Assisted photon and heavy quark production at high energy within $k_T$-factorization

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Abstract. In the framework of the $k_T$-factorization approach, the production of prompt photons in association with a heavy (charm or beauty) quarks at high energies is studied. The consideration is based on the $O(\alpha_s^2)$ off-shell amplitudes of gluon-gluon fusion and quark-(anti)quark interaction subprocesses. The unintegrated parton densities in a proton are determined using the Kimber-Martin-Ryskin prescription. Our numerical predictions are compared with the D0 and CDF experimental data. Also we extend our results to LHC energies.

Keywords: QCD, $k_T$-factorization, prompt photon, heavy quark

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INTRODUCTION

Recently the D0 and CDF Collaborations reported data [1, 2, 3] on associated (with a heavy quark jets) prompt photon production at the Tevatron. The D0 Collaboration showed that the measured cross sections are in agreement with the NLO QCD predictions [4] within theoretical and experimental uncertainties in the region up to $p_T^\gamma \sim 70$ GeV. However, the substantial disagreement between theory and data for both $\gamma + b$-jet and $\gamma + c$-jet production at large $p_T^\gamma$ was observed. The cross section slopes in data significantly differ from the predicted ones. The results indicate a need for higher order perturbative QCD corrections in the large $p_T^\gamma$ region.

In the D0 papers [1, 3] it was demonstrated also that the $k_T$-factorization predictions [5] are in a better agreement with the data.

First application of $k_T$-factorization approach to production of photons associated with the charm or beauty quarks have been performed in our previous paper [6]. The consideration was based on the $O(\alpha_s^2)$ amplitude for the production of a single photon associated with a quark pair in the fusion of two off-shell gluons $g^*g^* \rightarrow \gamma Q\bar{Q}$. A good agreement between the numerical predictions and the Tevatron data was obtained in the region of relatively low $p_T^\gamma$ where off-shell gluon fusion dominates. However, the quark-induced subprocesses become more important at moderate and large $p_T^\gamma$ and therefore should be taken into account. Here we extend a previous predictions [6] by including into the consideration two additional $O(\alpha_s^2)$ subprocesses, namely $q\bar{q} \rightarrow \gamma Q\bar{Q}$ and $q(\bar{q})Q \rightarrow \gamma q(\bar{q})Q$, where $Q$ is the charm or beauty quark [5].
THEORETICAL FRAMEWORK

According to the $k_T$-factorization theorem, the cross section of the prompt photon and associated heavy quark production can be written as a convolution of the relevant off-shell partonic cross sections and unintegrated parton distribution functions (uPDF) in the proton $f_{i,j}(x, k_T^2, \mu^2)$:

$$
\sigma = \sum_{i,j} \int \hat{\sigma}_{ij}(x_1, x_2, k_{1T}^2, k_{2T}^2) f_i(x_1, k_{1T}^2, \mu^2) f_j(x_2, k_{2T}^2, \mu^2) \, dx_1 dx_2 \, dk_{1T}^2 dk_{2T}^2 \, \frac{d\phi_1 \, d\phi_2}{2\pi^2},
$$

where $\hat{\sigma}_{ij}(x_1, x_2, k_{1T}^2, k_{2T}^2), (i, j = q, g)$ is the relevant partonic cross section. The initial off-shell partons have fractions $x_1$ and $x_2$ of initial protons longitudinal momenta, non-zero transverse momenta $k_{1T}$ and $k_{2T}$ and azimuthal angles $\phi_1$ and $\phi_2$.

In what concerns the uPDF, we took them in the KMR form [7]. The KMR formalism is a prescription for constructing the uPDF from the known standard PDF $^1$. It gives $k_T$-dependent uPDF for both gluon and quark.

The analytic expressions of the corresponding off-shell matrix elements were listed in [5]. In the $k_T$-factorization approach the gluon polarization density matrix takes so-called BFKL form: $\sum_{\mu, \nu} e^\mu e^{*\nu} = k_T^2 k_{T'}^2 / k_T^2$. The spin density matrix for the off-shell spinors is taken in the form $\hat{u}(q) \bar{u}(q) = x \hat{p}$, where $q$ and $p$ are the quark and the proton momenta in the small $x$ and massless approximation [5].

In our numerical calculations we took the renormalization and factorization scales $\mu_R^2 = \mu_F^2 = \xi^2 p_T^2$. In order to evaluate theoretical uncertainties, we varied $\xi$ between 1/2 and 2 about the default value $\xi = 1$. We used the LO formula for the strong

![Graph 1](image1.png)

**FIGURE 1.** Differential cross section $d\sigma / dp_T^\gamma$ of associated $\gamma + b \rightarrow jet$ production at $\sqrt{s} = 1960$ GeV, $|y^{jet}| < 1.5$ and $p_T^{jet} > 15$ GeV. The dashed, dotted and dash-dotted curves correspond to the contributions of $gg \rightarrow \gamma Q \bar{Q}, q \bar{q} \rightarrow \gamma Q \bar{Q}, g(q\bar{q}) \rightarrow \gamma q(q\bar{q})$ subprocesses. The solid curve represents their sum. The experimental data are from [1].

$^1$ Numerically, we used the MSTW-2008 set [8] in the proton as the input.
coupling constant $\alpha_s(\mu^2)$ with $n_f = 4$ active quark flavours at $\Lambda_{QCD} = 200$ MeV, so that $\alpha_s(M_Z) = 0.1232$. We set the charm and beauty quark masses to $m_c = 1.5$ GeV and $m_b = 4.75$ GeV. We use the experimental isolation cut for produced photons [1, 2, 3]:

$$E_T^{had} \leq E_{\text{max}}$$

$$(\eta^{had} - \eta)^2 + (\phi^{had} - \varphi)^2 \leq R^2.$$  

We took $R = 0.4$ and $E_{\text{max}} = 1$ GeV as in the Tevatron experimental data. The isolation not only reduces the background from the secondary photons produced by the decays of $\pi^0$ and $\eta$ mesons but also significantly reduces the so called fragmentation components, connected with collinear photon radiation ($10\%$).

Similarly to the traditional QCD approach the calculated cross section split into two pieces:

$$d\sigma = d\sigma_{\text{direct}}(\hat{\mu}^2) + d\sigma_{\text{fragm}}(\hat{\mu}^2),$$

where $d\sigma_{\text{direct}}(\hat{\mu}^2)$ is the perturbative contribution, $d\sigma_{\text{fragm}}(\hat{\mu}^2)$ is the fragmentation contribution, and $\hat{\mu}^2$ is the fragmentation scale. In our calculations $\hat{\mu}$ is the invariant mass of the produced photon and any final quark and we restrict the direct contribution to $\hat{\mu} > M = 1$ GeV in order to eliminate the collinear divergences in the direct cross section. Then the mass of light quark can be safely sent to zero.

**NUMERICAL RESULTS**

In Figs. 1 – 3 some of the results of our calculation [5] are shown (more details see in [5]). We have found that the full set of experimental data is reasonably well described by the $k_T$-factorization approach. One can see that the property of the unintegrated parton distribution and the non-vanishing transverse momentum of the colliding partons lead
FIGURE 3. Differential cross section $d\sigma / dp_{T}^{\gamma}$ of associated $\gamma + b - jet$ (left panel) and $\gamma + c - jet$ (right panel) production at $\sqrt{s} = 1960$ GeV. Figs. are taken from [1, 3].

to a broadening of the photon transverse momentum distributions in comparision with the collinear pQCD results. As it was noted in [1, 3] our results agree better with the Tevatron data than the NLO QCD ones (see Fig. 3)

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