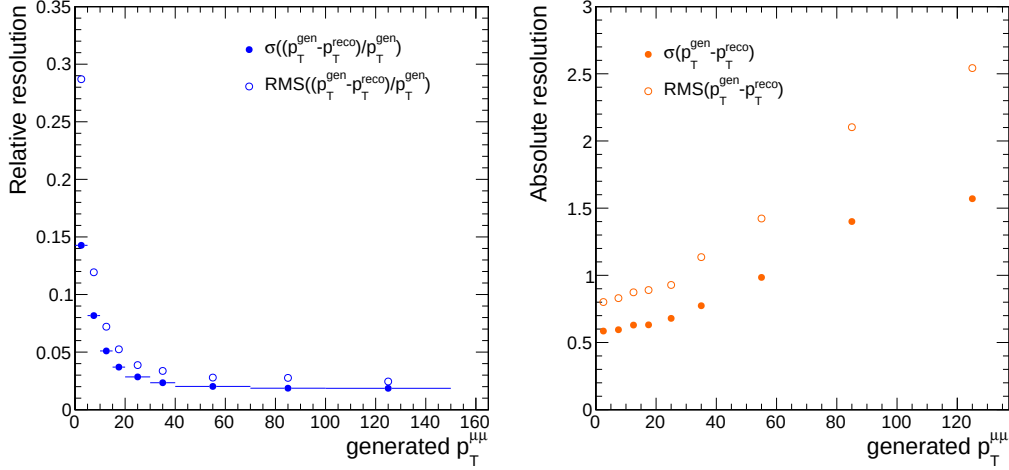


Figure 7.26: Relative (*left*) and absolute (*right*) transverse momentum resolution of Z boson reconstruction from PYTHIA+HIJING simulation as a function of transverse momentum.

is reduced to solving a linear matrix equation:

$$\underline{x} = \underline{\underline{R}} \underline{y} , \quad (7.8)$$

where $\underline{x}$ ($\underline{y}$) is the number of events in the reconstructed (generated) p_T bins. If the binning is sufficiently coarse, it is possible to invert R such that

$$\underline{y} = \underline{\underline{R}}^{-1} \underline{x} \quad (7.9)$$

with

$$\underline{\underline{\delta}}^y = \underline{\underline{R}}^{-1} \underline{\underline{\delta}}^x \underline{\underline{R}}^{-1} , \quad (7.10)$$

where $\underline{\underline{\delta}}^x$ is the vector of the statistical errors of the number of events in the reconstructed p_T bins.

The response matrix is constructed using the detector simulation. The reconstructed Z bosons are filled in a two dimensional array with the first coordinate being the reconstructed p_T and the second being the generated p_T of the dimuon. Once all events are considered, the rows are normalized by the generated p_T spectrum (i.e. the number of events in the generated p_T bins). With this construction the response matrix element R_{ij} is the probability of a dimuon with p_T in bin i migrating to a reconstructed p_T bin j .

The response matrix constructed from the PYTHIA+HIJING MC sample is shown in the left-hand side of fig. 7.27. When examining the response matrix, it is important to note the values of the diagonal elements, that are closely related to the bin-to-bin spill. The binning is chosen according to the analysis of p-p data at 7 TeV [33]. It is determined to have a bin-to-bin spill lower than 30%, which is

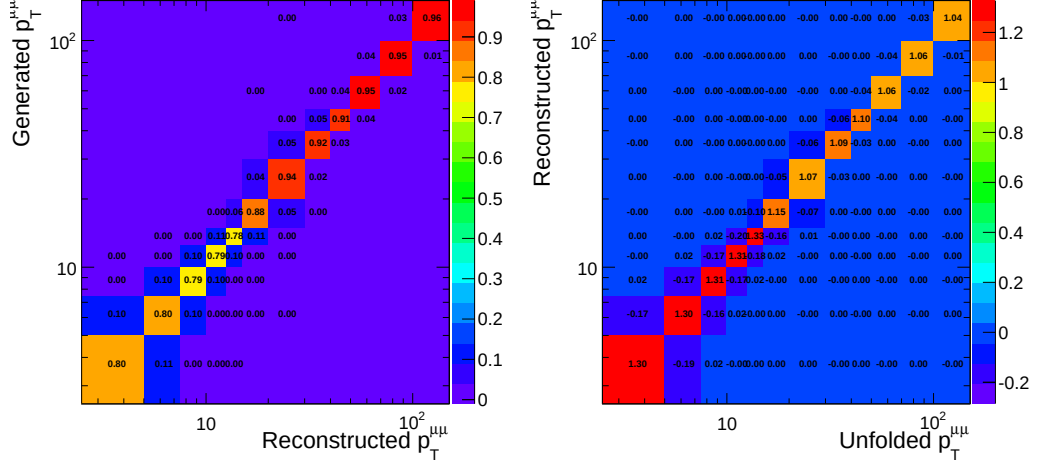


Figure 7.27: The response matrix (*left*) from PYTHIA+HIJING simulation and its inverse (*right*).

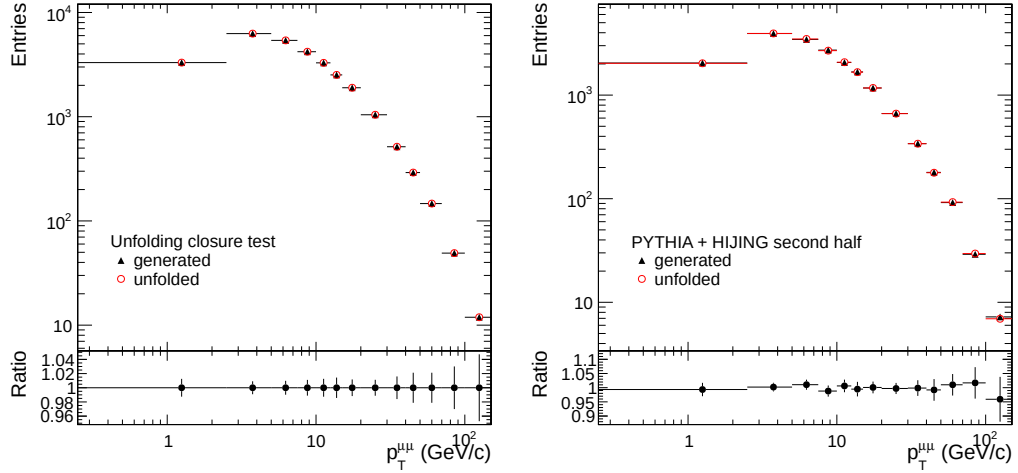


Figure 7.28: Comparison of the generated and the unfolded transverse momentum distribution of Z bosons from the first half of the PYTHIA+HIJING sample (which was used to determine the response matrix) and the second half of the sample.

visible in fig. 7.27.

The response matrix is inverted with the standard matrix inversion routine in the ROOT program library, which uses the LU matrix decomposition algorithm. The inverted matrix is shown in the right-hand side of fig. 7.27, which is interpreted as the mapping from the measured p_T spectrum to the unfolded p_T spectrum.

As a closure test, the inverted response matrix is applied on the original reconstructed p_T spectrum from simulation. If the unfolding procedure was done correctly, the resulting unfolded p_T spectrum should agree with the generator level spectrum. The result of this closure test is presented in the left-hand side of fig. 7.28, where it is shown that the unfolding was executed properly. The matrix and this closure test was determined from the first half of the main MC sample and then the second half

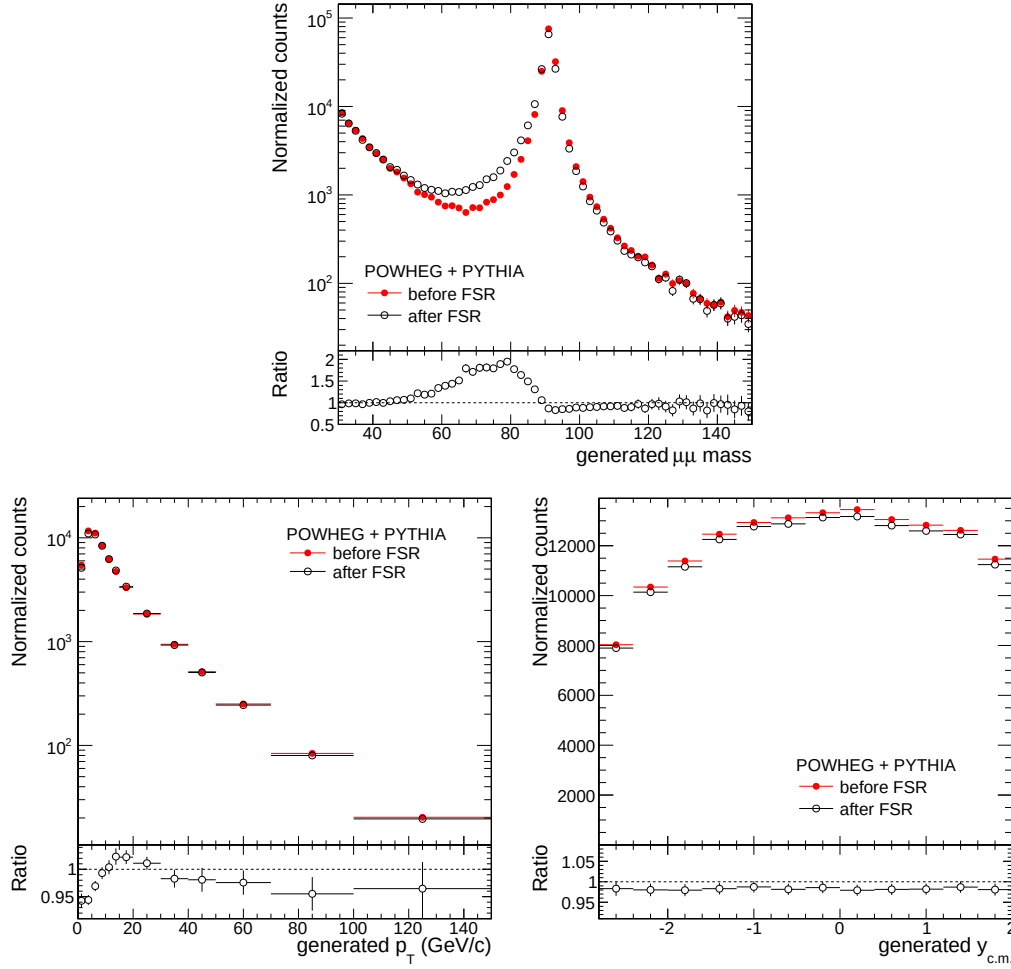


Figure 7.29: Comparison of Z boson mass, transverse momentum and rapidity distribution before and after final state radiation from POWHEG+PYTHIA generator.

was also checked with applying the inverted response matrix to the reconstructed spectrum and compared to the generated spectrum in the second half. The result of this test is shown in the right-hand side of fig. 7.28, where one can see some differences between the generated and unfolded spectrum. The differences are comparable with the statistical uncertainties of the distributions. For the final results, the full embedded MC sample was used to determine the response matrix and its inverse.

7.7 Final state radiation

Up to this point the generated dimuon quantities in the acceptance, efficiency and resolution corrections were used after the final state radiation (FSR). In this section, the effect of the FSR is investigated by comparing dimuon quantities defined by the status 3 (before FSR) or status 1 (after FSR) muons in the PYTHIA event generator.

Fig. 7.29 shows the comparison of the mass, transverse momentum and rapidity

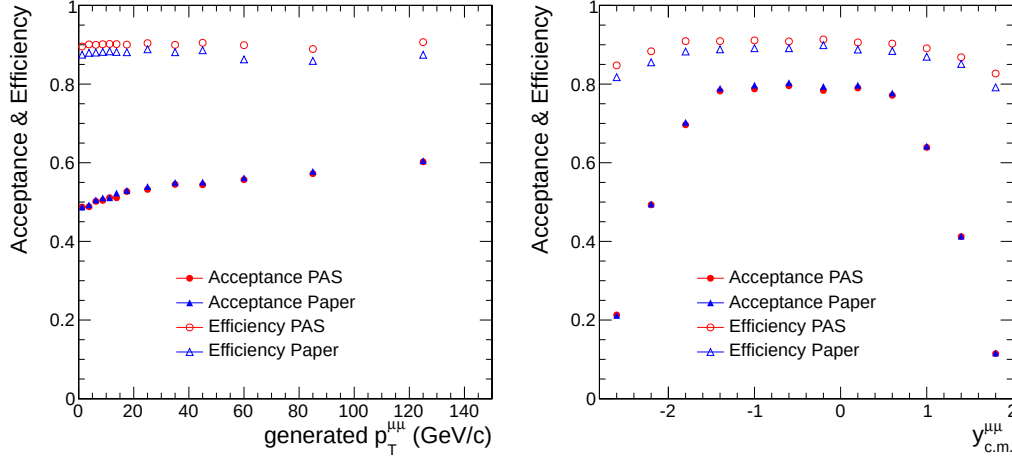


Figure 7.30: Effect of FSR on the acceptance and efficiency as a function of Z boson transverse momentum and rapidity. The label Paper (PAS) refers to quantities with (without) FSR correction.

distribution of the generated Z bosons before and after final state radiation from POWHEG+PYTHIA generator. The rapidity distribution is only affected by the final state radiation by a normalization factor that comes from the fact that the mass distribution becomes wider because of the FSR. The shape of the Z boson transverse momentum spectrum depends on the presence of the final state radiation.

For the final results in p-Pb collisions, the FSR correction is applied, so the combination with the electron channel is possible, where part of the final state radiation is collected by the ECAL clustering algorithm. The correction is done by incorporating it in the acceptance and the efficiency calculation by taking the generated status 3 muons instead of the status 1 muons when counting generated dimuons. The overall acceptance increases by 0.9% and the efficiency decreases by 2.2% due to this correction. Fig. 7.30 shows the effect on the acceptance and efficiency as a function of dimuon transverse momentum and rapidity. There is a larger effect on the p_T spectrum as shown above, therefore the FSR is also taken into account in the determination of the unfolding matrix.

7.8 Systematic uncertainties

In this section, the systematic uncertainties associated with each component of the Z boson analysis are described: background, acceptance, efficiency and unfolding. Finally, the correlated systematic uncertainties of the normalization are summarized.

7.8.1 Signal and background

The systematic uncertainty of the raw yield comes from the uncertainty of the background estimation that is different between the analysis of p-p, Pb-Pb and p-Pb data.

In the case of p-p and Pb-Pb collisions, the background is considered negligible and only the same-charge pairs are subtracted. The possible remaining background is estimated by subtracting the simulated virtual photon and Z boson contribution from the data and then fitting the lower mass region with an exponential function and extrapolating to the 60–120 GeV/ c^2 mass range. The result of the fit is taken as a conservative systematic uncertainty of 0.1% for p-p and 0.5% for Pb-Pb collisions.

In the case of p-Pb collisions, the background is estimated from the $e\mu$ -method as detailed in Section 7.2. The number of subtracted electron-muon events is varied by $\pm 100\%$ to assign a systematic uncertainty on the raw yield. This results in a 1.7% uncertainty on the inclusive cross section. Similarly for the differential cross sections, the amount of background determined from simulations is varied by $\pm 100\%$ in each bin. The uncertainty goes from 0.5% to 8.6% with increasing transverse momentum and it varies from 0.1% to 2.5% from forward/backward rapidity bins to midrapidity bins.

7.8.2 Acceptance

The uncertainty of the acceptance comes from the uncertainty of the theoretical description of the Z boson production in heavy-ion collisions. In the p-Pb data analysis, the acceptance is extracted from the simulated Z boson production from the POWHEG generator. The systematic uncertainty of the acceptance is determined by changing the shape of the generated rapidity and transverse momentum spectrum in the range of the different theoretical models.

The rapidity spectrum is reweighted by linear functions that change from 0.7 to 1.3 in the region of -3 to 3 both ways that results in an asymmetry as expected from the nuclear PDFs but also the symmetric changes with 30% from -3 to 0 and then from 0 to 3 are calculated. Some predictions from PYTHIA with p-p or p-N collisions and MCFM predictions with and without EPS09 nPDFs are compared to the default POWHEG rapidity shape in fig. 7.31 together with their ratios and the reweighting functions. The functions are chosen such that the possible variations due to isospin and other nuclear effects are covered.

The p_T spectrum is reweighted by a linear function that changes $\pm 10\%$ from 0 to 150 GeV/ c both ways and also a logarithmic parametrization that is taken from the MCFM generator with and without nuclear modification. Fig. 7.32 shows the predictions from PYTHIA, POWHEG and MCFM with and without nuclear effects

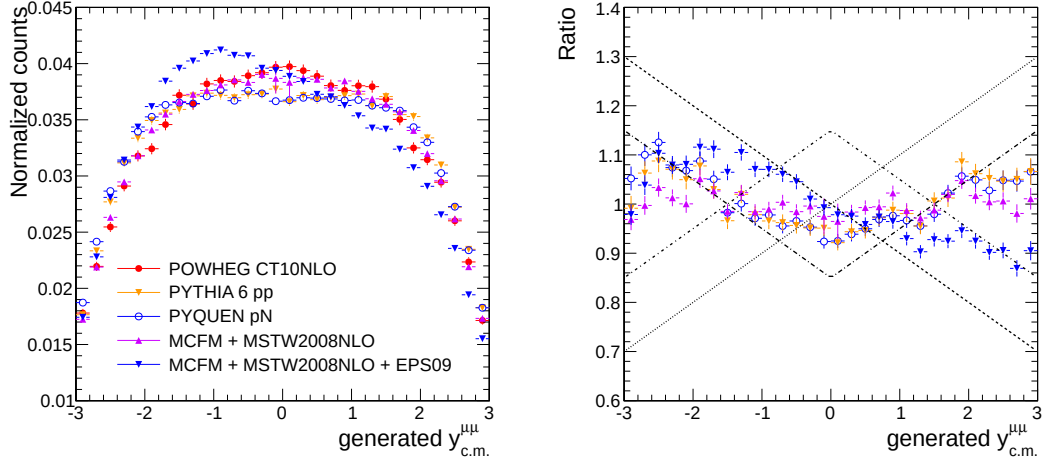


Figure 7.31: Comparison of different predictions for the rapidity distribution (*left*) and their ratios together with the reweighting functions (*right*).

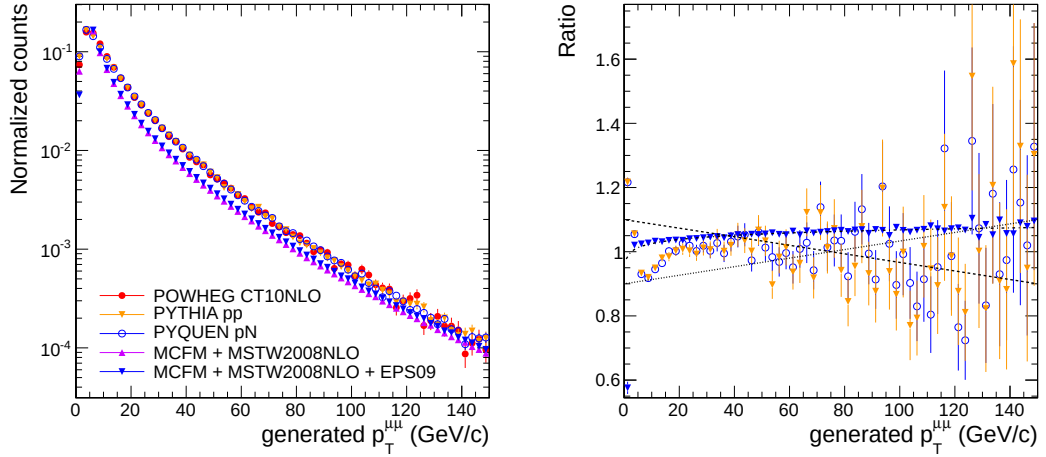


Figure 7.32: Comparison of different predictions for the p_T distribution (*left*) and their ratios together with the reweighting functions (*right*).

and their ratios together with the reweighting functions.

The above variations cover the predicted nuclear effects to the rapidity and p_T differential cross section from different groups [54, 72, 73] as well as the statistical uncertainties of the present measurement. The changes in y and p_T are taken as the uncertainty of the acceptance and combined in quadrature but the dominant component is just changing the shape of the rapidity. The acceptance has an uncertainty of 4.7% for the inclusive cross section which is the reason for presenting the Z boson production cross section also in the fiducial region where no acceptance correction is applied. The uncertainty from the acceptance varies between 2.4% and 6.0% as a function of p_T and is less than 1.1% in bins of rapidity.

In the case of Pb-Pb and p-p collisions, the measurement is done in the restricted $|y| < 2$ region where the acceptance has an uncertainty of less than 2%. It is

estimated by applying to the generated Z boson p_T and y distributions a weight that varies $\pm 30\%$ linearly over the ranges $p_T < 100 \text{ GeV}/c$ and $|y| < 2$.

7.8.3 Efficiency

The systematic uncertainty on the efficiency comes from two different sources. First the shapes of the underlying rapidity and transverse momentum distributions are varied with the same functions as for the acceptance. Second the uncertainty on the scale factors from the ratio of data and simulation in the tag-and-probe method is propagated to the dimuon efficiency.

The shape changes introduce a small uncertainty of about 0.2% on the dimuon efficiency as calculated from PYTHIA+HIJING simulations. It varies between 0.1%–0.3% and 0.1%–0.9% in bins of Z boson p_T and rapidity, respectively. In Pb-Pb and p-p collisions, the acceptance and efficiency corrections are combined into one factor and the shape changes are accounted for in the uncertainty quoted for the acceptance previously that is less than 2% in every bin.

The uncertainty of the scale factors has three components: uncertainty from the fit results that includes the statistical uncertainty of the data and simulation, uncertainty on the fitting method itself, and the uncertainty from the factorization assumption. The statistical uncertainties of the measured correction factors are taken into account by recomputing the dimuon efficiency multiple times using an ensemble of single muon correction factor maps in muon η where the entries are modified randomly within ± 1 standard deviation of the uncertainties. The tag-and-probe technique carries itself an uncertainty of 0.2% for the trigger and 0.5% for the muon identification efficiency taken from detailed 7 and 8 TeV muon studies. The closure test of the factorization assumption gives an additional conservative 0.5% uncertainty on the scale factors.

Finally, the uncertainty from the three different components of the efficiency scale factors are combined in quadrature resulting in an overall uncertainty on the dimuon efficiency of 1.7%. This uncertainty shows an increase from 1.7% to 3.4% going from midrapidity to forward/backward rapidity bins but no significant variations as a function of p_T .

In the case of Pb-Pb and p-p collisions, the combined uncertainty from the scale factors is 1.8% and 1.9%, respectively. It comes from taking the difference between the tag-and-probe efficiency from data and simulation as the uncertainty on each component and then combining in quadrature the uncertainties of the three different tag-and-probe single muon efficiencies.

7.8.4 Unfolding

The uncertainty on the p_T spectrum from the matrix inversion procedure is determined from varying the shape of the generated Z boson p_T spectrum and the single muon p_T resolution in the simulation. The generated p_T distribution from PYTHIA+HIJING and POWHEG simulations as well as the weighted p_T spectrum accounting for possible nuclear effects are all probed and the effect on the results directly evaluated.

The single muon momentum resolution can be estimated from fitting the dimuon mass shape in different phase space regions and comparing the width of the distributions in data and simulation. The largest difference between them is found to be below 10%. Variations of this size are introduced to influence the reconstructed p_T of the muons and evaluated the effect on the reconstructed p_T of the Z bosons. The difference between the unfolded results with and without varying the single muon p_T resolution is taken as the systematic uncertainty.

The two sources of uncertainties are independent thus combined in quadrature, resulting in an uncertainty on the unfolded p_T spectrum of about 0.1%–2.2%. In the case of Pb-Pb and p-p collisions, such detailed studies are not possible because of the low statistics in data. The uncertainty of the matrix inversion procedure is estimated with varying the shape of the simulated p_T spectrum and found to be less than 1%.

7.8.5 Normalization

In the case of p-p and p-Pb collisions, the Z boson production cross section is calculated as introduced in eq. (7.1), where the corrected yield is normalized by the integrated luminosity of the analyzed data. The value of the luminosity used in the cross section determination is calibrated by van der Meer scans [115] performed with both p-p and p-Pb collisions in 2013. The systematic uncertainty of the luminosity is 3.7% in p-p and 3.5% in p-Pb collisions as determined in the calibration procedure [116]. This uncertainty dominates the systematic uncertainty of the cross section measurements.

In the case of Pb-Pb collisions instead of cross sections, invariant yields are presented in the final results. The corrected yield is normalized by the number of minimum bias events and the average of the nuclear overlap function in the corresponding centrality bin. Both of these quantities have an associated systematic uncertainty as described in Section 6.4. The average T_{AA} for results integrated in centrality has an uncertainty of 6.2% that includes the uncertainty of the event selection efficiency. When the results are presented as a function of centrality, the uncertainty of the average T_{AA} decreases from 15% to 4.3% when moving from

peripheral to central events. Similarly to p-p and p-Pb collisions, the normalization uncertainty dominates the systematic uncertainty of the invariant yields measured in Pb-Pb collisions.

7.9 Summary of the analysis in the electron decay channel

The study of electron pairs follows similar procedures as presented in detail for muons and the differences are summarized in this section. The actual calculation in the electron channel was performed by other students but I provided the analysis code and methods.

The electrons are selected with a set of quality criteria studied in p-p collisions [84] that reduce the different backgrounds. The most effective requirements are found to be the energy-momentum combination between the supercluster and the track, the variables measuring the η and ϕ spatial matching between the track and the supercluster, the supercluster shower shape width, the hadronic leakage (the ratio of energy deposited in the HCAL and ECAL), and a transverse distance of closest approach from the measured primary vertex.

In order to suppress the background from multijet events, the electrons are required to have a high transverse momentum well above the trigger threshold, $p_T^e > 20$ GeV/c. The acceptance cut on the electron pseudorapidity is $|\eta^e| < 2.4$ in the case of p-Pb collisions following the muon detector coverage. However in the case of Pb-Pb collisions, the electrons are restricted to $|\eta^e| < 1.44$ to be within the ECAL barrel, to take advantage of a higher reconstruction efficiency and a better resolution in this region.

The Z boson candidates are selected by requiring two electrons that pass the quality and acceptance requirements, have opposite charge and are within the 60–120 GeV/ c^2 invariant mass range. Additionally in Pb-Pb and p-p collisions, the dielectron rapidity is restricted to $|y| < 1.44$. The number of found Z boson candidates is 1571 in p-Pb collisions and in the more restricted region in Pb-Pb and p-p collisions it is 328 and 388, respectively. The invariant mass of the selected electron pairs is shown in fig. 7.33 for the three collision systems and compared to the corresponding simulations. The Z boson mass peak in the electron decay channel is slightly wider than in the muon decay channel due to the worse resolution of the electron energy measurement. The level of background is also higher in this channel as demonstrated by the higher number of same-charge electron pairs shown in the figure.

The electrons in the barrel and endcap region are separately treated when cal-

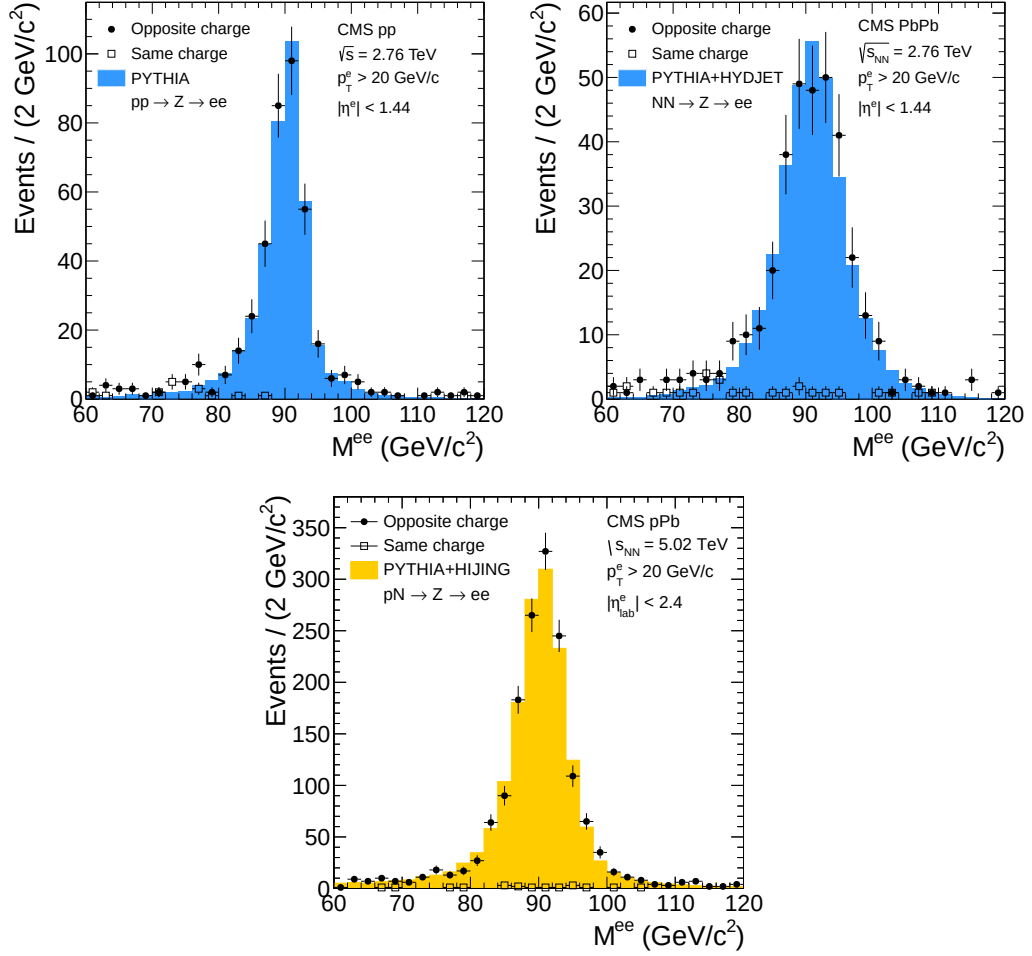


Figure 7.33: The invariant mass distribution of selected electron pairs from p-p, Pb-Pb and p-Pb collision data compared to simulations. The MC samples are normalized to the number of events in the data.

culating corrections in p-Pb collisions and the electrons in the transition region between barrel and endcap ($1.44 < |\eta| < 1.57$) are excluded. The signal yield of electrons is corrected for possible misidentification of the charge of one or two of the electrons in the event. The charge confusion rate is determined by a method based on three different charge measurements of the electrons and found to be 0.25% in the barrel and 1.4% in the endcap. Applying a correction for charge confusion results in 1% increase of the signal yield before background subtraction. In Pb-Pb and p-p collisions, where only barrel electrons are used, a similar 1% correction is applied on the signal yield for charge misidentification.

The background is estimated by the same method as in the muon decay channel by using electron-muon pairs in p-Pb collisions. As a function of Z boson p_T and rapidity, the background subtraction is done using the shape of the distributions from simulated background samples. Additionally, the number of same charge pairs is subtracted from the yield in all three collision systems.

The efficiency, acceptance and resolution corrections are determined from sim-

ulation with the same definitions as used in the case of the muon analysis. The simulation samples are reweighted according to centrality and the position of the primary vertex in order to ensure an agreement with the data. An additional correction to the energy resolution of the electrons in simulation is applied that was found to be negligible in the case of muons. The energy resolution is estimated by comparing the width of the dielectron invariant mass distribution in data and simulation after smearing the energy of the electrons by different amounts. The best smearing factor is determined from a χ^2 test of the agreement of the distributions in data and simulation. The electron energy resolution in the barrel region is smeared by an additional 2% and in the endcap region by 4% before calculating the efficiency and unfolding corrections.

The single electron efficiency is estimated with the tag-and-probe method separating three components: the reconstruction, the selection and the trigger efficiency. Each efficiency is calculated separately in the barrel and endcap regions and in three different bins of the electron transverse momentum. The ratio of the efficiencies in data and simulation are applied as scale factors on each electron when calculating the efficiency for Z bosons from simulation. The single electron efficiencies from data and simulation agree quite well resulting in scale factors close to unity. The efficiency for dielectrons in the Z boson mass range is found to be 0.605 in p-Pb collisions. In the case of Pb-Pb and p-p collisions, the Z boson efficiency is approximately 0.55 and 0.80, respectively.

The unfolding correction is calculated with the same matrix inversion technique as previously presented and after applying the resolution smearing on the electron energy. The acceptance correction only depends on the Z boson decay kinematics simulated by the POWHEG generator, thus it is very similar between the two decay channels. The systematic uncertainties on each component of the analysis are estimated with the same methods as used in the case of muons with the addition of uncertainties associated with the charge misidentification and the resolution corrections.

8 Results and discussion

In this chapter, the results of the Z boson analyses described in the previous chapter are presented. These results were published as two papers from the CMS collaboration [117, 118] and I presented them at various international conferences representing the collaboration [119, 120, 121, 122].

8.1 Z boson production in Pb-Pb and p-p collisions at 2.76 TeV

In order to calculate the nuclear modification factor for Z bosons, the invariant yield in Pb-Pb collisions and the cross section in p-p collisions are determined and compared to various theoretical predictions. Finally, the muon and electron decay channel results are combined in the common kinematic region and the significance of the results is discussed.

8.1.1 Invariant yield in Pb-Pb collisions

The yield of Z bosons is measured in Pb-Pb collisions at a nucleon-nucleon center-of-mass energy of 2.76 TeV. The invariant yield is calculated by the following equation

$$\frac{dN_{\text{PbPb}}}{dy} = \frac{S}{\alpha \cdot \epsilon \cdot \Delta y \cdot N_{\text{MB}}} , \quad (8.1)$$

where S is the number of Z boson candidates in the 60–120 GeV/ c^2 mass range, α the acceptance, ϵ the efficiency, Δy the bin width in rapidity and N_{MB} the number of sampled minimum bias events. The total number of minimum bias events is $N_{\text{MB}} = (1.16 \pm 0.03) \cdot 10^9$ after correcting for the event selection efficiency as described in Section 6.1. The invariant yield of Z bosons is studied as a function of centrality, rapidity and transverse momentum separately in the muon and electron decay channels.

The centrality dependence of the Z boson yield in Pb-Pb collisions is presented in fig. 8.1 after dividing by the average of the nuclear overlap function in each centrality class. The statistical uncertainties are represented with errorbars and

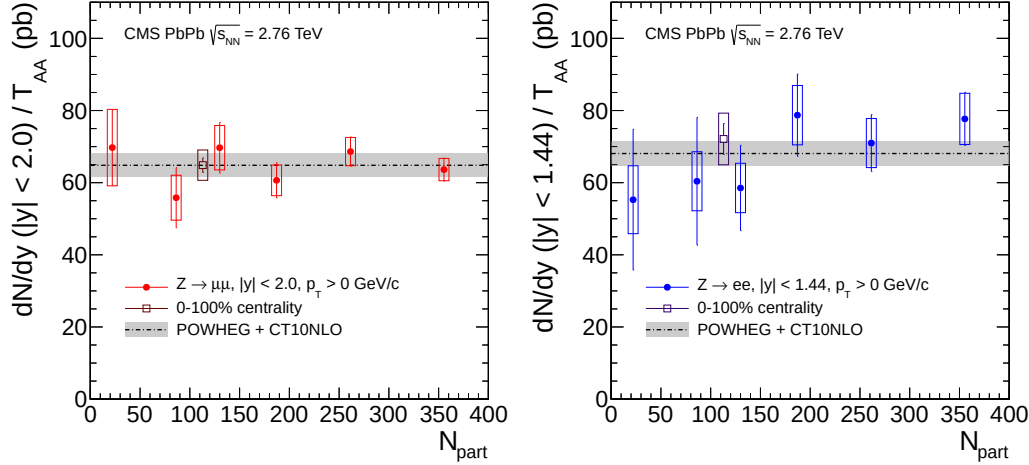


Figure 8.1: Invariant yield of Z bosons as a function of event centrality (depicted as the average number of participating nucleons) measured in the muon (*left*) and electron (*right*) decay channels. The dash-dotted line shows the p-p cross section as predicted by the POWHEG generator and the grey band represents its assumed 5% theoretical uncertainty.

the systematic uncertainties with boxes around the data points in all figures. The centrality on the horizontal axis of the figure is translated to the average number of participating nucleons. The average values of $T_{AA} = N_{\text{coll}}/\sigma_{\text{inel}}^{\text{NN}}$ and N_{part} are based on the Glauber model and summarized in table 6.1. The signal yield and the efficiency are evaluated in each centrality bin and the N_{MB} is multiplied by the corresponding fraction of the hadronic inelastic cross section included in the event class. The 0–100% centrality integrated yield divided by the average T_{AA} is also shown in the figure at the average N_{part} of Pb-Pb collisions of 113. This can be directly compared to the Z boson production cross section predicted by the POWHEG generator indicated on the figure as a horizontal line. The POWHEG prediction has about 5% uncertainty indicated by the gray band coming from missing higher order corrections and from uncertainties in the proton PDFs. No strong centrality dependence is observed in either the muon or the electron decay channel that confirms the expectation that the yield of Z bosons in Pb-Pb collisions scales with the number of binary nucleon-nucleon collisions.

The measured Z boson yield as a function of rapidity is presented in fig. 8.2 compared to predictions with and without applying nuclear modification to the PDFs. The signal yield and the corrections are evaluated in bins of rapidity and integrated over event centrality and Z boson p_T . The cross section predictions were provided by the authors of [54] and are calculated with the MCFM generator using the CT10 [95] free proton PDF set with and without the nuclear modification from EPS09 [47]. In order to compare with the Pb-Pb yield, the p-p cross section of Z boson production is multiplied by the 0–100% centrality averaged T_{AA} of $(5.67 \pm$

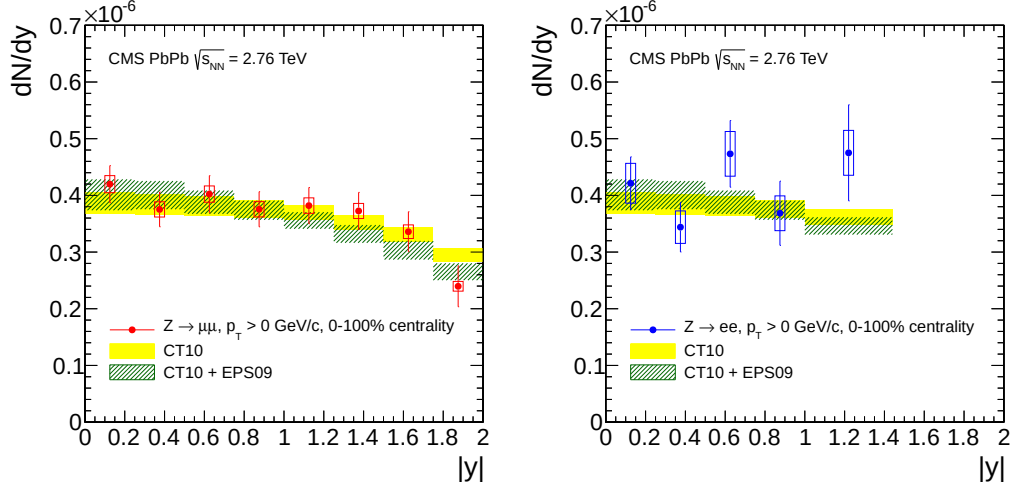


Figure 8.2: Invariant yield of Z bosons as a function of rapidity measured in the muon (*left*) and electron (*right*) decay channels. The results are compared to predictions with (green band) and without (yellow band) nuclear modification of PDFs where the bands represent the PDF and scale uncertainties of the model [54].

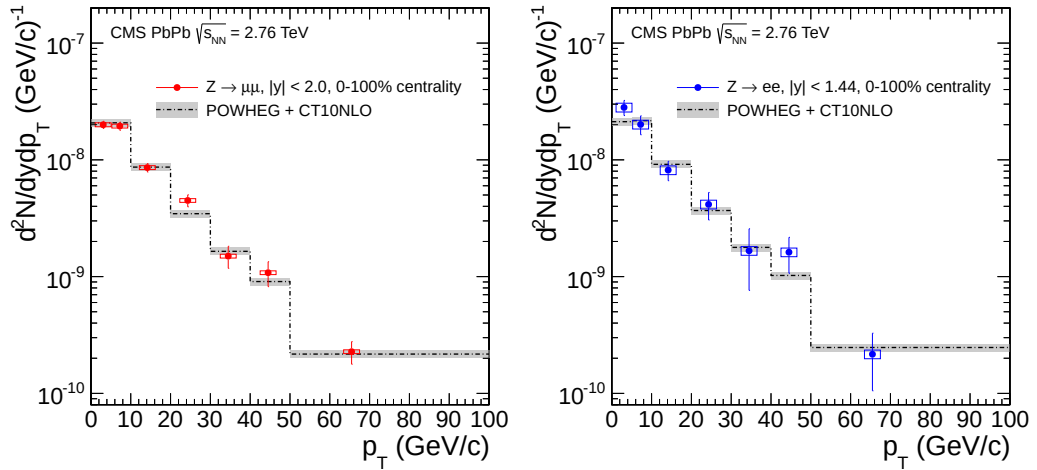


Figure 8.3: Invariant yield of Z bosons as a function of transverse momentum measured in the muon (*left*) and electron (*right*) decay channels. The results are compared with POWHEG p-p predictions scaled by the 0 – 100% centrality averaged T_{AA} shown as the dash-dotted line. The gray band represents the theoretical uncertainty of 5% combined with the uncertainty of 6.2% due to the T_{AA} scaling.

0.32) mb^{-1} calculated from the Glauber model. The measured Z boson yield in both the muon and the electron decay channels is consistent with the predictions.

The measured transverse momentum dependence of the Z boson yield in Pb-Pb collisions is presented in fig. 8.3 compared to the p-p cross section predicted by the POWHEG generator multiplied by the centrality averaged T_{AA} . The signal yield and the corrections are evaluated in bins of Z boson p_T in the $|y| < 2.0$ range for muon pairs and in the $|y| < 1.44$ range for electron pairs. The results are consistent with the predictions in both decay channels.

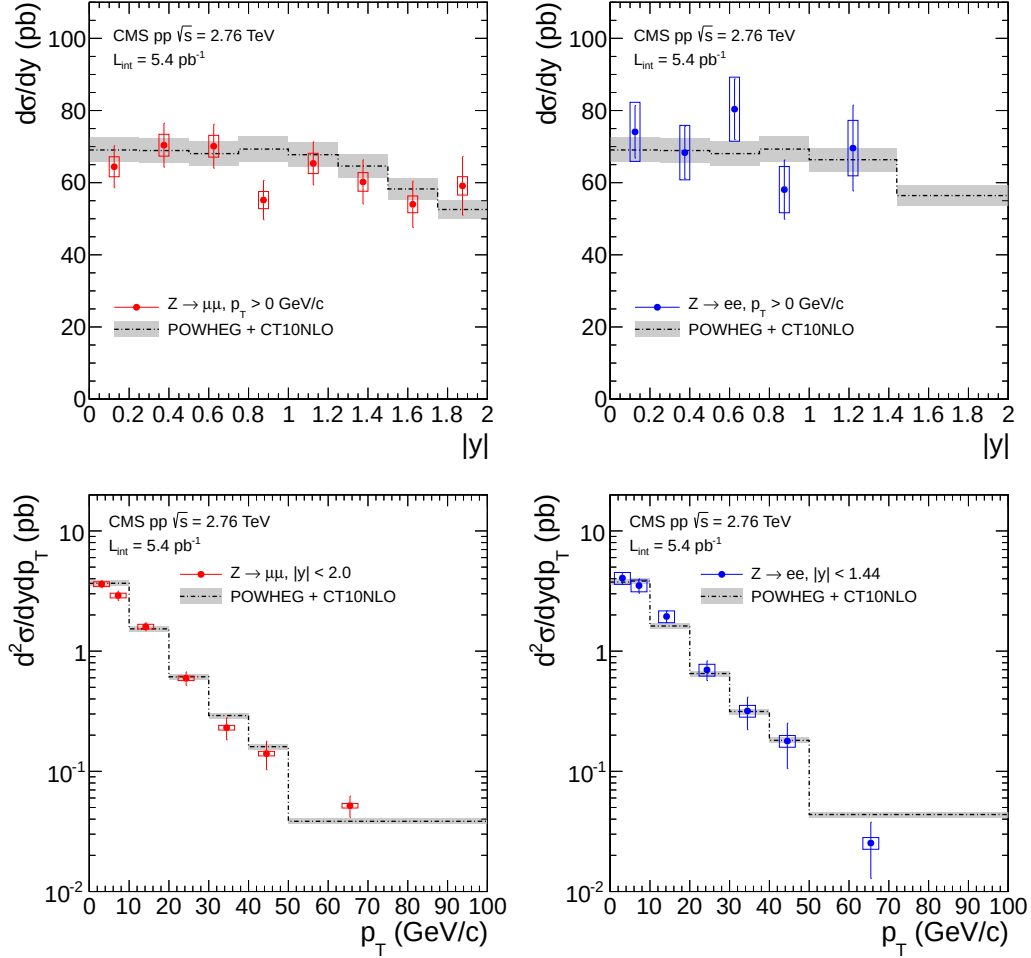


Figure 8.4: Differential Z boson production cross section as a function of rapidity (*top*) and transverse momentum (*bottom*) measured in the muon (*left*) and electron (*right*) decay channels. The dash-dotted line shows the prediction from the POWHEG generator and the grey band represents its assumed 5% theoretical uncertainty.

8.1.2 Reference cross section in p-p collisions

The Z boson production cross section is calculated in p-p collisions at the same 2.76 TeV center-of-mass energy by

$$\frac{d\sigma_{pp}}{dy} = \frac{S}{\alpha \cdot \epsilon \cdot \Delta y \cdot \mathcal{L}_{int}}, \quad (8.2)$$

where S is the number of Z boson candidates in the 60–120 GeV/ c^2 mass range, α the acceptance, ϵ the efficiency, Δy the width of the rapidity range and $\mathcal{L}_{int}$ the integrated luminosity. The p-p collision sample corresponds to an integrated luminosity of $\mathcal{L}_{int} = 5.4 \text{ pb}^{-1}$ measured by the HF detectors and calibrated by van der Meer scans with an uncertainty of 3.7% [116].

The differential cross section of Z boson production measured as a function of rapidity and transverse momentum is presented in fig. 8.4 compared to predictions

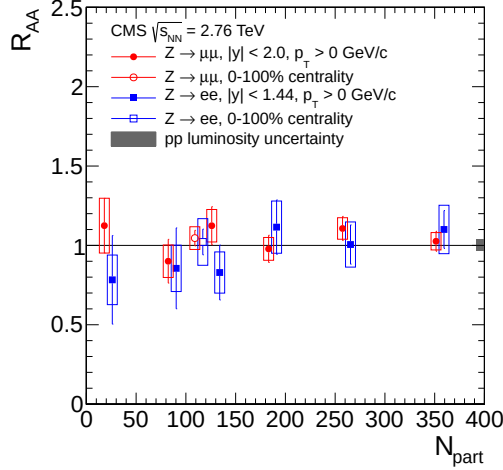


Figure 8.5: The nuclear modification factor of Z bosons as a function of N_{part} measured in the muon (red circles) and electron (blue squares) decay channels. The horizontal line at $R_{\text{AA}} = 1$ is drawn as a reference and the grey bar corresponds to the 3.7% p-p luminosity uncertainty.

from the POWHEG generator using the CT10 PDF set. The data are consistent with the theoretical predictions within the experimental uncertainties.

8.1.3 Nuclear modification factor

Based on Pb-Pb and p-p data at the same center-of-mass energy, the nuclear modification is computed as

$$R_{\text{AA}} = \frac{dN_{\text{PbPb}}}{T_{\text{AA}} \cdot d\sigma_{\text{pp}}} , \quad (8.3)$$

where dN_{PbPb} and $d\sigma_{\text{pp}}$ are the Z boson invariant yield in Pb-Pb and the cross section in p-p collisions as defined in eq. (8.1) and (8.2), while T_{AA} is the nuclear overlap function proportional to the number of elementary nucleon-nucleon collisions. By definition, $R_{\text{AA}} = 1$ implies that the yield of a measured quantity is not modified in AA collisions compared to p-p collisions but it scales with N_{coll} , whereas $R_{\text{AA}} < 1$ indicates suppression and $R_{\text{AA}} > 1$ points to an enhancement in AA collisions.

The nuclear modification factor of Z bosons is shown in fig. 8.5 as a function of centrality comparing the muon and electron decay channels, where the points have been shifted horizontally for better visibility. The 0–100% centrality integrated values of R_{AA} shown at $N_{\text{part}} = 113$ by open symbols are 1.06 ± 0.05 (stat.) ± 0.08 (syst.) in the $|y| < 2.0$ region in the muon decay channel and 1.02 ± 0.08 (stat.) ± 0.15 (syst.) in the $|y| < 1.44$ region in the electron decay channel. These values are consistent with unity within the statistical and systematic uncertainties of the measurement, confirming the binary collision scaling of Z boson production in Pb-Pb collisions. The results in the two decay channels agree within their uncertainties and the R_{AA} shows no dependence on centrality.

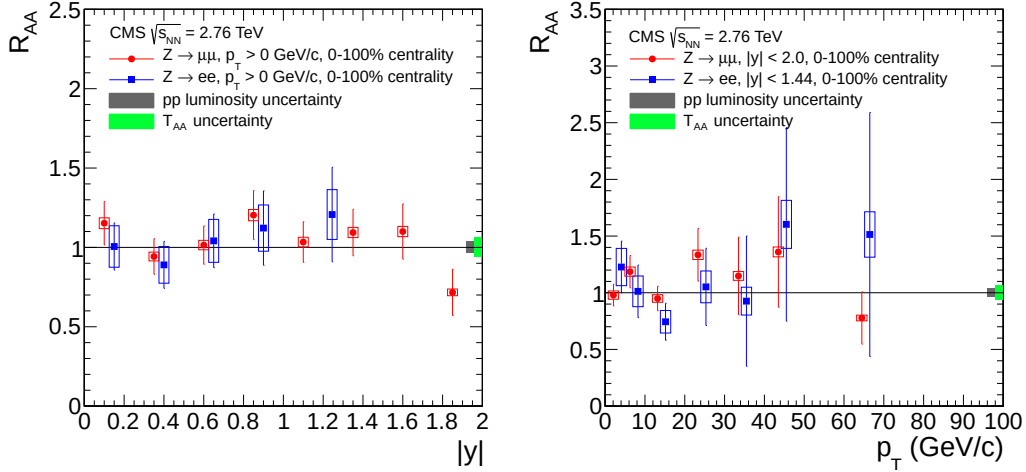


Figure 8.6: The nuclear modification factor of Z bosons as a function of rapidity (*left*) and transverse momentum (*right*) measured in the muon (red circles) and electron (blue squares) decay channels. The horizontal line at $R_{AA} = 1$ is drawn as a reference, the grey bar corresponds to the 3.7% p-p luminosity uncertainty and green bar corresponds to the 6.2% uncertainty on the average T_{AA} .

The rapidity and transverse momentum dependence of the Z boson nuclear modification factor is shown in fig. 8.6 comparing the muon and electron decay channels. The R_{AA} values show no dependence and hence no variation of nuclear effects within the current experimental uncertainties as a function of p_T or y in both decay channels in the kinematic region studied.

8.1.4 Combined results for the two decay channels

According to lepton universality and given its large mass, the Z boson is expected to decay into muon and electron pairs with branching ratios within 1% of each other. Also, neither muons nor electrons are expected to interact strongly with the medium formed in the collisions. The two decay channels can therefore be used to measure combined $Z \rightarrow \ell\ell$ yields and R_{AA} , where ℓ refers to either a muon or an electron. I have done the combination following the best linear unbiased estimate (BLUE) technique [123] in the region of overlap of the measurements, in $|y| < 1.44$.

The combined invariant yield of Z bosons in Pb-Pb collisions is shown in fig. 8.7 as a function of centrality, rapidity and transverse momentum. The results are compared with theoretical predictions from the POWHEG generator in the centrality and the p_T -dependent figures and show an agreement between the data and the theory in the $|y| < 1.44$ region. The dependence of the yield on rapidity is shown for the combined decay channel in the $|y| < 1.44$ region and extended with the dimuon measurements for the $1.5 < |y| < 2.0$ range. The rapidity differential yield is compared with predictions with and without nuclear effects demonstrating that the current precision of the measurements does not allow to distinguish between the

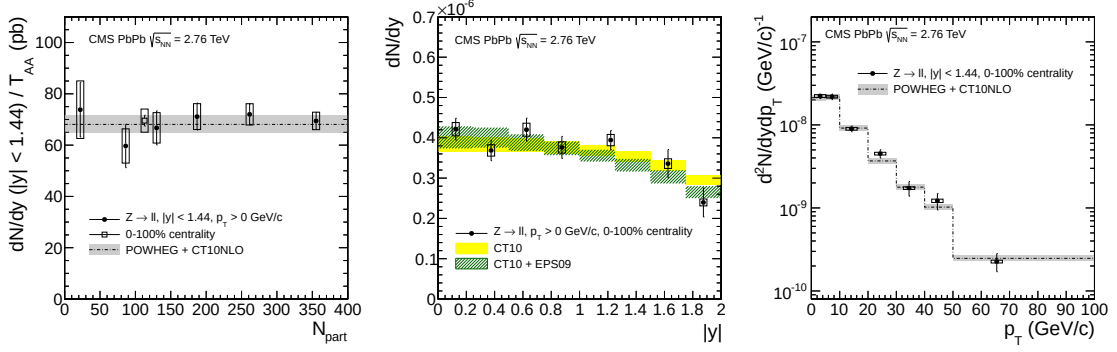


Figure 8.7: Invariant yield of Z bosons in Pb-Pb collisions as a function of event centrality (*left*), rapidity (*middle*) and transverse momentum (*right*) in the combined leptonic decay channel compared to the theory predictions as described above.

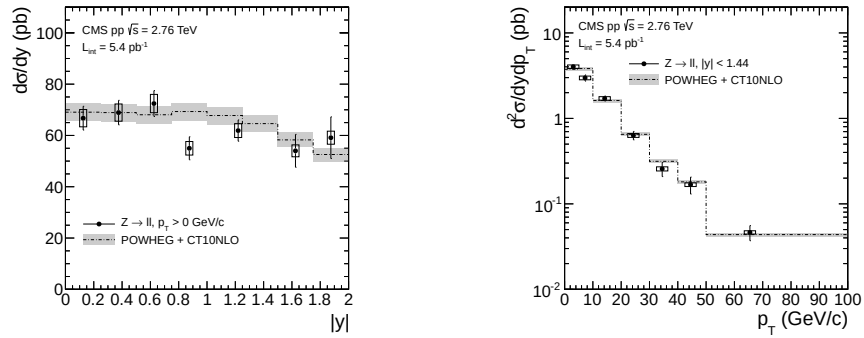


Figure 8.8: Differential cross section of Z boson production in p-p collisions as a function of rapidity (*left*) and transverse momentum (*right*) in the combined leptonic decay channel compared to POWHEG predictions as described above.

unbound proton PDF sets and modified nuclear PDF sets.

The Z boson production cross section in p-p collisions is shown in fig. 8.8 in the combined decay channel as a function of rapidity and transverse momentum and compared to predictions from the POWHEG generator. This cross section is used to calculate the nuclear modification factor of Z bosons in the combined decay channel shown in fig. 8.9 as a function of centrality, rapidity and transverse momentum. The combination is performed in the common $|y| < 1.44$ region and the rapidity dependent figures are extended with the muon measurements in the $1.5 < |y| < 2.0$ range. The combined centrality integrated nuclear modification factor is found to be 1.10 ± 0.05 (stat.) ± 0.09 (syst.) in the $|y| < 1.44$ common kinematic region.

8.1.5 Discussion

The yield per event of Z bosons in Pb-Pb collisions and their cross section in p-p collisions have been measured at $\sqrt{s_{NN}} = 2.76$ TeV. The Z boson yields have been compared with various theoretical predictions, including PDFs that incorporate nuclear effects. The calculated yields are found to be consistent with the measured

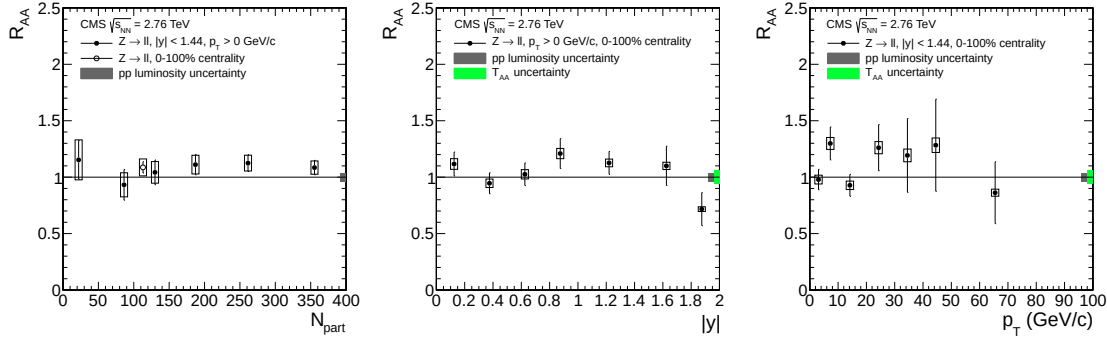


Figure 8.9: Nuclear modification factor of Z bosons as a function of event centrality (*left*), rapidity (*middle*) and transverse momentum (*right*) in the combined leptonic decay channel. The horizontal line at $R_{AA} = 1$ is drawn as a reference, the grey bar corresponds to the 3.7% p-p luminosity uncertainty and green bar corresponds to the 6.2% uncertainty on the average T_{AA} .

results that verifies that the Z boson production scales with the number of inelastic nucleon-nucleon collisions. Furthermore, nuclear effects such as isospin or shadowing are small compared to the statistical uncertainties, hence it is not possible to discriminate among these nuclear effects with the available data.

These results are compared to new theoretical calculations of electroweak boson production in heavy-ion collisions [124] that shows the interest of the measurements in the community. They can be included in future global analyses of nuclear parton distributions in order to constrain the modification of quark and antiquark PDFs [125]. They provide an important confirmation for future heavy-ion measurements where the Z boson can be used as a reference for processes that are modified in the hot and dense QCD medium. In the next heavy-ion data taking period at the LHC at the end of 2015, one of the first measurements planned by CMS is the study of jet quenching in Z+jet events.

8.2 Z boson production in p-Pb collisions

The Z boson production cross section is calculated in the muon decay channel using the ingredients described in detail in Chapter 7. The results are compared with the electron decay channel and combined in order to improve the statistical precision of the measurement. Finally, the inclusive and differential cross sections are compared with theoretical predictions.

8.2.1 Results in the muon decay channel

The Z boson production cross section is calculated in p-Pb collisions at a nucleon-nucleon center-of-mass energy of 5.02 TeV by the following equation

$$\sigma = \frac{S - B}{\epsilon \cdot \alpha \cdot \mathcal{L}_{\text{int}}} , \quad (8.4)$$

where S is the number of Z boson candidates, B the estimated background based on electron-muon and same-charge muon pairs, ϵ the efficiency from simulation corrected by scale factors based on data, α the acceptance and $\mathcal{L}_{\text{int}}$ the integrated luminosity. The p-Pb collision sample corresponds to an integrated luminosity of $\mathcal{L}_{\text{int}} = 34.6 \text{ nb}^{-1}$ calibrated by van der Meer scans with an uncertainty of 3.5% [116].

The inclusive cross section of Z boson production measured in the muon decay channels is found to be

$$\sigma_{\text{pPb} \rightarrow \text{Z} \rightarrow \mu\mu} = 135.6 \pm 3.0 \text{ (stat.)} \pm 7.2 \text{ (syst.)} \pm 4.6 \text{ (lumi.) nb.}$$

The NLO pQCD calculation of POWHEG predicts a p-p cross section of $654 \pm 33 \text{ pb}$ for Z boson production in the 60–120 GeV/ c^2 mass range at 5.02 TeV using the CT10 PDF set. Its 5% uncertainty comes from missing higher order corrections and from uncertainties in the proton PDFs. Scaling this value by the number of nucleons in the Pb nucleus, $A = 208$, one gets $136 \pm 7 \text{ nb}$ cross section for p-Pb collisions, which agrees well with the measurement.

In order to reduce the systematic uncertainty due to the acceptance correction, the inclusive cross section is measured in the fiducial region. The cross section of Z bosons decaying to muon pairs, where both muons fulfil the acceptance requirement, is

$$\sigma(p_{\text{T}}^{\mu} > 20 \text{ GeV}/c, |\eta^{\mu}| < 2.4) = 70.1 \pm 1.5 \text{ (stat.)} \pm 1.7 \text{ (syst.)} \pm 2.5 \text{ (lumi.) nb,}$$

that is in agreement with the 70.4 nb predicted by the POWHEG generator.

The differential cross section as a function of rapidity is calculated by evaluating

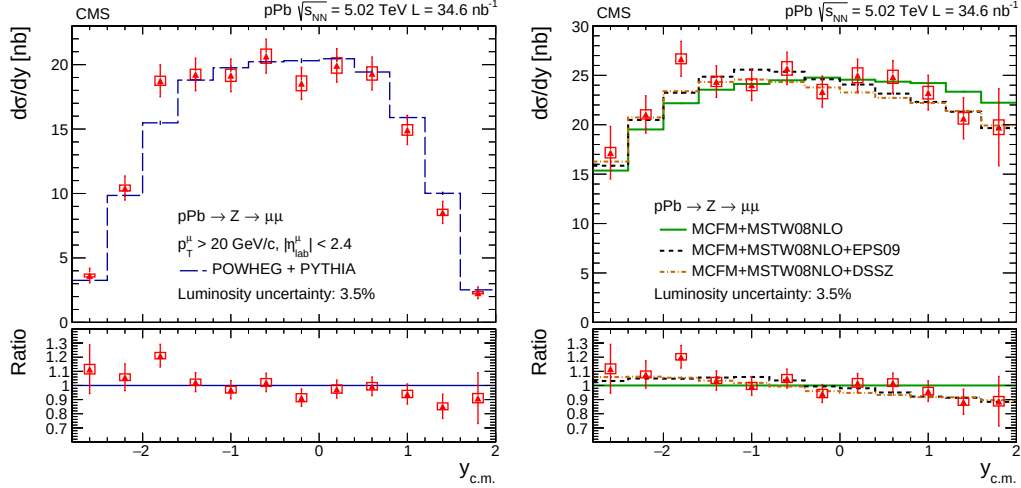


Figure 8.10: Differential Z boson production cross section as a function of rapidity in the fiducial region (*left*) and corrected to the full acceptance (*right*) compared to theoretical predictions from the POWHEG and the MCFM generators with and without nuclear effects.

each component of eq. (8.4) in bins of rapidity. The differential cross section of Z boson production in p-Pb collisions measured as a function of rapidity in the fiducial region and corrected to the full acceptance is presented in fig. 8.10. The statistical uncertainties are represented by errorbars, the systematic uncertainties by boxes and the luminosity uncertainty is not shown. Note that the points are shifted from the laboratory frame to the center-of-mass frame that leads to an asymmetry in the horizontal axis.

The fiducial cross section is compared to p-p calculation from POWHEG using CT10 PDF set scaled by $A = 208$ and shows that the measurement is consistent with the prediction, though some deviations are seen in the forward and backward regions. The rapidity differential cross section corrected to the full acceptance is compared to predictions from MCFM generator using the MSTW [52] free proton PDF set with and without the nuclear modification from EPS09 [47] or DSSZ [48] nuclear PDF sets. The results are consistent with the predictions with and without nuclear effects however, better agreement is observed with the nuclear PDF sets.

The forward-backward asymmetry is calculated from the rapidity differential cross section in the center-of-mass frame as

$$R_{\text{FB}} = \frac{d\sigma(+y)/dy}{d\sigma(-y)/dy} . \quad (8.5)$$

Note the convention for forward or positive rapidity corresponding to the proton fragmentation region in proton-nucleus collisions. The forward-backward asymmetry is expected to be more sensitive to nuclear effects [54] because some of the experimental and theoretical uncertainties cancel in the ratio. The measured forward-backward

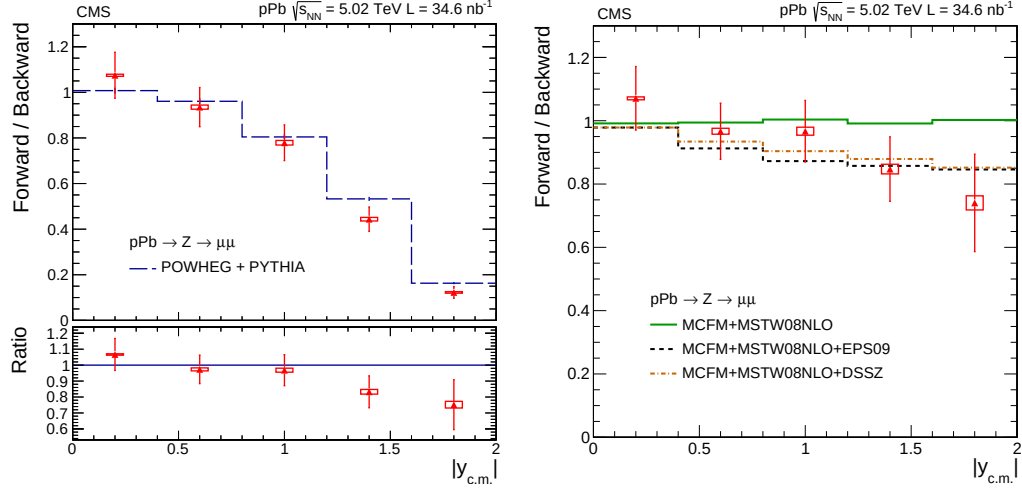


Figure 8.11: Forward-backward asymmetry of Z boson production as a function of rapidity in the fiducial region (*left*) and corrected to the full acceptance (*right*) compared to theoretical predictions from the POWHEG and the MCFM generators with and without nuclear effects.

asymmetry as a function of $|y|$ is shown in fig. 8.11 in the fiducial region and corrected to the full acceptance. It is compared with the same theoretical predictions as the rapidity differential cross section. When corrected for acceptance, the forward-backward asymmetry is unity for p-p collisions because it is a symmetric system. However in p-Pb collisions, it can deviate from unity as a result of nuclear effects. The results are consistent with both predictions with and without the presence of nuclear modification of PDFs but better agreement is observed with EPS09 and DSSZ.

The differential cross section as a function of transverse momentum is calculated by the following equation

$$\frac{d\sigma}{dp_T^i} = \frac{\sum_j R_{ij} \cdot (S_j - B_j)}{\epsilon_i \cdot \alpha_i \cdot \Delta p_T^i \cdot \mathcal{L}_{\text{int}}}, \quad (8.6)$$

where S_i , B_i , ϵ_i and α_i are the signal, background, efficiency and acceptance in each p_T bin, R_{ij} is the unfolding matrix accounting for the detector resolution effects, Δp_T^i is the bin width and $\mathcal{L}_{\text{int}}$ is the integrated luminosity. The measured Z boson p_T spectrum in the fiducial region and that corrected to the full acceptance is shown in fig. 8.12 compared to predictions from the POWHEG generator using the CT10 free proton PDF set. The expected nuclear modification of the Z boson transverse momentum distribution is small compared to the theoretical uncertainties [72, 73]. The measured spectrum is consistent with the prediction from the POWHEG generator except at the lowest transverse momentum values. The differences are similar to the ones observed in the measurement of the Z boson spectrum in p-p collisions at 7 and 8 TeV by CMS [33, 35].

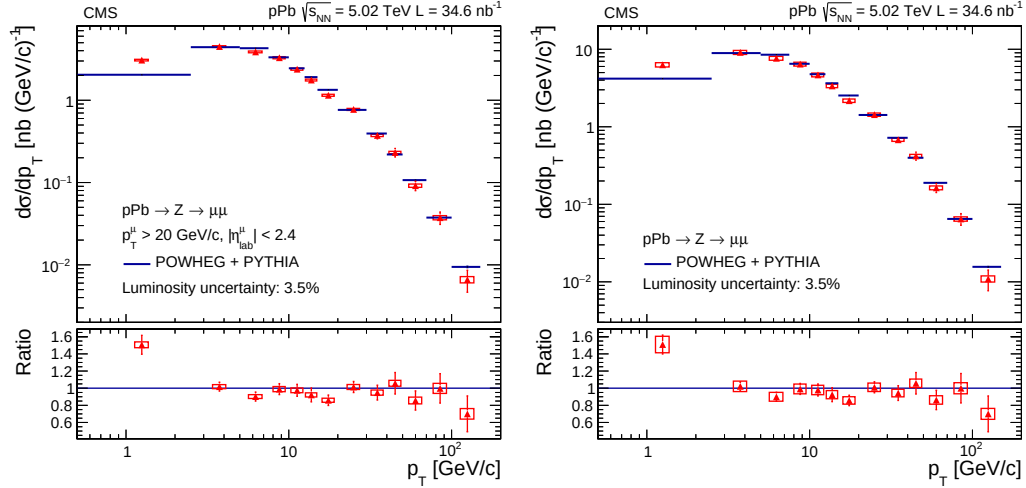


Figure 8.12: Differential Z boson production cross section as a function of transverse momentum in the fiducial region (*left*) and corrected to the full acceptance (*right*) compared to theoretical predictions from the POWHEG generator.

8.2.2 Comparison and combination with the electron decay channel

The Z boson production cross section is determined in the electron decay channel as summarized in Section 7.9. The inclusive cross section in the fiducial region measured with electron pairs is found to be

$$\sigma(p_T^e > 20 \text{ GeV}/c, |\eta^e| < 2.4) = 73.9 \pm 1.9 \text{ (stat.)} \pm 4.5 \text{ (syst.)} \pm 2.6 \text{ (lumi.) nb},$$

that agrees with the muon decay channel result. After correcting for the acceptance, the total cross section in the electron decay channel is

$$\sigma_{\text{pPb} \rightarrow Z \rightarrow ee} = 143.5 \pm 3.8 \text{ (stat.)} \pm 10.1 \text{ (syst.)} \pm 5.0 \text{ (lumi.) nb}.$$

The differential cross section as a function of rapidity and transverse momentum in the fiducial region is shown in fig. 8.13 together with the forward-backward asymmetry comparing the muon and electron decay channels. The results agree within statistical and systematic uncertainties thus a combination is performed.

The BLUE technique [123] is applied in the combination taking into account the possible correlations of the uncertainties in the two decay channels. The combination in the fiducial region is quite simple because the electron and muon samples are statistically independent and the sources of systematic uncertainties are different. Practically speaking, after the uncertainty due to luminosity is separated, the uncertainties are uncorrelated between the two decay channels and a weighted average is computed for the combined result. The combined Z boson production cross section

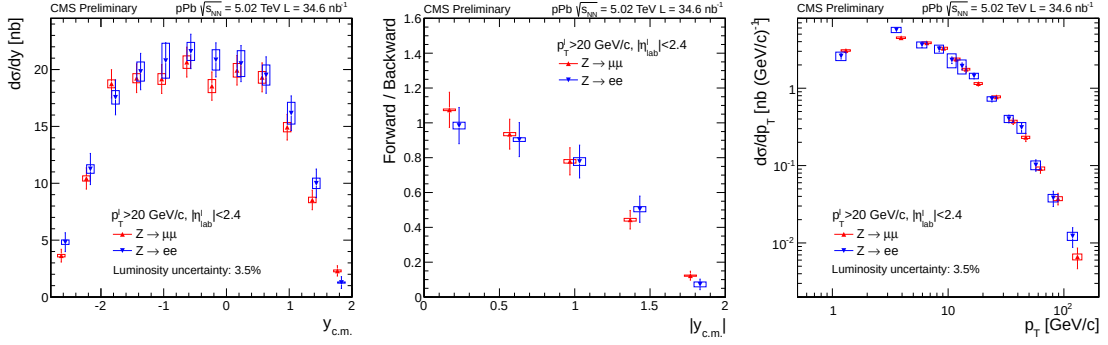


Figure 8.13: Z boson production cross section as a function of rapidity (*left*), forward-backward asymmetry (*middle*) and cross section as a function of transverse momentum (*right*) in the fiducial region compared between the electron and muon decay channels.

in the fiducial region is

$$\sigma(p_T^\ell > 20 \text{ GeV}/c, |\eta^\ell| < 2.4) = 71.3 \pm 1.2 \text{ (stat.)} \pm 1.5 \text{ (syst.)} \pm 2.5 \text{ (lumi.) nb.}$$

The prediction of the POWHEG generator gives a cross section of 70.4 ± 3.5 nb for Z boson production in the 60–120 GeV/ c^2 mass range after applying the acceptance cuts on the leptons and scaling by $A = 208$ for p-Pb collisions.

For the acceptance-corrected total cross section, the systematic uncertainty of the acceptance is correlated between the two decay channels which is taken into account in the BLUE method. The combined Z boson production cross section is

$$\sigma_{\text{pPb} \rightarrow \text{Z} \rightarrow \ell\ell} = 138.1 \pm 2.4 \text{ (stat.)} \pm 8.6 \text{ (syst.)} \pm 4.8 \text{ (lumi.) nb.}$$

This measurement has an uncertainty of about 5% from the extrapolation of the detector acceptance to the full phase space. The prediction from the POWHEG generator after scaling gives a cross section of 136.1 ± 6.8 nb, which is consistent with the measured value.

The differential cross section of Z bosons in p-Pb collisions as a function of rapidity is shown in fig. 8.14 for the combined leptonic decay channel in the fiducial region. The measurement is compared with predictions from the MCFM generator calculated at NLO using the CT10 [95] and MSWT [52] free proton PDF sets with and without applying the nuclear modification from EPS09 [47] or DSSZ [48] nuclear PDF sets. The theory predictions are scaled by $A = 208$. The luminosity normalization uncertainty of 3.5% is not shown in the figure. The measured differential cross section is consistent with the theory predictions within uncertainties that are dominated by the statistical uncertainty.

Nuclear effects are expected to modify the rapidity distribution asymmetrically and thus they can be further quantified by the forward-backward asymmetry defined

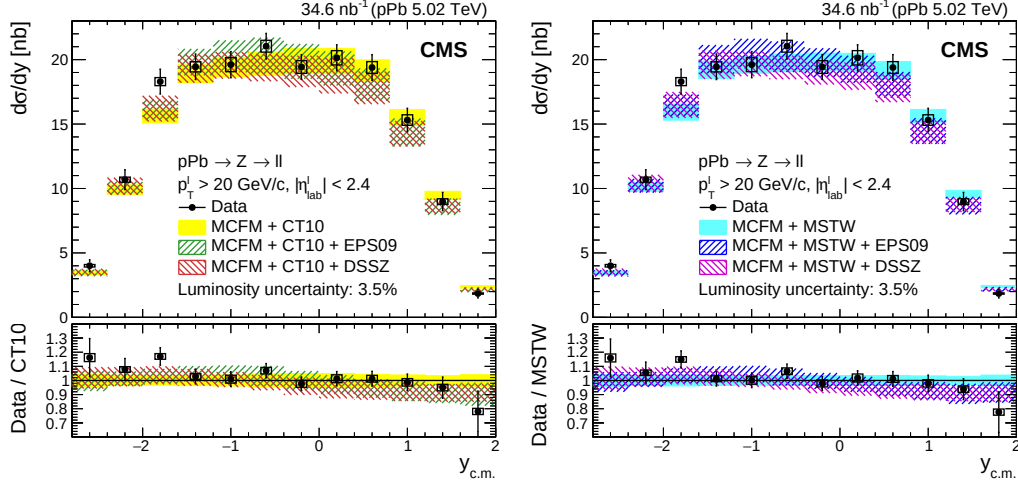


Figure 8.14: Differential Z boson production cross section as a function of rapidity in the fiducial region for the combined leptonic decay channel. The measurement is compared to theoretical predictions from the MCFM generator with and without applying the EPS09 or DSSZ nPDFs on the CT10 (*left*) and MSTW (*right*) free proton PDF sets.

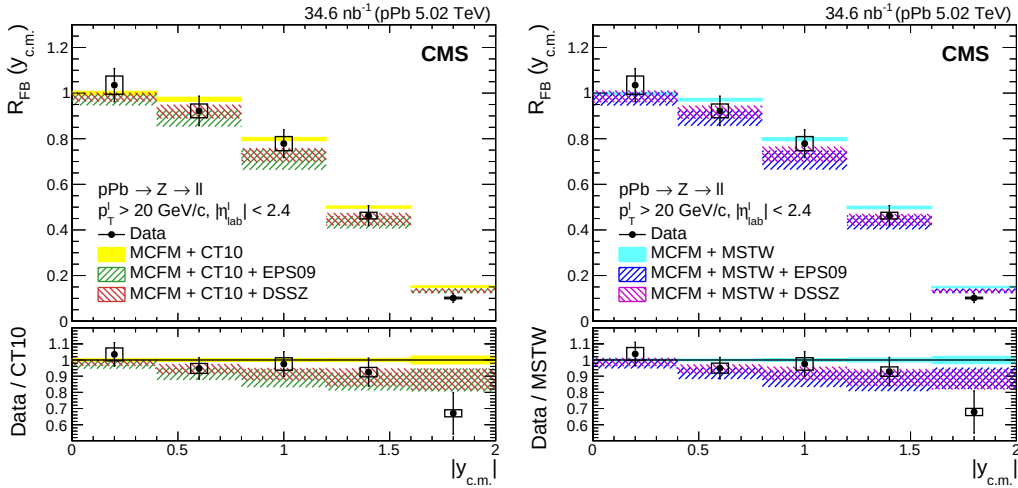


Figure 8.15: Forward-backward asymmetry of Z boson production in the fiducial region for the combined leptonic decay channel. The measurement is compared to theoretical predictions from the MCFM generator with and without applying the EPS09 or DSSZ nPDFs on the CT10 (*left*) and MSTW (*right*) free proton PDF sets.

in eq. (8.5). This quantity is expected to be more sensitive to nuclear effects because normalization uncertainties cancel both in theory and in experiment. The measured forward-backward asymmetry as a function of $|y|$ is shown in fig. 8.15 compared to the MCFM predictions with and without nuclear effects.

The calculated cross sections do not show a strong dependence on the free proton PDFs. The data tend to agree with the presence of nuclear effects in PDFs and together with the measured W boson production in p-Pb collisions [126] can constrain the nPDF uncertainties by adding new data to the global fits in a previously unexplored region of the (Q^2, x) phase space.

Observable PDFs	$d\sigma/dy$		R_{FB}	
	χ^2	probability	χ^2	probability
CT10	10.8	54%	7.3	20%
CT10+EPS09	7.4	83%	3.9	56%
CT10+DSSZ	6.6	88%	3.4	64%
MSTW	10.3	59%	6.9	23%
MSTW+EPS09	7.9	80%	4.2	53%
MSTW+DSSZ	6.4	90%	2.7	75%

Table 8.1: Results of the χ^2 test between the measurements and the theoretical predictions with and without nuclear modification of the PDFs. The differential cross section and the forward-backward asymmetry have twelve and five degrees of freedom, respectively.

In order to quantify the agreement between the measurements and the predictions with the different PDF sets, a χ^2 test is performed for the rapidity-dependent cross section and the forward-backward asymmetry. The few correlations in experimental uncertainties, only relevant for the cross section but not for the asymmetry, are taken into account, as well as the correlations in the theoretical uncertainties. The resulting χ^2 values and probabilities are given in table 8.1. The theory calculations including nuclear effects provide better description of the measurements.

The differential cross section as a function of transverse momentum is shown in fig. 8.16 for the combined leptonic decay channel in the fiducial region. The results are compared to the scaled p-p theoretical prediction from POWHEG with CT10 PDF, because the expected nuclear modification of the p_T spectrum is small compared to the uncertainties of the theory [72, 73]. No large deviations are found from the p-p theory cross section scaled by the number of nucleons in the Pb nucleus apart from the lowest dilepton p_T bins where the differences from POWHEG are similar to the ones observed in the p-p measurements at 7 and 8 TeV [33, 35].

8.2.3 Discussion

The Z boson production cross section has been measured in the muon and electron decay channels in p-Pb collisions at a nucleon-nucleon center-of-mass energy of 5.02 TeV. The inclusive cross sections are in agreement with NLO theoretical predictions from POWHEG p-p simulation scaled by the number of elementary nucleon-nucleon collisions. The differential cross section as a function of Z boson rapidity is consistent with the theoretical predictions. At large rapidity, the forward-backward asymmetry deviates from free proton PDFs by an amount which is compatible with EPS09 and DSSZ nPDF modifications, though the statistical precision of the measurement precludes making a definitive statement. The differential cross section as a function of Z boson transverse momentum has been measured and apart from very low transverse momenta it is in agreement with the predictions from POWHEG.

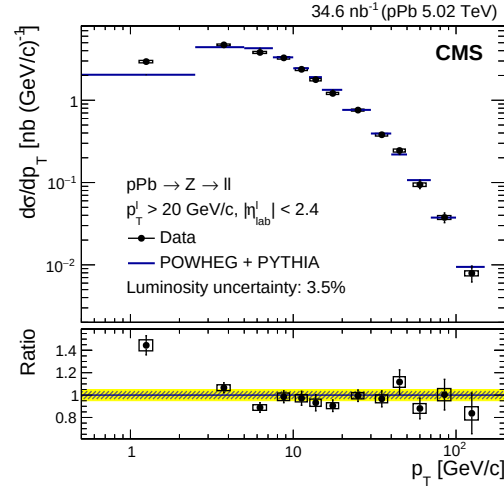


Figure 8.16: Differential Z boson production cross section as a function of transverse momentum in the fiducial region compared to theoretical predictions from the POWHEG generator.

The results of the presented measurement together with the measured W boson production provide new data in a previously unexplored region of phase space for constraining nuclear PDF fits.

9 Summary

The energies reached at the LHC opened up the possibility to study the production of the high mass electroweak bosons in proton-nucleus and nucleus-nucleus collisions for the first time. The production of Z and W bosons represents an important benchmark process because it is expected to depend only on the initial geometry of the collisions and not to be modified by the hot and dense medium produced in the collisions. By studying the Z boson decays to electron and muon pairs that do not participate in the strong interaction thus pass through the medium freely, one can access the initial conditions of nuclear collisions. The distribution of the quarks and gluons in the nucleus can be studied, which is a necessary non-perturbative input to the theoretical calculations of high-energy processes, and can shed light on the nature of nuclear binding at high energies.

The CMS experiment collected large amount of lead-lead and proton-lead collision data in 2011 and 2013. In this thesis I presented the analysis of these datasets in two aspects: First, I showed how the Glauber model is used for the estimation of the initial geometry or centrality of the collisions based on measured quantities in the detector. Second, I presented the details of the analysis of Z boson production in the muon decay channel through the example of the p-Pb data pointing out the differences between the three studied collision systems. In the analysis I made use of simulated datasets produced by different Monte Carlo generators for comparing with the data, calculating correction factors and estimating systematic uncertainties.

My main results presented in this thesis are summarized in the following points:

1. I estimated the number of participating nucleons and the number of elementary nucleon-nucleon collisions in different event classes using two different methods for connecting the Glauber-model quantities with experimental observables. I found the average values to be the same using measured particle multiplicity in different parts of the detector even though different type of events are selected in each centrality class [96, 98].
2. I showed that the yield of Z bosons in Pb-Pb collisions does not depend on centrality after scaling by the average number of binary nucleon-nucleon collisions

in each centrality class. This confirms the geometrical scaling of hard processes in heavy-ion collisions. I have drawn the same conclusions when calculating the nuclear modification factor using the Z boson production cross section in p-p collisions at the same center-of-mass energy [108, 117, 119, 121, 122].

3. I measured the Z boson yield as a function of transverse momentum and rapidity in Pb-Pb collisions and found that it agrees with the theoretical expectations and the measured cross section in p-p collisions. This demonstrates that possible initial state nuclear effects are small and within the experimental uncertainties [108, 117, 119, 121, 122].
4. I determined the inclusive Z boson production cross section in p-Pb collisions, that agrees with the p-p theoretical calculation scaled by the number of nucleons in the Pb nucleus. This confirms that at first approximation the Z boson production scales with the number of binary nucleon-nucleon collisions also in p-Pb collisions [109, 110, 118, 120, 121, 122].
5. I measured the rapidity differential cross sections of Z bosons in p-Pb collisions that shows some deviations from the p-p theoretical calculations in the forward and backward regions and this effect is enhanced when calculating the forward-backward asymmetry. The results tend to agree better with the presence of nuclear effects though the statistical precision of the measurement does not allow a definitive statement. These new experimental data allow for better constraints of the nuclear parton distribution functions in a previously unexplored region of phase space [109, 110, 118, 120, 121, 122].

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