DIRECT PHOTON PRODUCTION IN $pp$ and $p\bar{p}$ COLLISIONS AT HIGH ENERGIES

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The invariant cross sections for direct photon production in hadron-hadron collisions are calculated for several initial energies (SPS, ISR, SppS, RHIC, Tevatron, LHC) in-cluding initial parton transverse momenta within the formalism of unintegrated parton distributions (UPDF). Kwieciński UPDFs provide very good description of all world data, especially at SPS and ISR energies. Inclusion of the QCD evolution effects and especially their effect on initial parton transverse momenta allowed to solve the long-standing problem of understanding the low energy and low transverse momentum data.

Keywords: direct photons, invariant cross section, parton transverse momenta

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1. Introduction

It was realized relatively early that the transverse momenta of initial (before a hard process) partons may play an important role in order to understand the distributions of produced direct photons, especially at small transverse momenta (see e.g. Ref. 1). The simplest way to include parton transverse momenta is via Gaussian smearing. This phenomenological approach is not completely justified theoretically.

The unintegrated parton distribution functions (UPDFs) are the basic theoretical quantities that take into account explicitly the parton transverse momenta. The UPDFs have been studied recently in the context of different high-energy processes

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These works concentrated mainly on gluon degrees of freedom which play the dominant role in many processes at very high energies. At somewhat lower energies also quark and antiquark degrees of freedom become equally important. Recently the approach which dynamically includes transverse momenta of not only gluons but also of quarks and antiquarks was applied to direct-photon production.

Up to now there is no complete agreement how to include evolution effects into the building blocks of the high-energy processes – the unintegrated parton distributions. In Ref. 14 we have discussed in detail a few approaches how to include transverse momenta of the incoming partons in order to calculate distributions of direct photons.

2. Unintegrated parton distributions

In general, there are no simple relations between unintegrated and integrated parton distributions. Some of UPDFs in the literature are obtained based on familiar collinear distributions, some are obtained by solving evolution equations, some are just modelled or some are even parametrized. A brief review of unintegrated gluon distributions (UGDFs) can be found in Ref. 10.

In some of the approaches mentioned above one imposes the following relation between the standard collinear distributions and UPDFs:

$$ a(x, \mu^2) = \int_0^{\mu^2} f_a(x, k_{1t}^2, \mu^2) \frac{dk_{1t}^2}{k_{1t}^2}, \quad (1) $$

where $a = xq$ or $a = xg$.

Since familiar collinear distributions satisfy sum rules, one can define and test analogous sum rules for UPDFs. We have discussed this issue in more detail in Ref. 14. Some other approaches for UPDFs are discussed e.g. in Ref. 10.

3. UPDFs and photon production

The cross section for the production of a photon and an associated parton (jet) can be written as

$$ \frac{d\sigma(h_1 h_2 \rightarrow \gamma, \text{parton})}{d^2 p_{1,t} d^2 p_{2,t}} = \int dy_1 dy_2 \frac{d^2 k_{1t}}{\pi} \frac{d^2 k_{2t}}{\pi} \frac{1}{16\pi^2 (x_1 x_2 s)^2} \sum_{i,j,k} |\mathcal{M}(ij \rightarrow \gamma k)|^2 \cdot \delta^2(\vec{p}_{1,t} + \vec{p}_{2,t} - \vec{p}_{1,t} - \vec{p}_{2,t}) f_i(x_1, k_{1t}^2) f_j(x_2, k_{2t}^2), \quad (2) $$

where $\vec{k}_{1,t}$ and $\vec{k}_{2,t}$ are transverse momenta of incoming partons. In the leading-order approximation: $(i, j, k) = (q, \bar{q}, g), (q, \bar{q}, g), (q, q, g), (q, g, q), (g, g, q)$, etc. (see Fig. 1).

If one makes the following replacements

$$ f_i(x_1, k_{1t}^2) \rightarrow x_1 p_i(x_1) \delta(k_{1t}^2)$$

and

$$ f_j(x_2, k_{2t}^2) \rightarrow x_2 p_j(x_2) \delta(k_{2t}^2) $$

(3) and (4)
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Fig. 1. The diagrams included in our $k_T$-factorization approach with the notation of kinematical variables.

Fig. 2. Invariant cross section for direct photons for $\sqrt{s} = 23$ GeV as a function of Feynman $x_F$ for different bins of transverse momenta. In this calculation off-shell matrix elements for subprocesses with gluons were used. The Kwieciński UPDFs were calculated with the factorization scale $\mu^2 = 100$ GeV$^2$. The theoretical results are compared with the WA70 collaboration data.\[\text{[15]}\]
then one recovers the standard collinear formula (see e.g.1).

The inclusive invariant cross section for direct photon production can be written

$$\frac{d\sigma(h_1h_2 \rightarrow \gamma)}{dy_1d^2p_{1,t}} = \int dy_2\frac{d^2k_{1,t}}{\pi} \frac{d^2k_{2,t}}{\pi} \left(\ldots\right)_{\vec{p}_{2,t}=\vec{k}_{1,t}+\vec{k}_{2,t}-\vec{p}_{1,t}}$$

$$= \int dk_{1,t}dk_{2,t} I(k_{1,t},k_{2,t};y_1,p_{1,t}).$$

(5)

The integrand $I(k_{1,t},k_{2,t};y_1,p_{1,t})$ defined above depends strongly on the UPDFs used.

In Fig. 3 we show inclusive invariant cross section as a function of Feynman $x_F$ for several experimental values of photon transverse momenta as measured by the WA70 collaboration.

It is well known that the collinear approach (dotted line) fails to describe the low transverse momentum data by a sizeable factor of 4 or even more. Also the $k_t$-factorization result with the KMR UPDFs (dashed line) underestimate the low-energy data. In contrast, the Kwieciński UPDFs (solid line) describe the WA70 collaboration data almost perfect [15].

Fig. 3. Cross section for direct photons for $\sqrt{s} = 1.96$ TeV. In this calculation off-shell matrix element for gluons were used. (a) standard KMR prescription, (b) Gaussian smearing ($\sigma_0 = 1,2$ GeV) versus Kwieciński UPDFs. The experimental data are from [16].

In Fig. 3 we compare results obtained with different UGDFs with a recent experimental data of the D0 collaboration. The unintegrated parton distribution approach with the KMR UPDFs is clearly inconsistent with the standard collinear approach at large transverse momenta. This is caused by the presence of large-$k_t$ tails (of the $1/k_t$ type) in the KMR UPDFs. It is not the case for the Gaussian and Kwieciński UPDFs which seem to converge to the standard collinear result at large photon transverse momenta. In this respect the latter UPDFs seems preferable.
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