

Measurement of the W -boson production cross sections in pp collisions at $\sqrt{s} = 13$ TeV in the forward region

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A precision measurement of the W -boson production cross section is performed using the $W \rightarrow \mu\nu$ decay channel, based on a sample of proton-proton collision data collected by the LHCb experiment at $\sqrt{s} = 13$ TeV and corresponding to an integrated luminosity of 5.1 fb^{-1} . The cross section is measured for muons with transverse momentum between 25 and 55 GeV and pseudorapidity between 2.0 and 4.5. The total production cross sections of W bosons are measured to be $\sigma_{W^+ \rightarrow \mu^+ \nu} = 1754.2 \pm 1.5 \pm 11.8 \pm 35.1 \text{ pb}$ $\sigma_{W^- \rightarrow \mu^- \bar{\nu}} = 1178.1 \pm 1.3 \pm 9.7 \pm 23.6 \text{ pb}$ where uncertainties are statistical, systematic, and due to the luminosity determination, respectively. Differential distributions $d\sigma_{W^\pm \rightarrow \mu^\pm \nu}/d\eta^{\mu^\pm}$ are also presented. The total and differential cross sections are in good agreement with theoretical predictions at next-to-next-to-leading order in perturbative quantum chromodynamics. This measurement is significantly more precise than previous results in this kinematic regime.

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I. INTRODUCTION

Proton parton distribution functions (PDFs) are a fundamental input for cross-section calculations at hadron colliders, and frequently represent the dominant source of systematic uncertainty in precision measurements [1,2]. As nonperturbative quantities are not directly calculable within the Standard Model (SM), PDFs must be extracted empirically through global analyses using experimental inputs, including a wide range of scattering processes [3–7]. Measurements of the electroweak (W and Z) boson production cross sections at Large Hadron Collider energies provide not only a stringent test of the SM, but also a critical constraint for global fits of proton PDFs [8].

Theoretical predictions for electroweak production cross sections, calculated up to next-to-next-to-next-to-leading order ($N^3\text{LO}$) in perturbative quantum chromodynamics (QCD) [9–18], critically depend on the parametrization of Bjorken- x distributions within the proton. Here, x represents the longitudinal momentum fraction carried by constituent partons [19], serving as a fundamental parameter that governs the nonperturbative QCD dynamics across

different energy scales. The LHCb experiment's forward acceptance ($2 < \eta < 5$) uniquely probes kinematic regimes that complement measurements from ATLAS [20–29], CMS [30–38] and ALICE [39–45], particularly in both the large and small- x regions that remain theoretically challenging. For typical W -boson production kinematics within the LHCb acceptance, the corresponding parton momentum fractions span approximately 10^{-4} and 10^{-1} at $Q^2 \approx 10^4 \text{ GeV}^2$. This complements the coverage of other experiments, with ATLAS and CMS probing roughly 10^{-3} to 10^{-2} .

The LHCb collaboration has previously published comprehensive measurements of inclusive W - and Z -boson production in proton-proton (pp) collisions at center-of-mass energies of $\sqrt{s} = 7, 8$, and 13 TeV [46–55] with integrated luminosities of approximately 1, 2, and 1.6 fb^{-1} respectively. The present analysis utilizes the Run 2 dataset collected during 2016–2018, corresponding to an integrated luminosity of 5.1 fb^{-1} . Precise measurements of inclusive W^+ and W^- -boson production cross sections are presented for muons in the fiducial region with transverse momentum p_T^μ between 25 and 55 GeV^1 and pseudorapidity η_μ between 2.0 and 4.5, complemented by differential cross-section measurements binned in muon pseudorapidity. In addition, a measurement of the muon charge asymmetry, using the same sample of W -boson decays, is presented in a companion Letter [56].

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¹Natural units with $\hbar = c = 1$ are used throughout.

The differential W -boson production cross section is measured in 18 η_μ intervals, according to

$$\frac{d\sigma_{W^\pm \rightarrow \mu^\pm \nu}}{d\eta^{\mu^\pm}} = \frac{N_{\text{yield}}^\pm \cdot f_{\text{FSR}}^{W^\pm}}{\Delta\eta^{\mu^\pm} \cdot \mathcal{L} \cdot \varepsilon_{W^\pm}}, \quad (1)$$

where $\Delta\eta^{\mu^\pm}$ is the size of the interval, $\mathcal{L}$ the integrated luminosity, $N_{\text{yield}}^\pm$ the $W^\pm$ candidate yield determined from a template fit to the muon p_T spectrum, $\varepsilon_{W^\pm}$ the total reconstruction and selection efficiency. Final state radiation corrections are applied using a ratio of ResBos 2 [57,58] predictions with Photos [59] to those without Photos, $f_{\text{FSR}}^{W^\pm}$, which maps bare-level muon kinematics to Born-level definitions. This allows direct comparison with theoretical predictions at Born level.

II. DETECTOR AND SIMULATION

The LHCb detector [60,61] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. The detector used to collect the data analyzed in this paper includes a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the pp interaction region [62], a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 T m, and three stations of silicon-strip detectors and straw drift tubes [63] placed downstream of the magnet. The tracking system provides a measurement of the momentum, p , of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV. The minimum distance of a track to a primary pp collision vertex (PV), the impact parameter (IP), is measured with a resolution of $(15 + 29/p_T) \mu\text{m}$, where p_T is the component of the momentum transverse to the beam, in GeV. The magnetic field deflects oppositely charged particles in opposite directions and this can lead to detection asymmetries. Periodically reversing the magnetic field polarity throughout the data taking almost cancels the effect. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors [64]. Photons, electrons and hadrons are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers [65].

The online event selection is performed by a trigger [66], which consists of a hardware stage based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction. Triggered data further undergo a centralized, offline processing step to deliver physics-analysis-ready data across the entire LHCb physics program [67].

Simulation is required to model the effects of the detector acceptance and the imposed selection requirements, and to describe the signal and background components when fitting data to extract yields. In the simulation, pp collisions are generated using Pythia [68] with a specific LHCb configuration [69], in which FSR is generated using Photos. The interaction of the generated particles with the detector, and its response, are implemented using the Geant4 toolkit [70,71] as described in Ref. [72]. To evaluate higher-order effects in the perturbative expansion, this analysis employs multiple event generators. DYTurbo [73] provides high-precision QCD p_T resummation for Drell-Yan cross sections, achieving approximate next-to-next-to-next-to-next-to-leading logarithmic ($N^4\text{LL}$) accuracy and serving as the weighting tool described in Sec. IV B. For the background cross-section predictions described in Sec. V, MCFM [74], a parton-level event generator that gives predictions for a wide range of processes at hadron colliders, is used. ResBos 2 and Powheg [75] are utilized to obtain theoretical predictions for experimental results. ResBos 2 integrates a next-to-next-to-leading order (NNLO) fixed-order calculation for high- p_T bosons with the Collins-Soper-Sterman resummation formalism [76–78] at low p_T , implementing an all-orders resummation of large logarithmic terms from gluon emissions. The Powheg generator simulates the hard interaction at NLO in perturbative QCD. For the $W \rightarrow \mu\nu$ process, all predictions refer to the fiducial region mentioned above.

III. EVENT SELECTION

The signal selection employs a multistage optimization strategy that balances signal purity against reconstruction efficiency. Muon candidates must satisfy stringent quality criteria including good track-fit quality, a precise momentum measurement ($\sigma(p)/p < 0.06$), physical momentum limits ($p < 2 \text{ TeV}$) and satisfy the fiducial criteria.

Additional selection requirements are imposed to reject specific backgrounds. Nonprompt muons from heavy-flavor decays are rejected by requiring less than 5.0 GeV energy deposition in the hadronic calorimeter cells surrounding the muon trajectory, combined with muon identification (ID) criteria. Track isolation requirements ($\sum p_T^{\text{track}} < 3.0 \text{ GeV}$ in a cone around the muon within $\sqrt{(\phi - \phi_\mu)^2 + (\eta - \eta_\mu)^2} < 0.5$, where ϕ is the azimuthal angle) effectively suppress hadronic backgrounds. A Z -boson veto is also added to reject events containing a second muon with opposite charge, which could form $Z \rightarrow \mu^+\mu^-$ candidates ($p_T' > 25 \text{ GeV}$, $2.0 < \eta' < 4.5$, where p_T' and η' are properties of the second muon). Tight impact parameter significance requirements ensure that tracks originate from the primary vertex, further suppressing contributions from $W \rightarrow \tau\nu$ and heavy-flavor

decays. After applying these selection criteria, around 6.3×10^6 (4.4×10^6) W^+ (W^-) candidates are retained with an approximate purity of 85% (80%).

IV. CORRECTIONS

To account for detector misalignment effects, imperfections in the simulation of the detector response and resolution, and missing higher-order effects in theoretical predictions, dedicated calibration and correction procedures are implemented for both data and simulation.

A. Data calibrations

The charged particle momentum measurements are affected by variations in detector conditions throughout the course of the data-taking period. These effects are suppressed using $\Upsilon(1S) \rightarrow \mu^+\mu^-$ decays in data, where the reconstructed $\Upsilon(1S)$ mass is corrected to the known value [79] for each year of data-taking. The mass distribution of the $\Upsilon(1S)$ peak is described by the sum of two Crystal Ball functions [80] with a common peak position, while the background is described by an exponential function. The Crystal Ball peak positions M_{CB} are then compared to the known $\Upsilon(1S)$ mass M_{PDG} [79] to determine the momentum scale correction $S_\alpha = M_{PDG}/M_{CB}$.

For remaining misalignment effects affecting high- p_T muons, the pseudomass method is employed [81,82]. This technique estimates two-particle final-state masses in the absence of full information on the final-state momenta. For $Z \rightarrow \mu^+\mu^-$ decays, pseudomasses are defined as

$$\mathcal{M}^\pm \equiv \sqrt{2p^\pm p_T^\pm \frac{p^\mp}{p_T^\mp} (1 - \cos \theta)}, \quad (2)$$

where $p^\pm$ ($p_T^\pm$) are the $\mu^\pm$ (transverse) momenta, and θ is the opening angle between the two muons. Unlike the invariant mass, where biases cancel between μ^+ and μ^- tracks, the pseudomasses maintain first-order sensitivity to curvature biases

$$\frac{q}{p} \rightarrow \frac{q}{S_\alpha p} + \delta, \quad (3)$$

where q is the muon charge and δ is the curvature bias. Simultaneous fits of $\mathcal{M}^+$ and $\mathcal{M}^-$ are performed in intervals of η_μ , ϕ_μ , data-taking year, and magnet polarity to determine the pseudomass asymmetry $\mathcal{A} \equiv (\mathcal{M}^+ - \mathcal{M}^-)/(\mathcal{M}^+ + \mathcal{M}^-)$. In turn, the curvature bias is determined from the asymmetry via $\delta = \frac{\mathcal{A}}{2}(\langle \frac{1}{p^+} \rangle + \langle \frac{1}{p^-} \rangle)$, where $\langle \frac{1}{p^\pm} \rangle$ are the mean values of the inverse of the muon momenta. The average values of $1 - S_\alpha$ and δ are on the order of 10^{-4} and 10^{-5} , respectively.

The momentum of each final-state particle is then transformed according to Eq. (3), using the measured values of S_α and δ . These corrections are validated using

the $Z \rightarrow \mu^+\mu^-$ mass peak in data, demonstrating that they lead to improved momentum resolution. Given the excellent angular resolution of the LHCb detector, negligible migrations are observed between pseudorapidity intervals in the analysis and no unfolding correction is applied.

B. Corrections to the simulation

To improve the modeling of momentum resolution for simulated events processed via the full LHCb detector simulation and reconstruction chain, a multiparameter smearing correction is applied to the particles' momenta as

$$p \rightarrow p(1 + \alpha)(1 + \mathcal{R}_1 \mathcal{N} \sigma_1)(1 + \mathcal{R}_2 p \sigma_2 / \cosh \eta), \quad (4)$$

where $\mathcal{R}_1$ and $\mathcal{R}_2$ are random variables from a standard normal distribution, $\mathcal{N}$ is a scaling factor accounting for the amount of material traversed by muon tracks up to the LHCb magnet and is set to 1.5 for muons with $\eta > 3.3$ and unity otherwise (it accounts for the increased material traversed by the higher- η tracks up to the LHCb magnet), α denotes the momentum scale calibration factor, while σ_1 and σ_2 describe the contributions to resolution from multiple scattering and curvature, respectively [1].

A simultaneous maximum-likelihood fit is performed on the dimuon invariant-mass spectra of J/ψ , $\Upsilon(1S)$ and Z -boson candidates, incorporating both magnet-polarity configurations to extract the optimal parameters of α , σ_1 , and σ_2 . The Z -boson invariant-mass distributions with corresponding fit results are shown in Fig. 1, while numerical results including statistical uncertainties for the fitted parameters are compiled in Table I.

The default LHCb simulation employs the Pythia generator, which lacks sufficient precision for modeling higher-order QCD effects. To account for these effects, simulation samples ($Z \rightarrow \mu^+\mu^-$, $W \rightarrow \mu\nu$ and $W \rightarrow \tau\nu$) are corrected to match NNLO predictions from the DYTurbo

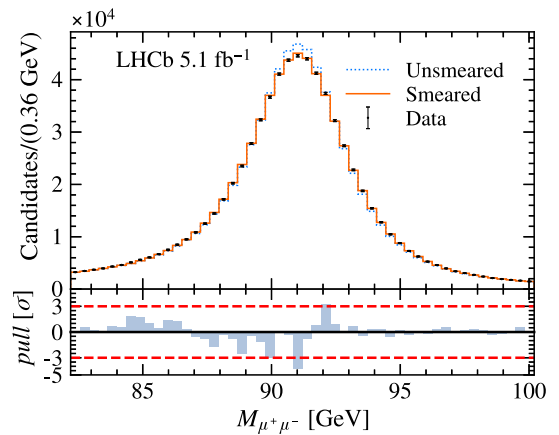


FIG. 1. Invariant-mass distributions of $Z \rightarrow \mu^+\mu^-$ candidates used in the momentum smearing fit, with the fit results also shown. The red and blue curves are simulated data.

TABLE I. Parameters of the simulation smearing model obtained from the fit procedure described in the text.

Name	Value
momentum scale ($\alpha \times 10^3$)	0.128 ± 0.003
momentum smear ($\sigma_1 \times 10^3$)	2.19 ± 0.01
curvature smear ($\sigma_2 \times 10^5$)	15.3 ± 0.5

generator. Two multiplicative correction factors are calculated and applied at generator level: an angular weight (w_{ang}) and a full phase-space cross-section weight (w_{xsec}). The angular coefficients for each process are determined using the projection method from Ref. [83], which computes a normalized weighted average over the dilepton angular coordinates (θ , ϕ). The angular weight is then calculated as

$$w_{\text{ang}} = \frac{1 + \cos^2\theta + \frac{1}{2}A_0^{\text{DyTurbo}}(1 - 3\cos^2\theta) + \dots}{1 + \cos^2\theta + \frac{1}{2}A_0^{\text{Pythia}}(1 - 3\cos^2\theta) + \dots}, \quad (5)$$

where A are coefficients in the angular expansion, and the missing additional terms are defined in Ref. [83].

For full phase-space cross-section corrections, interpolated σ_{full} histograms are used to reweight simulated events. The histograms are generated with axes corresponding to W rapidity, M_W and $\log_{10}(p_T^W)$ for a grid of fixed values of α_s (the strong coupling constant) and k_T (the intrinsic transverse momentum of the initial state partons). Two interpolation methods are employed: trilinear interpolation between histogram bins, and bicubic spline interpolation across parameter spaces of α_s and k_T . This involves arrays of histograms corresponding to different parameter values. The default full phase-space cross-section weight is derived from the ratio of DyTurbo to Pythia predictions.

This comprehensive weighting strategy ensures proper modeling of both angular distributions and absolute cross sections in the simulated samples.

V. SIGNAL YIELD

The signal yield determination employs a binned maximum-likelihood fit to the muon p_T spectra across 36 η_μ bins (18 intervals $\times$ 2 charges). The background contributions considered in this analysis include heavy-flavor processes ($c\bar{c}$, $b\bar{b}$ and $t\bar{t}$), electroweak processes ($Z \rightarrow \mu^+\mu^-$, $W \rightarrow \tau\nu$, $Z \rightarrow \tau^+\tau^-$, etc.) and QCD multijet background.

The QCD background primarily arises from hadrons produced in pp collisions misidentified as muons via two mechanisms: decay-in-flight (kaons/pions decaying into muons during detector traversal) and punch-through (energetic hadrons penetrating calorimeters to reach muon detectors). These misidentification rates are parametrized as functions of momenta using simulated samples with dedicated fits for pions, kaons, and protons, as

$$\begin{aligned} \text{pion and kaon rate} = & a_0 e^{\beta p} + a_1 \left(1 - e^{-\frac{md}{\tau p}}\right) \\ & + (a_2 + a_3 p), \end{aligned} \quad (6)$$

$$\text{proton rate} = a_0 e^{\beta p} + (a_2 + a_3 p). \quad (7)$$

Here $a_1(1 - e^{-\frac{md}{\tau p}})$ describes the decay-in-flight probability, where p is the momentum, τ the lifetime, d the flight distance, and m the mass of the light hadron. The term $(a_2 + a_3 p)$ models the punch-through probability as a linear function of momentum. The $a_0 e^{\beta p}$ functions are used to model hadrons near the edge of the LHCb detector acceptance (around $\eta = 2.1$), where isolation requirements fail to sufficiently suppress the QCD background, and β takes a negative value. The $a_{0,1,2,3}$ coefficients are different for protons, pions, kaons. The misidentification rates are parametrized as event weights, ω_{misid} , in simulation. The misidentification fits for the three primary species (pion, kaon, proton) are performed on simulated events tagged with true particle types (pion, kaon, proton,

TABLE II. Fiducial regions and cross sections that are assumed in the signal yield fit. Here, M refers to the invariant mass of the dilepton system.

Process	σ^{fid} [pb]	Fiducial region
$W \rightarrow \mu\nu$	3558	$p_T^\mu > 20 \text{ GeV}, 2.0 < \eta_\mu < 4.5$
$Z \rightarrow \mu\mu$	193.5	$p_T^\mu > 20 \text{ GeV}, 2.0 < \eta_\mu < 4.5, 60 < M < 120 \text{ GeV}$
$Z \rightarrow \tau\tau$	4.999	$p_T^\tau > 20 \text{ GeV}, 2.0 < \eta_\tau < 4.5, 60 < M < 120 \text{ GeV}$
$W \rightarrow \tau\nu$	379.3	$p_T^\tau > 20 \text{ GeV}, 2.0 < \eta_\tau < 4.5$
$\gamma^* \rightarrow \mu\mu$	339.7	$p_T^\mu > 1 \text{ GeV}, 2.0 < \eta_\mu < 4.5, 20 < M < 40 \text{ GeV}$
$q\bar{q} \rightarrow t\bar{t}$	9.259	$p_T^\mu > 17 \text{ GeV}, 2.0 < \eta_\mu < 4.5$
$gg \rightarrow t\bar{t}$	36.00	$p_T^\mu > 17 \text{ GeV}, 2.0 < \eta_\mu < 4.5$
tW	6.723	$p_T^\mu > 17 \text{ GeV}, 2.0 < \eta_\mu < 4.5$
WW	1.023	$p_T^\mu > 15 \text{ GeV}, 2.0 < \eta_\mu < 4.5$
$c\bar{c}$	2347	$p_T^\mu > 14 \text{ GeV}, 2.0 < \eta_\mu < 4.5$
$b\bar{b}$	1.091×10^4	$p_T^\mu > 14 \text{ GeV}, 2.0 < \eta_\mu < 4.5$

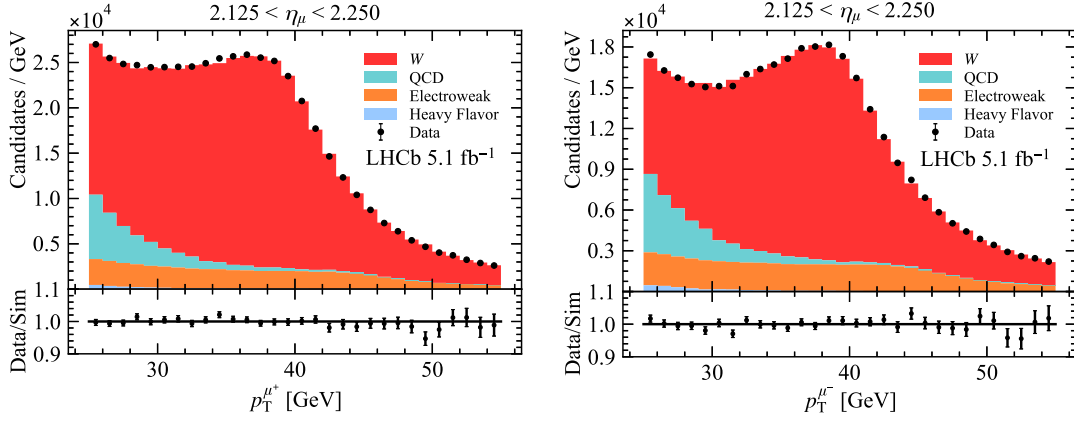


FIG. 2. Distribution of the muon p_T for selected (left) W^+ and (right) W^- bosons for the example interval $2.125 < \eta_\mu < 2.250$, with the fit results also shown. The distributions in the data are compared with those from simulation. The normalizations of the contributions labeled W and QCD are determined by the fit described in the text. Error bars combine the contributions from statistical and systematic uncertainties.

or others), with hadron charges combined to improve statistical precision. This systematic methodology ensures robust background modeling in the subsequent analysis. Additional exponential weight factors $\omega_{\text{data/sim}}$ are applied to correct for residual discrepancies in charge asymmetry and p_T distributions between data and simulation. These weights, $\omega_{qcd} = \omega_{\text{misid}} \cdot \omega_{\text{data/sim}}$, correct the misidentification results from full simulation for each individual event.

In the fit model, the normalization parameters for W boson and QCD backgrounds are left free to vary, while all other background processes are normalized relative to the observed number of $Z \rightarrow \mu^+\mu^-$ candidates selected with the same fiducial cuts as listed in Table II across η_μ bins via

$$f_i^{\text{expected}} = \frac{N_Z^{\text{obs}}}{N_W^{\text{obs}}} \times \frac{\sum w_i}{\sum w_Z} \times \frac{\sigma_i^{\text{fid}}}{\sigma_Z^{\text{fid}}} \times \frac{N_Z^{\text{gen,fid}}}{N_i^{\text{gen,fid}}}, \quad (8)$$

where f_i^{expected} denotes the estimated fraction for a given process i , N_W^{obs} (N_Z^{obs}) the observed event yields of selected W (Z) boson candidates, and w_i corresponds to the simulation weights incorporating the efficiency. The last two factors essentially comprise a luminosity ratio relative to the $Z \rightarrow \mu^+\mu^-$ simulation production, with σ_i^{fid} denoting fiducial cross sections and $N_i^{\text{gen,fid}}$ the generator-level event yields passing fiducial criteria. The considered fiducial cross sections are shown in Table II. The $Z \rightarrow \mu^+\mu^-$, $Z \rightarrow \tau\tau$, $W \rightarrow \mu\nu$ and $W \rightarrow \tau\nu$ cross sections are predicted by MCFM. Cross sections of other processes are estimated by Pythia with the Gauss [69] configuration. Example fit results for the second pseudorapidity bin are presented in Fig. 2, where only statistical uncertainties are included on the data points.

VI. EFFICIENCIES

The total reconstruction and selection efficiency for a given η_μ interval is defined as

$$\varepsilon_{W^\pm} = \frac{\sum_{\text{reco } W} \omega_{\text{rec}} \cdot \omega_{\text{sel}} \cdot \omega_{\text{gen}}}{\sum_{\text{true } W} \omega_{\text{gen}}}, \quad (9)$$

where the numerator aggregates weights from events in the W -boson simulated samples passing all selection criteria: ω_{rec} , the reconstruction efficiency, combines tracking/ID/trigger efficiencies; ω_{sel} corresponds to selection efficiencies; and ω_{gen} denotes generator-level weights. The denominator sums generator-level weights for generated W bosons passing fiducial requirements.

The muon reconstruction efficiency is quantified using a data-driven tag-and-probe method [84] applied to $Z \rightarrow \mu^+\mu^-$ decays. The efficiencies are defined as the fraction of events passing sequential selection criteria, with each stage's denominator determined by the prior stage's numerator to enable backward propagation of corrections to the fiducial selection. The total reconstruction efficiency is factorized as

$$\varepsilon = \varepsilon_{\text{trk}} \times \varepsilon_{\text{ID|trk}} \times \varepsilon_{\text{trig|ID}}. \quad (10)$$

The tracking efficiency (ε_{trk}) quantifies the fraction of fiducial-acceptance events with reconstructed charged tracks meeting quality requirements; the muon identification efficiency ($\varepsilon_{\text{ID|trk}}$) represents the fraction of charged tracks passing muon identification criteria; and the trigger efficiency ($\varepsilon_{\text{trig|ID}}$) denotes the fraction of identified muon tracks satisfying the trigger selection. The efficiency and efficiency ratio, $\varepsilon_{\text{data}}/\varepsilon_{\text{sim}}$, are evaluated separately in each η_μ and p_T^μ interval. Instead of bin-by-bin corrections, the efficiency and efficiency ratio are parametrized via

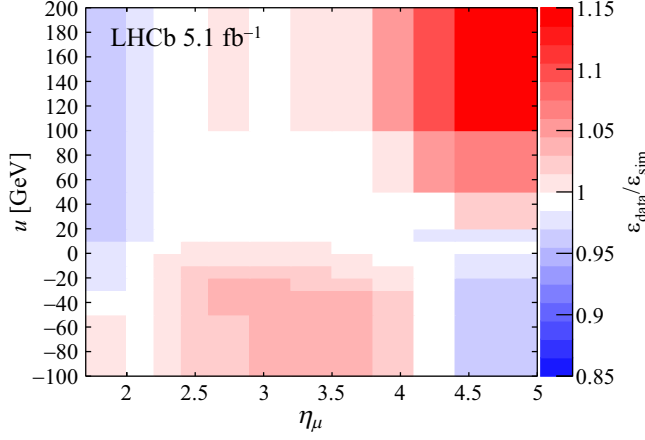


FIG. 3. Data-to-simulation efficiency ratios for muon selection requirements, shown as functions of the recoil projection variable u and pseudorapidity η_μ .

functional fits, producing continuous weight templates. Simulated events are further weighted using the efficiency ratio between data and simulation to correct for residual mismodeling.

The isolation requirement has a dominant influence on all selection criteria since its efficiency is much lower than that of other requirements. At generator level, the isolation distribution arises from two physically distinct mechanisms: underlying event activity and hard-process recoil effects. To address this complexity, a recoil projection variable is introduced for each muon, defined as

$$u = \frac{\vec{p}_T^V \cdot \vec{p}_T^\mu}{p_T^\mu}, \quad (11)$$

where $\vec{p}_T^\mu$ and $\vec{p}_T^V$ respectively denote the transverse momentum vectors of the muon and its parent boson in the laboratory frame. This kinematic variable unifies selection studies across W and Z -boson processes, with measurable corrections extracted from Z events as functions of reconstructed u . The variable effectively disentangles physical regimes: hard-process recoil effects dominate at small/negative u , while underlying event activity becomes dominant at large u . LHCb operates in the forward region. Here, alignment corresponds to the particles being boosted to high rapidity, with typically low p_T . The selection efficiency exhibits greater universality when parametrized versus u compared to traditional variables like p_T^μ . Data-to-simulation efficiency ratios binned in u and η_μ are presented in Fig. 3. The trends in this figure are caused by the simulation's limited ability to describe data in the region of negative u (increasing recoil contribution) and at the detector edge.

All efficiency corrections are incorporated as event weights in the final fit to determine signal yields, ensuring accurate consideration of reconstruction effects in the

cross-section measurements. The binning schemes are designed to capture critical kinematic dependencies while preserving statistical precision in each bin.

VII. SYSTEMATIC UNCERTAINTIES AND STABILITY CHECKS

Various sources of systematic uncertainty are investigated, with the total obtained as the quadrature sum of all components. Uncertainties in the total cross section are compiled in Table III; those for the differential cross sections in Tables IV and V. The notable difference in generator-weight uncertainties between W^+ and W^- originates from the contribution within the pseudorapidity

TABLE III. Relative uncertainties affecting the $W^\pm$ boson total cross-section measurements.

Source	$\Delta\sigma_{W^+ \rightarrow \mu^+ \nu} [\%]$	$\Delta\sigma_{W^- \rightarrow \mu^- \bar{\nu}} [\%]$
Statistical	0.08	0.11
Reconstruction efficiency	0.33	0.33
Generator weight	0.26	0.51
QCD background	0.06	0.09
Selection efficiency	0.51	0.52
Smearing	0.02	0.03
FSR	0.10	0.15
Total Systematic (excl. lumi.)	0.68	0.83
Luminosity	2.00	2.00
Total	2.11	2.17

TABLE IV. Summary of relative systematic uncertainties on the W^+ η_μ -differential cross-section measurement from the reconstruction efficiency (ϵ_{rec}), generator correction, smearing, selection efficiency (ϵ_{sel}), QCD background and FSR correction, presented in percent.

η_μ	ϵ_{rec}	Generator	Smearing	ϵ_{sel}	QCDBkg	FSR
2.000–2.125	0.61	0.51	0.10	0.74	0.44	0.04
2.125–2.250	0.58	0.46	0.05	0.82	0.22	0.05
2.250–2.375	0.64	0.43	0.06	0.72	0.12	0.23
2.375–2.500	0.49	0.45	0.05	0.70	0.09	0.03
2.500–2.625	0.44	0.44	0.06	0.73	0.05	0.18
2.625–2.750	0.42	0.31	0.04	0.57	0.05	0.09
2.750–2.875	0.52	0.20	0.06	0.57	0.07	0.19
2.875–3.000	0.46	0.17	0.04	0.49	0.09	0.17
3.000–3.125	0.51	0.11	0.06	0.46	0.12	0.11
3.125–3.250	0.41	0.22	0.05	0.47	0.12	0.10
3.250–3.375	0.49	0.63	0.08	0.53	0.17	0.14
3.375–3.500	0.57	1.14	0.05	0.52	0.13	0.13
3.500–3.625	0.49	1.58	0.06	0.43	0.10	0.14
3.625–3.750	0.53	1.66	0.07	0.42	0.14	0.06
3.750–3.875	0.58	1.58	0.09	0.42	0.17	0.16
3.875–4.000	0.67	1.40	0.06	0.44	0.20	0.28
4.000–4.250	0.63	1.22	0.07	0.40	0.36	0.16
4.250–4.500	0.96	2.21	0.22	0.52	0.69	0.10

TABLE V. Summary of relative systematic uncertainties on the $W^- \eta_\mu$ -differential cross-section measurement from the reconstruction efficiency (ϵ_{rec}), generator correction, smearing, selection efficiency (ϵ_{sel}), QCD background and FSR correction, presented in percent.

η_μ	ϵ_{rec}	Generator	Smearing	ϵ_{sel}	QCDBkg	FSR
2.000–2.125	0.59	0.26	0.07	0.78	0.51	0.10
2.125–2.250	0.53	0.21	0.04	0.86	0.25	0.15
2.250–2.375	0.61	0.17	0.06	0.76	0.14	0.18
2.375–2.500	0.48	0.17	0.02	0.73	0.08	0.18
2.500–2.625	0.45	0.22	0.03	0.76	0.06	0.05
2.625–2.750	0.39	0.29	0.04	0.60	0.07	0.03
2.750–2.875	0.51	0.31	0.05	0.60	0.08	0.16
2.875–3.000	0.54	0.33	0.05	0.51	0.09	0.09
3.000–3.125	0.54	0.30	0.05	0.48	0.11	0.14
3.125–3.250	0.61	0.28	0.05	0.49	0.13	0.03
3.250–3.375	0.53	0.19	0.08	0.55	0.16	0.26
3.375–3.500	0.52	0.12	0.06	0.55	0.19	0.19
3.500–3.625	0.59	0.25	0.07	0.45	0.17	0.03
3.625–3.750	0.58	0.43	0.11	0.44	0.19	0.07
3.750–3.875	0.59	0.91	0.14	0.43	0.20	0.27
3.875–4.000	0.58	1.29	0.08	0.44	0.23	0.30
4.000–4.250	0.67	2.53	0.10	0.57	0.29	0.24
4.250–4.500	0.94	4.75	0.31	0.75	0.52	0.39

interval $4.0 < \eta < 4.5$, as detailed in the aforementioned tables.

Three sources contribute to the systematic uncertainty from the reconstruction efficiency: the statistical uncertainty from finite tag-and-probe sample sizes, assessed via Gaussian fluctuations of ϵ_{sim} and $\epsilon_{\text{data}}/\epsilon_{\text{sim}}$ within uncertainties before efficiency fitting; alternative parametrizations for tracking/ID/trigger efficiencies; and variations in denominator selection criteria.

Generator-level systematic uncertainties comprise three components: scale variations quantified via the envelope of 7-point scale variations ([renormalization scale, factorization scale]: [0.5, 0.5], [0.5, 1], [1, 0.5], [1, 1], [1, 2], [2, 1], [2, 2]) for angular coefficients and full phase-space cross sections; the basic configuration uncertainty determined by comparing DYTurbo vs Powheg + Pythia (NLO) predictions with/without full phase-space cross sections weights. The associated uncertainty for W^- is much larger than for W^+ , which is driven by the contribution from the highest η_μ interval (see Tables IV and V).

Systematic uncertainties in QCD background estimation comprise two components: the statistical uncertainty in data/simulation and misidentification fit parameters, assessed via multivariate Gaussian resampling; and the assumed pion, kaon, and proton abundances, quantified by repeating the measurement with these varied independently and conservatively by $\pm 20\%$.

The selection efficiency systematic uncertainty has three components: the RMS of cross-section variations derived from repeating efficiency corrections with

Gaussian-smear data/simulation efficiency ratios per bin; the envelope of the cross-section variations from alternative binning schemes for Fig. 3; and the cross-section variation due to the tightening of the Z-boson mass window of the denominator from $60 < M < 120$ GeV to $70 < M < 110$ GeV.

The systematic uncertainty from track smearing comprises two components: the statistical uncertainty in smearing model parameters, assessed via multivariate Gaussian resampling of parameter correlations from the covariance matrix of the fit; and the statistical uncertainty on the curvature bias δ .

To estimate the systematic uncertainty from the treatment of FSR, the Powheg generator is used, where the FSR is modeled using Pythia. The differences of FSR corrections between ResBos + Photos and Powheg + Pythia are assigned as the systematic uncertainty.

In addition to the experimental systematic uncertainties, an overall cross-section uncertainty of 2.0% is assigned to account for the limited precision on the integrated luminosity of the sample [85]. This uncertainty is 100% correlated between bins in the differential measurements.

To validate the result robustness, the full analysis has been repeated in subsamples obtained partitioning by year and magnet polarity, with all results being consistent. Alternative fits include those with: an alternative p_T binning scheme; the $W \rightarrow \tau\nu$ cross section varied by $\pm 1\%$; the $c\bar{c}/b\bar{b}$ cross sections varied by $+50\%$; the efficiency correction split into two independent ϕ regions; and an alternative QCD background simulation with the p_T threshold reduced from 18 to 14 GeV. The resulting variations are consistent with statistical fluctuations.

VIII. RESULTS

The measured cross-section results are computed from Eq. (1) and presented in Table VI, Figs. 4 and 5. Theoretical predictions employ NNLO ResBos 2 coupled to CT18 [86], NNPDF40 [87], and MSHT20 [88] PDF sets; additional comparisons use NLO Powheg + Pythia with CT18 configurations.

The total production cross sections of W -boson and the ratios of W to Z -boson total cross sections [54] are determined to be

$$\sigma_{W^+ \rightarrow \mu^+ \nu} = 1754.2 \pm 1.5 \pm 11.8 \pm 35.1 \text{ pb}$$

$$\sigma_{W^- \rightarrow \mu^- \bar{\nu}} = 1178.1 \pm 1.3 \pm 9.7 \pm 23.6 \text{ pb}$$

$$R_{W^+Z} \equiv \frac{\sigma_{W^+ \rightarrow \mu^+ \nu}}{\sigma_{Z \rightarrow \mu^+ \mu^-}} = 8.932 \pm 0.012 \pm 0.081,$$

$$R_{W^-Z} \equiv \frac{\sigma_{W^- \rightarrow \mu^- \bar{\nu}}}{\sigma_{Z \rightarrow \mu^+ \mu^-}} = 5.999 \pm 0.009 \pm 0.060,$$

$$R_{WZ} \equiv \frac{\sigma_{W \rightarrow \mu\nu}}{\sigma_{Z \rightarrow \mu^+ \mu^-}} = 14.930 \pm 0.026 \pm 0.134,$$

TABLE VI. Measured differential $W \rightarrow \mu\nu$ cross sections, as a function of muon pseudorapidity. The first uncertainty is statistical, the second systematic, and the third due to the luminosity (which is 100% correlated between bins).

η_μ	$d\sigma_{W^+}/d\eta_\mu$ [pb]	$d\sigma_{W^-}/d\eta_\mu$ [pb]
2.000–2.125	$1067.6 \pm 3.2 \pm 12.6 \pm 21.4$	$691.0 \pm 2.7 \pm 7.9 \pm 13.8$
2.125–2.250	$1069.3 \pm 3.0 \pm 12.0 \pm 21.4$	$679.1 \pm 2.6 \pm 7.3 \pm 13.6$
2.250–2.375	$1060.3 \pm 3.1 \pm 11.5 \pm 21.2$	$646.2 \pm 2.5 \pm 6.6 \pm 12.9$
2.375–2.500	$1034.0 \pm 3.2 \pm 10.0 \pm 20.7$	$633.8 \pm 2.5 \pm 5.8 \pm 12.7$
2.500–2.625	$1014.3 \pm 3.2 \pm 9.9 \pm 20.3$	$602.5 \pm 2.4 \pm 5.5 \pm 12.1$
2.625–2.750	$1004.0 \pm 3.1 \pm 7.8 \pm 20.1$	$588.5 \pm 2.4 \pm 4.6 \pm 11.8$
2.750–2.875	$965.1 \pm 3.0 \pm 7.9 \pm 19.3$	$568.8 \pm 2.3 \pm 4.9 \pm 11.4$
2.875–3.000	$926.7 \pm 3.0 \pm 6.7 \pm 18.5$	$551.7 \pm 2.4 \pm 4.6 \pm 11.0$
3.000–3.125	$883.2 \pm 3.1 \pm 6.4 \pm 17.7$	$527.0 \pm 2.4 \pm 4.2 \pm 10.5$
3.125–3.250	$832.4 \pm 2.9 \pm 5.7 \pm 16.6$	$508.0 \pm 2.1 \pm 4.3 \pm 10.2$
3.250–3.375	$755.3 \pm 2.4 \pm 7.4 \pm 15.1$	$481.7 \pm 2.2 \pm 4.1 \pm 9.6$
3.375–3.500	$691.2 \pm 2.5 \pm 9.6 \pm 13.8$	$457.5 \pm 2.1 \pm 3.7 \pm 9.1$
3.500–3.625	$610.8 \pm 2.4 \pm 10.5 \pm 12.2$	$427.9 \pm 2.2 \pm 3.5 \pm 8.6$
3.625–3.750	$532.8 \pm 2.3 \pm 9.6 \pm 10.7$	$395.7 \pm 2.1 \pm 3.5 \pm 7.9$
3.750–3.875	$446.0 \pm 2.0 \pm 7.8 \pm 8.9$	$373.0 \pm 2.2 \pm 4.6 \pm 7.5$
3.875–4.000	$361.0 \pm 1.7 \pm 6.0 \pm 7.2$	$334.4 \pm 2.0 \pm 5.1 \pm 6.7$
4.000–4.250	$251.3 \pm 1.2 \pm 3.7 \pm 5.0$	$281.3 \pm 1.4 \pm 7.6 \pm 5.6$
4.250–4.500	$138.3 \pm 1.2 \pm 3.6 \pm 2.8$	$197.9 \pm 1.5 \pm 9.8 \pm 4.0$

where the uncertainties are statistical, systematic, and where relevant, due to the luminosity determination, respectively.

In determining these ratios, all uncertainties are assumed to be uncorrelated, with the exception of the systematic uncertainty relating to the reconstruction efficiency, where a 50% positive correlation is assumed. The results are compared to theoretical predictions in Fig. 6, while the W and Z -boson total cross section [54] correlations are shown in Fig. 7. There is a tension of approximately 2.5 (2.0) σ

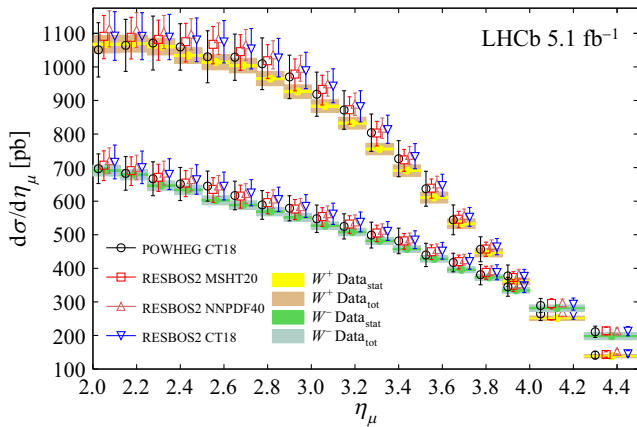


FIG. 4. Differential $W \rightarrow \mu\nu$ cross sections, as a function of η_μ . The bands represent the data, with the inner (outer) region corresponding to the statistical (total) uncertainty. For theoretical predictions, the error bars incorporate both PDF and scale uncertainties.

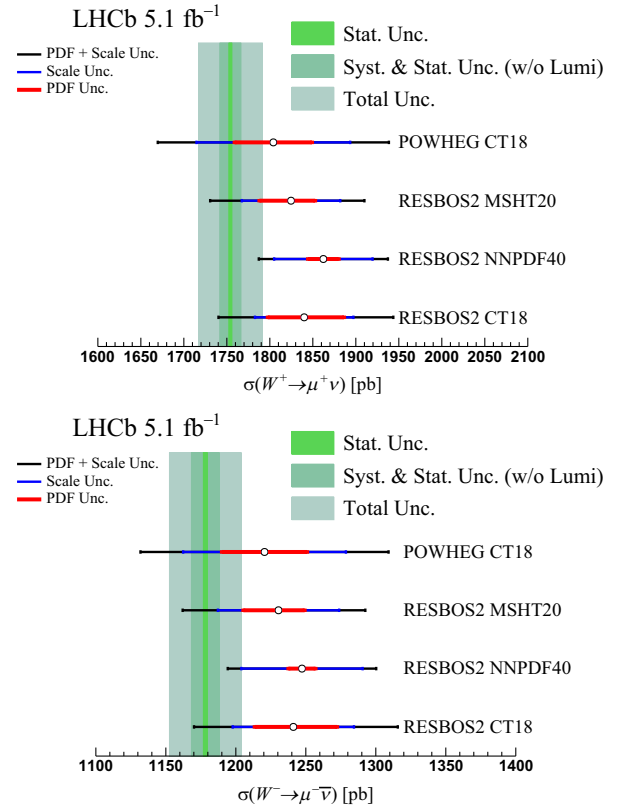


FIG. 5. Total (top) $W^+ \rightarrow \mu^+ \nu_\mu$ and (bottom) $W^- \rightarrow \mu^- \bar{\nu}_\mu$ cross sections compared with theoretical predictions. The bands denote the measurements, with the inner (outer) region corresponding to the statistical (total) uncertainty. For the theoretical predictions, the error bars incorporate both PDF and scale uncertainties.

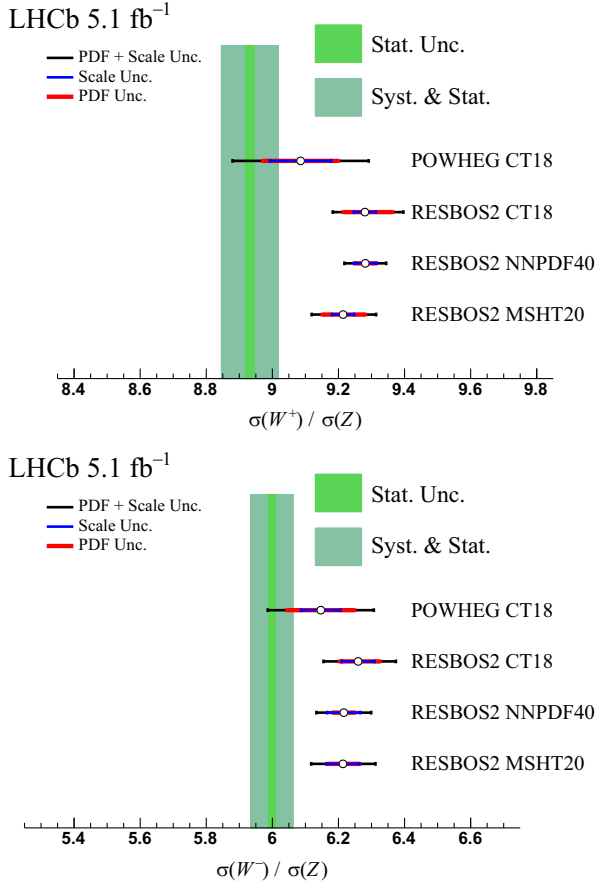


FIG. 6. Results for the (top) $\sigma_{W^+ \rightarrow \mu^+ \nu} / \sigma_{Z \rightarrow \mu^+ \mu^-}$ and (bottom) $\sigma_{W^- \rightarrow \mu^- \bar{\nu}} / \sigma_{Z \rightarrow \mu^+ \mu^-}$ cross-section ratios compared with theoretical predictions. The p_T^μ range used for the W (Z) cross-section measurement is $25 < p_T^\mu < 55$ GeV ($p_T^\mu > 20$ GeV). The bands denote the measurements, with the inner region corresponding to the statistical uncertainty and the outer region corresponding to the statistical and systematic uncertainty. The theoretical points correspond to the different predictions, with error bars including both PDF and scale uncertainties.

between the R_{W^+Z} (R_{W^-Z}) measurement and the NNLO theory predictions.

IX. CONCLUSION

Precision measurements of $W^\pm$ -boson production in proton-proton collisions at $\sqrt{s} = 13$ TeV are presented using muon decay channels. The analysis utilizes 5.1 fb^{-1} of data collected by the LHCb detector during Run 2 (2016–2018). Inclusive $W \rightarrow \mu\nu$ production cross sections are measured within the fiducial region defined by muon transverse momentum $25 < p_T^\mu < 55$ GeV and pseudorapidity $2.0 < \eta_\mu < 4.5$.

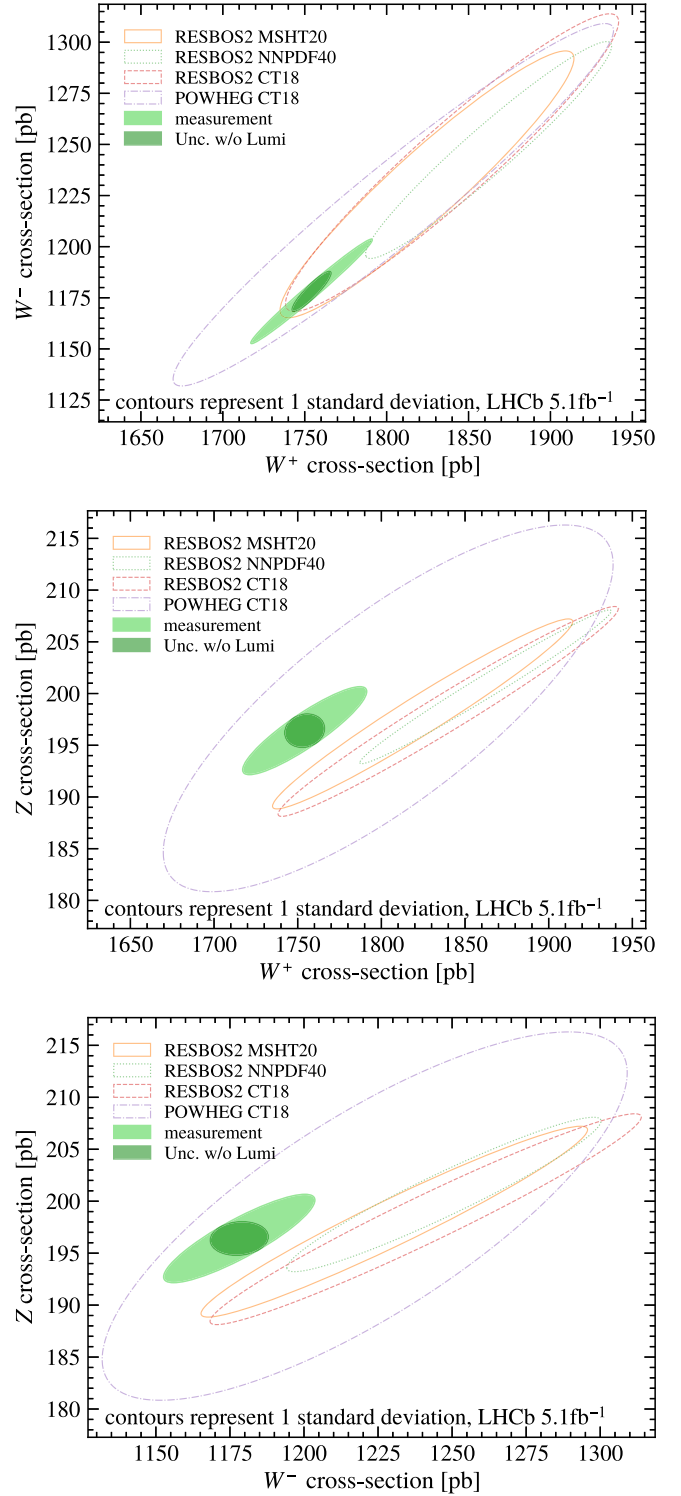


FIG. 7. total cross-sections measurements of (top) W^+ and W^- , (middle) W^+ and Z , and (bottom) W^- and Z , compared with theoretical predictions. The p_T^μ range used for the W (Z) cross-sections measurement is $25 < p_T^\mu < 55$ GeV ($p_T^\mu > 20$ GeV). The inner ellipse of the measurement includes statistical and systematic uncertainties, but excludes the luminosity uncertainty.

The measured differential cross sections exhibit excellent consistency with NNLO perturbative QCD predictions calculated via ResBos 2 using CT18 PDFs. These high-precision measurements impose stringent constraints on parton distribution functions, particularly in sparsely constrained small- x and large- x regions, with experimental uncertainties matching current theoretical precision. The findings underscore the unique capability of forward muon measurements at the LHCb experiment to probe PDFs in kinematic regimes inaccessible to other general-purpose detectors.

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DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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- [1] R. Aaij *et al.* (LHCb Collaboration), Measurement of the W boson mass, *J. High Energy Phys.* **01** (2022) 036.
 - [2] R. Aaij *et al.* (LHCb Collaboration), Measurement of the effective leptonic weak mixing angle, *J. High Energy Phys.* **12** (2024) 026.
 - [3] H. Abramowicz *et al.* (H1 and ZEUS Collaborations), Combination of measurements of inclusive deep inelastic $e^\pm p$ scattering cross sections and QCD analysis of HERA data, *Eur. Phys. J. C* **75**, 580 (2015).
 - [4] A. Aktas *et al.* (H1 Collaboration), Measurement of $F_2^{\bar{c}}$ and $F_2^{b\bar{b}}$ at high Q^2 using the H1 vertex detector at HERA, *Eur. Phys. J. C* **40**, 349 (2005).
 - [5] G. Moreno *et al.*, Dimuon production in proton-copper collisions at $\sqrt{s} = 38.8$ GeV, *Phys. Rev. D* **43**, 2815 (1991).
 - [6] R. S. Towell *et al.* (NuSea Collaboration), Improved measurement of the $\bar{d}/\bar{u}$ asymmetry in the nucleon sea, *Phys. Rev. D* **64**, 052002 (2001).
 - [7] F. D. Aaron *et al.* (H1 Collaboration), Measurement of the inclusive $e^\pm p$ scattering cross section at high inelasticity y and of the structure function F_L , *Eur. Phys. J. C* **71**, 1579 (2011).
 - [8] Q. Deng, Q. Han, H. Yin, S. Dulat, T.-J. Hou, and C.-P. Yuan, Impact of LHCb 13 TeV W and Z pseudodata on the parton distribution functions, *Chin. Phys. C* **45**, 023110 (2021).
 - [9] P. J. Rijken and W. L. van Neerven, Order α_s^2 contributions to the Drell-Yan cross section at fixed target energies, *Phys. Rev. D* **51**, 44 (1995).
 - [10] R. Hamberg, W. L. van Neerven, and T. Matsuura, A complete calculation of the order α_s^2 correction to the Drell-Yan K -factor, *Nucl. Phys.* **B359**, 343 (1991); *Nucl. Phys.* **B644**, 403(E) (2002).
 - [11] W. L. van Neerven and E. B. Zijlstra, The $O(\alpha_s^2)$ corrected Drell-Yan K factor in the DIS and $\overline{\text{MS}}$ scheme, *Nucl. Phys.* **B382**, 11 (1992); *Nucl. Phys.* **B680**, 513(E) (2004).
 - [12] R. V. Harlander and W. B. Kilgore, Next-to-next-to-leading order Higgs production at hadron colliders, *Phys. Rev. Lett.* **88**, 201801 (2002).
 - [13] C. Anastasiou, L. J. Dixon, K. Melnikov, and F. Petriello, High-precision QCD at hadron colliders: Electroweak gauge boson rapidity distributions at next-to-next-to leading order, *Phys. Rev. D* **69**, 094008 (2004).
 - [14] W.-L. Ju and M. Schönherr, The q_T and $\Delta\phi$ spectra in W and Z production at the LHC at $N^3\text{LL}' + N^2\text{LO}$, *J. High Energy Phys.* **10** (2021) 088.
 - [15] S. Alioli, A. Broggio, A. Gavardi, S. Kallweit, M. A. Lim, R. Nagar, D. Napoletano, C. W. Bauer, and L. Rottoli, Matching NNLO predictions to parton showers using $N^3\text{LL}$ color-singlet transverse momentum resummation in GENEVA, *Phys. Rev. D* **104**, 094020 (2021).

- [16] M. A. Ebert, J. K. L. Michel, I. W. Stewart, and F. J. Tackmann, Drell-Yan q_T resummation of fiducial power corrections at N^3LL , *J. High Energy Phys.* **04** (2021) 102.
- [17] W. Bizon, A. Gehrmann-De Ridder, T. Gehrmann, N. Glover, A. Huss, P. F. Monni, E. Re, L. Rottoli, and D. M. Walker, The transverse momentum spectrum of weak gauge bosons at N^3LL + NNLO, *Eur. Phys. J. C* **79**, 868 (2019).
- [18] G. Billis, J. K. L. Michel, and F. J. Tackmann, Drell-Yan transverse-momentum spectra at N^3LL' and approximate N^4LL with SCETlib, *J. High Energy Phys.* **02** (2025) 170.
- [19] S. J. Brodsky, V. A. Bednyakov, G. I. Lykasov, J. Smiesko, and S. Tokar, The physics of heavy quark distributions in hadrons: Collider tests, *Prog. Part. Nucl. Phys.* **93**, 108 (2017).
- [20] G. Aad *et al.* (ATLAS Collaboration), Measurement of the inclusive $W^\pm$ and Z/γ cross sections in the e and μ decay channels in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector, *Phys. Rev. D* **85**, 072004 (2012).
- [21] G. Aad *et al.* (ATLAS Collaboration), Precise measurements of W - and Z -boson transverse momentum spectra with the ATLAS detector using pp collisions at $\sqrt{s} = 5.02$ TeV and 13 TeV, *Eur. Phys. J. C* **84**, 1126 (2024).
- [22] G. Aad *et al.* (ATLAS Collaboration), Measurement of the Z/γ^* boson transverse momentum distribution in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector, *J. High Energy Phys.* **09** (2014) 145.
- [23] G. Aad *et al.* (ATLAS Collaboration), Measurement of the transverse momentum and ϕ_η^* distributions of Drell-Yan lepton pairs in proton-proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, *Eur. Phys. J. C* **76**, 291 (2016).
- [24] G. Aad *et al.* (ATLAS Collaboration), Measurement of the transverse momentum distribution of Drell-Yan lepton pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, *Eur. Phys. J. C* **80**, 616 (2020).
- [25] G. Aad *et al.* (ATLAS Collaboration), Measurement of $W^\pm$ -boson and Z -boson production cross sections in pp collisions at $\sqrt{s} = 2.76$ TeV with the ATLAS detector, *Eur. Phys. J. C* **79**, 901 (2019).
- [26] M. Aaboud *et al.* (ATLAS Collaboration), Measurements of W and Z boson production in pp collisions at $\sqrt{s} = 5.02$ TeV with the ATLAS detector, *Eur. Phys. J. C* **79**, 128 (2019); *Eur. Phys. J. C* **79**, 374(E) (2019).
- [27] M. Aaboud *et al.* (ATLAS Collaboration), Precision measurement and interpretation of inclusive W^+ , W^- and Z/γ^* production cross sections with the ATLAS detector, *Eur. Phys. J. C* **77**, 367 (2017).
- [28] G. Aad *et al.* (ATLAS Collaboration), Measurement of $W^\pm$ and Z -boson production cross sections in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, *Phys. Lett. B* **759**, 601 (2016).
- [29] G. Aad *et al.* (ATLAS Collaboration), Measurement of vector boson production cross sections and their ratios using pp collisions at $\sqrt{s} = 13.6$ TeV with the ATLAS detector, *Phys. Lett. B* **854**, 138725 (2024).
- [30] A. M. Sirunyan *et al.* (CMS Collaboration), Measurements of the W boson rapidity, helicity, double-differential cross sections, and charge asymmetry in pp collisions at $\sqrt{s} = 13$ TeV, *Phys. Rev. D* **102**, 092012 (2020).
- [31] S. Chatrchyan *et al.* (CMS Collaboration), Measurement of the inclusive W and Z production cross sections in pp collisions at $\sqrt{s} = 7$ TeV, *J. High Energy Phys.* **10** (2011) 132.
- [32] S. Chatrchyan *et al.* (CMS Collaboration), Measurement of inclusive W and Z boson production cross sections in pp collisions at $\sqrt{s} = 8$ TeV, *Phys. Rev. Lett.* **112**, 191802 (2014).
- [33] V. Khachatryan *et al.* (CMS Collaboration), Measurement of the Z boson differential cross section in transverse momentum and rapidity in proton-proton collisions at 8 TeV, *Phys. Lett. B* **749**, 187 (2015).
- [34] S. Chatrchyan *et al.* (CMS Collaboration), Measurement of the rapidity and transverse momentum distributions of Z bosons in pp collisions at $\sqrt{s} = 7$ TeV, *Phys. Rev. D* **85**, 032002 (2012).
- [35] A. Tumasyan *et al.* (CMS Collaboration), Measurement of the mass dependence of the transverse momentum of lepton pairs in Drell-Yan production in proton-proton collisions at $\sqrt{s} = 13$ TeV, *Eur. Phys. J. C* **83**, 628 (2023).
- [36] S. Chatrchyan *et al.* (CMS Collaboration), Study of Z production in PbPb and pp collisions at $\sqrt{s_{NN}} = 2.76$ TeV in the dimuon and dielectron decay channels, *J. High Energy Phys.* **03** (2015) 022.
- [37] A. Hayrapetyan *et al.* (CMS Collaboration), Measurement of the inclusive cross sections for W and Z boson production in proton-proton collisions at $\sqrt{s} = 5.02$ and 13 TeV, *J. High Energy Phys.* **04** (2025) 162.
- [38] V. Khachatryan *et al.* (CMS Collaboration), Measurements of inclusive W and Z cross sections in pp collisions at $\sqrt{s} = 7$ TeV, *J. High Energy Phys.* **01** (2011) 080.
- [39] S. Sakai (ALICE Collaboration), Electroweak vector-boson production in hadronic collisions with ALICE at the LHC, *EPJ Web Conf.* **339**, 05007 (2025).
- [40] S. Acharya *et al.* (ALICE Collaboration), $W^\pm$ -boson production in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV and Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, *J. High Energy Phys.* **05** (2023) 036.
- [41] N. Valle (ALICE Collaboration), Electroweak boson production in heavy-ion collisions with ALICE, *Nuovo Cimento Soc. Ital. Fis.* **44C**, 81 (2021).
- [42] D. Stocco (ALICE Collaboration), Electroweak boson production in p-Pb and Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with ALICE, *Nucl. Phys.* **A967**, 309 (2017).
- [43] J. Adam *et al.* (ALICE Collaboration), W and Z boson production in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, *J. High Energy Phys.* **02** (2017) 077.
- [44] E. Z. Buthelezi (ALICE Collaboration), Production of W -bosons in p-Pb collisions measured with ALICE at the LHC, *Proc. Sci. DIS2015* (2015) 100 [arXiv:1511.06128].
- [45] K. Senosi (ALICE Collaboration), Measurement of W -boson production in p-Pb collisions at the LHC with ALICE, *Proc. Sci. Bormio2015* (2015) 042 [arXiv:1511.06398].
- [46] R. Aaij *et al.* (LHCb Collaboration), Inclusive W and Z production in the forward region at $\sqrt{s} = 7$ TeV, *J. High Energy Phys.* **06** (2012) 058.
- [47] R. Aaij *et al.* (LHCb Collaboration), Measurement of the cross-section for $Z \rightarrow e^+e^-$ production in $p p$ collisions at $\sqrt{s} = 7$ TeV, *J. High Energy Phys.* **02** (2013) 106.

- [48] R. Aaij *et al.* (LHCb Collaboration), Measurement of the forward W boson production cross-section in $p p$ collisions at $\sqrt{s} = 7$ TeV, *J. High Energy Phys.* **12** (2014) 079.
- [49] R. Aaij *et al.* (LHCb Collaboration), Measurement of forward $Z \rightarrow e^+e^-$ production at $\sqrt{s} = 8$ TeV, *J. High Energy Phys.* **05** (2015) 109.
- [50] R. Aaij *et al.* (LHCb Collaboration), Measurement of the forward Z boson cross-section in $p p$ collisions at $\sqrt{s} = 7$ TeV, *J. High Energy Phys.* **08** (2015) 039.
- [51] R. Aaij *et al.* (LHCb Collaboration), Measurement of forward W and Z boson production in $p p$ collisions at $\sqrt{s} = 8$ TeV, *J. High Energy Phys.* **01** (2016) 155.
- [52] R. Aaij *et al.* (LHCb Collaboration), Measurement of the forward Z boson production cross-section in $p p$ collisions at $\sqrt{s} = 13$ TeV, *J. High Energy Phys.* **09** (2016) 136.
- [53] R. Aaij *et al.* (LHCb Collaboration), Measurement of forward $W \rightarrow e\nu$ production in $p p$ collisions at $\sqrt{s} = 8$ TeV, *J. High Energy Phys.* **10** (2016) 030.
- [54] R. Aaij *et al.* (LHCb Collaboration), Precision measurement of forward Z boson production in proton-proton collisions at $\sqrt{s} = 13$ TeV, *J. High Energy Phys.* **07** (2022) 026.
- [55] R. Aaij *et al.* (LHCb Collaboration), Measurement of the Z boson production cross-section at 5.02 TeV, *J. High Energy Phys.* **02** (2024) 070.
- [56] R. Aaij *et al.* (LHCb Collaboration), companion Letter, Precision measurement of the muon charge asymmetry from W -boson decays in pp collisions at $\sqrt{s} = 13$ TeV in the forward region, *Phys. Rev. Lett.* **137**, 111801 (2026).
- [57] C. Balázs and C.-P. Yuan, Soft gluon effects on lepton pairs at hadron colliders, *Phys. Rev. D* **56**, 5558 (1997).
- [58] J. Wang, C. Sheng Li, H. T. Li, Z. Li, and C.-P. Yuan, Improved resummation prediction on Higgs production at hadron colliders, *Phys. Rev. D* **86**, 094026 (2012).
- [59] N. Davidson, T. Przedzinski, and Z. Was, PHOTOS interface in C++: Technical and physics documentation, *Comput. Phys. Commun.* **199**, 86 (2016).
- [60] A. A. Alves Jr. *et al.* (LHCb Collaboration), The LHCb detector at the LHC, *J. Instrum.* **3**, S08005 (2008).
- [61] R. Aaij *et al.* (LHCb Collaboration), LHCb detector performance, *Int. J. Mod. Phys. A* **30**, 1530022 (2015).
- [62] R. Aaij *et al.*, Performance of the LHCb vertex locator, *J. Instrum.* **9**, P09007 (2014).
- [63] P. d'Argent *et al.*, Improved performance of the LHCb outer tracker in LHC Run 2, *J. Instrum.* **12**, P11016 (2017).
- [64] M. Adinolfi *et al.*, Performance of the LHCb RICH detector at the LHC, *Eur. Phys. J. C* **73**, 2431 (2013).
- [65] A. A. Alves Jr. *et al.*, Performance of the LHCb muon system, *J. Instrum.* **8**, P02022 (2013).
- [66] R. Aaij *et al.*, The LHCb trigger and its performance in 2011, *J. Instrum.* **8**, P04022 (2013).
- [67] N. Grieser *et al.*, The LHCb stripping project: Sustainable legacy data processing for high-energy physics, *Comput. Software Big. Sci.* **9**, 21 (2025).
- [68] T. Sjöstrand, S. Mrenna, and P. Skands, A brief introduction to PYTHIA 8.1, *Comput. Phys. Commun.* **178**, 852 (2008).
- [69] I. Belyaev *et al.*, Handling of the generation of primary events in Gauss, the LHCb simulation framework, *J. Phys. Conf. Ser.* **331**, 032047 (2011).
- [70] J. Allison *et al.* (Geant4 Collaboration), Geant4 developments and applications, *IEEE Trans. Nucl. Sci.* **53**, 270 (2006).
- [71] S. Agostinelli *et al.* (Geant4 Collaboration), Geant4: A simulation toolkit, *Nucl. Instrum. Methods Phys. Res., Sect. A* **506**, 250 (2003).
- [72] M. Clemencic, G. Corti, S. Easo, C. R. Jones, S. Miglioranza, M. Pappagallo, and P. Robbe, The LHCb simulation application, Gauss: Design, evolution and experience, *J. Phys. Conf. Ser.* **331**, 032023 (2011).
- [73] S. Camarda *et al.*, dYTurbo: Fast predictions for Drell–Yan processes, *Eur. Phys. J. C* **80**, 251 (2020); *Eur. Phys. J. C* **80**, 440(E) (2020).
- [74] Campbell, John, Neumann, and Tobias, Precision phenomenology with MCFM, *J. High Energy Phys.* **12** (2019) 034.
- [75] S. Alioli, P. Nason, C. Oleari, and E. Re, NLO vector-boson production matched with shower in POWHEG, *J. High Energy Phys.* **07** (2008) 060.
- [76] J. C. Collins, D. E. Soper, and G. Sterman, Transverse momentum distribution in Drell–Yan pair and W and Z boson production, *Nucl. Phys.* **B250**, 199 (1985).
- [77] J. C. Collins and D. E. Soper, Back-to-back jets in QCD, *Nucl. Phys.* **B193**, 381 (1981).
- [78] J. C. Collins and D. E. Soper, Back-to-back jets: Fourier transform from b to k_T , *Nucl. Phys.* **B197**, 446 (1982).
- [79] S. Navas *et al.* (Particle Data Group), Review of particle physics, *Phys. Rev. D* **110**, 030001 (2024).
- [80] T. Skwarnicki, A study of the radiative cascade transitions between the Upsilon-prime and Upsilon resonances, Ph.D. thesis, Institute of Nuclear Physics, Krakow, 1986 Report No. DESY-F31-86-02.
- [81] R. Aaij *et al.* (LHCb Collaboration), Curvature-bias corrections using a pseudomass method, *J. Instrum.* **19**, P03010 (2024).
- [82] W. Barter, M. Pili, and M. Vesterinen, A simple method to determine charge-dependent curvature biases in track reconstruction in hadron collider experiments, *Eur. Phys. J. C* **81**, 251 (2021).
- [83] R. Gauld, A. Gehrmann-De Ridder, T. Gehrmann, E. W. N. Glover, and A. Huss, Precise predictions for the angular coefficients in Z -boson production at the LHC, *J. High Energy Phys.* **11** (2017) 003.
- [84] R. Aaij *et al.* (LHCb Collaboration), Measurement of the track reconstruction efficiency at LHCb, *J. Instrum.* **10**, P02007 (2015).
- [85] R. Aaij *et al.* (LHCb Collaboration), Precision luminosity measurements at LHCb, *J. Instrum.* **9**, P12005 (2014).
- [86] T.-J. Hou *et al.*, New CTEQ global analysis of quantum chromodynamics with high-precision data from the LHC, *Phys. Rev. D* **103**, 014013 (2021).
- [87] R. D. Ball *et al.* (NNPDF Collaboration), The path to proton structure at 1% accuracy, *Eur. Phys. J. C* **82**, 428 (2022).
- [88] S. Bailey, T. Cridge, L. A. Harland-Lang, A. D. Martin, and R. S. Thorne, Parton distributions from LHC, HERA, Tevatron and fixed target data: MSHT20 PDFs, *Eur. Phys. J. C* **81**, 341 (2021).
- [89] LHCb Collaboration, Precision measurement of the muon charge asymmetry from W -boson decays in pp collisions at $\sqrt{s} = 13$ TeV in the forward region (2026), <https://cds.cern.ch/record/2958920>.

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