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# $b$, $b\bar{b}$ and $b\gamma$ production at the Tevatron in the Regge limit of QCD

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We consider inclusive and photon-associated $b$-jet hadroproduction in the quasi-multi-Regge-kinematics approach based on the hypothesis of gluon and quark Reggeization in $t$-channel exchanges at high energies. The preliminary data on inclusive $b$-jet and $b\bar{b}$-dijet production taken by the CDF Collaboration and the data on photon-associated $b$-jet production taken by the D0 Collaboration at the Fermilab Tevatron are well described without adjusting parameters. We find the main contribution to inclusive $b$-jet production to be the scattering of a Reggeized gluon and a Reggeized $b$ quark to a $b$ quark, which is described by the effective Reggeon-Reggeon-quark vertex, and the one to $b\bar{b}$-pair production to be the scattering of two Reggeized gluons to a $b\bar{b}$ pair, which is described by the effective Reggeon-Reggeon-quark-quark vertex. The main contribution to $b\gamma$ production arises from the scattering of a Reggeized $b$ quark and a Reggeized gluon to a $b\gamma$ pair. Our analysis is based on the Kimber-Martin-Ryskin prescription for unintegrated gluon and quark distribution functions using as input the Martin-Roberts-Stirling-Thorne collinear parton distribution functions of the proton.

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## 1. Introduction

The study of $b$-jet production at high-energy colliders is of great interest for the test of perturbative quantum chromodynamics (QCD). The presence of a heavy $b$ quark, with mass $m_b \gg \Lambda_{\rm QCD}$, where $\Lambda_{\rm QCD}$ is the asymptotic scale parameter of QCD, in such processes guarantees a large momentum transfer even if the transverse momentum of the produced $b$ quark is small. Thus, the strong-coupling constant remains small in the processes discussed here, $\alpha_s(m_b) \lesssim 0.1$.

The total center-of-mass energy at the Tevatron, $\sqrt{S} = 1.96$ TeV in Run II, sufficiently exceeds the scale $\mu$ of the relevant hard processes, so that $\sqrt{S} \gg \mu \gg \Lambda_{\rm QCD}$. In such a high-energy regime, the contributions to the production cross section from subprocesses involving $t$-channel exchanges of partons (gluons and quarks) may become dominant. Then, 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. In this so-called quasi-multi-Regge kinematics (QMRK), the particles (multi-Regge) or groups of particles (quasi-multi-Regge) produced in the collision are strongly separated in rapidity. In the case of inclusive $b$-jet production, this implies the following: a single $b$ quark is produced in the central region of rapidity, while other particles, including a $\bar{b}$ quark, are produced at large rapidities. In the case of $b\bar{b}$ pair and $b\gamma$ associated production in the central rapidity region, we also assume that there are no other particles in this region, so that these particles are considered as quasi-multi-Regge pairs. The 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 quarks [3].

## 2. Single $b$-jet inclusive production

The first subject of our investigation is inclusive single $b$-jet production in $p\bar{p}$ collisions. To leading order (LO) in the QMRK approach there is only one partonic subprocess, $Q_b(q_1) + R(q_2) \to b(k)$, where $R$ and $Q_b$ are the Reggeized gluon and $b$ quark, respectively, and the four-momentum labels are indicated in parentheses. Its squared amplitude reads [4]: $\overline{|\mathscr{M}(Q_bR \to b)|^2} = \frac{2}{3}\pi\alpha_s\vec{k}_T^2$.

At next-to-leading order (NLO), the main contribution arises from the partonic subprocess $R(q_1) + R(q_2) \to b(k_1) + \bar{b}(k_2)$, where the $b$ and $\bar{b}$ quarks are produced close in rapidity, and its squared amplitude was obtained in Ref. [5]. The contributions due to the other NLO processes, $R + Q_b \to g + b$, $Q_q + \bar{Q}_q \to b + \bar{b}$ and $Q_q(\bar{Q}_q) + Q_b \to q(\bar{q}) + b$ are suppressed because, in the small-$x$ region, the parton distribution function (PDF) of the gluon greatly exceeds the relevant quark PDFs. In our numerical analysis, we adopt the Kimber-Martin-Ryskin prescription [6] for unintegrated gluon and quark PDFs, using as input the Martin-Roberts-Stirling-Thorne collinear PDFs of the proton [7].

Recently, the CDF Collaboration presented preliminary data on inclusive single $b$-jet production in $p\bar{p}$-collisions at Tevatron Run II [8]. In Fig. 1(a), the data are compared with our predictions. imposing the acceptance cut $R_{\rm cone} > 0.7$, where $R_{\rm cone} = \sqrt{\Delta y^2 + \Delta\phi^2}$, as in Ref. [8]. Since the lower bound of the $k_{2T}$ integration is zero, we allow for the $b$-quark mass to be finite, $m_b = 4.75$ GeV. Throughout all our analysis the renormalization and factorization scales are identified and chosen to be $\mu = \xi k_T$, where $\xi$ is varied between 1/2 and 2 about its default value 1 to estimate the theoretical uncertainty, and the resulting errors are indicated as shaded bands. In Fig. 1(a), we observe that the contribution due to LO subprocess greatly exceeds the one due to NLO subprocess, by about one order of magnitude, and practically exhausts the full result. It nicely agrees with the CDF data throughout the entire $k_T$ range. The QMRK results have to be taken with a grain of salt for $k_T \gtrsim 150$ GeV, where the average values of the scaling variables $x_1$ and $x_2$ in the unintegrated PDFs exceed 0.1, so that, strictly speaking, the QMRK approach ceases to be valid.

## 3. $b\bar{b}$-dijet inclusive production

At LO, $b\bar{b}$-dijet production receives contributions from both subprocess $R(q_1) + R(q_2) \to b(k_1) + \bar{b}(k_2)$ and the annihilation of a Reggeized quark-antiquark pair, $Q_q(q_1) + \bar{Q}_q(q_2) \to b(k_1) + \bar{b}(k_2)$, where $q = u,d,s,c,b$. The induced vertex of the latter was obtained in Ref. [3] and the squared amplitudes in Ref. [9].

The CDF Collaboration measured the inclusive $b\bar{b}$-dijet production cross section in Run II at the Tevatron [10]. The two jets were required to be in the central region of rapidity, with $|y_1|, |y_2| < 1.2$, to be separated by $R_{\text{cone}} > 0.4$, and to have transverse energies satisfying the conditions $E_{1T} > 35$ GeV and $E_{2T} > 32$ GeV, where the jet with the maximal transverse energy is called the leading one. Given these acceptance cuts, the massless approximation is clearly applicable, so that $E_{iT} = k_{iT}$ and $y_i = \eta_i$, where $\eta_i$ denote the pseudorapidities of the jets $i = 1,2$. These data come as distributions in the leading-jet transverse energy $E_{1T}$, the dijet invariant mass $M_{b\bar{b}}$, and the azimuthal separation angle $\Delta\phi$. They are compared with our QMRK predictions in Figs. 1(b)–(d), where the two LO contributions are shown separately along with their superpositions. We observe that the total QMRK predictions nicely describe all the three measured cross section distributions. The contributions due to Reggeized gluon fusion dominate for $E_{1T} \lesssim 200$ GeV and $M_{b\bar{b}} \lesssim 300$ GeV and over the whole $\Delta\phi$ range considered. The peak near $\Delta\phi = 0.4$ in Fig. 1(d), arises from the isolation cone condition.

## 4. Associated $b\gamma$ production

There are two mechanisms of photon-associated $b$-quark production: direct photon production and the fragmentation of final-state partons into photons, which can be described by perturbative fragmentation functions [11]. In the former case, there is only one partonic subprocess at LO in the QMRK approach, $Q_b(q_1) + R(q_2) \to b(k_1) + \gamma(k_2)$. The relevant effective vertex and squared amplitude were obtained in Ref. [12]. In the case of photon production by fragmentation, we need to take into account partonic subprocesses with at least one heavy quark in the final state.

In Fig. 2 the data collected by the D0 Collaboration [13] in the two kinematical regions, $y_b y_\gamma > 0$ and $y_b y_\gamma < 0$, are compared with our predictions obtained in the QMRK approach. We observe that the contribution due to direct photon production greatly exceeds the one due to photon production by fragmentation, by about of one order of magnitude at $k_{T\gamma} > 40$ GeV and by about a factor 5 at $k_{T\gamma} \approx 30$ GeV. The direct photon contribution practically exhausts the full result. It nicely agrees with the D0 data throughout the entire $k_{T\gamma}$ range considered.

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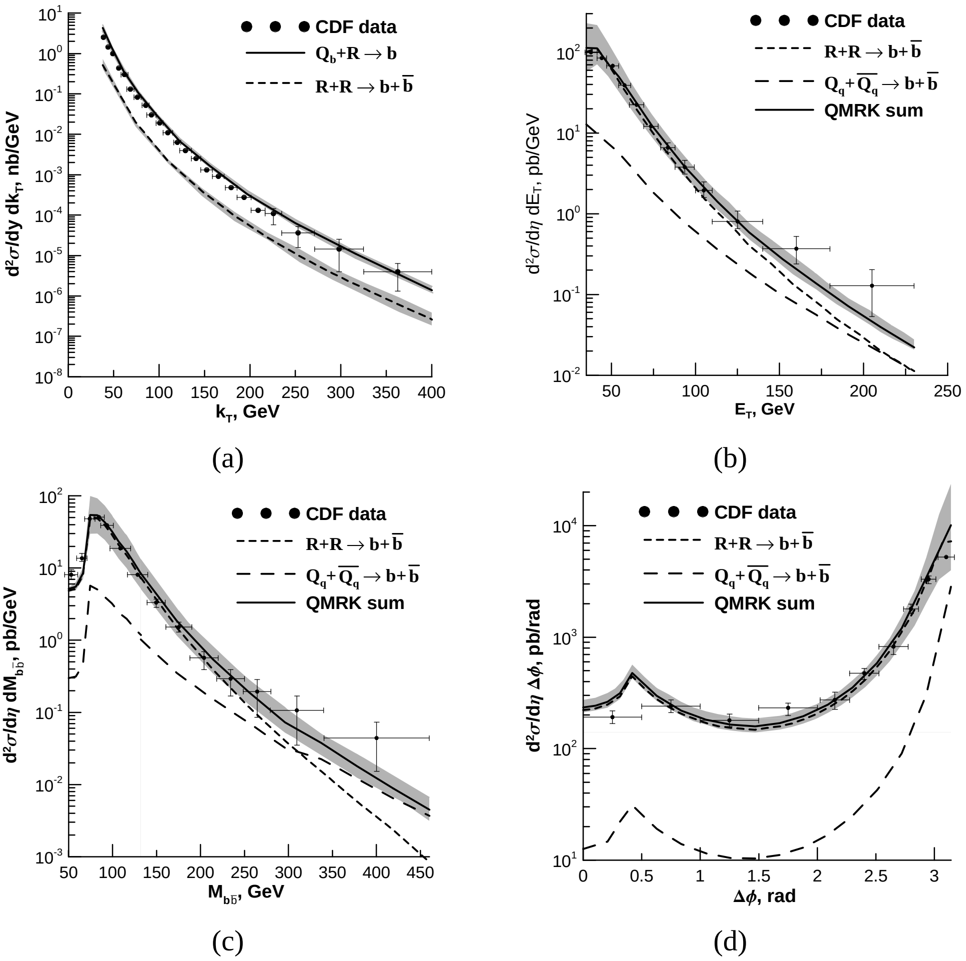


**Figure 1:** The distribution in (a) transverse momentum of inclusive single $b$-jet hadroproduction [8] and the ones in (b) leading-jet transverse energy, (c) dijet invariant mass, and (d) azimuthal separation angle of inclusive $b\bar{b}$-dijet hadroproduction [10] are compared with the QMRK predictions. The shaded bands indicate the theoretical uncertainties.

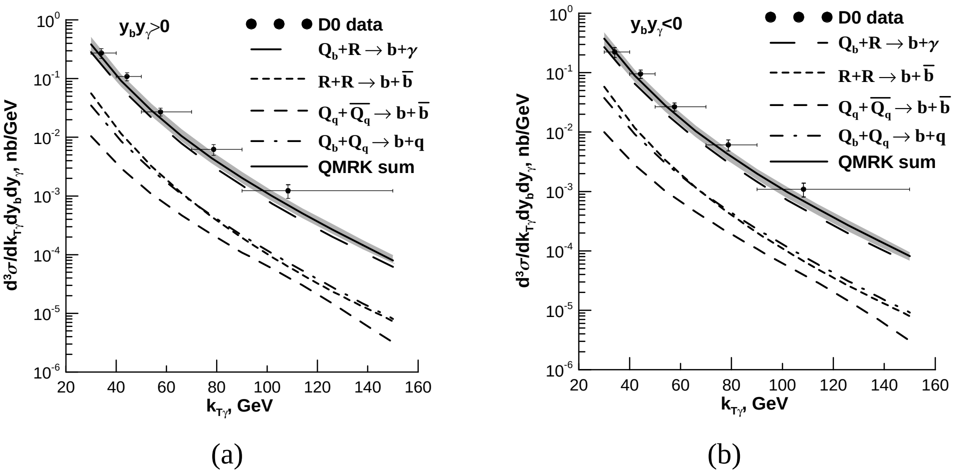


**Figure 2:** The transverse-momentum distributions of $b\gamma$ hadroproduction [13] for (a) $y_b y_\gamma > 0$ and (b) $y_b y_\gamma < 0$ are compared with the QMRK predictions. The shaded bands indicate the theoretical uncertainties.