Quasi-Multi-Regge-Kinematics Approach, Quark Reggeization and Applications

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We study inclusive production of prompt photons and D mesons at HERA and the Tevatron within the framework of the quasi-multi-Regge-kinematics approach applying the quark Reggeization hypothesis. We use the Reggeon-Reggeon to particle and the particle-Reggeon to particle effective vertices in the leading order approximation of the quasi-multi-Regge-kinematics approach. We describe well and without free parameters the relevant data obtained at HERA and the Tevatron. At the stage of numerical calculations we use the Kimber-Martin-Ryskin prescription for unintegrated quark and gluon distribution functions, with the Martin-Roberts-Stirling-Thorne collinear parton densities for a proton as input.

1 Introduction

The study of the inclusive production of photons and D mesons with large transverse momenta originating from the hard interaction between photon and parton or between two partons in the high-energy collisions provide precision tests of perturbative quantum chromodynamics (QCD) as well as information on the parton densities within proton and photon. Also, these studies increase our potential for the observation of a new dynamical regime, namely the high-energy Regge limit, which is characterized by the following condition $\sqrt{S} >> \mu >> \Lambda_{QCD}$, where $\sqrt{S}$ is the total collision energy in the center of mass reference frame, Λ_{QCD} is the asymptotic scale parameter of QCD, μ is the typical energy scale of the hard interaction. At this high-energy limit, the contribution from the partonic subprocesses involving $t-$channel parton (quark or gluon) exchanges to the production cross section can become dominant. In the region under consideration, the transverse momenta of the incoming partons and their off-shell properties can no longer be neglected, and we deal with "Reggeized" $t-$channel partons.

The quasi-multi-Regge-kinematics (QMRK) approach [1] is particularly appropriate for this kind of high-energy phenomenology. It is based on an effective quantum field theory implemented with the non-Abelian gauge-invariant action including fields of Reggeized gluons [2] and Reggeized quarks [3]. Roughly speaking, the Reggeization of amplitudes is a trick that offers an opportunity to take into account efficiently large radiation corrections to the processes under Regge limit condition beyond the collinear approximation of the parton model. The particle Reggeization is known in high-energy quantum electrodynamics (QED) for electrons only [4] and for gluons and quarks in QCD [5, 6].

In the leading order (LO) approximation of the QMRK approach an inclusive production of particles is described by the Reggeon-Reggeon to particle and the particle-Reggeon to particle effective vertices. The relevant squared matrix elements of the $2 \to 1$ inclusive particle production processes can be presented as follows:

$$\overline{|M(Q\bar{Q} \to \gamma)|^2} = \frac{4}{3}\pi\alpha e_q^2(t_1 + t_2), \tag{1}$$

$$\overline{|M(RQ \to q)|^2} = \frac{2}{3}\pi\alpha_s(t_1 + t_2 + 2\sqrt{t_1 t_2}\cos\phi), \tag{2}$$

$$\overline{|M(\gamma Q \to q)|^2} = 4\pi\alpha e_q^2 t_2, \tag{3}$$

$$\overline{|M(RR \to g)|^2} = \frac{3}{2}\pi\alpha_s(t_1 + t_2 + 2\sqrt{t_1 t_2}\cos\phi), \tag{4}$$

where R is the Reggeized gluon, Q is the Reggeized quark, e_q is the quark electric charge, $t_i = \vec{q}_{iT}^{\,2}$ is the transverse momentum of the Reggeized particle, $i = 1, 2$, and ϕ is the azimuthal angle between $\vec{q}_{1T}$ and $\vec{q}_{2T}$.

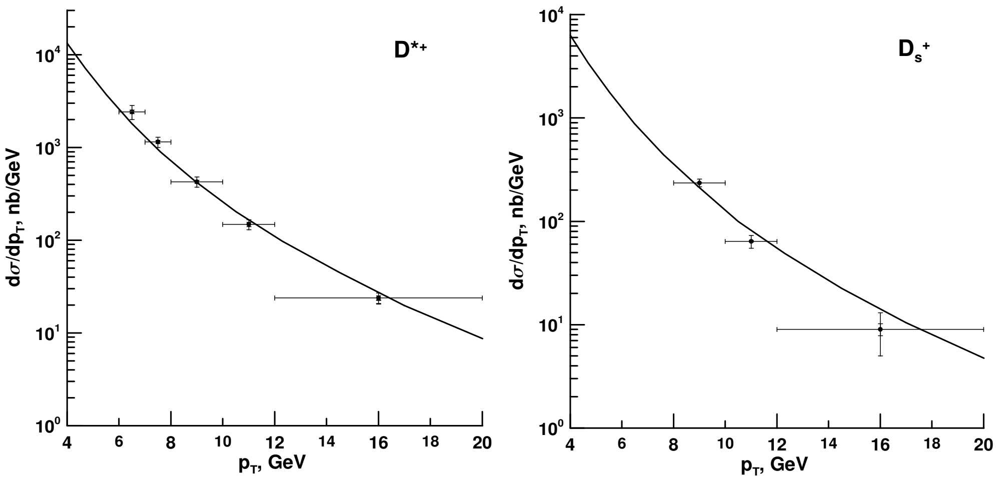

Figure 1: The p_T distributions of inclusive D^{*+} (left) and D_s^+ (right) hadroproduction for $\sqrt{S} = 1.96$ TeV and $|y| \leq 1$. The CDF data from Ref. [12] are compared with LO predictions from the QMRK approach with the quark Reggeization hypothesis.

2 Inclusive open charm production

In this section we study D-meson production via charm-quark fragmentation under HERA and Tevatron experimental conditions for the first time in the framework of the QMRK approach complemented with the quark Reggeization hypothesis [7]. In our numerical calculations below, we adopt the prescription proposed by Kimber, Martin, and Ryskin [8] to obtain unintegrated gluon and quark distribution functions for the proton from the conventional integrated ones, as implemented in Watt's code [9]. As input for this procedure, we use the Martin-Roberts-Stirling-Thorne [10] proton PDFs. As for the $c \to D$ fragmentation function $D_{c\to D}$, we adopt the non-perturbative D-meson sets determined in the zero-mass variable-flavor-number scheme with initial evolution scale $\mu_0 = m_c$ [11] from fits to OPAL data from CERN LEP1.

2.1 D-meson production at the Tevatron

CDF [12] measured the p_T distributions of D^0, D^+, D^{*+}, and D_s^+ mesons with rapidity $|y| \le 1$ inclusively produced in hadroproduction in run II at the Tevatron, with $\sqrt{S} = 1.96$ TeV. To leading order (LO) in the QMRK approach there is only one partonic subprocess $C_{p(\overline{p})}R_{\overline{p}(p)} \to c$, where the subscript indicates the mother particle. This subprocess is described via the Reggeized-quark–Reggeized gluon effective vertex C_{RQ}^q from Ref. [3].

In Fig. 1, our results for D^{*+} and D_s^+ mesons are compared with the CDF data [12]. We find that the theoretical predictions generally agree rather well with the experimental data, except perhaps for the slope. In fact, the predictions exhibit a slight tendency to undershoot the data at small values of p_T and to overshoot them at large values of p_T. However, we have to bear in mind that these are just LO predictions, so that there is room for improvement by including higher orders.

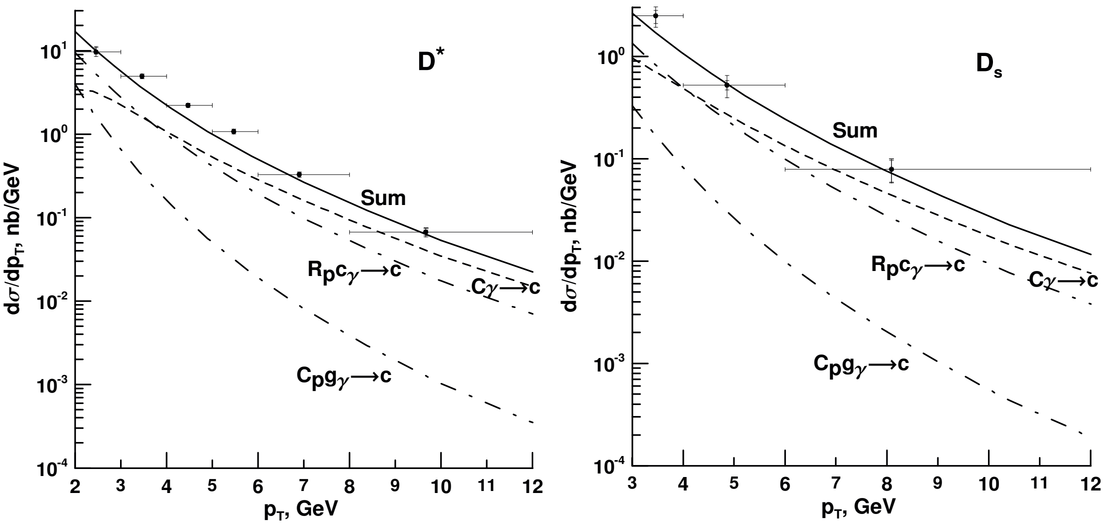

Figure 2: The p_T distributions of inclusive $D^{*\pm}$ (left) and $D_s^\pm$ (right) photoproduction for $\sqrt{S} = 300$ GeV and $|y| \le 1.5$. The ZEUS data from Ref. [13] and Ref. [14] are compared with LO predictions from the QMRK approach with the quark Reggeization hypothesis.

2.2 D-meson photoproduction at HERA

On the experimental side, ZEUS measured the p_T distributions of $D^{*\pm}$ [13] and $D_s^\pm$ [14] mesons with rapidity $|y| \le 1.5$ inclusively produced in photoproduction at HERA I, with proton energy $E_p = 820$ GeV and lepton energy $E_e = 27.5$ GeV in the laboratory frame, in the ranges $2 \le p_T \le 12$ GeV and $3 \le p_T \le 12$ GeV, respectively. Since we neglect finite quark and hadron mass effects, pseudorapidity and rapidity coincide. In this section, we compare this data with our QMRK predictions. At leading order (LO), we need to consider only three $2 \to 1$ partonic subprocesses, namely $C_p\gamma \to c$ for direct photoproduction and $C_p g_\gamma \to c$ and $R_p c_\gamma \to c$ for resolved photoproduction, using the effective vertices $C_{Q\gamma}^q$ from Ref.[3], C_{Qg}^q and C_{Rq}^q, respectively.

In Fig. 2 our results for $D^{*\pm}$ and $D_s^{\pm}$ mesons, respectively, are broken down to the $C_p\gamma \to c$, $C_p g_\gamma \to c$, and $R_p c_\gamma \to c$ contributions and are compared with the ZEUS data [13, 14]. We find that the theoretical predictions are dominated by direct photoproduction and agree rather well with the experimental data over the whole p_T range considered.

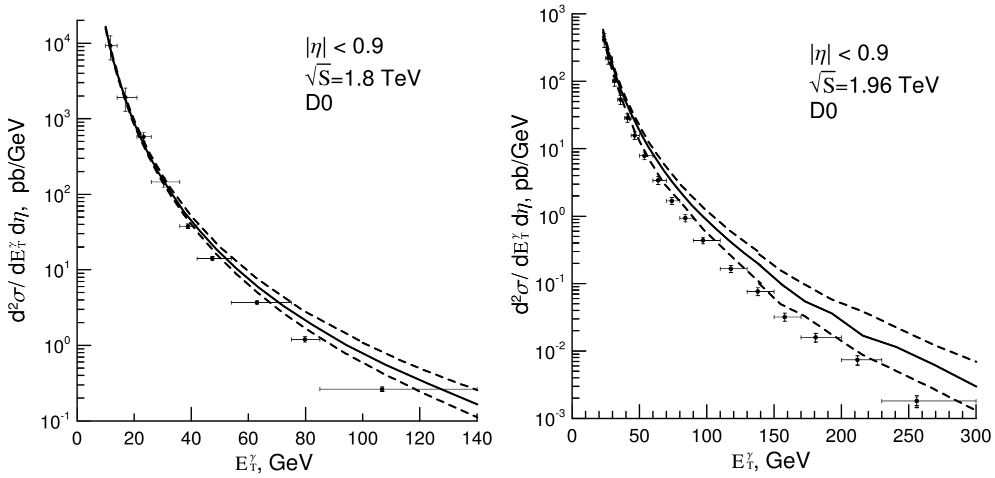

Figure 3: The E_T spectra of prompt photons at $\sqrt{S} = 1.8$ TeV (left) and $\sqrt{S} = 1.96$ TeV (right), and $|\eta| < 0.9$. The data are from D0 Collaboration [19].

3 Inclusive prompt photon production

In this part we consider an inclusive production of isolated photons at the Fermilab Tevatron and DESY HERA Colliders. In the QMRK approach the leading order (LO) contribution comes from the direct Reggeized quark-Reggeized antiquark annihilation into a photon ($Q\bar{Q} \to \gamma$) via the effective vertices $C^{\gamma}_{\bar{Q}Q}$ [3, 6]. In case of photoproduction at HERA it takes place in the resolved production, in which one quark (or anti-quark) comes from a photon. The additional small contributions originate from the fragmentation of produced quarks and gluons into the photon, which is described by the parton to photon fragmentation functions. We have obtained, the same as it was shown in Ref. [15], the contribution of the fragmentation mechanism is strongly suppressed by the isolation cone condition, which is applied to the experimental data [16, 17, 18, 19]. Such a way, we estimate the above mentioned contribution as a small one and do not take it into account in the presented analysis.

3.1 Prompt photon production at the Tevatron

The transverse momentum p_T spectra of isolated photons were studied by the CDF and D0 Collaborations [18, 19] at the energies $\sqrt{S} = 1.8$ TeV and $\sqrt{S} = 1.96$ TeV. The inclusive prompt photon production cross sections were measured in the range of $10 \le p_T \le 300$ GeV, both in the central region of pseudorapidity $|\eta| < 0.9$, and in the forward region, where one takes values in the range of $1.6 < |\eta| < 2.5$.

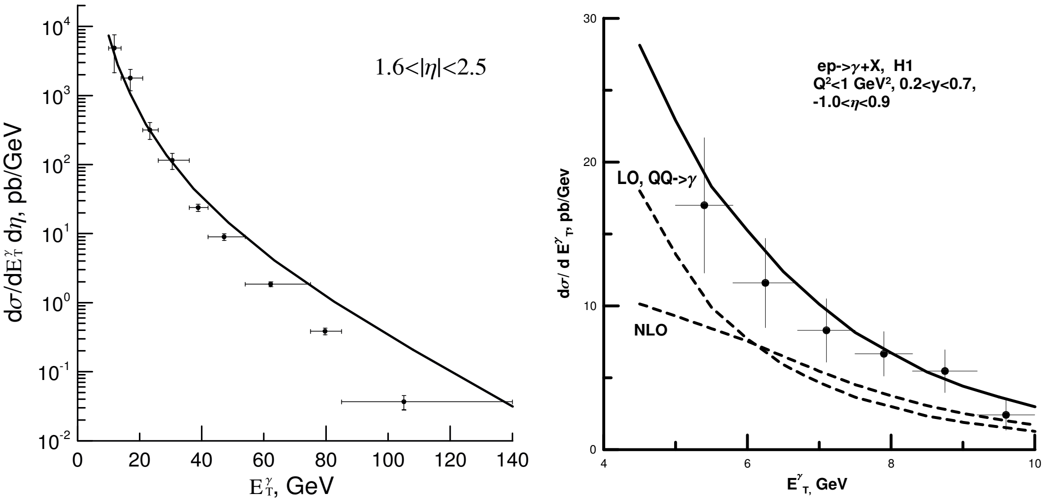

Figure 4: The E_T spectrum of prompt photons at $\sqrt{S} = 1.8$ TeV and $1.6 < |\eta| < 2.5$; the data are from D0 Collaboration [19](left). The E_T spectrum of prompt photons at $\sqrt{S} = 319$ GeV, $-1.0 < \eta < 0.9$, and $0.2 < y < 0.7$; the data are from H1 Collaboration [16] (right).

In the Figure 3 one can find the agreement between our calculations and the experimental data in the central pseudorapidity region of Run-I (Fig. 3, left) and Run-II (Fig. 3, right), up to $p_T \simeq 100$ GeV. That directly demonstrates valid behavior and correct normalization of the quark unintegrated structure functions $\Phi_q^p(x, t, \mu^2)$ obtained by using KMR prescription [8], in the wide range of parameters x, μ^2 and t. The solid and dashed lines correspond to the different choices of factorization scale μ^2, which is taken as $\mu^2 = p_T^2/4, p_T^2$, and $4p_T^2$. The above choices have strong effects in the region of $p_T > 100$ GeV, where theoretical results overestimate the experimental data. Note that in this region of the photon transverse momentum the parton longitudinal momentum fractions become non-small and no longer satisfy the conditions of particle Reggeization. At very large p_T one has $x_{1,2} \geq 0.1$ and so far the collinear parton model should be applied, where the squared Reggeized amplitude $|M(Q\bar{Q} \to \gamma)|^2 \to 0$ and the $2 \to 2$ parton subprocesses ($qg \to q\gamma, q\bar{q} \to g\gamma$, etc.) are needed to take into account.

The similar situation takes place also considering the prompt photon production in the interval of large pseudorapidity $1.6 < |\eta| < 2.5$ (Figure 4, left). In this case we consider the parton Reggeization in the one channel, because the only one parton has the longitudinal momentum fraction $x \ll 1$ under the non-symmetric kinematical conditions at the $|\eta| > 1.6$. We have found that the number of events involving both interacting partons with non-small x is large even at $p_T > 50$ GeV. This fact provides an explanation of the discrepancy between our predictions and the experimental data at the large p_T.

3.2 Prompt photon production at HERA

The H1 Collaboration [16] has measured the inclusive prompt photon production at the HERA Collider in the region of a small exchange photon virtuality $Q^2 < 1$ GeV^2, i.e. in the photoproduction processes. Figure 4 (right) shows that LO contribution, coming from parton subprocesses $Q_p\bar{q}_\gamma \to \gamma$ and $\bar{Q}_p q_\gamma \to \gamma$, does not describe data. The preliminary study of the next-to-leading order (NLO) corrections have been performed in the Ref. [20], where the contributions of the $2 \to 2$ subprocesses ($\gamma R_p \to \gamma g$, $\gamma Q_p \to \gamma q$, $R_\gamma Q_p \to gq$, $Q_\gamma R_p \to gq$ and $Q\bar{Q} \to \gamma g$) were analyzed. The Reggeon-particle to particle-particle effective vertices $C^{\gamma g}_{\gamma R}$ and $C^{\gamma q}_{\gamma Q}$ were written down in the same manner as in the Ref. [3] and the relevant contributions were calculated. Note, if we take into account isolation cone conditions the contribution of the $2 \to 2$ subprocesses to the inclusive photon spectra is free from singularities. The inclusion of such type of NLO corrections makes the agreement between theoretical predictions and experimental data more adequate. To perform this comparison more precise, for prompt photons we need to take into account the so-called hadronization effects too [16], which inclusion slightly decrease the resulting cross section.

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