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PHYSICS OF ELEMENTARY PARTICLES AND ATOMIC NUCLEI. EXPERIMENT

Z-Boson p_T-Spectrum and Lepton Angular Coefficients in the LO High-Energy Factorization with the Real NLO Correction

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Abstract—We study Z boson production in the high-energy proton-proton collisions. Z boson p_T-spectrum and lepton angular coefficients are calculated in the parton Reggeization approach using event generator KaTie. We find good agreement of our predictions with the recent data from LHCb collaboration at the $\sqrt{s} = 13$ TeV

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1. INTRODUCTION

Production of Z bosons in high-energy collisions is a very important process to verify electro-weak theory, perturbative quantum chromodynamics (QCD) and to get information on parton distribution functions (PDFs) in a proton [1]. Nowadays, Z boson production was studied by the different LHC collaborations (ATLAS, CMS, LHCb) at the energies 7–13 TeV. The most important data are the values of lepton angular coefficients A_n, which describe in the Collins-Soper frame [2] the lepton angular distribution after decay of Z boson ($Z \to l\bar{l}$),

$$\frac{d\sigma}{dQdq_T^2dyd\Omega_l} = \frac{3}{16\pi}\frac{d\sigma}{dQdq_T^2dy}\Big\{(1+\cos^2\theta_l) + \frac{A_0}{2} \times (1-3\cos^2\theta_l) + A_1\sin 2\theta_l\cos\phi_l + \frac{A_2}{2}\sin^2\theta_l\cos 2\phi_l + A_3\sin\theta_l\cos\phi_l + A_4\cos\theta_l + A_5\sin^2\theta_l\sin 2\phi_l + A_6\sin 2\theta_l\sin\phi_l + A_7\sin\theta_l\sin\phi_l\Big\}, \quad (1)$$

where q_T is the Z boson transverse momentum, y is the rapidity of Z boson, $Q = M_{l\bar{l}} = \sqrt{(q_l + q_{\bar{l}})^2}$ is the invariant mass of lepton pair.

Angular coefficients depend on a spin structure of the relevant parton amplitude as well as on high-order QCD corrections. In the collinear parton model, Z boson production has been studied in the next-to-leading order (NLO) and in the next-to-next-leading order (NNLO) approximations in the strong coupling of pQCD using Monte-Carlo generators: DYNNLO [3], FEWZ [4] and some others.

Processes in the multi-Regge kinematics play a dominant role at the high-energy. At these conditions, the collinear factorization is broken and k_T-factorization [5] becomes more relevant. Gauge-invariant description off-shell partons with non-zero transverse momenta may be archived due to the theory of parton Reggeization [6]. Here we study lepton pair production via Z boson decay in the framework of the parton Reggeization approach (PRA) [7–9],

$$p + p \to Z \to l + \bar{l} + X. \quad (2)$$

In [9], this process was studied in the LO PRA, where only $2 \to 1$ partonic subprocess contributes:

$$Q_q + \bar{Q}_q \to Z \to l + \bar{l}, \quad (3)$$

where $Q_q(\bar{Q}_q)$ is Reggeized quark (antiquark), $q = u, d, s, c, b$. As it was shown in [8], the main NLO contribution is coming from $2 \to 3$ subprocess of quark-gluon scattering

$$Q_q(\bar{Q}_q) + R \to q(\bar{q}) + Z \to q(\bar{q}) + l + \bar{l}, \quad (4)$$

where R is the Reggeized gluon.

2. PARTON REGGEIZATION APPROACH

PRA is based on k_T-factorization [5]. Transverse momentum dependent PDFs of off-shell partons, so called unintegrated PDFs, are calculated in the Kimber–Martin–Ryskin–Watt (KMRW) model [10, 11] with the sufficient revision which was suggested in [9]. Reggeized amplitudes in the PRA can be calculated by Feynman rules of the Lipatov Effective Field Theory (EFT) [12].

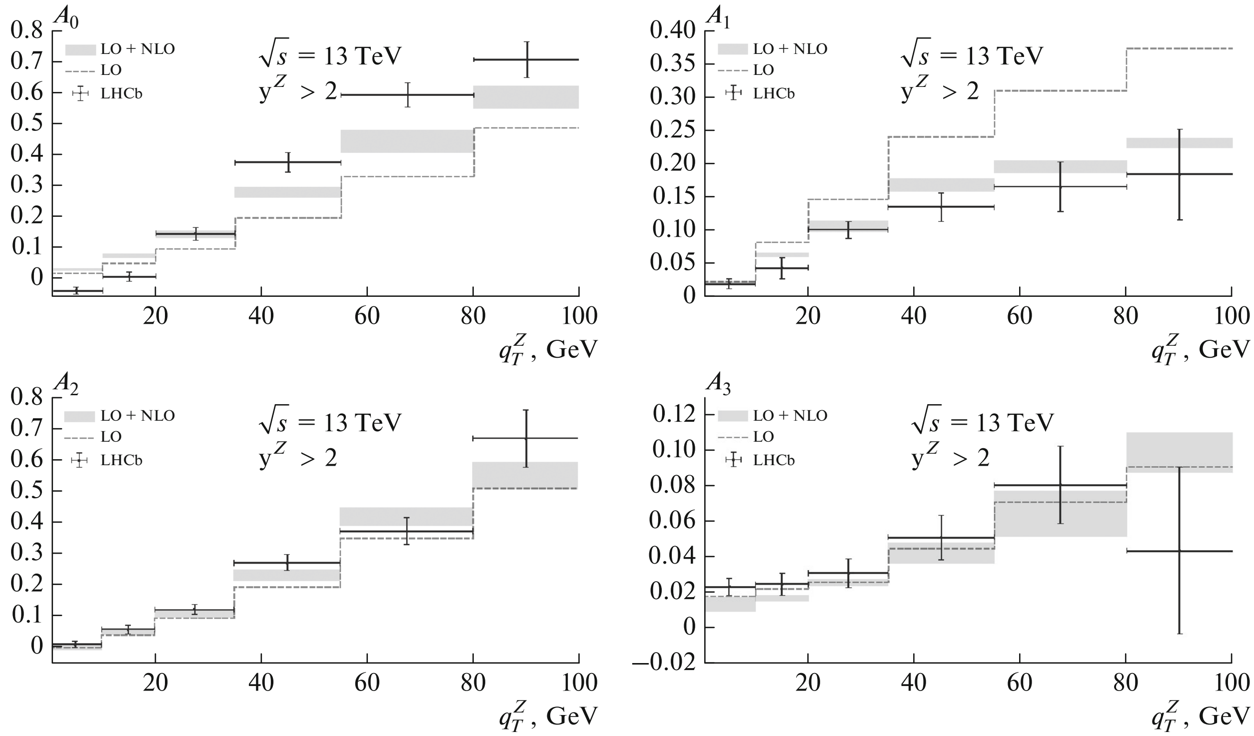

Fig. 1. Lepton angular coefficients A_{0-3} as a function of q_T at the $\sqrt{s} = 13$ TeV, $60 < Q < 120$ GeV, $2 < y < 5$. Dotted histogram corresponds the LO PRA calculation, shaded box histogram corresponds the sum of LO and NLO PRA calculations. Experimental data are from LHCb collaboration [17].

In the PRA, proton-proton cross section and parton-parton cross section are connected by the factorization formula

$$d\sigma = \sum_{i,\bar{j}} \int_0^1 \frac{dx_1}{x_1} \int \frac{d^2 q_{T1}}{\pi} \Phi_i(x_1, t_1, \mu^2) \times \int_0^1 \frac{dx_2}{x_2} \int \frac{d^2 q_{T2}}{\pi} \Phi_j(x_2, t_2, \mu^2) d\hat{\sigma},$$

where $t_{1,2} = -q_{T1,2}^2$, $\hat{\sigma}$ is the parton-parton cross section for Reggeized partons. Unintegrated PDFs are calculated in the modified KMRW model [9]:

$$\Phi_i(x, t, \mu) = \frac{\alpha_s(\mu)}{2\pi} \frac{T_i(t, \mu^2, x)}{t} \times \sum_{j=q,\bar{q},g} \int_x^1 dz P_{ij}(z) F_j\left(\frac{x}{z}, t\right) \theta(\Delta(t, \mu) - z),$$

where $F_i(x, \mu_F^2) = x f_i(x, \mu_F^2)$, $P_{ij}(z)$ are DGLAP splitting functions, $\mu_F = \mu_R = \mu$, and $\Delta(t, \mu^2) = \sqrt{\mu^2} \big/ \left(\sqrt{\mu^2} + \sqrt{t}\right)$ [10]. $T_i(t, \mu^2, x)$ is the Sudakov form-factor with boundary conditions $T_i(t = 0, \mu^2, x) = 0$ and $T_i(t = \mu^2, \mu^2, x) = 1$. The exact formula for $T_i(t, \mu^2, x)$ is obtained in [9].

3. PRA AND MC KaTie

LO PRA calculations in [9, 13] were done mostly analytically, because of simple structure for $2 \to 1$ Reggeized amplitude (3). Such a way, for lepton angular coefficients A_n (1) analytical formulas were derived too. However, at the NLO level of calculation with $2 \to 3$ (4) partonic subprocess, it is very difficult task for analytical calculation and we use here numerical method based on Monte-Carlo simulation of Z boson events in (3) and (4) subprocesses.

In [14], the approach to numerical modeling of gauge-invariant amplitudes with off-shell partons were developed. The approach is based on formalism of spiral amplitudes and recurrent relation BCFW-type (Britto–Cachazo–Feng–Witten) and it is realized in the Monte-Carlo event generator KaTie [15]. As it was shown in [8, 16], at the tree level calculations using KaTie are equivalent to the analytical calculations by Feynman rules of Lipatov EFT [12]. We use generator KaTie [15] for the presented calculations demand accuracy 0.05% for the total cross sections.

4. RESULTS AND DISCUSSION

In this part, we present results of calculations for the lepton angular coefficients A_n as a function of

Z boson transverse momentum $\sqrt{s} = 13$ TeV and $2 < y^z < 5$, as it was measured by the LHCb collaboration [17]. We take value of the hard scale as $\mu = \xi\sqrt{Q^2 + \vec{q}_T^{\,2}}$ with $\xi = 0.5, 1.0, 2.0$ to show theoretical uncertainties of the LO PRA calculations.

The average value for a function of lepton angles in the Collins-Soper reference frame $\langle F(\theta_l, \phi_l)\rangle$ is calculated for all events with fixed values of q_T and y of the lepton pair. As result we obtained simple master formulas for A_{0-3}:

$$A_0 = 4 - 10\langle\cos^2\theta_l\rangle, \quad A_1 = 5\langle\sin 2\theta_l \cos\phi_l\rangle,$$
$$A_2 = 10\langle\sin^2\theta_l \cos 2\phi_l\rangle, \quad A_3 = 4\langle\sin\theta_l \cos\phi_l\rangle.$$

Our predictions for A_{0-3}, as a function of q_T at the $\sqrt{s} = 13$ TeV, $60 < Q < 120$ GeV and $2 < y < 5$ are shown in Fig. 1 with LHCb data [17]. We see that accounting of the NLO correction sufficiently improve agreement between PRA results and LHCb data.

5. CONCLUSIONS

Production of lepton pair with invariant mass near the Z boson peak is studied in the LO PRA with the real NLO correction. Our predictions for the q_T-spectrum and lepton angular coefficients are in good agreement with the LHCb data at the $\sqrt{s} = 13$ TeV after inclusion of NLO correction. There is only one exclusion for A_0 coefficient which underestimates data about 20% at the $q_T > 40$ GeV. The PRA predictions are basically the same results of NNLO calculations in the collinear parton model [18], but they are highly dependent on the choice of hard scale. This defect may be vanish at the level of full NLO PRA calculation with including of loop corrections.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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