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DOI:

[10.1103/PhysRevLett.129.091801](https://doi.org/10.1103/PhysRevLett.129.091801)

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Document Version

Publisher's PDF, also known as Version of record

Citation for published version (Harvard):

LHCb Collaboration, Swallow, P, Calladine, R, Bifani, S, Sahoo, N & Cooke, N 2022, 'First measurement of the $Z \rightarrow \mu^+ \mu^-$ angular coefficients in the forward region of pp collisions at $\sqrt{s} = 13$ TeV', *Physical Review Letters*, vol. 129, no. 9, 091801. <https://doi.org/10.1103/PhysRevLett.129.091801>

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First Measurement of the $Z \rightarrow \mu^+ \mu^-$ Angular Coefficients in the Forward Region of pp Collisions at $\sqrt{s} = 13$ TeV

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 (Received 7 March 2022; accepted 13 July 2022; published 24 August 2022)

The first study of the angular distribution of $\mu^+ \mu^-$ pairs produced in the forward rapidity region via the Drell-Yan reaction $pp \rightarrow \gamma^*/Z + X \rightarrow \ell^+ \ell^- + X$ is presented, using data collected with the LHCb detector at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 5.1 fb^{-1} . The coefficients of the five leading terms in the angular distribution are determined as a function of the dimuon transverse momentum and rapidity. The results are compared to various theoretical predictions of the Z-boson production mechanism and can also be used to probe transverse-momentum-dependent parton distributions within the proton.

DOI: [10.1103/PhysRevLett.129.091801](https://doi.org/10.1103/PhysRevLett.129.091801)

Drell-Yan muon pairs ($\mu^+ \mu^-$) produced near the Z-boson mass pole provide an excellent source of information about electroweak (EW) parameters, probe the proton structure, and test the underlying strong-interaction dynamics of Z-boson production in proton-proton (p - p) collisions, as described by quantum chromodynamics (QCD). With a dedicated detector instrumented in the forward region, the LHCb experiment plays a unique role in the study of $Z \rightarrow \mu^+ \mu^-$ processes in the forward rapidity (y^Z) region [1], especially for $y^Z > 3.5$. Therefore, the LHCb experiment is complementary to the ATLAS and CMS experiments, which are more efficient in the central region. The distributions of the Z-boson transverse momentum, p_T , and the scattering angle ϕ_{η}^* of the muons with respect to the proton beam direction in the rest frame of the dimuon system [2] have already been measured by the LHCb collaboration [1,3–5]. Key information is also encoded in the $Z \rightarrow \mu^+ \mu^-$ angular distribution in the forward region, which has not been fully explored.

In the Drell-Yan neutral-current process, the lepton pair is produced via a spin-1 gauge boson. The kinematic distribution of the final-state leptons (ℓ^\pm) provides a direct probe of the polarization of the intermediate gauge boson, which is in turn sensitive to the underlying QCD production mechanisms. The QCD mechanisms of the process p - $p \rightarrow \gamma^*/Z + X \rightarrow \ell^+ \ell^- + X$, where X represents any other particles, can be expressed using eight frame-dependent angular coefficients, A_i ($i = 0, \dots, 7$). The coefficients

depend on the invariant mass, p_T , and the rapidity of the lepton pair. At Born level, the angular distribution of the leptons in the boson rest frame is given by [6,7]

$$\begin{aligned} \frac{d\sigma}{d\cos\theta d\phi} \propto & (1 + \cos^2\theta) + \frac{1}{2}A_0(1 - 3\cos^2\theta) \\ & + A_1 \sin 2\theta \cos \phi + \frac{1}{2}A_2 \sin^2\theta \cos 2\phi \\ & + A_3 \sin \theta \cos \phi + A_4 \cos \theta + A_5 \sin^2\theta \sin 2\phi \\ & + A_6 \sin 2\theta \sin \phi + A_7 \sin \theta \sin \phi, \end{aligned} \quad (1)$$

where θ and ϕ are the polar and azimuthal angles of the μ^+ lepton in the Collins-Soper frame [8]. At leading-order (LO) approximation within the framework of QCD, all angular coefficients vanish as the dilepton transverse momentum approaches zero, with the exception of A_4 , which is nonzero due to parity violation in the weak interaction. At next-to-leading order (NLO), A_{0-3} become nonzero, while A_{5-7} have small deviations from zero only at next-to-next-to-leading order (NNLO).

The equality $A_0 = A_2$ is known as the Lam-Tung relation [9], which is valid for both $q\bar{q}$ and gq processes at LO [10]. However, small violations of the Lam-Tung relation occur in higher-order perturbative QCD calculations [11,12], as well as in QCD resummation calculations to all orders [13]. Therefore, precision measurements of $A_0 - A_2$ can test the Lam-Tung relation. Nonperturbative effects can lead to a violation of the Lam-Tung relation via a correlation between the transverse spin and transverse momentum of the initial-state quark or antiquark, represented by the Boer-Mulders transverse-momentum-dependent (TMD) parton distribution function (PDF) [14,15]. Significant violation of the Lam-Tung relation, with large $\cos 2\phi$ modulations, has been observed in pion-induced Drell-Yan measurements

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[16–18]. The $\cos 2\phi$ coefficient (A_2) in Eq. (1) is proportional to the convolution of two Boer-Mulders functions, of the quark and the antiquark [15]. Therefore, the angular measurements of the Drell-Yan process can improve constraints on nonperturbative partonic spin-momentum correlations within unpolarized protons via phenomenological extractions of the Boer-Mulders TMD PDF from these data in conjunction with data from other experiments. The Z -boson cross section measurements at low p_T ($\lesssim 20$ GeV/ c) by the LHCb collaboration have already been used to extract the unpolarized TMD PDF [19].

Previously, the CDF collaboration published the first measurement [20] of the angular coefficients of lepton pairs produced near the Z -boson mass pole at a hadron collider. Measurements of the W -boson angular coefficients have been published by the CDF [21], CMS [22], and ATLAS [23] collaborations. The CMS collaboration measured A_0 , A_1 , A_2 , and A_4 with $Z \rightarrow \mu^+\mu^-$ decays [24], while the ATLAS collaboration reported measurements of the complete set of coefficients [25].

This Letter reports the first measurement of the $Z \rightarrow \mu^+\mu^-$ angular coefficients in the forward rapidity region ($2 < y^Z < 5$) by the LHCb experiment, using Z -boson candidates selected in the mass region $50 < M_{\mu\mu} < 120$ GeV/ c^2 , where $M_{\mu\mu}$ is the invariant mass of the $\mu^+\mu^-$ pair. The parameters A_0 , A_1 , A_2 , and A_3 are determined as a function of the Z -boson p_T and y^Z , with the candidates selected in the mass region $75 < M_{\mu\mu} < 105$ GeV/ c^2 . Events in the low mass range, $50 < M_{\mu\mu} < 75$ GeV/ c^2 , and high mass range, $105 < M_{\mu\mu} < 120$ GeV/ c^2 , are used to probe the Boer-Mulders function; these regions are dominated by contributions from virtual photons and their interference with the Z -boson amplitude, with measurements in multiple mass regions adding sensitivity to the evolution of the TMD PDF with the hard scale. With the higher-order QCD effects related to the Z -boson p_T being integrated out, the measurements of the angular coefficients as a function of y^Z can be used to test the resummation calculations in the forward region. Because of the relatively small data sample containing high- p_T (> 50 GeV/ c) $Z \rightarrow \mu^+\mu^-$ events, the coefficients A_5 to A_7 are fixed to zero. Since this study focuses on probing the QCD dynamics of the Z -boson production, the A_4 coefficient, sensitive to the weak mixing angle [26], is not reported. Nevertheless, in order to investigate its variation across the kinematic range, the difference with respect to its mean value, ΔA_4 , is measured.

The LHCb detector [27,28] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. A silicon-strip vertex detector [29] surrounding the p - p interaction region allows c and b hadrons to be identified from their relatively long flight distance. A tracking system [30] provides a measurement of momentum, p , of charged particles, and two imaging Cherenkov detectors [31] are

able to discriminate between different species of charged hadrons. 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 [32]. The online event selection is performed by a trigger system [33], which consists of a hardware stage, based on information from the calorimeter and muon systems [34,35], followed by a software stage, which applies a full event reconstruction incorporating near-real-time alignment and calibration of the detector [36].

Simulated p - p collisions are generated using PYTHIA [37] with a specific LHCb configuration [38]. The interaction of the generated particles with the detector, and its response, are implemented using the GEANT4 toolkit [39] as described in Ref. [40]. Various theoretical predictions at the Born level are compared with the measured results, including analytic resummed calculations, RESBOS [41], and DYTURBO [42], and a fixed-order calculation with matching algorithms to veto the double counting of quantum electrodynamic final-state radiation (FSR) and parton shower, POWHEG-BOX [43–46]. Predictions from the RESBOS [41] generator are produced using the PDF known as CT14HERA2 [47]. The RESBOS calculation combines NLO fixed-order perturbative calculations at high boson p_T , with the soft-gluon Collins-Soper-Sterman resummation formalism [48–50] at low boson p_T , with consideration of a nonperturbative contribution from the parton intrinsic transverse momentum, which is an all-orders summation of large terms from gluon emission. The DYTURBO [42] program is a NNLO generator for the calculation of the QCD transverse-momentum resummation of Drell-Yan cross sections up to next-to-next-to-leading logarithmic accuracy combined with the fixed-order results. DYTURBO includes the full kinematic dependence of the lepton pair with the corresponding spin correlations and finite-width effects. POWHEG-BOX is a NLO generator and can be interfaced with PYTHIA for QCD and EW showering, but without the angular damping factors.

Measurements are performed using 5.1 fb $^{-1}$ of data at a center-of-mass energy of 13 TeV collected by the LHCb detector during the years 2016–2018. For each $Z \rightarrow \mu^+\mu^-$ candidate, at least one of the muons is required to pass hardware and software single-muon trigger decision stages. All muon candidates are required to have transverse momentum $p_T^\mu > 20$ GeV/ c and be in the range $2.0 < \eta < 4.5$. The relative uncertainty in the momentum of the muon track must be less than 10%. To further suppress background sources, muon candidates are required to pass an isolation requirement which is parametrized as $z = p_T^\mu / p_T^{\mu\text{-cone}} > 0.85$, where $p_T^{\mu\text{-cone}}$ is the sum of the muon p_T and that of the tracks within $\delta R < 0.5$, and δR is $\sqrt{\delta\eta^2 + \delta\Phi^2}$. The quantities $\delta\eta$ and $\delta\Phi$ give the separation between the muon and neighboring tracks in

pseudorapidity η and the laboratory azimuthal angle Φ , respectively. Candidate Z bosons are composed of two muon candidates with opposite charge that originate from a common primary p - p interaction vertex. In total, 818 074 (745 343) $Z \rightarrow \mu^+\mu^-$ candidates are selected in the mass region $50 < M_{\mu\mu} < 120 \text{ GeV}/c^2$ ($75 < M_{\mu\mu} < 105 \text{ GeV}/c^2$). Background contributions from heavy-flavor processes and misidentified hadrons are estimated using data control samples [1], while background sources from W^+W^- , $W^\pm Z$, ZZ , $Z \rightarrow \tau^+\tau^-$, and $t\bar{t}$ processes are estimated from simulation. The total background contribution is determined to be 0.2%.

Detector misalignment effects are studied and suppressed using the $Z \rightarrow \mu^+\mu^-$ data events, where the mass peak position of the selected Z -boson candidates is calibrated in different kinematic and geometric regions to the world average value [51]. To improve the agreement between data and simulation, selection efficiencies determined from simulation are corrected to corresponding values measured in the data. The selection efficiencies include the muon trigger, muon track reconstruction, muon isolation, and identification. These efficiencies are estimated using $Z \rightarrow \mu^+\mu^-$ data and simulation events, with the tag-and-probe method [1], as functions of muon η and Φ . Additionally, corrections to the momentum scale and resolution are applied to the simulation.

The angular coefficients are determined in six intervals of the Z -boson p_T and five intervals of y^Z , by fitting the two decay angles $\cos\theta$ and ϕ of the selected $Z \rightarrow \mu^+\mu^-$ candidates, using an unbinned maximum-likelihood method in each interval. The probability density function used in the fit consists of a signal-only function, obtained from Eq. (1), convoluted with the detector resolution and acceptance effects. The angular coefficients (A_{0-4}) are the only free parameters in the fit, while the background contributions are effectively subtracted from the data sample by including background events with negative weights derived from simulation and data control samples. Simulated PYTHIA events are used to study the background modeling along with the detector resolution and acceptance effects, with FSR turned on at the generator level, thereby including the corrections of Born level predictions to that at Born level [52]. This way, the measured A_i coefficients are corrected to the Born level. The normalization weights method is used to avoid computing-intensive numerical integration of the probability density function in the fit. This method was introduced and used by the BABAR collaboration [53,54], and has been extensively used in LHCb heavy-flavor studies [55]. To avoid potential bias from the input angular coefficients in the simulation, an iterative method is used. The measured results are found to be stable after four iterations.

Several sources of systematic uncertainty are considered. Simulation is used to determine the detector acceptance effects in the fit process. To estimate the uncertainty from

the finite number of simulated events, the bootstrap method [56] is used. This uncertainty varies from 0.0016 to 0.0402 in different kinematic regions and is the dominant systematic uncertainty. Another significant uncertainty arises from the selection efficiencies. In the determination of the uncertainty from the efficiency corrections, two independent sources are considered: an uncertainty from the size of the control sample and one from the kinematic dependence of the corrections. For the second uncertainty, the default two-dimensional (muon η and ϕ) efficiency corrections are replaced with one-dimensional corrections, and variations of the results are taken as uncertainties. The fit method is validated with simulation samples. The angular coefficients of the simulation are changed to values far from the default (increased by a factor of 1.5, or set to 0). In the validation, the new angular coefficients are compared with the values from the fit, and differences between them are taken as uncertainties. The uncertainty from the muon momentum scaling and smearing are calculated by varying the corrections by their uncertainties, and the changes in the measured results are taken as the associated systematic uncertainties. These are found to be negligible.

The systematic uncertainties associated to the background are estimated by varying the background contribution by $\pm\sigma$, where σ includes the uncertainties from the theoretical predictions of the cross sections and the statistical uncertainties from the simulation. The systematic uncertainty from the FSR is estimated by comparing the measured results using the simulation sample weighted to the POWHEG prediction with different FSR algorithms of PHOTOS and PYTHIA. Differences from different FSR approaches are taken as uncertainties. The systematic uncertainty from the PDF is estimated using 58 sub-PDF sets of CT18NNLO [57], with the prescription recommended by the PDF set groups [58]. All systematic uncertainties are considered as uncorrelated, and the total systematic uncertainty is taken as their sum in quadrature.

The measured angular coefficients A_{0-3} as well as ΔA_4 and the difference $A_0 - A_2$, are presented as a function of the Z boson p_T in Fig. 1. The measurements are compared with the predictions of RESBOS, DYTURBO, POWHEG-BOX + PYTHIA, and PYTHIA with LHCb tuning. The measurement of A_0 is in good agreement with DYTURBO, RESBOS, and POWHEG-BOX predictions, but disfavors the PYTHIA results in the high- p_T region ($>20 \text{ GeV}/c$). However, the PYTHIA calculations show increasing trends similar to the measurements in the high- p_T region. The measurement of A_1 disagrees with the PYTHIA result, but is in good agreement with other calculations in all p_T regions. Within large statistical uncertainties, the measurements of A_2 are mostly in reasonable agreement with predictions, while for A_3 there is a noticeable underestimation of most predictions up to $55 \text{ GeV}/c^2$. The measured ΔA_4 is in good agreement with theoretical predictions in all p_T regions. Finally, for the

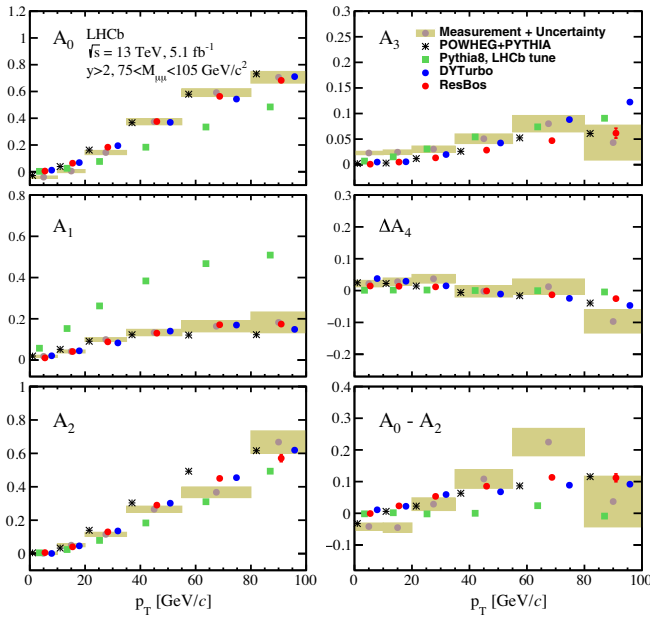


FIG. 1. Comparison of the measured angular coefficients with different predictions, as a function of the Z boson p_T , in the rapidity region of Z boson $y^Z > 2$ and $75 < M_{\mu\mu} < 105 \text{ GeV}/c^2$. The total uncertainty (shown in the figure) is dominated by the statistical component. The theoretical predictions correspond to the same Z -boson p_T bins as data and the p_T shifts of the theoretical markers in all plots are for visualization purposes only. DYTURBO and RESBOS predictions include the theoretical uncertainties.

$A_0 - A_2$ measurement, the LHCb results are compatible with zero only in the highest p_T interval, but there the uncertainty is relatively large. Also, most predictions are not compatible with zero in the high- p_T intervals. This violation of the Lam-Tung relations measured by the LHCb collaboration is consistent with previous results from the CMS [24] and ATLAS collaborations [25]. The measured $A_0 - A_2$ results are significantly smaller than the predictions at low p_T ($< 20 \text{ GeV}/c$) and slightly smaller at high p_T ($> 80 \text{ GeV}/c$), while larger than the predictions in other p_T regions. A summary of the full results, including measurements in bins of y^Z , is provided in the Supplemental Material [59]. With the exception of A_0 , the measured angular coefficients do not vary significantly as a function of y^Z , when the measurement is performed for the full p_T range. There is reasonable agreement between the measurements and RESBOS calculations for A_{1-3} and ΔA_4 , while for A_0 there is tension between the measurements and predictions, especially in the highest y^Z region. The p value between measurements and theoretical predictions is calculated to be 0.06. The differences between A_0 and the RESBOS predictions in the y^Z distribution indicate that there is a y^Z dependence in the QCD resummation or additional higher-order effects. More detailed studies on the predictions as a function of y^Z are necessary.

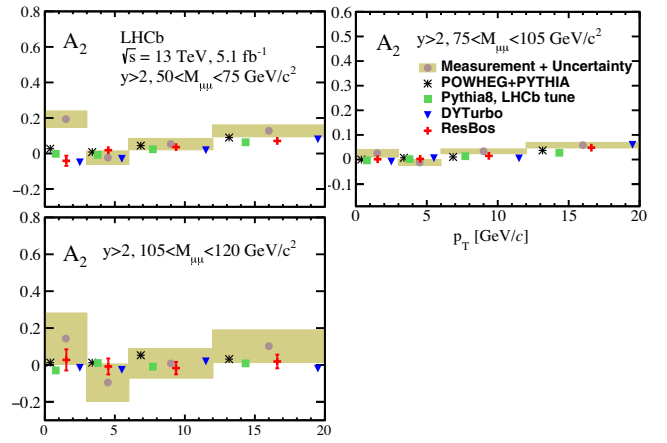


FIG. 2. Comparison of the measured angular coefficient A_2 with different predictions, as a function of the Z boson p_T , in the rapidity region of Z boson $y^Z > 2$ and $50 < M_{\mu\mu} < 75 \text{ GeV}/c^2$ (left), $50 < M_{\mu\mu} < 75 \text{ GeV}/c^2$ (middle), and $105 < M_{\mu\mu} < 120 \text{ GeV}/c^2$ (right). The total uncertainty (shown in the figure) is dominated by the statistical component. The horizontal positions of the theoretical predictions within the bins are adjusted to increase visibility. DYTURBO and RESBOS predictions include the theoretical uncertainties.

The nonperturbative Boer-Mulders TMD PDF can be probed with the measurement of A_2 in the lower p_T region. Measurements of A_2 in the low, middle, and high $M_{\mu\mu}$ regions are shown in Fig. 2, where the dimuon p_T region is divided into four intervals from 0 to 20 GeV/c . Despite the limited sample size with the finer p_T intervals, several observations can be made. In the low $M_{\mu\mu}$, the measured A_2 value in the lowest dimuon p_T region ($p_T < 3 \text{ GeV}/c$) deviates significantly from all predictions. It is unclear if nonperturbative spin-momentum correlations in the proton, described by the Boer-Mulders distribution, could lead to such variations as no phenomenological calculations are available. None of the calculations used in the comparison include this type of nonperturbative effect. In other p_T regions, reasonable agreement between measurements and predictions is seen.

In summary, the first measurements of the angular coefficients of Drell-Yan $\mu^+\mu^-$ pairs in the forward rapidity region of p - p collisions are presented. These quantities provide more information on the Z -boson production compared with other traditional observables. The measurements, which are given as a function of the Z boson p_T and y^Z , in both the Z peak and lower and higher $M_{\mu\mu}$ regions, are compared with various predictions. Some tension between the measurements and the theoretical predictions appears in the lower $M_{\mu\mu}$ and low- p_T region, and in the y^Z dependence (See the Supplemental Material [59] for further details). More studies of the theoretical models are needed to shed light on the apparent discrepancies. This analysis provides important and unique inputs for future phenomenological extractions of spin-momentum correlations in

the proton in terms of the Boer-Mulders TMD PDF and its evolution with the hard scale.

We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national agencies: CAPES, CNPq, FAPERJ, and FINEP (Brazil); MOST and NSFC (China); CNRS/IN2P3 (France); BMBF, DFG, and MPG (Germany); INFN (Italy); NWO (Netherlands); MNiSW and NCN (Poland); MEN/IFA (Romania); MinES and FASO (Russia); MinECo (Spain); SNSF and SER (Switzerland); NASU (Ukraine); STFC (United Kingdom); NSF (USA). We acknowledge the computing resources that are provided by CERN, IN2P3 (France), KIT and DESY (Germany), INFN (Italy), SURF (Netherlands), PIC (Spain), GridPP (United Kingdom), RRCKI and Yandex LLC (Russia), CSCS (Switzerland), IFIN-HH (Romania), CBPF (Brazil), PL-GRID (Poland), and OSC (USA). We are indebted to the communities behind the multiple open-source software packages on which we depend. Individual groups or members have received support from AvH Foundation (Germany); EPLANET, Marie Skłodowska-Curie Actions and ERC (European Union); ANR, Labex P2IO and OCEVU, and Région Auvergne-Rhône-Alpes (France); Key Research Program of Frontier Sciences of CAS, CAS PIFI, and the Thousand Talents Program (China); RFBR, RSF, and Yandex LLC (Russia); GVA, XuntaGal, and GENCAT (Spain); Herchel Smith Fund, the Royal Society, the English-Speaking Union, and the Leverhulme Trust (United Kingdom); Laboratory Directed Research and Development program of LANL (USA).

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