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ELEMENTARY PARTICLES AND FIELDS
Theory

B-Meson Production at Tevatron and the LHC in the Regge Limit of Quantum Chromodynamics*

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Abstract—We study the inclusive hadroproduction of B^0, B^+, and B_s^0 mesons in the leading order in the parton Reggeization approach. We have described B-meson transverse momentum distributions measured in the central region of rapidity by the CDF Collaboration at Fermilab Tevatron and CMS Collaboration at LHC within uncertainties and without free parameters, applying Kimber–Martin–Ryskin unintegrated gluon distribution function in a proton.

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1. INTRODUCTION

The study of the B-meson production at high energies provides a crucial test of the next-to-leading-order (NLO) calculations in perturbative quantum chromodynamics (QCD) due to the smallness of strong coupling constant $\alpha_s(\mu)$, as the lowest limit of typical energy scale of the hard interaction μ is controlled by the bottom quark mass $m \gg \Lambda_{\rm QCD}$, where $\Lambda_{\rm QCD}$ is the asymptotic scale parameter of QCD. At the same time, we achieve a new dynamical regime, Regge limit, where $\sqrt{S} \gg \mu \gg \Lambda_{\rm QCD}$ and the large coefficients of new type $\log^n(\sqrt{S}/\mu)$ should be resummed in all-order terms of perturbative QCD series, introducing a new small parameter $x = \mu/\sqrt{S}$. For this purpose we develop the k_T-factorization framework [1–3] endowed with the fully gauge-invariant amplitudes with Reggeized gluons in the initial state and call this combination the Parton Reggeization Approach (PRA).

2. BASIC FORMALISM

We study the production of B mesons with high transverse momenta treating a b quark as a massless parton and using the factorization theorem of QCD for the B cross section:

$$\frac{d\sigma(p+p\to B+X)}{dp_{BT}dy} \quad (1)$$

$$= \sum_i \int_0^1 \frac{dz}{z} D_{i\to B}(z,\mu^2) \frac{d\sigma(p+p\to i(p_i)+X)}{dp_{iT}dy_i},$$

where $D_{i\to B}(z,\mu^2)$ is the fragmentation function for producing the B meson from the parton i, created at the hard scale μ, the fragmentation parameter z is defined through the relation $p_i = p_B/z$, with p_B and p_i to be B-meson and i-parton four-momenta, correspondingly, and their rapidities $y_B = y_i$. It was shown in [4], that the significant part of B mesons is produced through the gluon and bottom quark fragmentation only, and the universal nonperturbative FFs were introduced, which we use in our study.

At large $\sqrt{S}$ the dominant contributions to cross sections of QCD processes gives multi-Regge kinematics (MRK), where all particles have limited (not growing with $\sqrt{S}$) transverse momenta and are combined into jets with limited invariant mass of each jet and strongly separated in rapidities. At leading logarithmic approximation of the Balitsky–Fadin–Kuraev–Lipatov (BFKL) approach [5] which gives the description of QCD scattering amplitudes in this region, where the logarithms of type $(\alpha_s\log(1/x))^n$ are resummed, only gluons can be produced, and each jet is actually a gluon. At next-to-leading logarithmic approximation (NLA) the terms of $\alpha_s(\alpha_s\log(1/x))^n$ are collected and a jet can contain a couple of partons (two gluons or quark–antiquark pair) with close rapidities. Such kinematics is called quasi-multi-Regge kinematics (QMRK). Despite of a great number of contributing Feynman diagrams, it turns out that at the Born level the MRK amplitudes acquire a simple factorized form. Moreover, radiative corrections to these amplitudes do not destroy this form, and this phenomenon is called gluon Reggeization.

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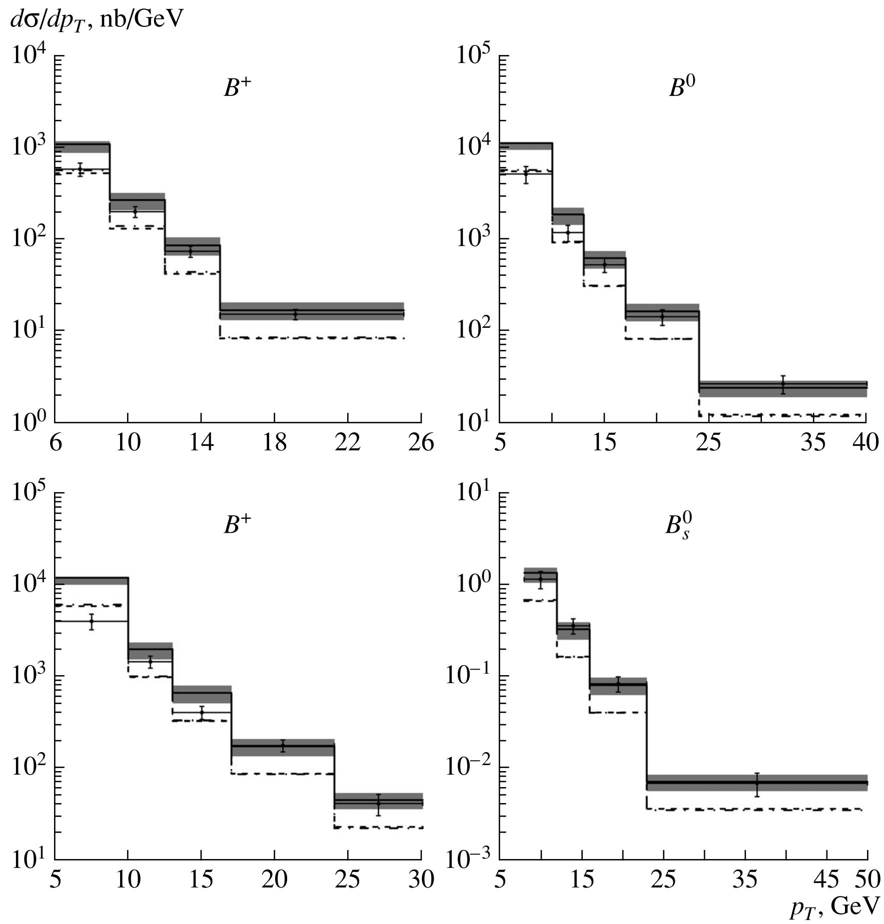

Transverse momentum distributions of B^+-meson production at Tevatron, $\sqrt{S} = 1.96$ TeV (left-top); B^0 (right-top), B^+ (left-bottom), and B_s^0 (right-bottom) mesons at LHC, $\sqrt{S} = 7$ TeV. Dashed line represents the contribution of gluon fragmentation, dash-dotted line—the b-quark-fragmentation contribution, solid line is their sum. The CDF data at Tevatron are from the [12], the CMS data at LHC are from the [13–15], correspondingly.

The full set of the induced and effective vertices of Reggeon–particle interactions together with Feynman rules was presented in [6] and [7]. The effective action which includes the fields of Reggeized gluons [8] and Reggeized quarks [7] was introduced and the non-Abelian gauge invariant theory was developed.

The lowest order in α_s parton subprocesses of PRA in which gluon or b quark are produced are: gluon production in MRK via two Reggeized gluons fusion $\mathcal{R} + \mathcal{R} \to g$ and the corresponding quark-antiquark pair production in QMRK $\mathcal{R} + \mathcal{R} \to b + \bar{b}$. We present the amplitudes of these processes and their matrix elements squared in the work [9].

In the k_T factorization, differential cross section for the $2 \to 1$ subprocess has the form:

$$\frac{d\sigma}{dy dp_T}(p + p \to g + X) \quad (2)$$
$$= \int d\phi_1 \int dt_1 \Phi(x_1, t_1, \mu^2)\Phi(x_2, t_2, \mu^2)$$
$$\times \frac{\overline{|\mathcal{M}(\mathcal{R} + \mathcal{R} \to g)|^2}}{p_T^3},$$

where ϕ_1 is the azimuthal angle between $\mathbf{p}_T$ and $\mathbf{q}_{1T}$, and the analogous formula for the $2 \to 2$ subprocess can be written in a similar way. The unintegrated over transverse momenta parton distribution functions (UPDFs) $\Phi(x, t, \mu^2)$ depend on the Reggeon transverse momentum $\mathbf{q}_T$ while its virtuality is $t = -|\mathbf{q}_T|^2$. The UPDFs are defined to be related with collinear ones through the equation $xG(x, \mu^2) \simeq \int^{\mu^2} dt\Phi(x, t, \mu^2)$. We obtain the UPDFs using the prescripton of Kimber, Martin, and Ryskin [10, 11] where the transverse momentum of a parton in the initial state of hard scattering comes entirely from the last step of evolution cascade, and the parton radiated at the last step is ordered in rapidity with the particles produced in the hard subprocess.

3. RESULTS

We compare the experimental data for B^+ mesons produced at the collision energy of $\sqrt{S} = 1.96$ TeV at central rapidities $|y| < 1.0$ [12], with our predictions in the LO of the PRA, in the figure, left-top panel. The dashed lines represent contributions of the MRK process while dash–dotted lines correspond to the ones of the QMRK process, and their sum is shown as a solid line. A theoretical uncertainty is estimated by varying factorization and renormalization scales between $1/2m_T$ and $2m_T$ around their central value of m_T, the transverse mass of a fragmenting parton. The resulting uncertainty is depicted in the figures by shaded bands. The analogous comparison of the recent data from the LHC at $\sqrt{S} = 7$ TeV for B^0 mesons at $|y| < 2.2$ [13], B^+ and B_s^0 mesons at $|y| < 2.4$ [14, 15], is presented in the figure, right-top, left-bottom and right-bottom panels, correspondingly. At both collision energies considered we find a good agreement between our predictions and experimental data for the large values of the B-meson transverse momenta, within experimental and theoretical uncertainties. Also we made the predictions for the planned LHC energy of $\sqrt{S} = 14$ TeV and keeping the other kinematic conditions as in the [13–15].

4. CONCLUSIONS

In the present work we performed the study of B^0, B^+, and B_s^0-meson fragmentation production in proton–(anti)proton collisions with central rapidities at Tevatron Collider and LHC in the framework of Parton Reggeization Approach. Here we take into account all the hard-scattering parton subprocesses appearing at the LO with Reggeized gluons in the initial state, and the $2 \to 1$ subprocess of gluon production via Reggeized-gluon fusion was considered for the first time. To describe the hard scattering stage we use the fully gauge invariant amplitudes introduced in the works of L. N. Lipatov and co-authors. The distributions of initial partons are taken in the form of UPDFs proposed by M. A. Kimber, A. D. Martin, and M. G. Ryskin, and the way of their definition is ideologically related to the above-mentioned amplitudes. We obtained a good agreement of our results for B meson central-rapidity production comparing with the experimental data from the Tevatron and the LHC, especially at large transverse momenta. The achieved degree of agreement for the central rapidity region is the same as the one obtained by NLO calculations in the conventional collinear parton model. The predictions for the B-meson production at central rapidities for the expected LHC energy of $\sqrt{S} = 14$ TeV are also presented. We describe B-meson production without any free parameters or auxiliary approximations.

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