Inclusive Jet Production at HERA: Next-to-Leading Order QCD Corrections to the Resolved and Direct Photon Contribution

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Abstract

We have calculated high transverse energy single-jet inclusive cross sections for γp-collisions at next-to-leading order superimposing direct and resolved photoproduction. The dependence on the scale and the scheme for the factorization of the photon structure is studied quantitatively. The accuracy of the predictions due to variations of all scales is investigated.

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1 Introduction

The production of high transverse energy (E_T) jets by quasi-real photons on protons has received much theoretical [1-6] and experimental [7] interest since the start of the HERA experiments. Further results by the H1 Collaboration [8] and the ZEUS Collaboration [9] have been presented recently.

Commonly, high energy photoproduction is divided into two components. Firstly, the incoming quasi-real photon may couple directly to a quark or anti-quark participating in the hard scattering process, similar to deep inelastic leptoproduction. In addition to this *direct part* the *resolved* component has to be taken into account. Here, the (almost) on-mass-shell photon dissolves into partons, one of which undergoes hard scattering with a parton originating from the incoming proton. This latter part looks very similar to high energy hadroproduction. Due to the presence of the pointlike photon-quark interaction, however, some substantial differences occur. At leading order (LO) the direct component is independent of the factorization scale M_γ which enters the photonic parton distributions. The next-to-leading order (NLO) corrections contain a singularity due to the splitting of the incoming photon into a collinear quark-antiquark pair. This singular contribution has to be factorized into the non-pertubative (anti-)quark distributions of the photon. This procedure introduces an explicit dependence on M_γ to the NLO corrections of the direct part. From this construction it is evident that direct and resolved photoproduction are related to each other through the factorization scale. The M_γ dependence of the NLO contributions to the direct cross section must cancel against the M_γ dependence present in the resolved cross section via the photon structure function, neglecting higher orders in α_s. This can be seen explicitely by considering the evolution equations for the photonic parton distributions. Similar to the well-known absorption of initial state collinear singularities into the parton distributions of hadrons additional finite and M_γ independent contributions can be absorbed into the photonic parton densities or shifted into the NLO corrections to the direct photon piece. This shows that at the NLO level the definition of direct/resolved photoproduction is ambiguous and only the sum of both contributions is physically meaningful.

So far direct and resolved photoproduction of jets were considered separately. It was found that the resolved process dominates at HERA energies for low E_T and/or negative rapidities (we assign the rapidity $\eta>0$ in the direction of the incoming electron). Near the maximum of the rapidity distribution ($\eta_{Lab} \approx -2$) the resolved and the direct part become of comparable size at $E_T \approx 25\,\mathrm{GeV}$. This result was obtained with a photon factorization scale $M_\gamma = E_T$, and equal to all other scales. As long as the jet transverse energy is not too large, say below 20 GeV, one could safely neglect the contribution from direct photoproduction. In the near future we expect HERA data also for $E_T>20\,\mathrm{GeV}$. For their interpretation we must combine the cross sections of the resolved and the direct process. Then we should also study the M_γ dependence of the combined cross section in this region. Since only the sum of both components is supposed to be stable with respect to the change of M_γ we must expect that any statement on the relative magnitude of direct and resolved cross section will change with the choice of the photon factorization scale.

It is the purpose of this note to investigate the M_γ dependence of the resolved and the direct cross section separately and to see whether their sum becomes stable. In addition we shall look for the effect of different factorization schemes for the photon structure function namely the $\overline{\rm MS}$ and the DIS$_\gamma$ scheme of Glück, Reya and Vogt [10].
In sect.2 we shall explain the theoretical input for our calculation and the precise definition of the NLO corrections. Numerical results are presented in sect.3.

2 Theoretical Input

We shall focus on the inclusive single-jet cross section in quasi-real photoproduction at HERA. We adopt the jet definition of the Snowmass meeting [11] defining a jet as an ensemble of outgoing particles contained within a cone of radius R in the plane of pseudorapidity and azimuth around the jet momentum. Within this jet algorithm in some region of phase space the jet multiplicity is not well-defined. Then, two partons may be viewed as a single jet and also as two seperate ones. In this case we have adopted the convention of [13] taking into account only the first choice.

The theoretical framework used in this paper is well known [12], so we shall restrict ourselves to some relevant details of our calculation. In resolved photoproduction the hard scattering is a pure parton-parton scattering process, i.e. only quarks and gluons are involved. The NLO, $\mathcal{O}(\alpha_s^3)$, corrections to the inclusive single-jet cross section have been worked out independently by two groups for $p\bar{p}$-scattering [13-15]. These groups used different methods in intermediate stages of their calculation. Their results agree nicely with CDF experimental data [16]. For resolved photoproduction the antiproton structure function has to be replaced by the photon structure function which must also be evaluated at NLO. For very small cone radii $R \ll 1$ the inclusive single-jet cross section has been calculated analytically by Aversa *et al.* [14], neglecting contributions vanishing in the limit $R \to 0$. For large cone sizes, $R \propto \mathcal{O}(1)$, the corresponding necessary corrections are calculated numerically from the 2→3 parton scattering cross section. The infrared and collinear singularities had been cancelled already in the analytical part against the virtual corrections and the redefinition of parton densities in the incoming particles. So, the *finite cone corrections* are finite. Further details can be found in [5,15].

The central variable to control the interplay between direct and resolved photoproduction is the factorization scale of the photon, M_γ. This occurs in the photonic parton densities $f_{i/\gamma}(x, {M_\gamma}^2)$ and in certain additional terms in the NLO parton-parton scattering cross section. In the formulas of Aversa *et al.* [14] the two factorization scales of the initial state hadrons have been set equal. We evaluated the additional pieces which result from $M_\gamma \neq M_p$ by eliminating the dependence on both factorization scales in [14] by fixing $M = \sqrt{s}$ to the parton-parton center-of-mass energy and then adding these scale dependent terms explicitely with $M_\gamma \neq M_p$. Then, the cross section has the following form:

$$
\begin{aligned}
\frac{d^2\sigma}{dE_T d\eta}(\gamma p \to jet + X) \;=\; & \frac{d^2\sigma}{dE_T d\eta}(\gamma p \to jet + X)\Big|_{M_\gamma^2 = M_p^2 = s} \qquad (1)\\
& + \frac{\alpha_s}{2\pi} \int_{VW}^{V} \frac{dv}{1-v} \int_{VW/v}^{1} \frac{dw}{w} \sum_{i,j} f_{i/\gamma}(\frac{VW}{vw}, M_\gamma^2) f_{j/p}(\frac{1-V}{1-v}, M_p^2) \\
& \Big\{ \sum_{i'} \mathcal{H}_{i' \leftarrow i}(w, M_\gamma) \frac{1}{v} \frac{d\sigma^{lo}}{dv}|_{i'j \to jet+X}(ws, v) \\
& \quad + \sum_{j'} \mathcal{H}_{j' \leftarrow j}(w', M_p) \frac{1}{v'} \frac{d\sigma^{lo}}{dv}|_{ij' \to jet+X}(w's, v') \Big\}
\end{aligned}
$$

with $v' = 1 - vw$, $w' = (1-v)/v'$ and

$$
\mathcal{H}_{b \leftarrow a}(x, M) = \frac{C_b}{C_a} P_{b \leftarrow a}(x) \log \frac{s}{M^2} \quad . \qquad (2)
$$

The variables $v = 1 + t/s$ and $vw = -u/s$ are defined in terms of the usual Mandelstam variables $s = (p_{a/\gamma} + p_{b/\gamma})^2$, $t = (p_{a/\gamma} - p_{jet})^2$ and $u = (p_{b/p} - p_{jet})^2$, respectively [14]. Remember that jet cross sections have to be invariant under the exchange $t \leftrightarrow u$. Here, lower case letters denote variables on the parton level whereas the corresponding upper case letters are defined within the γp context. The colour factors C_i are $C_q = N_c$, $C_G = N_c^2 - 1$, and $C_\gamma = 1$. We remark, that the extra terms in (1) are $\mathcal{O}(\alpha_s^3)$. They are needed for consistency when the scales of the parton densities in the photon and the proton are varied independently. The additional terms in (1) have a characteristic form in terms of the partonic splitting functions $P_{b \leftarrow a}$ and the LO 2→2 parton cross sections, $(d\sigma/dv)^{\mathrm{lo}}$.

The NLO corrections for the direct process have been calculated by one of us using the method of Ellis *et al.* [13]. The phase space integral for the 2⟶3 parton scattering contribution has been made finite by subtracting appropriate terms from the integrand. On the other hand, the phase space integral for the subtracted terms have been calculated analytically. The resulting terms have been added to the virtual 2⟶2 parton scattering contribution yielding a finite result after the factorization of the initial state collinear singularities. The relevant formulas can be found in [3]. There the two factorization scales M_γ and M_p appear explicitely, so that they can be varied independently. Some numerical results have been presented in a short communication [2]. In ref. [3] also the inclusive two-jet cross section was calculated. The results in ref. [3] have been obtained in the $\overline{\mathrm{MS}}$ factorization scheme for the photon. The transformation to the DIS_γ scheme is described in ref. [10].

Concerning structure functions we used for the proton the set MRS-D_0 of Martin *et al.* [17] which are in the NLO approximation with $\overline{\mathrm{MS}}$ factorization. For the photon we have chosen the NLO parmetrizations of Glück, Reya and Vogt [10] in the $\overline{\mathrm{MS}}$ scheme. The transformation from the DIS_γ scheme, which was chosen for the fit to the photon structure function in [10], to the $\overline{\mathrm{MS}}$ scheme has been done with the formulas given in

[10][1]. The MRS-D_0 version of Martin *et al.* does not describe recent structure function measurements at very low x at HERA [18]. However, this does not affect our results since the jet cross sections in the HERA region are not sensitive to the low-x region if $E_T \geq 5\,\mathrm{GeV}$. The running coupling $\alpha_s(\mu)$ is used in 2-loop approximation [19] with four flavours and $\Lambda_{\mathrm{QCD}} = 191$ MeV. We define the rapidity to be positive in the direction of the incoming electron. We took $p_e = 27\,\mathrm{GeV}$ and $p_p = 820\,\mathrm{GeV}$ giving a center-of-mass energy of $\sqrt{S} = 298\,\mathrm{GeV}$.

Within the Weizsäcker-Williams approximation the spectrum of quasi real photons carrying a longitudinal momentum fraction x is given by

$$x f_{\gamma/e}(x) = \frac{\alpha}{2\pi}(1 + (1-x)^2) \log\left(\frac{\hat{Q}^2(1-x)}{m_e^2 x^2}\right), \qquad (3)$$

where $\hat{Q}^2 = 0.01\,GeV^2$ is the upper limit of the photon virtuality and m_e is the electron mass.

3 Results

The first issue is the compensation of the M_γ dependence between direct and resolved cross sections. For comparison we show in Fig.1a the LO cross sections for direct (dotted line) and resolved (dashed line) photoproduction at $\eta_{Lab} = -1.5$ and $E_T = 25\,\mathrm{GeV}$. While the LO direct cross section is independent of $\xi_\gamma = M_\gamma/E_T$, the resolved cross section increases with ξ_γ due to the M_γ dependence of the photon structure function. Then also the sum of both cross sections in LO, which we shall call the LO complete photon cross section, has the same dependence on ξ_γ as the LO resolved cross section. Due to this strong scale dependence and the missing sensitivity to the jet recombination cut at LO it does not make sense to compare it to experimental data. Next we present the same cross sections in NLO in Fig.1b, again for $\eta_{Lab} = -1.5$ and $E_T = 25\,\mathrm{GeV}$. We see that the NLO direct (dotted lines) and the NLO resolved (dashed lines) cross sections have opposite ξ_γ dependencies. The sum of both, the complete photon cross section at NLO, is fairly constant. In Fig.1b we have plotted our results for $R = 0.3$, 0.7 and 1.0. Note, that the cross section increases monotonically with R. Comparing Figs.1a and 1b we notice that the ξ_γ dependence of the NLO resolved photon cross sections in all three cases is reduced as compared to the LO cross section in Fig.1a. The independence is best for $R = 0.3$. The compensation observed in Fig.1b should eliminate exactly the dependence on M_γ up to $\mathcal{O}(\alpha\alpha_s^2)$. Since the NLO resolved cross section contains already important pieces of $\mathcal{O}(\alpha\alpha_s^3)$ the compensation can not be complete, some NNLO (next-to-next-to-leading order) effects are still visible. Results very similar to those shown in Fig.1 have been obtained also for other values of E_T and η_{Lab}.

[1] One should keep in mind that this $\overline{\mathrm{MS}}$ parametrization has not been obtained by a new fit to all photon structure function data, as it should have been done.

However, to get an idea what kind of ξ_γ dependence we can expect for the complete cross section we should study the dependence of all three NLO cross sections (direct, resolved and complete) as a function of the proton factorization scale ξ_p defined by $M_p = \xi_p E_T$. The result for the ξ_p variation is shown in Fig.2 for $E_T = 25\,\mathrm{GeV}$, $\eta_{Lab} = -1.5$ and $R = 0.7$ and 1.0. All cross sections show a very flat behaviour as a function of ξ_p, as we should expect since all three are complete NLO evaluations with respect to the proton structure function. To establish a simple quantitative measure of the scale dependences ξ_m ($m = p, \gamma$ and $p + \gamma$) of the various cross sections we define

$$\rho_m = \frac{d\sigma(\xi_m = 4) - d\sigma(\xi_m = 0.25)}{d\sigma(\xi_m = 4) + d\sigma(\xi_m = 0.25)}. \tag{4}$$

At $E_T = 25\,\mathrm{GeV}$, $\eta_{Lab} = -1.5$ and $R = 1$ we found the values given in Tab.1 for LO and NLO direct, resolved and complete cross section. Comparing $\rho_\gamma(LO)$ with $\rho_\gamma(\mathrm{NLO})$ for the complete photon we see that the dependence on M_γ is reduced by a factor of 2. Nearly the same factor occurs when comparing $\rho_p(LO)$ and $\rho_p(\mathrm{NLO})$ for all three cross sections. The remaining ξ_m sensitivities at NLO are of comparable size for $m = \gamma$ and $m = p$, respectively.

In the last column we show $\rho_{p+\gamma}(\mathrm{NLO})$, which measures the scale variation of the three cross sections with $\xi_{p+\gamma} = M_\gamma/E_T = M_p/E_T$, i.e. where both factorization scales are varied simultaneously while $\mu = E_T$ is fixed. Comparing with the values of $\rho_\gamma(\mathrm{NLO})$ and $\rho_p(\mathrm{NLO})$ we find good agreement with

$$\rho_{p+\gamma} = \rho_p + \rho_\gamma \quad . \tag{5}$$

We observe that $\rho_{p+\gamma}$ is indeed small for the complete photon cross section. At least in the ξ-range examined, the cross sections can be written as

$$d\sigma(\xi_\gamma, \xi_p) = d\sigma(1,1)\ (1 + a_\gamma \log \xi_\gamma + a_p \log \xi_p)\ . \tag{6}$$

Then, (5) is nothing else but $a_{p+\gamma} = a_p + a_\gamma$. Because of the R dependence of the coefficients a_m, for cone sizes $R \neq 1$ the values of ρ_m in Tab.1 are in general different. However, the structure in (6) is only an approximate one and is not expected to hold, when higher orders are included.

Up to now we used the $\overline{\mathrm{MS}}$ scheme in the photon structure function $\mathcal{F}_2^\gamma$. Glück *et al.* introduced a so-called DIS$_\gamma$ scheme, which eliminates terms that are logarithmically singular when x→1. These terms must then be taken into account in the direct photon cross section and we shall expect that the sum will not change very much when comparing to the $\overline{\mathrm{MS}}$ factorization scheme. We show in Fig.3a the ξ_γ dependence of the NLO cross sections of the direct, resolved and complete photon, for both the DIS$_\gamma$ scheme (lines without circles) and in the $\overline{\mathrm{MS}}$ scheme (lines with extra circles). The direct and the resolved components change only slightly. The cross section of the complete photon is nearly independent of the scheme. These results are for $E_T = 25\,\mathrm{GeV}$, $\eta_{Lab} = -1.5$ and $R = 1$. However, because of the explicit form of the corresponding transformations [10] this behaviour depends in fact on E_T and the rapidity considered. Clearly the difference vanishes in the domain of the unaffected gluon density in the photon, $f_{G/\gamma}$, i.e. for small

E_T. This is demonstrated in Fig.3b where we show the equivalent results for $E_T = 5\,\mathrm{GeV}$. Both, the direct and the resolved component show little variation when we switch from the $\overline{\mathrm{MS}}$ to the DIS$_\gamma$ scheme and so does their sum (the small wiggles with ξ_γ are caused by the interpolation routine used and have no significance). Compared to our earlier results in Fig.1b where we demonstrated the ξ_γ dependence of the two components in the $\overline{\mathrm{MS}}$ scheme for $E_T = 25\,\mathrm{GeV}$ we see in Fig.3b also how they change for $E_T = 5\,\mathrm{GeV}$. We remark the strong variation of the ratio *direct/resolved* at $E_T = 5\,\mathrm{GeV}$. Consequently, any statement of pertubation theory concerning the dominance of one part relative to the other is strongly a matter of the photon factorization scale.

As our last point we investigated the behaviour under simultaneous variation of all three scales, i.e. $\mu = M_p = M_\gamma = \xi_{all} E_T$, again for $E_T = 25\,\mathrm{GeV}$ and $\eta_{Lab} = -1.5$. In Fig.4a the well-known scale dependence of the LO cross sections, essentially dominated by the μ dependence of α_s, is seen. When adding the NLO corrections, the resolved part shows a R dependent local maximum in ξ_{all} (see Fig.4b). At $R = 0.7$ the scale dependence within the range of ξ shown becomes most stable. This was already obtained in our earlier work [5]. The complete photoproduction cross section at NLO behaves very similar to this, but the value of the *best* R is lowered somewhat down to $R \approx 0.3$. This is due to the different scale dependence of the direct part caused by the photon factorization scale [2]. Clearly, the interesting similarities between photoproduction and hadroproduction [20] disappear when including the direct coupling of the photon to the quarks which is necessary for large E_T and scales near $\xi = 1$.

To conclude, we have seen that the separation of direct versus resolved NLO photoproduction, is a matter of definition. Only the sum of both leads to a dependence on the factorization scale M_γ of consistently negligible higher orders at NLO pertubative QCD. The separate use of one part only has to be done carefully even in those kinematic (E_T, η_{Lab}) ranges where 'obviously' one part dominates. At NLO the ratio direct/resolved depends on M_γ even stronger then at LO. The dependence on the factorization scale in the proton, on the other hand, always shows up to be very flat. Adding the direct contribution to the inclusive single-jet cross section in resolved photoproduction modifies the value of the *best* R, where an optimimal stability under variation of all three scales should allow for rather accurate theoretical predictions. The problems we discussed in this note are due to the structure of the quasi-real photon and should be very similar in other photoproduction processes, rather independent of the final state under consideration as demonstrated for single-charged hadron cross sections in [21].

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Figure Captions

Fig.1 Inclusive single-jet cross section $d\sigma/dE_T d\eta_{Lab}$ for direct(dotted lines), resolved (dashed lines) and complete(full lines) photoproduction, as a function of the factorization scale in the photon. (a) Leading order, (b) NLO with $R = 0.3, 0.7$ and 1.0 (cross section increases with R).

Fig.2 Inclusive single-jet cross section $d\sigma/dE_T d\eta_{Lab}$ for direct(dotted lines), resolved (dashed lines) and complete(full lines) photoproduction as a function of the factorization scale in the proton at NLO with $R = 0.7$ and 1.0 (cross section increases with R).

Fig.3 Comparison of factorization schemes. The full NLO contributions of the direct(dotted lines) and of the resolved (dashed lines) photon are shown as well as the sum of both (full lines). The $\overline{\rm MS}$ results are indicated by additional circles. $R = 0.7$, $\eta_{Lab} = -1.5$ and $E_T = 25$GeV (Fig.3a) and $E_T = 5$GeV (Fig.3b).

Fig.4 $d\sigma/dE_T d\eta_{Lab}$ for direct(dotted lines), resolved(dashed lines) and complete(full lines) photoproduction as a function of all three scales with $\mu = M_p = M_\gamma = \xi_{all} E_T$. (a) Leading order, (b) NLO with $R = 0.3$ and 0.7 (cross sections increase with R).

Table Captions

Tab.1 Normalized variations ρ of the inclusive single-jet cross section $d\sigma/dE_T d\eta_{Lab}$ with the factorization scales M_γ and M_p at $E_T = 25$ GeV, $R = 1$, as defined in (4). The simultaneous change of both scales is indicated by the index '$p + \gamma$'.

Tables

	ρ_γ (LO)	ρ_γ (NLO)	ρ_p (NLO)	ρ_p (LO)	$\rho_{p+\gamma}$(NLO)
direct	0.00	-0.29	-0.04	-0.12	-0.32
resolved	0.26	0.28	-0.07	-0.16	0.23
complete	0.15	0.07	-0.06	-0.15	0.01

Tab.1