Real and Virtual Photoproduction of Large-$p_{\perp}$ Particles at NLO

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Abstract

In the first part of this paper we assess the possibility of observing the gluon distribution in a real photon by measuring the photoproduction cross section of large-$p_{\perp}$ photons. In the second part we calculate the virtual photoproduction of large-$p_{\perp}$ forward $\pi^0$. The theoretical results are compared with data and with BFKL-inspired predictions. These studies are done at the NLO approximation.

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1 Introduction

The real and virtual photoproduction of large-$p_{\perp}$ particles gives rise to interesting tests of the QCD dynamics and enables to measure the parton distribution and fragmentation functions [1]. In particular it offers a unique opportunity to measure the parton distributions in the (real or virtual) photon. In this paper I shall concentrate on this feature of photoproduction reactions. In the first part, I assess the possibility to determine the gluon distribution in a real photon by measuring the photoproduction of large-$p_{\perp}$ photons, and in the second part, I study the importance of the virtual photon structure function in the forward (along the initial proton direction) production of large $-p_{\perp}$ $\pi^0$. This latter reaction is also interesting from the point of view of the underlying QCD dynamics. In fact it has been proposed by Mueller [2] in order to study the importance of the BFKL contribution to the forward cross section.

2 The gluon distribution in the real photon

Over the past years, the ZEUS [3, 4] and H1 [5] collaborations at HERA have been able to observe the photoproduction of large-$p_{\perp}$ photons, and the comparisons of data with existing NLO QCD predictions [3, 6, 7, 8, 9, 10] appear successful. In photoproduction reactions, a quasi-real photon, emitted at small angle from the electron, interacts with a parton from the proton. The photon can either participate directly in the hard scattering or be resolved into a partonic system, in which case the parton stemming from the photon takes part in the hard interaction. Therefore photoproduction is a privileged reaction to measure or constrain the parton distributions in the photon and in the proton. Here I will put the emphasize on the gluon distribution in the real photon, a distribution which is hardly known [11].

The interest of the reaction $\gamma + p \rightarrow \gamma + jet + X$ comes from the fact that the final photon offers a clear experimental signal. On the theoretical side, this cross section is hardly sensitive to the factorization and renormalization scales, a fact which should allow us an accurate determination of the parton distributions.

As observables which serve to reconstruct the longitudinal momentum fraction of the parton stemming from the photon, it is common to use

$$x_{\text{obs}}^\gamma = \frac{p_T^\gamma e^{-\eta^\gamma} + E_T^{\text{jet}} e^{-\eta^{\text{jet}}}}{2E_T^\gamma}. \tag{1}$$

However, as the measurement of $E_T^{\text{jet}}$ can be a substantial source of systematic errors at low $E_T$ values, we propose a slightly different variable which does not depend on $E_T^{\text{jet}}$,

$$x_{\text{LL}}^\gamma = \frac{p_T^\gamma(e^{-\eta^\gamma} + e^{-\eta^{\text{jet}}})}{2E_T^\gamma}. \tag{2}$$

At leading order, for the non-fragmentation contribution, the variables $x_{\text{obs}}$ and $x_{\text{LL}}$ coincide, and they are also equal to the “true” partonic longitudinal momentum.
The jet rapidities have been integrated over $-2 < \eta_{\text{jet}} < 4$, and $E_{T,\text{jet}} > 5$ GeV, $p_T > 6$ GeV.

fraction, i.e. the argument of the parton distribution function. At NLO, the real corrections involve 3 partons in the final state (with transverse momenta $p_{T,3}$, $p_{T,4}$, $p_{T,5}$), one of which – say parton 5 – is unobserved. Therefore, $d\sigma/x_{\text{obs}}$ and $d\sigma/x_{\text{LL}}$ will be different at NLO.

Before presenting numerical results, let us further discuss the problem of the cuts on the photon and jet transverse momenta. It is well known that symmetrical cuts on the minimum transverse energies of the photon and of the jet should be avoided as they amount to including a region where the fixed order perturbative calculation shows infrared sensitivity. As explained in detail in Ref. [11], the problem stems from terms $\sim \log^2(|1 - p_{\gamma}^2/E_{T,\text{min}}^2|)$ which become large as $p_T^\gamma$ approaches $E_{T,\text{min}}^\gamma$, the lower cut on the jet transverse energy. Therefore the partonic NLO cross section has a singular behaviour at $p_T^\gamma = E_{T,\text{min}}^\gamma$. Obviously, $d\sigma/dp_{\gamma}^2$ will not exhibit a problem as long as $E_{T,\text{min}}^\gamma < p_T^\gamma$ since the critical point $p_T^\gamma = E_{T,\text{min}}^\gamma$ will not be reached in this case.

On the other hand, one often would like to have a more inclusive cross section such as $d\sigma/d\eta^\gamma$, obtained by integrating the differential cross section over $p_T^\gamma$ and $E_{T,\text{jet}}$. In this case one should not choose $p_{T,\text{min}}^\gamma = E_{T,\text{min}}^\gamma$ as this amounts to integrating the spectrum over the $\log^2(|1 - p_{\gamma}^2/E_{T,\text{min}}^\gamma|)$ contribution. As a result, the theoretical prediction although being finite, is infrared sensitive as a consequence of choosing symmetrical cuts. This point has been discussed in detail in Ref. [11].

Our studies are based on the program EPHOX [12], which is a NLO partonic
Figure 2: Effect of rapidity cuts to enhance the contribution from the gluon in the photon.

Monte Carlo event generator. Unless stated otherwise, we use the following input for our numerical results: A center of mass energy $\sqrt{s} = 318$ GeV with $E_e = 27.5$ GeV and $E_p = 920$ GeV is used. The cuts on the minimum transverse energies of photon and jet are $E_{jet}^T > 5$ GeV, $p_T^\gamma > 6$ GeV. The rapidities have been integrated over in the domain $-2 \leq \eta^\gamma, \eta^{jet} \leq 4$ unless stated otherwise. For the parton distributions in the proton we take the MRST01 parametrization, for the photon we use AFG04\cite{13} distribution functions and BFG\cite{14} fragmentation functions. We take $n_f = 4$ flavours, and for $\alpha_s(\mu)$ we use an exact solution of the two-loop renormalization group equation, and not an expansion in log($\mu/\Lambda$). The default scale choice is $M = M_F = \mu = p_T^\gamma$. Jets are defined using the $k_T$-algorithm. The rapidities refer to the $ep$ laboratory frame, with the HERA convention that the proton is moving towards positive rapidity. One must also note that the final photon verifies an isolation criterion\cite{11}.

The main result of the study is shown in Fig. 1 which details the various contributions to the cross section.

The gluon distribution $g^\gamma(x^\gamma,Q^2)$ only contributes at small values of $x^\gamma$, corresponding to large values of $\eta^\gamma$, and we shall try, by various cuts, to enhance the relative contribution of this component. Cuts in the photon and jet rapidities are quite effective to enhance the gluon in the photon, as shown in Fig. 2.
Figure 3: Scale dependence of $d\sigma/dx_{LL}^{\gamma}$ in the presence of forward rapidity cuts.
Note that the lower cuts on the transverse momenta are rather large, $p_T^\gamma > 6$ GeV, $E_T^{jet} > 5$ GeV. One can increase the cross section by choosing lower $p_T^\gamma$ cuts, as shown in Fig. 3. This figure also shows the scale dependence of $d\sigma / dx_{LL}^\gamma$ in the presence of the cuts $\eta^\gamma > 0$, $\eta^{jet} > 0$ respectively $\eta^\gamma > 0.5$, $\eta^{jet} > 1.5$. The behaviour of the cross section $d\sigma / dx_{LL}^\gamma$, varies by $\pm 8\%$ under the scale changes. One must keep in mind that the distribution $g^\gamma$ is poorly known and that a determination of the latter with an accuracy of $\pm 10\%$ would be quite welcome.

3 The forward leptoproduction of large-$p_T$ $\pi^0$

This reaction has been put forward by Mueller [2] to observe the BFKL dynamics. In fact in the collision between the virtual photon of virtuality $Q^2 = |q^2|$ and a gluon from the incident proton, we can have the reaction $\gamma^* (\rightarrow q \bar{q}) + g \rightarrow q \bar{q} + n g$ with $n$ gluons emitted in the final state by a ladder of gluons exchanged between the $q\bar{q}$-pair and the initial gluon. In the configuration in which the large-$p_T$ forward $\pi^0$ is a fragment of the first (closest to the proton) gluon, we have a gluonic ladder, starting at virtuality $p_T^2$ and ending at the virtuality $Q^2$. When $p_T^2 \sim Q^2$, there is no room for a DGLAP evolution. However, when $x_{Bj} = Q^2 / 2 P \cdot q$ is small, the $\ln x_{Bj}$ terms generated by the latter can be resumed by the BFKL equation [15]; this leads to a large contribution to the forward cross section if we follow the estimations of ref. [16].

In this work we follow another way and calculate the electroproduction cross section at the NLO approximation. The cross section is the sum of a direct term and of a resolved term. For both of them, we calculate HO corrections the parton distributions in the virtual photon also are calculated at the NLO approximation [17, 18]. This cross section has been measured by the H1 collaboration [19, 20] and we here present results for $d\sigma / dx_{Bj}$ [19] which verifies the following constraints. In the laboratory system a $\pi^0$ is observed in the forward direction with $5^\circ \leq \theta_{\pi^0} \leq 25^\circ$; the laboratory momentum of the pion is constrained by $x_{\pi^0} = E_{\pi^0} / E_P \geq .01$ and an extra cut is put on the $\pi^0$ transverse momentum in the $\gamma^* - p$ center of mass system: $p_{T_{\pi^0}} > 2.5$ GeV. The inelasticity $y = Q^2 / x_{Bj} S$ is restricted to the range $.1 < y < .6$, where $S = (p_e + p_P)^2 = (300$ GeV$)^2$. We use $\Lambda_{\overline{MS}}^{(4)} = 300$ MeV and the fragmentation functions of ref. [21]. All the factorization and renormalization scales are taken equal to $Q^2 + E_{\pi^0}^2$. The direct HO corrections from which the (lowest order) resolved part is subtracted are called HO$_s$.

In Fig. 4 we notice the importance of the HO$_s$ corrections to the direct Born cross section. These large corrections come from the subprocesses $\gamma^* + g \rightarrow q + \bar{q} + g$ and $\gamma^* + q \rightarrow q + \bar{q} + q$ that have a gluon exchanged in the $t$-channel. We also notice the importance of the resolved contribution (approximately one half of the total cross section) with large HO corrections: HO (resolved)/Born (resolved) $\simeq 1$. All these large corrections are associated to small values of $E_{\perp}$ due to the small cut $p_{T_{\pi^0}} > 2.5$ GeV. As a consequence the total cross section is quite sensitive to
variation of the renormalization scale $\mu$. For the choice $\mu^2 = Q^2 + E_{\perp}^2$, we obtain a good agreement between data and theory with little room left for a BFKL contribution as estimated in ref. [16].

References

[1] M. Klasen, Rev. Mod. Phys. 74 (2002) 1221.

[2] A. H. Mueller, Nucl. Phys. (Proc. Suppl.) B18c (1990) 125.

[3] J. Breitweg et al. [ZEUS Collaboration], Phys. Lett. B472 (2000) 175 [hep-ex/9910045];
J. Breitweg et al. [ZEUS Collaboration], Phys. Lett. B413 (1997) 201 [hep-ex/9708038].

[4] S. Chekanov et al. [ZEUS Collaboration], Phys. Lett. B511 (2001) 19 [hep-ex/0104001].

[5] H1 Collaboration, submitted to the Int. Europhysics Conference on High Energy Physics, EPS03, July 2003, Aachen (Abstract 093), and to the XXI Int. Symposium on Lepton and Photon Interactions, LP03, August 2003, Fermilab.

[6] L. E. Gordon, Phys. Rev. D57 (1998) 253 [hep-ph/9707546].

[7] M. Fontannaz, J. P. Guillet and G. Heinrich, Eur. Phys. J. C21 (2001) 303 [hep-ph/0105121].
[8] M. Fontannaz, J. P. Guillet and G. Heinrich, Eur. Phys. J C22 (2001) 303 hep-ph/0107262.

[9] M. Krawczyk and A. Zembrzuski, Phys. Rev. D64 (2001) 114017 hep-ph/0105166.

[10] A. Zembrzuski and M. Krawczyk, hep-ph/0309308

[11] M. Fontannaz and G. Heinrich, Eur. Phys. J. C34 (2004) 191.

[12] The program together with detailed documentation is available at http:\\www.lapp.in2p3.fr\lapth\PHOX\_FAMILY\main.html.

[13] P. Aurenche, J. P. Guillet and M. Fontannaz, Z. Phys. C64 (1994) 621 ;
P. Aurenche, J. P. Guillet and M. Fontannaz, new version of AFG, publication in preparation.

[14] L. Bourhis, M. Fontannaz and J. P. Guillet, Eur. Phys. J. C2 (1998) 529

[15] V. S. Fadin, E. A. Kuraev, L. N. Lipatov, Sov. Phys. JETP 44 (1976) 199.
Y. Y. Balitsky, L. N. Lipatov, Sov. J. Nucl. Phys. 28 (1978) 822.

[16] J. Kwiecinski, A. D. Martin, J. Outhwaite, Eur. Phys. J. C9 (1999) 611.

[17] P. Aurenche, Rahul Basu, M. Fontannaz, R. Godbole, Eur. Phys. J. C34 (2005) 277.

[18] M. Fontannaz, in preparation, preprint LPT-ORSAY-04-48.

[19] H1 collaboration, C. Adloff et al., Phys. Lett. B462 (1999) 440.

[20] H1 Collaboration, A. Aktas et al., DESY 04-051, hep-ex/0404009

[21] B. A. Kniehl, G. Kramer, B. Pötter, Nucl. Phys. B582 (2000) 514