Angular decorrelations in $\gamma + 2\text{jet}$ events at high energies in the parton Reggeization approach

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Abstract. We discuss associated production of prompt photon plus two jets at high energies in the framework of the parton Reggeization approach, which is based on multi-Regge factorization of hard processes and Lipatov’s effective theory of Reggeized gluons and quarks. In this approach, initial-state off-shell effects and transverse momenta of initial partons are included in a gauge-invariant way. We compute transverse momentum spectra of prompt photons in inclusive $\gamma-$production, in $\gamma + \text{jet}$ and $\gamma + 2\text{jets}$ events, and azimuthal angle difference spectrum in $\gamma + 2\text{jet}$ events. We compare our results with the experimental data from D0 Collaboration at Tevatron and with the theoretical predictions obtained in conventional NLO approximation of the collinear parton model. The relation between SPS and DPS production mechanisms is also studied.

1 Introduction

Theoretical and experimental study of associated production of prompt photon and jets with large transverse momenta in high-energy hadronic collisions is very important task for various reasons. First, this is a challenging test of our understanding of higher-order corrections in quantum chromodynamics (QCD). In general, it is a nontrivial task to provide reliable predictions for multiscale and correlational observables, based on the conventional Collinear Parton Model (CPM) of QCD. Second, correlational observables in photon plus jets production are primary tools in experimental searches of manifestations of Double Parton Scattering (DPS) mechanism in hadron-hadron collisions at high energies \cite{1}.

In the present contribution we discuss associated production of prompt photon and jets in $p\bar{p}$ collisions at the $\sqrt{S} = 1.8$ and 1.96 TeV which has been observed by the D0 Collaboration \cite{2,3,4}. Comparison of theoretical predictions obtained in the next-to-leading order (NLO) approximation of CPM with the measured cross-sections and the differential distributions pointed towards DPS as the reliable production mechanism \cite{4}. However, in the similar case \cite{5}, we have found that total cross sections and different spectra of same-sign (DD) pairs at LHCb \cite{6} can be described only by the Single Parton Scattering (SPS) mechanism, if higher-order QCD corrections are approximately taken into account using the parton Reggeization approach (PRA) \cite{7,8}. Such a way, we can suggest some reduction of DPS contribution in the other pair-production or multi-production processes. In the present note, we present the study of photon plus jets associated production in the framework of PRA.

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2 Parton Reggeization Approach

The brief description of LO approximation of PRA is presented below. More details can be found in [8], the development of PRA in the NLO approximation is further discussed in [9]. The main ingredients of PRA are factorization formula, unintegrated parton distribution functions (unPDF’s) and gauge-invariant amplitudes with off-shell initial-state partons, derived using the Lipatov’s Effective Field Theory (EFT) of Reggeized gluons [10] and Reggeized quarks [11].

Factorization formula of PRA in LO approximation for the process \( p + p \rightarrow Y + X \), can be obtained from factorization formula of the collinear parton model (CPM) for the auxiliary hard subprocess \( g + g \rightarrow Y + g \). In the Ref. [8] the modified Multi-Regge Kinematics (mMRK) approximation for the auxiliary amplitude is constructed, which correctly reproduces the multi-Regge and collinear limits of corresponding QCD amplitude. This mMRK-amplitude has \( t \)-channel factorized form, which allows one to rewrite the cross-section of auxiliary subprocess in a \( k_T \)-factorized form:

\[
\frac{d\sigma}{dt} = \int \frac{d\Theta}{\pi} \Phi_g(\Theta, t, \mu^2) \cdot \frac{d\sigma_{PRA}}{dt},
\]

where \( t_{1,2} = -q_{1,2}^2 \), the partonic cross-section \( \sigma_{PRA} \) in PRA is determined by squared PRA amplitude, \( |A_{PRA}|^2 \). Despite the fact that four-momenta \( (q_{1,2}) \) of partons in the initial state of \( A_{PRA} \) are off-shell \( (q_{1,2}^2 = -t_{1,2} < 0) \), the PRA hard-scattering amplitude is gauge-invariant because the initial-state off-shell partons are treated as Reggeized gluons \( (R) \) or Reggeized quarks \( (Q) \) in a sense of gauge-invariant EFT for QCD processes in MRK, introduced by L.N. Lipatov in [10]. The Feynman rules of this EFT are written down in Ref. [11, 12].

The tree-level “unintegrated PDFs” (unPDFs) \( \Phi_g(x, \mu^2) \) and DGLAP splitting function \( P_{gg}(z) \) with the factor \( 1/t_{1,2} \). Consequently, the cross-section (1) with such “unPDFs” contains the collinear divergence at \( t_{1,2} \rightarrow 0 \) and infrared (IR) divergence at \( z_{1,2} \rightarrow 1 \). To regularize the latter, we observe that the mMRK expression gives a reasonable approximation for the exact matrix element only in the rapidity-ordered part of the phase-space \( y_{g1} > y_{Y} > y_{g2} \). From this requirement, the following cutoff on \( z_{1,2} \) can be derived: \( z_{1,2} < 1 - \Delta_{KMR}(t, \mu^2) \), where \( \Delta_{KMR}(t, \mu^2) = \sqrt{t}/(\sqrt{t^2} + \sqrt{t}) \) is the KMR cutoff function [13], and we have taken into account that \( \mu^2 \sim M^2_{T,Y} \). The collinear singularity is regularized by the Sudakov formfactor:

\[
T_i(t, \mu^2) = \exp \left[ -\int \frac{dt}{t} \frac{\alpha_s(t')}{2\pi} \sum_{j=q,R} \int_0^1 dz \cdot P_{ij}(z) \theta \left( 1 - \Delta_{KMR}(t', \mu^2) - z \right) \right],
\]

which resums doubly-logarithmic corrections \( \sim \log^2(t/\mu^2) \) in the LLA.

The final form of our unPDF in PRA is:

\[
\Phi_i(x, t, \mu^2) = \frac{T_i(t, \mu^2)}{t} \frac{\alpha_s(t)}{2\pi} \sum_{j=q,R} \int_0^1 dz \cdot P_{ij}(z) \frac{x}{z} f_j \left( \frac{x}{z}, t \right) \theta \left( 1 - \Delta_{KMR}(t, \mu^2) - z \right),
\]

which coincides with Kimber, Martin and Ryskin (KMR) unPDF [13]. The KMR unPDF is actively used in the phenomenological studies employing \( k_T \)-factorization, but to our knowledge, the derivation, presented in [8] is the first systematic attempt to clarify it’s relationships with MRK limit of the QCD amplitudes.
In contrast to most of studies in the $k_T$-factorization, the gauge-invariant matrix elements with off-shell initial-state partons (Reggeized quarks and Reggeized gluons) of Lipatov’s EFT \cite{10,11} allow one to study arbitrary processes involving non-Abelian structure of QCD without violation of Slavnov-Taylor identities due to the nonzero virtuality of initial-state partons. This approach, together with KMR unPDF gives stable and consistent results in a wide range of phenomenological applications, which include the description of the different spectra of single jet and prompt-photon inclusive production \cite{14,15}, two jets \cite{7} or two photons \cite{16} in $pp$ and $p\bar{p}$ collisions, and photon plus jet in $\gamma p$ collisions at HERA Collider \cite{17}.

3 Reggeized amplitudes and cross sections

To describe experimental data of prompt photon spectra we should take into account two production mechanisms. The first one is direct production, when photons are produced in hard quark-gluon collisions. The second one is fragmentation production, when quarks produced in hard collisions (we will neglect small contribution from gluon to photon fragmentation) emit collinear photons. Fragmentation production of prompt photons can be strongly suppressed by experimental cuts, but there can be about a few percents from total number of events at small photon transverse momentum and it should be taken into consideration in precise calculations.

The LO PRA contribution to the inclusive prompt photon production is the process of direct production in the Reggeized quark – anti-quark annihilation,

\[ Q + \bar{Q} \rightarrow \gamma. \]  

(4)

Because we study large-$p_T$ photon production ($p_{\gamma T} \gg m_c$), we can use 4-flavor massless quark scheme. The fragmentation production of single photons originates from LO $2 \rightarrow 1$ processes

\[ Q + R \rightarrow q[\rightarrow \gamma]. \]  

(5)

Associated production of direct photon and jet in LO PRA is described by two partonic processes:

\[ Q + R \rightarrow q + \gamma, \]  

(6)

\[ Q + \bar{Q} \rightarrow \gamma + g. \]  

(7)

To describe fragmentation production of photon and jet we should take into account following processes:

\[ Q + R \rightarrow q[\rightarrow \gamma] + g, \]  

(8)

\[ R + R \rightarrow q[\rightarrow \gamma] + \bar{q}, \]  

(9)

\[ Q + Q(Q') \rightarrow q[\rightarrow \gamma] + q(q'), \]  

(10)

\[ Q + \bar{Q} \rightarrow q(q')[\rightarrow \gamma] + q(q'). \]  

(11)

The LO PRA processes which contribute in direct $\gamma + 2\text{jets}$ events are following:

\[ Q + R \rightarrow q + g + \gamma, \]  

(12)

\[ R + R \rightarrow q + \bar{q} + \gamma, \]  

(13)

\[ Q + Q \rightarrow Q + Q + \gamma, \]  

(14)

\[ Q + \bar{Q} \rightarrow q(q') + \bar{q}(\bar{q}') + \gamma. \]  

(15)
Processes of fragmentation production via quark fragmentation into photon are obtained from last set of direct processes by replacement of $\gamma \to g$.

The amplitudes of all above mentioned LO PRA processes can be obtained in analytical form using model-file ReggeQCD [13], which implements the Feynman rules of Lipatov’s EFT in FeynArts [19] at tree level. To generate the gluon, $\Phi_g(x,t,\mu^2)$, and quark, $\Phi_q(x,t,\mu^2)$, unPDFs, according to the Eq. (3) we use the LO PDFs from the MSTW-2008 set [20]. Quark fragmentation into photon is described by the BFG LO fragmentation functions $F_{g\to\gamma}(z,\mu^2)$ [21], where $p^\gamma_\mu = z p^g_\mu$. In this case, prompt photon isolation condition is taken in following manner, $E^\gamma \geq E^q - \Delta E$, where $\Delta E \sim 2$ GeV as it follows from experimental data [2-4].

We set the renormalization and factorization scales to be equal to the photon transverse momenta, $\sigma^\gamma_p(E^\gamma_T)$. Such a way, photon transverse-momentum spectrum is fully defined between sum of SPS (direct) and prompt photon isolation condition is $\sigma^\gamma_p(E^\gamma_T) = \sigma^\gamma_1(\gamma + X)$. Such a way, photon transverse-momentum spectrum is fully defined by unPDFs of quarks. In the right panel of Fig. 1, prompt photon transverse-momentum spectra in associated production with leading jet are presented. The level of agreement between data and LO PRA prediction is the same as for NLO CPM calculation with JETPHOX [22]. In the Fig. 2, left panel, we predict spectrum for azimuthal angle difference between $p^1_T$ and $p^2_T$ although there are no such experimental data for comparison yet. In Ref. [4], it was shown that study of azimuthal decorrelations in $\gamma + 2 \text{jets}$ events is a more sensitive tool for the search of DPS signal. They measured azimuthal angle difference $\Delta \phi$ between sum of photon plus leading jet transverse momenta $p^A_T = p^1_T + p^2_T$ and transverse momentum of second (sub-leading) jet $p^2_T$. In the Fig. 2 right panel, we present our results for $\gamma + 2 \text{jets}$ in LO PRA together with these experimental data. One can find that SPS (direct $\gamma + 2 \text{jets}$ events, green line) provides a good description of data only in the region of $\Delta \phi \geq \pi/2$ while at $\Delta \phi < \pi/2$ it is necessary to introduce the DPS mechanism, expressed in LO PRA by a convolution of $2 \to 1$ and $2 \to 2$ partonic subprocesses:

$$
\sigma^{DPS}(p\bar{p} \to \gamma + j_1 + j_2 + X) = \left[ \sigma^{SPS}(p\bar{p} \to \gamma + X) \times \sigma^{SPS}(p\bar{p} \to j_1 + j_2 + X) + \sigma^{SPS}(p\bar{p} \to \gamma + j_1 + X) \times \sigma^{SPS}(p\bar{p} \to j_2 + X) + \sigma^{SPS}(p\bar{p} \to \gamma + j_2 + X) \times \sigma^{SPS}(p\bar{p} \to j_1 + X) \right] \frac{1}{\sigma_{eff}},
$$

where $j_1$ is a leading jet and $j_2$ is a sub-leading jet, and the parameter $\sigma_{eff}$ controls the absolute value of DPS contribution. To calculate single-jet production cross section $\sigma^{SPS}(p\bar{p} \to j_1 + X)$, we take into account following partonic processes: $R + R \to g$, $R + Q \to q$ and $Q + \bar{Q} \to g$. In case of pair-jet production, $\sigma^{SPS}(p\bar{p} \to j_1 + j_2 + X)$, the main partonic processes are $R + R \to g + g$, $R + R \to q + \bar{q}$, $R + Q \to g + q$ and $Q + \bar{Q} \to g + g$.
As in the CPM, we find this DPS contribution to be constant through the whole ∆φ region (blue line). The sum of SPS and DPS contributions (red line) shows a nice agreement with experimental data at the same level as the one using Monte-Carlo generators with multiparton interactions in CPM included [4].

Following Ref.[4], we can define β as a fraction of DPS events:

\[
\frac{1}{\sigma} \frac{d\sigma}{d\Delta\phi} = (1 - \beta) \frac{1}{\sigma^{SPS}} \frac{d\sigma^{SPS}}{d\Delta\phi} + \beta \frac{1}{\sigma^{DPS}} \frac{d\sigma^{DPS}}{d\Delta\phi}
\] (17)

Our estimation for parameter β in LO PRA is β^{PRA} = 10.4 ± 1.2% that is very close to the value extracted in the NLO CPM calculations, β^{NLO} = 11.6 ± 1.4%.

![Figure 1.](image)

**Figure 1.** Left panel: Inclusive prompt photon \( p_T^\gamma \)-spectra at the \( \sqrt{S} = 1.8 \) TeV and \(|y^\gamma| < 0.9\). Right panel: Prompt photon \( p_T^\gamma \)-spectra in \( \gamma + \text{jet} \) production at the \( \sqrt{S} = 1.96 \) TeV, \(|y^\gamma| < 1.0 \) and \(|y^{|\text{jet}|}| < 0.8\). Green line is direct production, blue - fragmentation production, red - their sum. The data are from D0 Collaboration [2, 3].

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Figure 2. Left panel: Prediction for azimuthal angle difference spectrum, \( \Delta \phi = \phi^\gamma - \phi^{\text{jet}} \), in \( \gamma + \text{jet} \) events at the \( \sqrt{S} = 1.96 \text{ TeV} \). Green line is direct production, blue - fragmentation production, red - their sum. Right panel: Azimuthal angle difference spectrum \( \Delta \phi \) in \( \gamma + 2\text{jets} \) production at the \( \sqrt{S} = 1.96 \text{ TeV} \), \( 15 < p_T^{\text{jet}} < 20 \text{ GeV} \). Green line corresponds to SPS contribution, blue line – DPS, red is their sum. Data are from D0 Collaboration [4].

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