Differential measurements of the Drell–Yan process in the 
muon channel in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV

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Abstract

Measurements of differential cross sections for the Drell–Yan process, including $Z$ boson production, in proton-lead (pPb) collisions at a nucleon-nucleon centre-of-mass energy of 8.16 TeV are presented, in the muon channel. A data sample recorded with the CMS detector at the LHC is used, corresponding to an integrated luminosity of $173.4 \pm 6.1 \text{nb}^{-1}$. The differential cross section $d\sigma/dm_{\mu\mu}$ in the dimuon mass range $15 < m_{\mu\mu} < 600$ GeV is measured with the CMS detector, for the first time in heavy ion collisions, and reported before and after correction to the full phase space, given by the dimuon rapidity $y_{CM}$ in the centre-of-mass frame from $-2.87$ to $1.93$. The differential cross section $d\sigma/dy_{CM}$ is also measured over the mass ranges $15 - 60$ and $60 - 120$ GeV, and same dimuon rapidity range. Ratios of dimuon yields for the proton-going over the Pb-going beam directions are built in the range $|y_{CM}| < 1.93$. In both mass ranges, the differential cross sections $d\sigma/dp_T$ and $d\sigma/d\phi^*$ are measured, where the kinematic observable $\phi^*$ correlates with the dimuon transverse momentum but only depends on angular quantities. Results are compared to predictions at next-to-leading order, including nuclear modifications of parton distribution functions, which they could help better constrain.
1 Introduction

The annihilation of a quark-antiquark pair into two oppositely charged leptons, through the exchange of a virtual photon or a Z boson in the $s$ channel, is known as the Drell–Yan ($Z/\gamma^*$) process. The perturbative theoretical derivation of the matrix element is available up to next-to-next-to-leading order (NNLO) in perturbative quantum chromodynamics (QCD) with next-to-leading order electroweak corrections [1–4], and a precise measurement can add valuable information on the nonperturbative part of the process, including parton distribution functions (PDFs).

Many measurements of the Drell–Yan process, including the mass dependence, have been performed in pp collisions, for instance by the ATLAS [5–9], CMS [10–13], LHCb [14], and PHENIX [15] experiments. Measurements of Z boson production have been performed in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV by the ALICE [16], ATLAS [17], and CMS experiments [18], as a function of rapidity, transverse momentum, or centrality (pPb collision geometry).

We report the measurement of the differential cross section for $\mu^+\mu^-$ production with the Drell–Yan process, as a function of the following variables:

- dimuon mass, in the interval $15 < m_{\mu\mu} < 600$ GeV,
- dimuon $p_T$, in two dimuon mass intervals ($15–60$ and $60–120$ GeV),
- dimuon rapidity in the centre-of-mass frame, in the same two mass intervals,
- $\phi^*$ [19–21] (defined below), in the same two mass intervals.

The dimuon mass and $\phi^*$ dependencies are reported for the first time in heavy ion collisions, as well as cross sections in the dimuon mass range $15–60$ GeV.

The variable $\phi^*$, used in numerous Z boson studies, is defined as

$$\phi^* \equiv \tan \left( \frac{\pi - \Delta\phi}{2} \right) \sin(\theta^*_\eta),$$

(1)

where $\Delta\phi$ is the opening angle between the leptons in the plane transverse to the beam axis and $\theta^*_\eta$ indicates the scattering angle of the dilepton with respect to the beam in a frame such that the two leptons are back-to-back in the $r-\theta$ plane, using a Lorentz boost along the beam direction. It is related to the pseudorapidities of the oppositely charged leptons by the relation

$$\cos(\theta^*_\eta) = \tanh(\Delta\eta/2),$$

(2)

where $\Delta\eta$ is the difference in pseudorapidity between the two leptons. By construction, $\phi^*$ is greater than zero. This quantity is strongly correlated with the dimuon $p_T$, while only depending on angular quantities for the leptons, thus measured with a better resolution, especially at low $p_T$ values. Since $\phi^* \sim p_T/m$, where $m$ is the mass of the dilepton system, the range $\phi^* < 1$ corresponds to dilepton $p_T$ up to about 100 GeV for a dilepton mass close to the Z boson mass.

Measurements of electroweak bosons are sensitive to the PDFs of the nucleon. Similarly, such measurements in proton-nucleus and nucleus-nucleus collisions are probing the nuclear modifications of the PDFs. The presence of a nuclear environment modifies the parton densities in the nucleus as compared to those in a free nucleon. Global fits of nuclear PDFs (nPDFs) [22–27] predict a suppression in the small Bjorken $x$ region $x \lesssim 10^{-2}$ (i.e. shadowing) and an enhancement in the intermediate $x$ region $10^{-2} \lesssim x \lesssim 10^{-1}$ (i.e. antishadowing), for quark and antiquark nPDFs, relative to free nucleon PDFs.
2 Experimental methods

2.1 Data-taking conditions and the CMS detector

The results reported in this note are using pPb collision data taken at a nucleon-nucleon centre-of-mass (CM) energy of 8.16 TeV by CMS at the end of 2016. The total integrated luminosity corresponds to $173.4 \pm 6.1 \text{nb}^{-1}$ [28]. In the first part of the pPb run, corresponding to $63 \pm 2 \text{nb}^{-1}$, the proton was heading towards negative pseudorapidity, according to the CMS detector convention [29], with an energy of 6.5 TeV and colliding on a lead nucleus beam with an energy of 2.56 TeV per nucleon. The beams were swapped for the second part of the run, corresponding to $111 \pm 4 \text{nb}^{-1}$. Because of the asymmetric collision system, massless particles produced in the proton-lead CM frame at an $\eta_{CM}$ are reconstructed at $\eta_{lab} = \eta_{CM} - 0.465$ in the laboratory frame, in the convention that the proton is heading towards positive pseudorapidity, which is used in this note. The measurements presented in this note are expressed in terms of the dimuon rapidity in the CM frame, $y_{CM}$.

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid.

The reconstructed vertex with the largest value of summed physics-object $p_T^2$ is taken to be the primary pPb interaction vertex. The physics objects are the jets, clustered using the jet finding algorithm [30, 31] with the tracks assigned to the vertex as inputs, and the associated missing transverse momentum, taken as the negative vector sum of the $p_T$ of those jets. During the data taking, the average number of collisions per bunch crossing was 0.18.

The particle-flow algorithm [32] aims to reconstruct and identify each individual particle in an event, with an optimised combination of information from the various elements of the CMS detector. The energy of photons is obtained from the ECAL measurement. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The energy of muons is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for zero-suppression effects and for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies.

The forward hadron (HF) calorimeter uses steel as an absorber and quartz fibres as the sensitive material. The two halves of the HF are located 11.2 m from the interaction region, one on each end, and together they provide coverage in the range $3.0 < |\eta| < 5.2$. They also serve as luminosity monitors.

Muons are measured in the pseudorapidity range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. The single muon trigger efficiency exceeds 90% over the full $\eta$ range, and the efficiency to reconstruct and identify muons is greater than 96%. Matching muons to tracks measured in the silicon tracker results in a relative transverse momentum resolution, for muons with $p_T$ up to 100 GeV, of 1%
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in the barrel and 3% in the endcaps. The $p_T$ resolution in the barrel is better than 7% for muons with $p_T$ up to 1 TeV [33].

Events of interest are selected using a two-tiered trigger system [34]. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of up to 100 kHz within a time interval of less than 4 $\mu$s. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimised for fast processing, and reduces the event rate to around 1 kHz before data storage.

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [29].

2.2 Data and simulated samples

The signal and most backgrounds are modelled using Monte Carlo (MC) simulated samples. The following processes are considered: Drell–Yan to $\mu^+\mu^-$ and to $\tau^+\tau^-$, $t\bar{t}$, diboson (WW, WZ and ZZ), and single top quark production ($tW$ and $t\bar{t}W$, collectively referred to as $tW$ in this note). Additional MC samples are used, for the production of $W$ bosons (decaying to muon and neutrino or $\tau$ lepton and neutrino) and QCD multijet events. These backgrounds are estimated using a data-driven method, described later in the text, and the MC simulation is only used for complementary studies.

The Drell–Yan, $W$ boson, $t\bar{t}$, and $tW$ MC samples are generated using the next-to-leading order (NLO) generator POWHEG BOX v2 [35–38], modified to account for the mixture of proton-proton (pp) and proton-neutron (pn) collisions occurring in pPb collisions. The CT14 [39] PDF set is used, with nuclear modifications from EPPS16 [24] on the lead nucleus. Parton showering is performed by PYTHIA 8.212 [40] with the CUETP8M1 underlying event (UE) tune [41]. The decay of $\tau$ particles in the $W \rightarrow \tau\nu$, MC samples is handled in POWHEG using TAUOLA 1.1.5 [42], including final state radiative (FSR) QED corrections using PHOTOS 2.15 [43]. The diboson and QCD multijet samples are generated using PYTHIA 8.212.

To consider a more realistic distribution of the underlying environment present in pPb collisions, simulated events are embedded into two separate minimum bias samples generated with EPOS [44], one for each pPb boost direction. The EPOS MC samples are tuned to reproduce the global event properties of the pPb data such as the charged-hadron transverse momentum spectrum and the particle multiplicity.

A difference is found between the dimuon $p_T$ in POWHEG MC and that observed in data, as reported in the results of this note. To improve the modelling in the simulation, the POWHEG $Z/\gamma^*$ samples are reweighted event by event, as a function of the generated boson $p_T$. The weight $w(p_T)$ is taken as the ratio of cross sections between data corrected to the full phase space and the POWHEG prediction, parametrised with an ad-hoc function, described by $w(p_T) = \frac{1}{(p_T/p_0)^{p_1} + p_2}$. This is done separately for low and high dimuon masses, such that $p_0 = -0.02 \pm 0.18$ GeV, $p_1 = 0.52 \pm 1.46$, $p_2 = 1.08 \pm 0.37$ for $m_{\mu\mu} < 60$ GeV, and $p_0 = -0.35 \pm 0.29$ GeV, $p_1 = -0.26 \pm 0.45$, $p_2 = 1.29 \pm 0.34$ for $m_{\mu\mu} > 60$ GeV. This weight is applied in simulation in the derivation of the various corrections described below. It is however not applied in the figures of this note, where the original $p_T$ spectrum from POWHEG is used.

The full detector response is simulated in all MC samples, based on GEANT4 [45], considering a realistic alignment and calibration of the beam spot and the different sub-detectors of CMS, tuned on data. The trigger decisions are also emulated and the MC events are reconstructed
with the standard CMS pp reconstruction algorithms used for the 2016 data.

The Z/γ∗, W, and tW samples are normalised to their NLO cross sections provided by POWHEG for pPb collisions, including EPPS16 modifications. The diboson samples are normalised to the cross section measured by the CMS Collaboration in pp collisions at √s = 8 TeV [46–48]. The tZ background is normalised to the CMS measurement in pPb collisions at √s_{NN} = 8.16 TeV [49]. All backgrounds, except WZ and ZZ, receive a data-driven correction, as described in Section 2.4.

Simulated events do not feature the same event activity (charged particle multiplicity or energy density) as the data, mostly because selecting two energetic muons favours higher activity events (more “central” events, with a larger number of binary nucleon-nucleon collisions), while the EPOS sample used for embedding simulates minimum bias events. To ensure a proper description of event activity in simulation, the distribution of the energy deposited in both sides of the HF calorimeter is reweighted so that it matches that observed in data (selecting Z → μ⁺μ⁻ events).

### 2.3 Object reconstruction and event selection

The events used in the analysis are selected with a single muon trigger, requiring p_T > 12 GeV for the muon reconstructed by the HLT. During offline muon reconstruction, the data from the muon detectors are matched and fitted to data from the silicon tracker to form muon candidates. Each muon is required to be within the geometrical acceptance of the detector, |η_{lab}| < 2.4. The leading muon is matched to the HLT trigger object and is required to have p_T > 15 GeV, in the plateau of the trigger efficiency (typically 95%, depending on η_{lab}). A looser selection of p_T > 10 GeV is applied to the other muon.

Muons are selected by applying the standard tight selection criteria [33], also used for instance in Ref. [50]. Requirements on the impact parameter and the opening angle between the two muons are further imposed to reject cosmic ray muons. Events are selected for further analysis if they contain oppositely charged muon pairs meeting the above requirements. The χ² divided by the number of degrees of freedom from a fit to the dimuon vertex should be smaller than 20, ensuring that the two muon tracks originate from a common vertex, reducing the contribution from heavy-flavour meson decays. The candidate with the smallest dimuon vertex χ² is kept, in the rare events (about 0.4%) where more than one selected dimuon pair is found.

To further suppress the background contributions due to muons originating from heavy-quark decays and nonprompt muons from hadron decays, muons are required to be isolated, based on the sum of the transverse momenta of the charged particle tracks around the muon. Isolation sums are evaluated in a circular region of the (η, φ) plane around the lepton candidate with ∆R < 0.3, where ∆R = √(∆η)² + (∆φ)². The relative isolation I_\text{rel}, obtained by dividing this isolation sum by the muon p_T (I_\text{rel} = (\sum_{\text{tracks}} p_T) / p_T^\mu), is required to be below 0.2.

In addition to the Drell-Yan process, lepton pairs can also be produced through photon interactions. Exclusive coherent photon-induced dilepton production is enhanced in pPb collisions compared to pp, because of the large charge of the lead nucleus. In order to suppress this background, characterised by almost back-to-back muons, events are required to contain at least one additional reconstructed track, in addition to the two reconstructed muons, which completely removes this background. Incoherent photon-induced dimuon production, where the photon is emitted off a parton instead of the whole nucleus, is considered part of the signal and is not removed nor subtracted.
2.4 Background estimation

Different backgrounds are estimated using one of the two techniques described below, depending on their respective nature. Processes involving two isolated muons, such as $Z/\gamma^* \rightarrow \tau\tau, t\bar{t}, tW,$ and $WW,$ are estimated from simulation, corrected using the “$e\mu$ method”. Processes with one or more muon in jets, namely $W+$jets and multijet, are estimated using the “misidentification rate method”. The WZ and ZZ backgrounds, which are almost negligible, are estimated directly from simulation.

The $e\mu$ method takes advantage of the fact that the electroweak backgrounds, as opposed to the $Z/\gamma^* \rightarrow \mu^+\mu^-$ signal, also contribute to the $e\mu$ final state. Events with exactly one electron and one muon of opposite charge are selected, where the muon is selected as described previously, matched to the HLT trigger muon and with $p_T > 15 \text{ GeV}$, while the electron [51] has to have $p_T > 20 \text{ GeV}$ and to fulfil the same isolation requirement. The small contribution from heavy-flavour meson decays is estimated from same-charge $e\mu$ events, with a transfer factor accounting for the average time-integrated B meson oscillation probability, estimated using simulation and world average data [52]. This transfer factor is also estimated using a Monte-Carlo-based study, and the difference, 27%, is used as a systematic uncertainty. The data-to-simulation ratio with this selection, in each bin of the measured variables and most of the time compatible with unity, is used to correct the simulated samples in the $\mu^+\mu^-$ final state.

The misidentification method estimates the probability for a muon inside a jet, passing the tight selection criteria, to pass the isolation requirements. This probability (the misidentification rate) is estimated as a function of $p_T$, separately for $|\eta_{\text{lab}}| < 1.2$ and $|\eta_{\text{lab}}| > 1.2$. A sideband in data is selected from opposite-charge dimuon events in which the dimuon vertex $\chi^2$ selection has been inverted. This sample is dominated by contributions from multijet and $W+$jets production, and the small contribution from electroweak processes, estimated using simulation, is removed. This misidentification rate is then applied to a control dimuon data sample, passing the dimuon vertex $\chi^2$ selection but in which none of the two muons passes the isolation requirement, to obtain the multijet contribution in the signal region, where both muons are isolated. The $W+$jets contribution is estimated with a similar procedure, using events in which exactly one of the two muons passes the isolation requirement. The small contribution from electroweak processes to these control data samples is estimated using simulation and removed. The multijet contribution in the sample with exactly one isolated muon is also accounted for, using the same data-driven technique. The validity of this method is checked in a control sample of same-charge dimuon data, which is also dominated by the multijet and $W+$jets processes. The same-charge data is found to be compatible with the predictions from the misidentification rate method in most bins, and the residual difference is applied as a correction in the opposite-charge signal region.

In Fig. 1, data are compared to the prediction from Drell–Yan simulation and background expectations estimated using the techniques described above. A good overall agreement is found between the data and the expectation, which is dominated by the Drell–Yan signal. Some hints for differences (data above expectation for $m_{\mu\mu} < 50 \text{ GeV}$, as well as for $y_{\text{CM}} > 0$ when $60 < m_{\mu\mu} < 120 \text{ GeV}$, and trend in dimuon $p_T$ and $\phi^*$ as mentioned earlier) will be discussed in more details in Sec 3.

2.5 Muon momentum scale and resolution corrections

The muon momentum scale and resolution are corrected in both data and simulation, following the standard CMS procedure described in Ref. [53]. These corrections have been derived on the pp data sample at $\sqrt{s} = 13 \text{ TeV}$ recorded by CMS in 2016, with the same detector conditions as
Figure 1: Comparison of the data (black points) with the total of the $Z/\gamma^*$ signal and background predictions (filled histograms), estimated as described in the text, as a function of invariant mass (top), rapidity in the center-of-mass frame (left), $p_T$ (center) and $\phi^*$ (right), for $15 < m_{\mu\mu} < 60 \text{ GeV}$ (middle row) and $60 < m_{\mu\mu} < 120 \text{ GeV}$ (bottom row). The first bins of the $p_T$ and $\phi^*$ distributions start at 0. Vertical error bars represent statistical uncertainties. The ratio of the data to the prediction is shown in the bottom panels. The boson $p_T$ reweighting described in the text is not applied to signal. The hatched regions show the quadratic sum of the systematic uncertainties (including luminosity, but excluding acceptance and unfolding uncertainties) and the nPDF uncertainties (CT14+EPPS16).
the pPb data set considered in the present analysis.

In addition, the measurement is unfolded for finite momentum resolution, with the biggest impact found on the mass and $p_T$ measurements. No regularisation is found to be needed given the good resolution and modest migrations between analysis bins, and the maximum likelihood estimate (obtained from the inversion of the response matrix, derived using the NLO POWHEG simulated samples) is used to obtain the unfolded results. The effect of unfolding is less than one percent in most cases, except for the mass dependence close to the Z boson mass peak, where it can amount to up to 15%.

2.6 Acceptance and efficiency

After subtraction of the contribution from the different background processes, correction for the muon momentum resolution and scale, and unfolding for detector resolution, the data are corrected for acceptance and efficiency. The acceptance is defined as the fraction of generated events in the full phase space (within the quoted dimuon mass range and $-2.87 < y_{CM} < 1.93$) passing the kinematic selection defining the fiducial region: leading muon $p_T > 15$ GeV, trailing muon $p_T > 10$ GeV, and $|\eta_{lab}| < 2.4$. Results are presented both with and without this acceptance correction, i.e. extrapolated to the full phase space and restricted to the fiducial region, respectively. The efficiency is the fraction of these events passing all other analysis selection criteria, including trigger selection, muon identification and isolation, and dimuon selection.

The efficiency is also checked in data, using Z boson events, with a tag and probe technique. The same procedure and corrections are used as in the measurement of W± bosons in pPb collisions [50]. The observed difference between the data and MC efficiencies, estimated separately for trigger, identification, and isolation, is accounted for as scale factors on a muon-by-muon basis and applied in simulation. These corrections are applied both in the efficiency estimation and in the construction of the background templates described in Sec. 2.4. When both muons in the event have $p_T > 15$ GeV, they can both pass the single muon trigger used in this data analysis, and the scale factor is computed from the product of inefficiencies. For muon and inner track reconstruction, the data and MC are found to give compatible efficiencies (higher than 99.9%) and no scale factor is applied for these two components of the efficiency.

2.7 Final-state QED radiation effects

Muons may undergo some final-state radiation before being measured in the CMS detector, biasing their momentum and shifting the dimuon mass to lower values. We unfold the measured distributions, after efficiency correction (as well as acceptance if applicable), to the “pre-FSR” quantities, defined from a dressed lepton definition. Generator-level muon four-momenta are recalculated adding the four-momenta of all generated photons found inside a cone of radius $\Delta R = 0.1$ around the muon. Again the response matrices for this unfolding procedure, derived using the NLO POWHEG simulated samples, are found to be close to diagonal, thus no regularisation is needed in the unfolding.

2.8 Systematic uncertainties

Several sources of systematic uncertainties are evaluated and are described below.

Theoretical uncertainties have an impact on the acceptance and efficiency. The renormalisation and factorisation scales have been varied from half to twice their nominal value (set to the dimuon mass), and the envelope of the variation is taken as an uncertainty. In addition, the strong coupling constant value is varied by 0.0015 from its default value, $\alpha_s(M_Z) = 0.118,$
as recommended by PDF4LHC [54]. The CT14 and EPPS16 uncertainties are also included, estimated using LHAPDF6 [55]. Finally, the full difference between acceptance and efficiency obtained with and without the data-driven boson $p_T$ reweighting is considered as a systematic uncertainty. The impact of these uncertainties is less than 1% on the efficiency, but up to 9% on the acceptance for low dimuon masses.

We also include uncertainties coming from the estimation of the data-driven efficiencies. Besides a statistical component coming from the limited $Z$ boson sample available, which is treated as a systematic uncertainty in this analysis, we also consider systematic effects coming from the choice of function used to model the $p_T$ behaviour of the efficiencies, the dimuon mass fitting procedure to the $Z$ boson peak in the extraction of the efficiencies, as well as from a possible data-MC difference in the muon reconstruction efficiency, and the effect of mismodellings in simulation of event activity and additional interactions per bunch crossing. The magnitude of these uncertainties ranges from 1.2% to 5.4% at low dimuon mass.

Regarding the estimation of electroweak backgrounds with the $e\mu$ method, the statistical uncertainty in the correction factors is included as a systematic uncertainty, as well as the effect of varying the $t\bar{t}$ cross section by its uncertainty, 18% [49], the uncertainty in the transfer factor for the heavy flavour contribution, and the difference between the data and simulation in the $e\mu$ distributions. The systematic uncertainty in the multijet and W+jets backgrounds, related to the misidentification rate method, receives several contributions. The statistical uncertainty in the data-driven templates is accounted for, and combined with the full difference between the nominal estimation and an alternative method (based on a different sideband in data, using same-charge dimuon events). The residual nonclosure in the same-charge data sample, as well as its statistical uncertainty, are also both added in quadrature with the other uncertainties related to the misidentification rate method. The total systematic uncertainty on background estimation ranges from less than 0.5% to 6% at low mass and 12% at large dimuon $p_T$.

A different reweighting of event activity in simulation is derived as a function of the number of offline tracks reconstructed with $|\eta_{\text{lab}}| < 2.5,$ instead of the nominal correction using the total energy deposited in the HF calorimeters, which modifies the efficiency and the background estimation. The observed difference in the measurements, which is less than 1% in most bins, is taken as a systematic uncertainty.

Uncertainties in muon momentum scale and resolution corrections have been evaluated, based on the 2016 pp data sample at $\sqrt{s} = 13$ TeV in which they are derived. These uncertainties, about 1% or less, arise from the limited data sample size available, from the boson $p_T$ reweighting, from the variation of the method used to derive the correction, and from varying the part of the 2016 data taking period considered in the derivation of the corrections, accounting for a possible time dependence.

Response matrices used in the muon momentum scale and FSR unfoldings have been recalculated using the first and second part of the run alone (accounting for statistical uncertainties in the simulation), and using the PYQUEN generator [56] instead of POWHEG (for a conservative estimation of the model dependence). Differences in the unfolded results, which are up to 2%, are taken into account a systematic uncertainty.

Finally, the uncertainty in the luminosity measurement is 3.5% [28].

Correlations between these uncertainties have also been evaluated. Theory uncertainties are assumed to be fully correlated, with the exception of the nPDF uncertainty, whose correlation is calculated using the CTEQ prescription for Hessian sets [57]. Systematic uncertainties in the data-driven efficiency scale factors are assumed to be uncorrelated since they could have
different effects in different kinematic regions, while statistical correlations between scale factors derived in the same region of the detector are accounted for. No correlation is assumed for uncertainties related to background estimation. Uncertainties related to the event activity reweighting, unfolding, and luminosity are fully correlated, as well as each of the sources of uncertainty in the muon momentum scale and resolution corrections. The correlation matrices for systematic uncertainties are shown in Fig. 2, excluding the fully correlated luminosity uncertainty for clarity.

3 Results and discussion

Fiducial cross section results, where the fiducial volume is defined from the single muon $p_T$ and $\eta_{lab}$ selection, are shown in Fig. 3, as functions of the dressed lepton kinematic variables (as discussed in Section 2.7), together with expectations from POWHEG, using the CT14 [39] or CT14+EPPS16 [24] PDF sets. Cross sections in the full phase space, $-2.87 < y_{CM} < 1.93$, i.e. including acceptance correction for the single muon kinematic cuts, are also presented in Fig. 4.

It can be seen that CT14+EPPS16 suffers from a larger uncertainty, which is coming from the parametrisation of the nuclear modification of the PDFs. Since the dimuon rapidity is strongly correlated with the longitudinal momentum fraction $x_{Pb}$ of the parton in the lead nucleus, one can identify the shadowing region in the rapidity dependence of the cross section, in the full measured rapidity range for $15 < m_{\mu\mu} < 60$ GeV and at positive rapidity for $60 < m_{\mu\mu} < 120$ GeV. In the latter mass range, rapidities $y_{CM} \lesssim -1$ correspond to anti-shadowing. The inclusion of EPPS16 nuclear PDF modifications tends to provide a better description of the rapidity dependence in data for $60 < m_{\mu\mu} < 120$ GeV than the use of the CT14 PDF alone. Uncertainties in the measurement are also smaller than nPDF uncertainties in the Z boson mass region for most analysis bins, showing that these data could bring strong constraints if included in future nPDF fits.

The mass dependence sheds further light on shadowing effects probed at low mass, i.e. at lower $x_{Pb}$ and lower scales than using Z bosons. The cross section measurement extends down to masses close to the $\Upsilon$ meson masses, with potential implications in the understanding of the interplay between nuclear PDF and other effects in quarkonium production on proton-nucleus collisions [58].

The difference between the fiducial cross sections, shown in Fig. 3, and the ones corrected to the full phase space, shown in Fig. 4, is largest for the low masses. The absence of acceptance correction in the former results reduces their model dependence and corresponding theoretical uncertainty, making clearer the trend for a higher cross section in data at low dimuon masses compared to the POWHEG expectation.

The $p_T$ and $\phi^*$ dependence of the cross section, especially in the Z boson mass region, both point to a mismodelling in POWHEG, reminiscent of the trend reported previously [18]. This precise measurement in proton-nucleus collisions provides new insight on the soft QCD phenomena dominating the production at low boson $p_T$ or $\phi^*$, and their modification with respect to proton-proton collisions.

Integrated cross sections are also reported, in two mass ranges, in the fiducial region (fid.) or in the full phase space for $-2.87 < y_{CM} < 1.93$ (full):
Figure 2: Correlation matrices for the systematic uncertainties, as a function of invariant mass (top), rapidity in the center-of-mass frame (left), $p_T$ (center) and $\phi^*$ (right), for $15 < m_{\mu\mu} < 60$ GeV (middle row) and $60 < m_{\mu\mu} < 120$ GeV (bottom row).
3. Results and discussion

Figure 3: Differential fiducial cross sections (without acceptance correction) for the Drell–Yan process measured in the muon channel, as a function of invariant mass (top), rapidity in the center-of-mass frame (left), \( p_T \) (center) and \( \phi^* \) (right), for \( 15 < m_{\mu\mu} < 60 \text{ GeV} \) (middle row) and \( 60 < m_{\mu\mu} < 120 \text{ GeV} \) (bottom row). The first bin of the \( p_T \) and \( \phi^* \) measurements starts at 0. The error bars on the data represent the quadratic sum of the statistical and systematic uncertainties. Theory predictions from the POWHEG NLO generator are also provided, using CT14 (blue) or CT14+EPPS16 (red). The boxes show the 68% confidence level (n)PDF uncertainty on this prediction. The ratio of the predictions to the data is shown in the bottom panels, where the data and nPDF uncertainties are given separately, respectively as error bars around one and coloured boxes.
Figure 4: Differential cross sections for the Drell–Yan process measured in the muon channel, as a function of invariant mass (top), rapidity in the center-of-mass frame (left), $p_T$ (center) and $\phi^*$ (right), for $15 < m_{\mu\mu} < 60\text{GeV}$ (middle row) and $60 < m_{\mu\mu} < 120\text{GeV}$ (bottom row). The first bin of the $p_T$ and $\phi^*$ measurements starts at 0. The error bars on the data represent the quadratic sum of the statistical and systematic uncertainties. Theory predictions from the POWHEG NLO generator are also provided, using CT14 (blue) or CT14+EPPS16 (red). The boxes show the 68% confidence level (n)PDF uncertainty on this prediction. The ratio of the predictions to the data is shown in the bottom panels, where the data and nPDF uncertainties are given separately, respectively as error bars around one and coloured boxes.
\[
\sigma(\text{pPb} \rightarrow \gamma^*/Z \rightarrow \mu^+\mu^-, \text{fid.}, 15 < m_{\mu\mu} < 60 \text{ GeV}) = 22.3 \pm 0.5 \text{ (stat)} \pm 0.8 \text{ (syst) nb}, \\
\sigma(\text{pPb} \rightarrow \gamma^*/Z \rightarrow \mu^+\mu^-, \text{fid.}, 60 < m_{\mu\mu} < 120 \text{ GeV}) = 122.3 \pm 0.9 \text{ (stat)} \pm 1.6 \text{ (syst) nb}, \\
\sigma(\text{pPb} \rightarrow \gamma^*/Z \rightarrow \mu^+\mu^-, \text{full}, 15 < m_{\mu\mu} < 60 \text{ GeV}) = 179.5 \pm 3.6 \text{ (stat)} \pm 15.8 \text{ (syst) nb}, \\
\sigma(\text{pPb} \rightarrow \gamma^*/Z \rightarrow \mu^+\mu^-, \text{full}, 60 < m_{\mu\mu} < 120 \text{ GeV}) = 177.7 \pm 1.3 \text{ (stat)} \pm 2.7 \text{ (syst) nb}.
\]

In Tables 1 and 2 the \( \chi^2 \) values between the data and the predictions are reported, accounting for bin-to-bin correlations between experimental (systematic uncertainties, shown in Fig. 2) and theoretical (nPDF) uncertainties. The observations discussed above from Figs. 3 and 4 can be made here more quantitatively, more precisely with fiducial cross sections thanks to the smaller systematic uncertainty. The inclusion of EPPS16 modifications of the PDFs in the lead nucleus tends to improve the description for \( y_{CM} \) in the Z mass region, but conclusions are not clear for other quantities, and even opposite in the case of \( p_T \) and \( \phi^* \) in the Z mass region. However, the seemingly imperfect modelling of the cross sections in POWHEG prevents from drawing strong conclusions on nPDFs.

Table 1: \( \chi^2 \) values between the data and the POWHEG predictions, from the fiducial cross sections, when experimental and theoretical correlations are taken into account. The luminosity uncertainty is also included in the experimental uncertainties.

<table>
<thead>
<tr>
<th>Observable</th>
<th>CT14</th>
<th>CT14+EPPS16</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \chi^2 )</td>
<td>Prob. [%]</td>
</tr>
<tr>
<td>( m_{\mu\mu} ) (GeV)</td>
<td>36</td>
<td>13</td>
</tr>
<tr>
<td>( y_{CM} ) (15 &lt; ( m_{\mu\mu} &lt; 60 ) GeV)</td>
<td>9.0</td>
<td>12</td>
</tr>
<tr>
<td>( p_T ) (GeV) (15 &lt; ( m_{\mu\mu} &lt; 60 ) GeV)</td>
<td>11</td>
<td>8</td>
</tr>
<tr>
<td>( \phi^* ) (15 &lt; ( m_{\mu\mu} &lt; 60 ) GeV)</td>
<td>9.2</td>
<td>9</td>
</tr>
<tr>
<td>( y_{CM} ) (60 &lt; ( m_{\mu\mu} &lt; 120 ) GeV)</td>
<td>51</td>
<td>24</td>
</tr>
<tr>
<td>( p_T ) (GeV) (60 &lt; ( m_{\mu\mu} &lt; 120 ) GeV)</td>
<td>27</td>
<td>17</td>
</tr>
<tr>
<td>( \phi^* ) (60 &lt; ( m_{\mu\mu} &lt; 120 ) GeV)</td>
<td>23</td>
<td>17</td>
</tr>
</tbody>
</table>

Table 2: \( \chi^2 \) values between the data and the POWHEG predictions, from the full phase space cross sections, when experimental and theoretical correlations are taken into account. The luminosity uncertainty is also included in the experimental uncertainties.

<table>
<thead>
<tr>
<th>Observable</th>
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<th>CT14+EPPS16</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \chi^2 )</td>
<td>Prob. [%]</td>
</tr>
<tr>
<td>( m_{\mu\mu} ) (GeV)</td>
<td>27</td>
<td>13</td>
</tr>
<tr>
<td>( y_{CM} ) (15 &lt; ( m_{\mu\mu} &lt; 60 ) GeV)</td>
<td>6.3</td>
<td>12</td>
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<tr>
<td>( p_T ) (GeV) (15 &lt; ( m_{\mu\mu} &lt; 60 ) GeV)</td>
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<td>8</td>
</tr>
<tr>
<td>( \phi^* ) (15 &lt; ( m_{\mu\mu} &lt; 60 ) GeV)</td>
<td>7.4</td>
<td>9</td>
</tr>
<tr>
<td>( y_{CM} ) (60 &lt; ( m_{\mu\mu} &lt; 120 ) GeV)</td>
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<td>24</td>
</tr>
<tr>
<td>( p_T ) (GeV) (60 &lt; ( m_{\mu\mu} &lt; 120 ) GeV)</td>
<td>29</td>
<td>17</td>
</tr>
<tr>
<td>( \phi^* ) (60 &lt; ( m_{\mu\mu} &lt; 120 ) GeV)</td>
<td>25</td>
<td>17</td>
</tr>
</tbody>
</table>

Forward-backward ratios (\( R_{FB} \)) are built from the rapidity-dependent cross sections in the two mass regions, defined as the ratio of the \( y_{CM} > 0 \) to the \( y_{CM} < 0 \) cross sections, and are shown in Fig. 5. Similar conclusions are drawn as from the rapidity dependence of the cross section, but the construction of these ratios allows the partial cancellation of theoretical and experimental
uncertainties, accounting for correlations described in the previous section. In particular, for $60 < m_{\mu\mu} < 120$ GeV and at large $|y_{\text{CM}}|$, an indication for a forward-backward ratio smaller than unity is found, consistent with the expectation from the combination of shadowing and anti-shadowing effects.

Figure 5: Forward-backward ratios for $15 < m_{\mu\mu} < 60$ GeV (left) and $60 < m_{\mu\mu} < 120$ GeV (right). The error bars on the data represent the quadratic sum of the statistical and systematic uncertainties. The theory predictions from the POWHEG NLO generator are also provided, using CT14 (blue) or CT14+EPPS16 (red). The boxes show the 68% confidence level (n)PDF uncertainty on this prediction. The ratio of the predictions to the data is shown in the bottom panels, where the data and nPDF uncertainties are given separately, respectively as error bars around one and coloured boxes.

4 Summary

Differential cross section measurements of the Drell–Yan process in the dimuon channel in proton-lead collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV have been reported, including the $p_T$ and rapidity dependencies in the $Z$ boson mass region ($60 < m_{\mu\mu} < 120$ GeV). For the first time in heavy ion collisions, the $p_T$ and rapidity dependence for smaller masses $15 < m_{\mu\mu} < 60$ GeV, the $\phi^*$ dependence for both $15 < m_{\mu\mu} < 60$ GeV and $60 < m_{\mu\mu} < 120$ GeV, and the mass dependence from 15 to 600 GeV are measured. In addition, forward-backward ratios have been built from the rapidity-dependent cross sections, highlighting the presence of nuclear effects in the parton distribution functions. These new results may help constrain the quark and antiquark nuclear parton distribution functions, but also point to an imperfect modelling of the process in the POWHEG event generator, especially at low dimuon masses.

References


References


