PROMPT PHOTON PRODUCTION WITH $K_T$–FACTORIZATION

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Abstract

We consider the prompt photon production at modern high energy colliders in the framework of $k_T$–factorization approach. We compare our theoretical predictions with recent experimental data at HERA and Tevatron, emphasizing the distinction between our theoretical predictions and the results of NLO QCD calculations. Finally, we extrapolate our predictions to LHC energies.

1 Introduction

It is well known that production of prompt (or direct) photons at high energies has provided a direct probe of the hard subprocess dynamics, since produced photons are largely insensitive to the final-state hadronization effects. Usually photons are called ”prompt” if they are coupled to the interacting quarks. In the framework of QCD these photons in $ep$ collisions can be produced via direct $\gamma q \rightarrow \gamma q$ and resolved $gq \rightarrow \gamma q$ production mechanisms. The last-named mechanism is dominant production one for the prompt photons in $pp$ collisions. It is clear that cross section of such processes is sensitive to the parton distributions in a proton and a photon. Also observed final state photons may arise from so called fragmentation processes, where a quark or gluon are transformed into $\gamma$. However, the isolation criterion which is usually introduced in experimental analyses substantially reduces the fragmentation component (see, for example, Ref. [1]). The prompt photon production in $ep$ and $pp$ collisions has been studied in a number of experiments at HERA [2 - 4] and Tevatron [5, 6].

In $pp$ collisions it was found [5, 6] that the shape of the measured cross sections as a function of photon transverse energy $E_T^\gamma$ is poorly described by next-to-leading order (NLO) QCD calculations: the observed $E_T^\gamma$ distribution is steeper than the predictions of perturbative QCD. These shape differences lead to a significant disagreement in the ratio of cross sections calculated at different center-of-mass energies $\sqrt{s} = 630$ GeV and $\sqrt{s} = 1800$ GeV as a function of scaling variable $x_T = 2E_T^\gamma/\sqrt{s}$. The disagreement in the $x_T$ ratio is difficult to explain with conventional theoretical uncertainties connected with scale dependence and parametrizations of the parton distributions [5, 6]. The origin of the disagreement has been ascribed to the effect of initial-state soft-gluon radiation [7, 8]. It was shown that observed discrepancy can be reduced by introducing some additional intrinsic transverse momentum $k_T$ of the incoming partons, which is usually assumed to have a Gaussian-like distribution [8, 9]. However, the average value of this $k_T$ increases from $\langle k_T \rangle \sim 1$ GeV to more than $\langle k_T \rangle \sim 3$ GeV in hard-scattering processes as the $\sqrt{s}$ increases from UA6 to Tevatron energies [8, 10].

The treatment of $k_T$–enhancement in the inclusive prompt photon hadroproduction at Tevatron proposed in Ref. [11], based on the $k_T$–factorization QCD approach, suggests
Figure 1: The differential cross sections for the prompt-photon + jet production compared to the QCD calculations and MC models [3].

possible modifications of the above simple $k_T$ smearing picture. The unintegrated parton distributions in a proton were obtained using the KMR formalism and the role of the both non-perturbative and perturbative components of partonic transverse momentum $k_T$ in describing of the observed $E^\gamma_T$ spectrum was investigated. However, the KMR unintegrated parton densities were obtained in the double leading logarithmic approximation (DLLA) only. Also in these calculations the usual on-shell matrix elements of hard partonic subprocesses were evaluated with precise off-shell kinematics.

In our papers [12, 13] we have applied the KMR method to obtain the unintegrated quark and gluon distributions $f_a(x, k^2_T, \mu^2)$ in a proton and a photon independently from other authors. Then we have studied prompt photon production at HERA and Tevatron in more detail. Here we present some of these results, which demonstrate our specific predictions in comparison with the results of NLO QCD calculations.

2 Prompt photon production at HERA

In $ep$ collisions at HERA prompt photons can be produced by one of three mechanisms: a direct production, a single resolved production and via parton-to-photon fragmentation processes. The direct process is the Deep Inelastic Compton scattering on a quark (antiquark): $\gamma q \rightarrow \gamma q$. The single resolved QCD processes are $qg \rightarrow \gamma q$ and $q\bar{q} \rightarrow \gamma g$. Photons can be also produced through the fragmentation of a parton into photon. However, the contribution of these fragmentation components is significantly reduced (up to 5-6 %) in HERA experiments [2] by special isolation criterion.

In Fig. 1 we show the differential cross sections for the prompt-photon events ($E^\gamma_T >$
5 GeV) with an accompanying jet ($E_T^\gamma > 6$ GeV) as functions of $E_T^\gamma$ and $\eta^\gamma$ (left panel), $E_T^{jet}$ and $\eta^{jet}$ (right panel) compared to the results of standard QCD [14, 15] and $k_T$–factorization calculations (with hadronization corrections) and MC models (the histograms) taken from Ref. [3]. The shaded bands correspond to the uncertainty in the renormalization scale which was changed by a factor of 0.5 and 2. Fig. 2 shows the distribution for $x_\gamma^{obs}$ defined as $\Sigma_{\gamma, jet}(E_i - P_{Zi}^i)/(2E_\gamma y)$ (the sum runs over the photon candidate and hadron jet). We see that the prediction based on the $k_T$–factorization approach [12]

![Figure 2: The $x_\gamma^{obs}$ cross section for the prompt-photon production compared to the QCD calculations and MC model.](image)

(corrected for hadronization effects [3]) gives the best description of the $E_T$ and $\eta$ cross sections. In particular it describes the lowest $E_T^\gamma$ region better than the KZ [14] and FGH [15] NLO predictions. The $\eta^{jet}$ cross section for the associated jet in the forward region and the $x_\gamma^{obs}$ distribution in the $x_\gamma^{obs} < 0.75$ region (the resolved photon contribution) are also better reproduced by the our calculation. However, it underestimates the observed cross section at low $E_T^{jet}$, in the forward jet region and at the $x_\gamma^{obs} > 0.75$ (Fig. 2). For the $E_T^\gamma > 7$ GeV cut (keeping the other cuts the same as before), both the NLO QCD and the $k_T$–factorization predictions agree well with the data [3]. The comparison of the the $k_T$–factorization predictions and the H1 data [4] was done in our paper [12].

3 Prompt photon hadroproduction

Experimental data for the inclusive prompt photon hadroproduction $p + \bar{p} \rightarrow \gamma + X$ come from both the D$\sigma$ [5] and CDF [6] collaborations. The results of our calculations for the double differential cross sections $d\sigma/dE_T^\gamma d\eta^\gamma$ in comparison with the data were shown in Ref. [13]. We have found that our predictions agree well with the D$\sigma$ [5] and CDF [6] data both in normalization and shape. The comparison between the results of NLO calculations and the CDF experimental data [6] has shown that the NLO ones agree
with the data more qualitatively. So, the shape of the measured cross sections is steeper than that of the NLO predictions [6].

Also the disagreement between data and NLO calculations is visible [5, 6] in the ratio of the cross sections at different energies. This quantity is known as a very informative subject of investigations and provides more precise test of the QCD calculations. It is because many factors which affect the absolute normalization partially or completely cancel out. In particular, the cross section ratio provides a direct probe of the matrix elements of the hard partonic subprocesses since the theoretical uncertainties due to the quark and gluon distributions are reduced.

The DØ collaboration has published the results of measurement [5] for the ratio of 630 GeV and 1800 GeV dimensionless cross sections $\sigma_D$ as a function of scaling variable $x_T$. The measured cross section $\sigma_D$ averaged over azimuth is defined as $\sigma_D = (1/2\pi)(E_T^\gamma)^3d\sigma/dE_T^\gamma d\eta^\gamma$. The ratio $\sigma_D(630\text{ GeV})/\sigma_D(1800\text{ GeV})$ compared with the DØ experimental data [5] in different pseudo-rapidity $\eta^\gamma$ regions is shown in Fig. 3. The solid lines represent the $k_T$-factorization predictions at default scale $\mu = E_T^\gamma$. For comparison we show also the results of the collinear leading-order (LO) QCD calculations with the GRV parton densities [16] of a proton (as a dashed lines). Note that when we perform the LO QCD calculations we take into account the partonic subprocesses $qg \rightarrow \gamma q$ and $q\bar{q} \rightarrow \gamma g$ and neglect the small fragmentation contributions, as it was done in the $k_T$-factorization case. It is clear that although the experimental points have large errors they tend to support the $k_T$-factorization predictions. We would like to point out again that now sensitivity of our results to the non-collinear evolution scheme is minimized. In the collinear approach, the NLO corrections improve the description of the data and then sum of LO and NLO contributions practically coincides with our results at $x_T > 0.05$ [5]. This fact is clear indicates that the main part of the collinear high-order corrections is already included at leading-order level in the $k_T$-factorization formalism. Nevertheless, the experimental data at the lowest $x_T$ are systematically higher [5] than NLO QCD pre-
dictions in both central and forward pseudo-rapidity regions, and this ratio is difficult to reconcile with the NLO QCD calculations [6].

Now we want to show some predictions for the prompt photon with associated muon production at Tevatron and for the differential cross section $d\sigma/d\gamma_T$ at LHC [13].

The experimental data for the $\gamma + \mu$ cross section at Tevatron come from CDF collaboration [6] taken at $|\eta\gamma| < 0.9$, $p_{\mu T} > 4$ GeV and $|\eta\mu| < 1.0$. The transverse momentum distribution $d\sigma/dp_{\gamma T}$ in comparison to experimental data [6] was shown in Ref. [13]. It was shown the shape of this distribution is well described by our calculations, but the theoretical results slightly overestimate the data in absolute normalization. However, in general the experimental points still lie within theoretical scale uncertainties (about 30%) of our calculations. It is important also that our predictions practically coincide with the results of collinear NLO QCD calculations [17], which are much larger than LO ones [6].

Further understanding of the process dynamics and in particular of the high-order effects may be obtained from the angular correlation between the transverse momenta of the final state particles [18].

The differential cross section $d\sigma/d\Delta\phi^{\gamma\mu}$ calculated at $p_{\mu T} > 4$ GeV, $|\eta\mu| < 1.0$ and $|\eta\gamma| < 0.9$ is shown in Fig. 4 (left panel). The solid curve corresponds to the default scale $\mu = E_T^\gamma$, whereas upper and lower dashed curves correspond to the $\mu = E_T^\gamma/2$ and $\mu = 2E_T^\gamma$ scales. The result of LO QCD calculations also shown (as a dash-dotted curve). One can see a striking difference in shape between $k_T$-factorization results and collinear LO QCD ones. The predictions of the NLO QCD calculations for this distribution are still unknown. Fig. 4 (right panel) shows also our prediction for the differential cross section $d\sigma/dE_T^\gamma$ of inclusive prompt photon hadroproduction at LHC. The direct comparison between NLO calculations, our results and the experimental data should give a number of interesting insights.

In summary, we have shown that the $k_T$-factorization approach describes the prompt photon production at HERA better than standard NLO calculations at certain cuts for transverse energy of observable photon and jet. We have found that the $k_T$-factorization
approach gives specific prediction for the ratio of two cross sections calculated at two Tevatron energies. It provides a direct probe of the off-shell mass matrix elements. It means that further experimental and theoretical investigations promise us a number exciting insights.

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