Inclusive and Associated $b$-jet Production at the Tevatron in the Regge Limit of QCD

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Abstract

We consider $b$-jet production in the quasi-multi-Regge-kinematics approach based on the hypothesis of the gluon and quark Reggeization in the $t$-channel exchanges at the high energy. The data on various spectra of $b$-jet production measured by the CDF and D0 Collaborations at the Tevatron Collider are described well and with no free parameters.

1 Introduction

The study of $b$-jet production at high energies is of great interest to test the perturbative quantum chromodynamics (QCD). The presence of a heavy $b$ quark ($m_b \gg \Lambda_{QCD}$, $\Lambda_{QCD}$ — asymptotic scale parameter of QCD) guarantees a large momentum transfer that keeps the strong-coupling constant small $\alpha_s(m_b) \leq 0.1$. In Refs. [1, 2, 3] the modulus of the $b$-quark transverse momentum $k_T \geq 32$ GeV $\gg m_b$, so that it is justified to work in massless approximation and to assume beauty to be an active flavor in the proton.

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 $\sqrt{S} \gg \mu \gg \Lambda_{QCD}$. In this regime, the contributions to the production cross section from subprocesses involving $t$-channel exchanges of partons (gluons and quarks) may become dominant. Then, the off-shell properties of the incoming partons can no longer be neglected, and $t$-channel partons become Reggeized. They can be described in quasi-multi-Regge kinematics (QMRK) approach [4], based on an effective quantum field theory implemented with the non-Abelian gauge-invariant action including fields of Reggeized gluons ($R$) [5] and quarks ($Q$) [6]. In QMRK, the particles (multi-Regge) or groups of particles (quasi-multi-Regge) produced in the collision are strongly separated in rapidity. For the inclusive $b$-jet production, this implies that 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. In the presented work we continue our investigation and acknowledge the results obtained in Refs. [7]–[10].

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2 Inclusive $b$-jet production

We examine inclusive single $b$-jet production in $p\bar{p}$ collisions in the fixed-flavor-number scheme with $n_f = 5$ active quark flavors. To leading order (LO) in the QMRK approach, there is only one partonic subprocess $Q_b(q_1) + R(q_2) \rightarrow b(k)$, where $Q_b$ is the Reggeized $b$ quark, and the four-momentum labels are indicated in parentheses. Using the effective vertex of the concerned transition given by \cite{6}, the squared amplitude of concerning subprocess is found to be $|M(Q_b R \rightarrow b)|^2 = \frac{2}{7} \alpha_s(\mu)^2 \frac{m_b}{k_T^2}$ \cite{11}.

At next-to-leading order (NLO) in the QMRK approach, the main contribution to inclusive $b$-quark production arises from the partonic subprocess $R(q_1) + R(q_2) \rightarrow b(k_1) + b(k_2)$, where the $b$ and $\bar{b}$ quarks are produced close in rapidity. The contributions due to the other NLO processes, $RQ_b \rightarrow gb$, $Q_q \bar{Q} q \rightarrow b\bar{b}$, and $Q_q(\bar{Q}_q) Q_b \rightarrow q(\bar{q})b$ are suppressed because, in the small-$x$ region, the parton distribution function (PDF) of the Reggeized gluon greatly exceeds the relevant Reggeized quark PDFs. The squared amplitude of subprocess $RR \rightarrow b\bar{b}$ can be found in Ref. \cite{12}.

Exploiting the hypothesis of high-energy factorization, we write the hadronic cross sections $d\sigma$ as convolutions of partonic cross sections with unintegrated PDFs. We adopt the Kimber-Martin-Ryskin prescription \cite{13} for unintegrated gluon and quark PDFs, using as input the Martin-Roberts-Stirling-Thorne collinear PDFs of the proton \cite{14}.

In Fig. 1 the preliminary CDF data \cite{11} are compared with our predictions obtained in the QMRK approach. The contributions due to LO and NLO subprocesses are shown separately. Since the lower bound of the $k_T$ integration is zero, we allow for the $b$-quark mass to be finite, $m_b = 4.75$ GeV. The renormalization and factorization scales are identified and chosen to be $\mu = \xi k_T$. Here and later $\xi$ is varied between $1/2$ and $2$ about its default value $1$ to estimate the theoretical uncertainty, and the resulting errors are indicated in figures as shaded bands. We observe that the contribution due to LO subprocess greatly exceeds the one due to NLO subprocess, by about one order of magnitude, resulting errors are indicated in figures as shaded bands. We observe that the contribution due to the other NLO processes, $RQ_b \rightarrow gb$, $Q_q \bar{Q} q \rightarrow b\bar{b}$, and $Q_q(\bar{Q}_q) Q_b \rightarrow q(\bar{q})b$ are suppressed because, in the small-$x$ region, the parton distribution function (PDF) of the Reggeized gluon greatly exceeds the relevant Reggeized quark PDFs. The squared amplitude of subprocess $RR \rightarrow b\bar{b}$ can be found in Ref. \cite{12}.

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3 $b\bar{b}$-pair production

The data measured by the CDF Collaboration on inclusive $b\bar{b}$-dijet production cross section \cite{2} come as distributions in transverse energy $E_{1T}$ of the leading-jet (jet with the maximal transverse energy), the dijet invariant mass $M_{bb}$, and the azimuthal separation angle $\Delta\phi$. They are compared with our QMRK predictions including the contributions from subprocesses $RR \rightarrow b\bar{b}$ and $Q_q \bar{Q}_q \rightarrow b\bar{b}$, where $q = u, d, s, c$, in Fig. 1. The common scale is set to be $\mu = \xi k_{1T}$. In Fig. 1 these two 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 subprocess $RR \rightarrow b\bar{b}$ dominate for $E_{1T} \leq 200$ GeV and $M_{bb} \leq 300$ GeV and over the whole $\Delta\phi$ range considered. The peak near $\Delta\phi = 0.4$ arises from the isolation cone condition \cite{2}.

4 Associated $b\gamma$ production

The D0 Collaboration presented data on photon associated heavy quark ($b, c$) production \cite{8}, which can be realized via two mechanisms: the direct photon production and the fragmentation of the final partons into photons. In the former case, to leading order (LO) in the QMRK approach, there is only one partonic subprocess $Q_b R \rightarrow b\gamma$. The second mechanism of prompt photon production is the fragmentation of the produced partons into photons, which can be described by the perturbative fragmentation functions \cite{15}. In this case we need to take into account partonic subprocesses with
at least one heavy quark in the final state: \( RR \rightarrow b\bar{b}, Q_q\bar{Q}_q \rightarrow b\bar{b}, Q_bQ_b \rightarrow b\bar{b}, \) and \( Q_bQ_b \rightarrow bb. \) The effective vertices of the concerned transitions are given by [6] and the squared amplitudes can be found in Refs. [16, 17].

In Fig. 2 top, the D0 data for \( b \) and \( c \) quarks are compared with our QMRK predictions with \( \mu = \xi k_\gamma T. \) We observe that the contribution due to direct photon production greatly exceeds the one due to fragmentation photon production, by about of one order of magnitude at large \( k_\gamma T > 40 \) GeV and by a factor 5 at the \( k_\gamma T \simeq 30 \) GeV. The direct photon contribution practically exhausts the full result. It nicely agrees with the D0 data throughout the entire \( k_\gamma T \) range for \( b\gamma \) production and in the region of \( k_\gamma T \lesssim 60 \) GeV for \( c\gamma \) production, while in the remaining region for the latter our prediction underestimates the data by factor about 2. We don’t observe any difference between description of the two kinematical ranges, distinguished by the experiment \(|y_{b,c}\gamma| > 0 \) and \(|y_{b,c}\gamma| < 0 [3].

We also present our predictions for the \( b(c)\gamma \) invariant mass and the azimuthal separation angle \( \Delta \phi \) distributions in Fig. 2 bottom.

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Figure 1: The distribution in (left, top) transverse momentum of inclusive single $b$-jet hadroproduction [1]; the ones in (right, top) leading-jet transverse energy, (left, bottom) dijet invariant mass, and (right, bottom) azimuthal separation angle of inclusive $b \bar{b}$-dijet hadroproduction [2] are compared with the QMRK predictions.

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Figure 2: The QMRK predictions in comparison with distributions in transverse momentum of associated $b\gamma$ (left, top) and $c\gamma$ (right, top) hadroproduction at $y_{b(c)\gamma}>0$ [3]; the ones for distributions in (left, bottom) $b\gamma$ invariant mass, and (right, bottom) $b\gamma$ azimuthal separation angle.