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INTERACTIONS OF PLASMA, PARTICLE BEAMS, AND RADIATION WITH MATTER

Measurement of Angular Coefficients in the Drell–Yan Process in the CMS Experiment at the LHC

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Abstract—A review is given of measurements of the first five polarization coefficients A_0–A_4 of angular distributions of muons resulting from the Z^0 boson decay in proton–proton collisions at the center-of-mass energy of 8 TeV. The data collected by the CMS Collaboration in 2011–2012 (LHC Run 1) are used. The statistics corresponds to the integrated luminosity of 19.7 fb^{-1}.

Keywords: Compact Muon Solenoid (CMS), Drell–Yan process, angular coefficients, polarization, Z boson, Large Hadron Collider (LHC)

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1. INTRODUCTION

Signals of new physics beyond the Standard Model of particle physics (SM) can be deviations of the behavior of the measured kinematic and spatial characteristics of SM processes from theoretical predictions [1]. One of these processes is lepton pair production via a gauge boson exchange in quark–antiquark annihilation $q\bar{q} \to \gamma^*/Z^0 \to l^+l^-$, the Drell–Yan process (Fig. 1) [2]. This process is utterly important for hadron collider physics, since measurement of its characteristics is a critical test of the SM in a new energy region.

Previous experiments made it possible to study this process in the region of transfer four-momenta Q of up to about a few hundred GeV/c [3]. Recent data from the LHC experiments ATLAS [4] and CMS [5] allows to extend this region up to few TeV/c, i.e., going beyond the TeV scale of interactions.

By now, the Drell–Yan process cross sections have been calculated in the next-to-leading (NLO) and next-to-next-leading (NNLO) orders of QCD perturbation theory (PT) with an accuracy of ~2–4% in the Z-boson mass region (~90 GeV/c^2) [6], and thus the characteristics should be measured with an accuracy not lower than that of the theoretical calculations. An advantage of this process is its simple experimental signature—two spatially well-isolated final-state leptons, which ensures highly efficient suppression of background processes and detection of signal events.

Additionally, the Drell–Yan process is a source of background events for a number of other processes being studied in the CMS experiment, such as four-lepton decay of the Higgs boson and production of gauge bosons and t-quark pairs, and is also used to estimate technical characteristics of detector systems.

The Drell–Yan proces studies is one of the traditional directions for many accelerator experiments, in particular, for the CMS experiment at the LHC [7]. The unique properties of the LHC allow collecting the necessary statistics for the precision measurement of differential cross sections [6] and the study of spatial regularities [8], specifically the dependence of the angular distributions on the kinematic variables of the lepton pair, namely, the rapidity, invariant mass, and transverse momentum. This work briefly reviews the results of measuring the angular distribution coefficients for muons produced in the Drell–Yan process that were measured by the CMS collaboration from the experimental data collected in 2011–2012 during

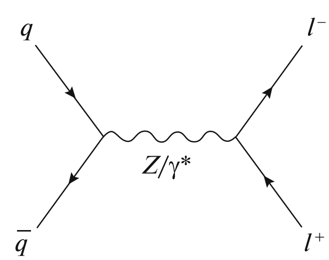

Fig. 1. Lepton pair production in the Drell–Yan process $q\bar{q} \to \gamma^*/Z \to l^+l^-$.

LHC Run 1 at the proton beam energy $\sqrt{s} = 8$ TeV and the corresponding integrated luminosity of 19.7 fb^{-1} [9].

2. ANGULAR COEFFICIENTS

The angular distributions of lepton pairs are sensitive to QCD higher order effects, proton polarization, etc. Therefore, it is of particular interest to measure coefficients A_i appearing in the expression for the double differential cross section at the corresponding angular polynomials. In the leading order of perturbation theory, this cross section is as follows:

$$\frac{d^2\sigma}{d\theta^* d\phi^*} = \sum_{i=0}^{5} \sigma_i = (1 + \cos^2\theta^*)$$
$$+ A_0 \frac{1}{2}(1 - 3\cos^2\theta^*) + A_1 \sin(2\theta^*)\cos\phi^*$$
$$+ A_2 \frac{1}{2}\sin^2\theta^* \cos(2\phi^*) + A_3 \sin\theta^* \cos\phi^*$$
$$+ A_4 \cos\theta^*,$$

where φ^* and θ^* are the polar and azimuthal angles in the center-of-mass system of the lepton pair (Collins–Soper frame [10]). Strictly speaking, angular coefficients A_i are functions of the kinematic variables of the Z boson—rapidity, invariant mass, and transverse momentum. Each coefficient is sensitive to the manifestation of a certain effect; e.g., the coefficients A_0, A_1, and A_2 are responsible for polarization of the Z boson, and the coefficients A_3 and A_4 depict the influence of the V–A structure of weak currents. In particular, the coefficient A_4 describes the spatial asymmetry of the escape of a lepton pair in the rest frame of the Z boson A_{FB} and is the only nonzero coefficient in the leading order of QCD when $q_T \to 0$ [8].

An important measured characteristic related to invariance under rotation of the coordinate system is the amount of violation of the so-called Lam–Tung relation $A_0 = A_2$ [11]. The nonzero difference between the coefficients A_0 and A_2 appearing at the increase in the transverse momentum of the Z boson was first observed in the NA10 experiment at CERN in 1988 [12]. A year later, the violation was also observed in one of the experiments at Fermilab [13], but the results of the CDF experiment at the Tevatron revealed that the Lam–Tung relation was preserved within statistical errors in the region $q_T < 55$ GeV/c [14]. Thus, the ATLAS and CMS data completely clear up the question as to the presence of the violation and allow it to be measured in a new region of transverse momenta.

3. ANALYSIS OF DATA AND SELECTION OF EVENTS

Signal and background processes were simulated to compare experimental data with SM predictions and estimate the efficiency of event selection and reconstruction. The signal process $q\bar{q} \to \gamma^*/Z \to l^+l^-$ was simulated by PT leading-order calculations using the MadGraph generator [15] with the set of quark and gluon structure functions (PDFs) CTEQ6L (Coordinated Theoretical/Experimental Project on QCD Phenomenology and Tests of the Standard Model) [16] and by the NLO calculations using the PYTHIA [17] + POWHEG [18] generators with the PDF set CT10 (abbreviation for CTEQ since 2010) [19]. The PT NNLO simulation of signal events was performed using the FEWZ generator [20]. Parton showers and some background processes (production of WW, WZ, and ZZ pairs) were simulated using the PYTHIA generator. The contributions of the W+jet, $\tau^+\tau^-$, and $t\bar{t}$ processes and the single t-quark production were taken into account using the MadGraph and POWHEG generators. Simulation of the passage of particles through the detector material with allowance for the CMS structure features was performed using the GEANT4 software package [21].

Muon pairs with the pair transverse momentum $q_T < 200$ GeV/c and rapidity $|y| < 2.1$ were selected for analysis. Measurements were carried out in the Z-boson mass region $81 < m < 101$ GeV/c^2. As many as 4.3×10^6 and 2.5×10^6 events were analyzed in the rapidity intervals $|y| < 1$ and $1.0 < |y| < 2.1$ respectively.

4. RESULTS

The measured values of the first five angular coefficients A_0, A_1, A_2, A_3, and A_4 and the difference of the coefficients A_0–A_2 as a function of the Z-boson transverse momentum in two rapidity intervals $|y| < 1$ and $1.0 < |y| < 2.1$ are shown in Fig. 2. The values of the coefficient A_4 obtained using the MadGraph generator are larger than the POWHEG and FEWZ results in almost all ranges of q_T, since the values of the weak mixing angle are calculated in MadGraph with radiation corrections ignored, but the measurements of the coefficients A_0 and A_2 better agree with the MadGraph predictions, especially in the region of high transverse momenta. It was also found that the values of the coefficients $A_0(q_T)$ and $A_2(q_T)$ measured in proton–proton collisions at the LHC turned out to be larger than those obtained in proton–antiproton beams at the Tevatron, which is explained by a large contribution made to signal events by the Compton quark–gluon scattering in pp collisions.

5. CONCLUSIONS

The results of measuring coefficients $A_0 - A_4$ of angular distributions of muons in the Drell–Yan pro-

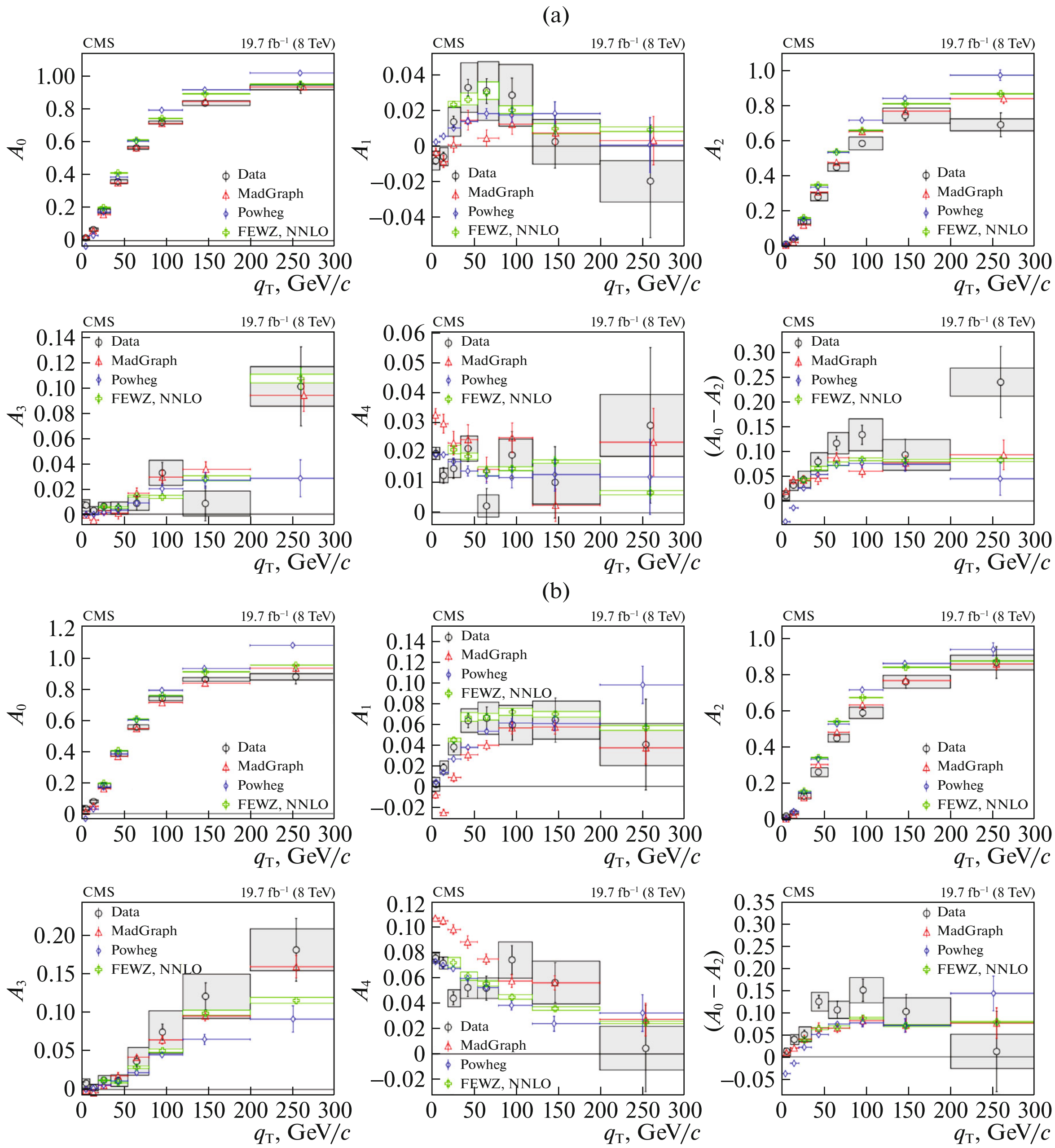

Fig. 2. Dependence of angular coefficients on the pair transverse momentum q_T in two rapidity intervals, (a) $0 < |y| < 1$ and (b) $1 < |y| < 2.1$, at $\sqrt{s} = 8$ TeV in the muon channel [9]. The measured values (open circles) are given with statistical errors, and systematic errors are indicated by gray regions. Triangles are the MadGraph predictions, diamonds are the POWHEG predictions, and crosses and rectangles are the FEWZ predictions and their uncertainties due to the PDF choice, respectively.

cess using the LHC Run 1 statistics clearly demonstrate violation of the Lam–Tung relation. It is shown that $A_0 > A_2$ in the investigated transverse momentum range $q_T < 300$ GeV/c, and the difference $A_0 - A_2$ increases with increasing q_T. Moreover, the amount of violation turned out to be larger than predicted on the basis of the NNLO calculations. The discrepancies can be due to QCD higher twists and correlations of the parton spin and initial-state nonzero momentum. However, getting a more definite answer to this question requires integrated study involving measurements based on higher statistics of experimental data and development of a theoretical description of the corresponding physical processes.

The reported results are very important for accurate estimation of the W-boson mass and upcoming measurements of the Weinberg angle: the value

$\sin^2\theta_{eff}^{W}$ is determined by the multiparameter approximation of angular distributions [22]. Now the LHC Run 2 data collected at the energy of 13 TeV corresponding to the integrated statistics of 140 fb^{-1} are being analyzed.

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REFERENCES

1. V. A. Rubakov, Phys. Usp. **55**, 949 (2012); A. V. Lanyov, Phys. At. Nucl. **78**, 521 (2015); S. V. Shmatov, Phys. At. Nucl. **76**, 1106 (2013); S. V. Shmatov, Phys. At. Nucl. **78**, 508 (2015); S. V. Shmatov, Phys. At. Nucl. **79**, 266 (2016); S. V. Shmatov, in *Proceedings of the Joint RDMS-CMS Seminar on Physics at the LHC, 2016,* Vol. 4, p. 13; M. V. Savina, Phys. At. Nucl. **78**, 532 (2015).
2. S. D. Drell and T.-M. Yan, Phys. Rev. Lett. **25**, 316 (1970); V. A. Matveev, R. M. Muradyan, and A. N. Tavkhelidze, Preprint JINR, P2-4543 (Dubna, 1969).
3. CDF Collab., Phys. Rev. Lett. **87**, 131802 (2011); CDF Collab., Phys. Lett. B **692**, 232 (2010); D0 Collab., Phys. Rev. Lett. **82**, 4769 (1999).
4. G. Aad et al. (ATLAS Collab.), Phys. Lett. B **725**, 223 (2013); G. Aad et al. (ATLAS Collab.), J. High Energy Phys. **2014** (6), 112 (2014);
5. I. A. Golutvin and S. V. Shmatov, Phys. At. Nucl. **48**, 604 (2017).
6. CMS Collab., J. High Energy Phys. **2019** (12), 61 (2019); V. Khachatryan et al., Eur. Phys. J. C **75**, 147 (2018), S. Chatrchyan et al. (CMS Collab.), J. High Energy Phys. **2011** (10), 007 (2011).
7. S. Chatrchyan et al. (CMS Collab.), J. Instrum. **3**, S08004 (2008).
8. CMS Collab., Eur. Phys. J. **76**, 325 (2016); CMS Collab., Phys. Lett. B **718**, 752 (2013); CMS Collab., Phys. Rev. D **84**, 112002 (2011).
9. V. Khachatryan et al. (CMS Collab.), Phys. Lett. B **750**, 154 (2015).
10. J. C. Collins and D. E. Soper, Phys. Rev. D: Part. Fields **16**, 2219 (1977).
11. C. S. Lam and W.-K. Tung, Phys. Rev. D: Part. Fields **18**, 2447 (1978).
12. M. Guanziroli et al. (NA10 Collab.), Z. Phys. C **37**, 545 (1988).
13. J. S. Conway et al., Phys. Rev. D: Part. Fields **39**, 92 (1989).
14. T. Aaltonen et al., Phys. Rev. Lett. **106**, 241801 (2011).
15. J. Alwall et al., J. High Energy Phys., No. 07, 079 (2014).
16. J. Pumplin et al., J. High Energy Phys., No. 07, 012 (2002).
17. T. Sjostrand, S. Mrenna, and P. Skands, J. High Energy Phys., No. 05, 026 (2006).
18. S. Frixione, P. Nason, and C. Oleari, J. High Energy Phys., No. 11, 070 (2007).
19. H.-L. Lai et al., Phys. Rev. D: Part. Fields **82**, 074024 (2010).
20. R. Gavin, Y. Li, F. Petriello, and S. Quackenbush, Comput. Phys. Commun. **182**, 2388 (2011).
21. GEANT4 Collab., Nucl. Instrum. Methods Phys. Res., Sect. A **506**, 250 (2003).
22. CMS Collab., Eur. Phys. J. C **78**, 701 (2018).

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