

Precision Measurement of the Muon Charge Asymmetry from W -Boson Decays in pp Collisions at $\sqrt{s} = 13$ TeV in the Forward Region

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A precision measurement of the muon charge asymmetry from W -boson decays in proton-proton collisions at $\sqrt{s} = 13$ TeV is presented. The analysis utilizes data corresponding to an integrated luminosity of 5.1 fb^{-1} , recorded by the LHCb detector during 2016, 2017, and 2018. The asymmetry is measured for muons with transverse momentum between 25 and 55 GeV and pseudorapidity between 2.0 and 4.5. This result represents the most precise determination of the muon charge asymmetry in the forward region to date, exhibiting excellent agreement with next-to-next-to-leading-order predictions in perturbative quantum chromodynamics. The measured asymmetries are corrected for experimental efficiencies, resolution, and final-state photon radiation.

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Precision measurements of electroweak boson production in proton-proton (pp) collisions [1–10] provide crucial constraints on the parton distribution functions (PDFs) of the proton [11–14], especially for the light-flavor (u and d) quark and antiquark components. The lepton charge asymmetry in $W \rightarrow \ell\nu$ decays, where ℓ denotes the charged lepton ($e^\pm, \mu^\pm$) from the W -boson decay, is particularly sensitive to PDFs of valence quarks, is essential in global PDF analyses, and has been extensively studied at both the Tevatron [15–22] and the Large Hadron Collider (LHC) [3,6,8,23–31].

At the LHC, the proton's composition, comprising two valence u quarks and one valence d quark, leads to a higher production rate of W^+ than W^- bosons. This imbalance, in addition to the effects of the left-handed couplings of the fermions to the W bosons, results in a measurable asymmetry, $\mathcal{A}$, in the pseudorapidity distribution of the final-state charged muons defined as

$$\mathcal{A}(\eta_\mu) \equiv \frac{d\sigma_{W^+ \rightarrow \mu^+ \nu} / d\eta_{\mu^+} - d\sigma_{W^- \rightarrow \mu^- \bar{\nu}} / d\eta_{\mu^-}}{d\sigma_{W^+ \rightarrow \mu^+ \nu} / d\eta_{\mu^+} + d\sigma_{W^- \rightarrow \mu^- \bar{\nu}} / d\eta_{\mu^-}}, \quad (1)$$

where η_μ is the muon pseudorapidity in the laboratory frame and $d\sigma/d\eta_\mu$ is the differential cross section for $W \rightarrow \mu\nu$ decays. Measurements in the forward region provide unique sensitivity to PDFs with both small and large Bjorken- x , as needed for the interpretation of LHC

precision measurements [32–34] and searches for new physics [35]. The muon charge asymmetry measurements at LHCb particularly constrain the quark PDFs at the Bjorken- x values around 10^{-4} and 10^{-1} [36], complementing ATLAS and CMS results spanning approximately 10^{-3} to 10^{-2} .

This Letter presents results with significantly improved precision for the muon charge asymmetry in inclusive $pp \rightarrow W(\rightarrow \mu\nu)X$ production at $\sqrt{s} = 13$ TeV, where X represents associated particles not used in the measurement. The analysis utilizes a data sample corresponding to an integrated luminosity of 5.1 fb^{-1} , collected with the LHCb detector during 2016–2018. A more comprehensive description of the associated W -boson production cross-section measurement is reported in a companion paper [37].

The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, described in detail in Refs. [38,39]. 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 [40] with a specific LHCb configuration [41]. The interaction of the generated particles with the detector, and its response, are implemented using the Geant4 toolkit [42] as described in Ref. [43].

To account for higher-order quantum chromodynamics (QCD) effects, the leading-order PYTHIA predictions are weighted to next-to-next-to-leading-order calculations from DYTurbo [44]. These weights are applied for the $W \rightarrow \mu\nu$, $Z \rightarrow \mu\mu$, and $W \rightarrow \tau\nu$ processes to the full five-dimensional kinematic distributions in the dilepton mass, rapidity, and transverse momentum, as well as the two angles in the Collins-Soper frame [32].

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Candidate $W \rightarrow \mu\nu$ decays are reconstructed from muons with momentum $p^\mu < 2$ TeV and satisfying the fiducial requirements of transverse momentum $25 < p_T^\mu < 55$ GeV and $2.0 < \eta_\mu < 4.5$ (natural units with $\hbar = c = 1$ are used throughout). The selected muons are required to have a relative momentum uncertainty of less than 6%, to be consistent with originating from a pp primary collision vertex, and to have good track-fit quality [45,46]. Furthermore, the muon isolation, defined as the scalar sum of the transverse momenta of all other particles within $\sqrt{(\phi - \phi_\mu)^2 + (\eta - \eta_\mu)^2} < 0.5$, where ϕ is the azimuthal angle, is required to be less than 3 GeV. A Z-boson veto excludes events with a second muon with opposite charge that might come from $Z \rightarrow \mu\mu$ decays. After all selection criteria, about 6.3×10^6 (4.4×10^6) W^+ (W^-) candidates are retained with an approximate purity of 85% (80%). The difference originates from the intrinsic muon charge asymmetry in W -boson decays.

The muon charge asymmetry, $\mathcal{A}$, is measured via Eq. (1), in which the cross section $\sigma_{W^\pm \rightarrow \mu^\pm \nu} = [(N^\pm \cdot f_{\text{FSR}}^{W^\pm}) / (\mathcal{L} \cdot \varepsilon_{W^\pm})]$ is evaluated for each η_μ interval, where $\mathcal{L}$ denotes the integrated luminosity and $N^\pm$ the measured $W^\pm$ candidate yield. The total efficiency $\varepsilon_{W^\pm}$ is determined as a fraction from simulation, with the numerator comprising weighted W -boson events passing all selection criteria and the denominator containing generator-level events satisfying only fiducial requirements. Correction weights are applied to the simulation and account for tracking, muon-identification, triggering, and selection efficiencies. The factor $f_{\text{FSR}}^{W^\pm}$ represents the final-state radiation (FSR) correction determined using ResBos [47,48] and PHOTOS [49], and it varies as a function of muon pseudorapidity. Given the excellent angular resolution of the LHCb detector, migration between η_μ intervals is negligible.

To suppress the effects of detector misalignment, charge-dependent curvature biases are corrected through the pseudomass method [50,51] using $Z \rightarrow \mu\mu$ decays in data. A simultaneous fit to the invariant masses of J/ψ , $\Upsilon(1S)$, and Z-boson dimuon final-states provides constraints on the smearing parameters of muon momentum corrections in simulation.

The background contributions from heavy-flavor ($b\bar{b}$, $c\bar{c}$, $t\bar{t}$) and electroweak processes ($W \rightarrow \tau\nu$, $Z \rightarrow \mu\mu$, $Z \rightarrow \tau\tau$, WW , Drell-Yan, and t -quark production) are estimated using simulated samples. These are calibrated and corrected with the selected $Z \rightarrow \mu\mu$ data candidates across η_μ intervals. The dominant background contribution originates from hadrons that are misidentified as muons. The shape of this background is estimated using simulation. The ratio of the p_T^μ distributions between data and simulation and the misidentification efficiencies are parametrized and applied as event weights in the simulation to better match the data [37].

The signal extraction employs a separate template-based binned likelihood fit to the p_T^μ distribution for each W -boson charge in the 18 η_μ intervals within the fiducial region. In the fitting procedure, both $W \rightarrow \mu\nu$ signal and QCD background fractions are treated as free parameters, fixing electroweak and heavy-flavor fractions to theory predictions. Many LHCb heavy-flavor measurements exist, yet they do not cover the high- p_T region. In addition, PYTHIA and parton distribution functions already incorporate results from previous experimental measurements. Statistical uncertainties in the template modeling are addressed through the Beeston-Barlow lite prescription [52]. The signal fraction in the data ranges from 63% to 88%, depending on the muon charge and η_μ region. Figure 1 displays examples of the signal extraction results for the first pseudorapidity bin, $2.000 < \eta_\mu < 2.125$.

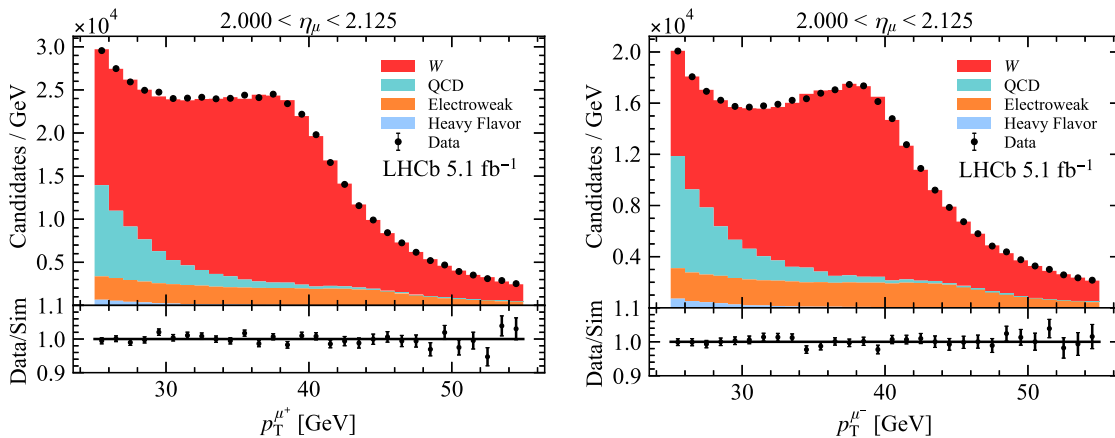


FIG. 1. Example p_T^μ distributions in data for (left) μ^+ and (right) μ^- , with the results of the fit also shown. The data distributions are compared with those from simulation. The normalizations of the contributions labeled W and QCD are determined by the fit described in the text. Error bars combine the contributions from statistical and systematic uncertainties.

The muon reconstruction efficiency is determined using a tag-and-probe method [53] in η_μ intervals from $Z \rightarrow \mu\mu$ and $\Upsilon(1S) \rightarrow \mu\mu$ samples [32]. The efficiency components are factorized into three contributions: the tracking efficiency quantifies the reconstruction probability of a charged track within the LHCb fiducial acceptance; the muon-identification efficiency measures the fraction of tracks consistent with the muon hypothesis, and the trigger efficiency represents the fraction of identified muons passing the hardware trigger selection. To account for kinematic dependencies, the efficiency corrections are implemented with a binned approach across the 18 η_μ intervals and two charge categories, with each interval featuring an independent p_T^μ parametrization. For all three terms, the ratios of efficiencies for data and simulation are used to weight simulated muon candidates. For all other selection requirements presented earlier in the text, a two-dimensional binning scheme in u and η_μ is used instead, where the recoil projection variable $u = [(\vec{p}_T^V \cdot \vec{p}_T^\mu)/p_T^\mu]$ quantifies the p_T alignment between the muon and the parent boson (V). The variable u distinguishes two physical contributions to the isolation inefficiency. The isolation requirement is the leading cause of inefficiency: the region with large positive u is primarily populated by hard process recoil, while with low or negative u is dominated by underlying event activity.

Several systematic uncertainties affecting the measured muon charge asymmetry are considered, as listed in Table I. The charge-asymmetry systematic uncertainty is obtained via error propagation from the W^+ and W^- uncertainties. FSR uncertainty fluctuations arise from finite statistics of

ResBos and POWHEG [54] simulation samples, while QCD and smearing fluctuations originate from statistical variations in both data and simulation, as well as covariance matrix fluctuations between W^+ and W^- differential cross sections. The reconstruction efficiency uncertainties comprise the limited tag-and-probe sample size, the fit-function dependence, and the kinematic adjustments to p_T^μ thresholds and Z-boson mass-window definitions. Uncertainties from generator modeling include scale variations in DYTurbo and comparisons between DYTurbo and POWHEG predictions. Uncertainties from the smearing model used to correct the simulated muon momenta are propagated in the fit. Selection efficiency uncertainties arise from limited data and simulation sample size, binning-scheme-dependent event topology variations, and the Z-boson selection criteria definitions. Uncertainties from QCD background modeling arise from the fluctuations in the ratio of data to simulation samples, misidentification function variations, and hadronic composition differences among pions, kaons, and protons. The FSR uncertainties are estimated by comparing differences of corrections between ResBos + PHOTOS and POWHEG + PYTHIA.

Figure 2 and Table II present the asymmetry measurement. For the measured results, both statistical and systematic uncertainties are presented, compared with theoretical predictions from POWHEG (using CT18) and ResBos 2 (using MSHT20, NNPDF40 [55], and CT18 PDF sets). Theoretical uncertainties arise from PDF uncertainties [56] and scale-dependent effects. The measured results show good agreement with theoretical predictions. Across all η_μ intervals, the experimental uncertainties are

TABLE I. Summary of uncertainty contributions (in units of 10^{-3}) on the W -boson charge asymmetry from the reconstruction efficiency (ϵ_{rec}), generator correction, smearing, selection efficiency (ϵ_{sel}), QCD background, and FSR correction to the measured results.

η_μ	ϵ_{rec}	Generator	Smearing	ϵ_{sel}	QCD background	FSR
2.000–2.125	3.6	1.3	0.8	0.2	0.6	0.3
2.125–2.250	2.7	1.3	0.4	0.2	0.3	1.0
2.250–2.375	2.6	1.4	0.5	0.2	0.3	0.2
2.375–2.500	2.7	2.8	0.3	0.2	0.3	0.7
2.500–2.625	1.9	3.0	0.4	0.2	0.2	0.6
2.625–2.750	1.9	2.7	0.4	0.2	0.2	0.6
2.750–2.875	2.5	2.3	0.5	0.1	0.5	0.1
2.875–3.000	2.7	2.3	0.3	0.1	0.5	0.4
3.000–3.125	3.1	1.7	0.5	0.1	0.3	0.1
3.125–3.250	3.3	0.4	0.5	0.1	0.7	0.6
3.250–3.375	2.8	2.1	0.7	0.1	0.8	0.6
3.375–3.500	2.6	5.9	0.5	0.1	1.0	0.3
3.500–3.625	3.8	8.8	0.6	0.1	0.4	0.5
3.625–3.750	3.1	10.1	0.8	0.2	0.9	0.1
3.750–3.875	3.1	12.2	1.1	0.1	0.4	2.2
3.875–4.000	3.8	13.4	0.6	0.3	0.4	0.1
4.000–4.250	3.5	18.7	0.8	1.0	0.7	0.4
4.250–4.500	6.2	12.9	2.4	1.2	1.5	1.4

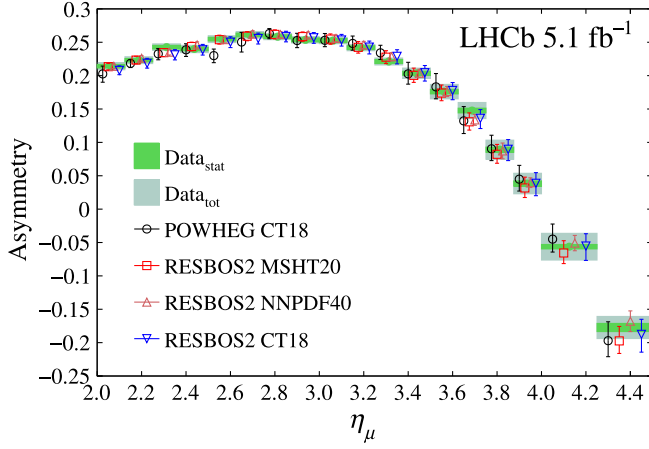


FIG. 2. Measured muon charge asymmetry, compared to the predictions with different generators and PDF sets. The bands correspond to the data, with the inner (outer) region corresponding to the statistical (total) uncertainty. The uncertainty bars of the predictions correspond to a 68% confidence level. The measured asymmetry is corrected for efficiencies, resolution, and final-state photon radiation.

comparable in magnitude to the PDF uncertainties from the MSHT20, NNPDF40, and CT18 sets and the scale uncertainties. This demonstrates the significance of the current analysis for constraining and improving PDFs.

In summary, a high-precision measurement is reported of the $W^\pm$ -boson muon charge asymmetry in pp collisions at

$\sqrt{s} = 13$ TeV, using data collected by the LHCb experiment during 2016–2018, corresponding to an integrated luminosity of 5.1 fb^{-1} . The asymmetry is measured for muons with transverse momentum $25 < p_T^\mu < 55$ GeV and pseudorapidity $2.0 < \eta_\mu < 4.5$, employing a binning scheme with finer granularity compared to previous LHCb results, representing the most precise determination in the forward region to date. Detector efficiencies, resolution, and final-state photon radiation are all corrected for in the asymmetry measurements. The results show good agreement with next-to-next-to-leading-order QCD predictions. The precision measurement provides crucial experimental constraints for the global fit of proton PDFs. The complete covariance matrix of the measured muon charge asymmetry and results without FSR corrections are provided in Supplemental Material [57], offering valuable input for future PDF determinations.

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TABLE II. Measured muon charge asymmetries $\mathcal{A}(\eta_\mu)$ (in units of 10^{-3}) with (first) statistical and (second) systematic uncertainties. Theoretical predictions are indicated for POWHEG with the CT18 PDF set and ResBos 2 with three PDF sets. The uncertainties correspond to (first) PDF uncertainties and (second) scale variations. The measured asymmetry is corrected for efficiencies, resolution and final-state photon radiation.

η_μ	Measurement	POWHEG	MSHT20	NNPDF40	CT18
2.000–2.125	$214 \pm 3 \pm 4$	203^{+4+7}_{-5-7}	213^{+3+2}_{-3-2}	$214 \pm 2 \pm 2$	208^{+5+2}_{-5-2}
2.125–2.250	$223 \pm 3 \pm 3$	218^{+4+1}_{-5-1}	223^{+3+2}_{-3-2}	$226 \pm 2 \pm 2$	218^{+5+2}_{-5-2}
2.250–2.375	$243 \pm 3 \pm 3$	233^{+4+4}_{-5-4}	234^{+4+2}_{-3-2}	$235 \pm 2 \pm 2$	231^{+5+2}_{-5-2}
2.375–2.500	$240 \pm 3 \pm 4$	239^{+4+5}_{-5-5}	244^{+4+3}_{-4-3}	$246 \pm 2 \pm 3$	239^{+5+3}_{-5-3}
2.500–2.625	$255 \pm 3 \pm 4$	230^{+5+5}_{-5-5}	254^{+4+3}_{-4-3}	$254 \pm 2 \pm 3$	250^{+5+3}_{-5-3}
2.625–2.750	$261 \pm 3 \pm 3$	250^{+5+10}_{-5-10}	259^{+4+3}_{-4-3}	$262 \pm 2 \pm 3$	256^{+5+3}_{-5-3}
2.750–2.875	$258 \pm 3 \pm 4$	263^{+5+3}_{-5-3}	262^{+4+2}_{-4-2}	$261 \pm 2 \pm 2$	259^{+5+2}_{-6-2}
2.875–3.000	$254 \pm 3 \pm 4$	253^{+5+5}_{-5-5}	258^{+5+2}_{-5-2}	$261 \pm 2 \pm 2$	257^{+5+2}_{-6-2}
3.000–3.125	$253 \pm 3 \pm 4$	253^{+6+4}_{-5-4}	255^{+5+3}_{-5-3}	$256 \pm 2 \pm 3$	253^{+6+3}_{-6-3}
3.125–3.250	$242 \pm 3 \pm 3$	248^{+6+5}_{-5-5}	242^{+6+3}_{-6-3}	$246 \pm 2 \pm 3$	243^{+6+3}_{-7-3}
3.250–3.375	$221 \pm 3 \pm 4$	234^{+7+4}_{-6-4}	228^{+6+4}_{-6-4}	$228 \pm 2 \pm 4$	229^{+6+4}_{-8-4}
3.375–3.500	$204 \pm 3 \pm 7$	203^{+8+9}_{-6-9}	200^{+7+4}_{-7-4}	$204 \pm 2 \pm 4$	204^{+7+4}_{-9-4}
3.500–3.625	$176 \pm 3 \pm 10$	183^{+9+11}_{-7-11}	174^{+8+4}_{-7-4}	$176 \pm 3 \pm 4$	178^{+7+4}_{-9-4}
3.625–3.750	$148 \pm 4 \pm 11$	132^{+10+11}_{-8-11}	131^{+9+5}_{-8-5}	$134 \pm 3 \pm 5$	136^{+8+5}_{-11-5}
3.750–3.875	$89 \pm 4 \pm 13$	90^{+12+9}_{-9-9}	82^{+10+5}_{-8-5}	$87 \pm 7 \pm 5$	90^{+9+5}_{-12-5}
3.875–4.000	$38 \pm 4 \pm 14$	45^{+13+7}_{-10-7}	32^{+11+5}_{-9-5}	$40 \pm 2 \pm 5$	39^{+11+5}_{-13-5}
4.000–4.250	$-56 \pm 3 \pm 19$	-45^{+16+7}_{-12-7}	-66^{+13+6}_{-10-6}	$-51 \pm 6 \pm 6$	-55^{+13+6}_{-16-6}
4.250–4.500	$-177 \pm 6 \pm 15$	-197^{+20+8}_{-16-8}	-197^{+15+6}_{-12-6}	$-168 \pm 9 \pm 6$	-188^{+16+6}_{-20-6}

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Data availability—The data that support the findings of this article are openly available [58], embargo periods may apply.

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