Factorization scheme and scale dependence in diffractive dijet production at low $Q^2$

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Abstract. We calculate diffractive dijet production in deep-inelastic scattering at next-to-leading order of perturbative QCD, including contributions from direct and resolved photons, and compare our predictions to preliminary data from the H1 collaboration at HERA. We study how the cross section depends on the factorization scheme and scale $M_\gamma$ at the virtual photon vertex for the occurrence of factorization breaking. The strong $M_\gamma$-dependence, which is present when only the resolved cross section is suppressed, is tamed by introducing the suppression also into the initial-state NLO correction of the direct part.

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1. Introduction

It is well known that in high-energy deep-inelastic $ep$-collisions a large fraction of the observed events are diffractive. These events are defined experimentally by the presence of a forward-going system $Y$ with four-momentum $p_Y$, low mass $M_Y$ (in most cases a single proton or a proton plus low-lying nucleon resonances), small momentum transfer squared $t = (p - p_Y)^2$, and small longitudinal momentum transfer fraction $x_F = q(p - p_Y)/qp$ from the incoming proton with four-momentum $p$ to the system $X$ (see Fig. 1). The presence of a hard scale, as for example the photon virtuality $Q^2 = -q^2$ in deep-inelastic scattering (DIS) or the large transverse jet momentum $p_T^\ast$ in the photon-proton center-of-momentum frame, should then allow for calculations of the production cross section for the central system $X$ with the known methods of perturbative QCD. Under this assumption, the cross section for the inclusive production of two jets, $e + p \rightarrow e + 2\text{jets} + X' + Y$, can be calculated from the well-known formulæ for jet production in non-diffractive $ep$ collisions, where in the convolution of the partonic cross section with the parton distribution functions (PDFs) of the proton the latter ones are replaced by the diffractive PDFs. In the simplest approximation, they are described by the exchange of a single, factorizable pomeron/Regge-pole.

The diffractive PDFs have been determined by the H1 collaboration at HERA from high-precision inclusive measurements of the DIS process $ep \rightarrow eXY$ using the usual DGLAP evolution equations in leading order (LO) and next-to-leading order (NLO) and the well-known formula for the inclusive cross section as a convolution of the inclusive parton-level cross section with the diffractive PDFs \[1\]. For a similar analysis of the inclusive measurements of the ZEUS collaboration see \[2\]. For inclusive diffractive DIS it has been proven by Collins that the formula referred to above is applicable without additional corrections and that the inclusive jet production cross section for large $Q^2$ can be calculated in terms of the same diffractive PDFs \[3\]. The proof of this factorization formula, usually referred to as the validity of QCD factorization in hard diffraction, also appears to be valid for the direct part of photoproduction ($Q^2 \simeq 0$) or low-$Q^2$ electroproduction of jets \[3\]. However, factorization does not hold for hard processes in diffractive hadron-hadron scattering. The problem is that soft interactions between the incoming two hadrons and their remnants occur in both the initial and final state. This agrees with experimental measurements at the Tevatron \[4\]. Predictions of diffractive dijet cross sections for $p\bar{p}$ collisions as measured by CDF using the same PDFs as determined by H1 \[1\] overestimate the measured cross section by up to an order of magnitude \[4\]. This suppression of the CDF cross section can be explained by considering the rescattering of the two incoming hadron beams which, by creating additional hadrons, destroy the rapidity gap \[5\].

Processes with real photons ($Q^2 \simeq 0$) or virtual photons with fixed, but low $Q^2$ involve direct interactions of the photon with quarks from the proton as well as re-
solved photon contributions, leading to parton-parton interactions and an additional remnant jet coming from the photon (for a review see [6]). As already said, factorization should be valid for direct interactions as in the case of DIS, whereas it is expected to fail for the resolved process similar as in the hadron-hadron scattering process. In a two-channel eikonal model similar to the one used to calculate the suppression factor in hadron-hadron processes [5], introducing vector-meson dominated photon fluctuations, a suppression by about a factor of three for resolved photoproduction at HERA is predicted [7]. Such a suppression factor has recently been applied to diffractive dijet photoproduction [8, 9] and compared to preliminary data from H1 [10] and ZEUS [11]. While at LO no suppression of the resolved contribution seemed to be necessary, the NLO corrections increase the cross section significantly, showing that factorization breaking occurs at this order for resolved photoproduction and that a suppression factor $R = 0.34$, in agreement with the prediction of [7], gives a reasonable description of the experimental data of [10] and [11].

As already mentioned in our earlier work [8, 9], describing the factorization breaking in hard photoproduction as well as in electroproduction at very low $Q^2$ [12] by suppressing the resolved contribution only may be problematic. An indication for this is the fact that the separation between the direct and the resolved process is uniquely defined only in LO. In NLO these two processes are related. The separation depends on the factorization scheme and the factorization scale $M_\gamma$. The sum of both cross sections

\[ e(k) s \rightarrow eXY, \]

where the hadronic systems $X$ and $Y$ are separated by the largest rapidity gap in the final state.
is the only physically relevant cross section, which is approximately independent of the factorization scheme and scale \cite{13}. We demonstrated already in \cite{8, 9} that by multiplying the resolved cross section with the suppression factor $R = 0.34$, the correlation of the $M_\gamma$-dependence between the direct and resolved part is destroyed and the sum of both parts has a stronger $M_\gamma$-dependence than for the unsuppressed case ($R = 1$), where the $M_\gamma$-dependence of the NLO direct cross section is compensated to a high degree against the $M_\gamma$-dependence of the LO resolved part. The introduction of the resolved cross section is dictated by perturbation theory. At NLO, collinear singularities arise from the photon initial state, which are absorbed at the factorization scale into the photon PDFs. This way the photon PDFs become $M_\gamma$-dependent. The equivalent $M_\gamma$-dependence, just with the opposite sign, is left in the NLO corrections to the direct contribution. With this knowledge, it is obvious that we can obtain a physical cross section at NLO, \textit{i.e.} the superposition of the NLO direct and LO resolved cross section, with a suppression factor $R < 1$ and no $M_\gamma$-dependence left, if we also multiply the $\ln M_\gamma$-dependent term of the NLO correction to the direct contribution with the same suppression factor as the resolved cross section.

It is the purpose of this paper to present the special form of the $\ln M_\gamma$-term in the NLO direct contribution and then, after multiplying it with the suppression factor $R$, to demonstrate that the $M_\gamma$-dependence of the physical cross section cancels to a large extent in the same way as in the unsuppressed case ($R = 1$), if we modify the suppression mechanism in the way as explained above. Of course, some small $M_\gamma$-dependence will remain, also in the case with the suppression of the $\ln M_\gamma$-part in the direct contribution, which is due to the evolution of the photon PDFs and/or the NLO correction to the resolved part, which is left uncompensated as long as the NNLO contribution to the direct part is not included.

In addition to checking the $M_\gamma$ scale dependence we shall study how the NLO cross section depends on the factorization scheme for the photon PDFs. These studies can be done for photoproduction ($Q^2 \simeq 0$) as well as for electroproduction with fixed, small $Q^2$. Since in electroproduction the initial-state singularity in the limit $Q^2 \to 0$ is more directly apparent than for the photoproduction case, where this singularity appears as a pole in $d-4$ using dimensional regularization, we shall consider in this paper the low-$Q^2$ electroproduction case just for demonstration. This diffractive dijet cross section has been calculated recently \cite{12}. In this work $d\sigma/dQ^2$ as a function of $Q^2$ and $d\sigma/dz_{IP}$ as a function of $z_{IP}$ for various $Q^2 + p_T^2$ bins was calculated for H1 kinematical conditions and compared to the preliminary experimental data from H1 \cite{14}. Here, $z_{IP}$ is the parton momentum fraction in the pomeron. In the following we shall consider these cross sections with the same kinematical constraints as in \cite{12}.

A consistent factorization scheme for low-$Q^2$ virtual photoproduction has been defined and the full (direct and resolved) NLO corrections for inclusive dijet production
have been calculated in [15]. In this work we adapt this inclusive NLO calculational framework to diffractive dijet production at low-$Q^2$ in the same way as in [12], except that we multiply the $\ln M_\gamma$ dependent terms as well as the resolved contributions with the same suppression factor $R = 0.34$ as in our earlier work [8, 9, 12]. The exact value of this suppression factor may change in the future, when better data for photoproduction and low-$Q^2$ electroproduction have been analyzed.

In the next Section, we shall define the H1 kinematical constraints and present the $\ln M_\gamma$-dependent terms in the NLO corrections to the direct cross section, as they are reported in [15]. We shall also define which specific contribution of this initial-state NLO correction will be suppressed with the same factor $R$ as the resolved part. Then we give our results concerning the scheme dependence of the photon PDFs by looking at $d\sigma/dQ^2$ and $d\sigma/dz_{IP}$ using two different schemes. After this we present the $\ln M_\gamma$-dependence of the partly suppressed NLO direct and the fully suppressed NLO resolved cross section $d\sigma/dQ^2$ and their sum for the lowest $Q^2$ bin. After this we study the $M_\gamma$-dependence of $d\sigma/dQ^2$ for the other $Q^2$-bins and of $d\sigma/dz_{IP}$ and compare always with the H1 data. As the last point we study the contribution of the hadron-like or vector-dominance part of the resolved cross section in order to see whether the suppression of this part alone could be an alternative to solve the $M_\gamma$ scale problem as suggested in [8, 9].

2. Kinematical constraints and results

The factorization scheme for virtual photoproduction has been defined and the full NLO corrections for inclusive dijet production have been calculated in [15]. They have been implemented in the NLO Monte Carlo program JETVIP [16]. We have adapted this NLO framework to diffractive dijet production. According to [15], the subtraction term, which is absorbed into the PDFs of the virtual photon $f_{a/\gamma}(x, M_\gamma)$, is of the form

$$S_{q_i \rightarrow \gamma}(z, M_\gamma) = \ln \left( \frac{M_\gamma^2}{Q^2(1-z)} \right) P_{q_i \rightarrow \gamma}(z) - N_c Q_i^2. \tag{1}$$

In Eq. (1), $z = p_1 p_2 / p_0 q \in [x; 1]$ and the splitting function $P_{q_i \rightarrow \gamma}(z)$ is

$$P_{q_i \rightarrow \gamma}(z) = 2 N_c Q_i^2 z^2 + (1-z)^2. \tag{2}$$

$Q_i$ is the fractional charge of the quark $q_i$, $p_1$ and $p_2$ are the momenta of the two outgoing jets, and $p_0$ and $q$ are the momenta of the ingoing parton and virtual photon, respectively. Since $Q^2 \ll M_\gamma^2$, the subtraction term in Eq. (1) is large and is therefore resummed by the DGLAP evolution equations for the virtual photon PDFs. After the subtraction of Eq. (1), the finite term, which remains in the matrix element for the NLO correction to the direct process, is [15]

$$M(Q^2)_{\overline{MS}} = - \frac{1}{2 N_c} P_{q_i \rightarrow \gamma}(z) \ln \left( \frac{M_\gamma^2 z}{(z Q^2 + y_s)(1-z)} \right) + \frac{Q_i^2}{2}. \tag{3}$$

This term is defined by the requirement that it is equal to $M_{\overline{MS}}$ for real photons, if $Q^2 = 0$. For our study of the $M_\gamma$-dependence of the physical cross section it is essential to
recognize that the $M_\gamma$-dependence in Eq. (3) is the same as in the subtraction term Eq. (1), i.e. ln $M_\gamma$ is multiplied with the same factor (except that the subtraction term $S$ has to be multiplied by $-1/(2N_c)$). As already mentioned, this yields the $M_\gamma$-dependence before the evolution is turned on. In the usual non-diffractive dijet photoproduction these two $M_\gamma$-dependences, i.e. in Eqs. (1) and (3), cancel, when the NLO correction to the direct part is added to the LO resolved cross section [13]. Then it is obvious that the approximate $M_\gamma$-independence is destroyed, if the resolved cross section is multiplied by the suppression factor $R$ to account for the factorization breaking in the experimental data. To remedy this deficiency, we propose to multiply the ln $M_\gamma$-dependent term in $M(Q^2)_{\overline{\text{MS}}}$ with the same suppression factor as the resolved cross section. This is done in the following way: We split $M(Q^2)_{\overline{\text{MS}}}$ into two terms using the scale $p^*_T$ in such a way that the term containing the slicing parameter $y_s$, which was used to separate the initial-state singular contribution, remains unsuppressed. In particular, we replace $M(Q^2)_{\overline{\text{MS}}}$ by

$$M(Q^2, R)_{\overline{\text{MS}}} = \left[ -\frac{1}{2N_c} P_{q_i\to\gamma}(z) \ln \left( \frac{M_\gamma^2}{p^2_T(1-z)} \right) + \frac{Q^2_i}{2} \right] R$$

$$-\frac{1}{2N_c} P_{q_i\to\gamma}(z) \ln \left( \frac{p^2_T}{zQ^2 + y_s s} \right),$$

where $R$ is the suppression factor. This expression coincides with $M(Q^2)_{\overline{\text{MS}}}$ in Eq. (3) for $R = 1$, as it should, and leaves the second term in Eq. (4) unsuppressed. In Eq. (4) we have suppressed in addition to ln($M^2/p^2_T$) also the $z$-dependent term ln($z/(1-z)$), which is specific to the $\overline{\text{MS}}$ subtraction scheme as defined in [15]. To keep this term unsuppressed, i.e. to move it to the second term in Eq. (4), would again produce an inconsistency with the suppressed resolved contribution. The second term in Eq. (4) must be left in its original form, i.e. being unsuppressed, in order to achieve the cancellation of the slicing parameter dependence of the complete NLO correction in the limit of very small $Q^2$ or equivalently very large $s$. With these arguments the splitting of the terms in Eq. (3), which can be suppressed, and those terms, which remain unsuppressed, is almost unique. It is clear that the suppression of this part of the NLO correction to the direct cross section will change the full cross section only very little as long as we choose $M_\gamma \approx p^*_T$. The first term in Eq. (4), which has the suppression factor $R$, will be denoted by DIR$_{\overline{\text{MS}}}$ in the following.

To study the left-over $M_\gamma$-dependence of the physical cross section, we have calculated the diffractive dijet cross section with the following kinematical constraints as in the H1 experiment [14]: The electron and proton beam energies are 27.5 and 820 GeV, respectively, $4 < Q^2 < 80$ GeV$^2$ is the range of the squared electron momentum transfer, $0.1 < y < 0.7$ is the interval of virtual photon energy fraction, $x_{FV} < 0.05$, $|t| < 1$ GeV$^2$, $M_T < 1.6$ GeV, $p^2_{T,\text{jet}1,2} > 5(4)$ GeV, and jet rapidities $-3 < \eta_{\text{jet}1,2} < 0$. Jets are defined by the CDF cone algorithm with jet radius equal to one. The asymmetric cuts for the transverse momenta of the two jets are required for infrared stable comparisons with the
NLO calculations [17]. The original H1 analysis actually used a symmetric cut of 4 GeV on the transverse momenta of both jets [18]. The data have, however, been reanalyzed for asymmetric cuts [14]. In the extraction of the diffractive parton densities the usual Regge factorization ansatz [19]

\[ f_i^D(\xi, Q^2, x_F, t) = f_{p/p}^i(x_F, t) f_i(\xi x_F, Q^2) \]  

(5)

has been employed, which we shall use also in our computations. This ansatz neglects a possible scale dependence of \( f_{p/p}^i \), which could be responsible for a change of the \( x_F \) dependence between the soft and the hard pomeron exchange. In the analysis of H1 [1] the intercept \( \alpha_s^P(0) \) is extracted from the diffractive DIS data. For an alternative approach, where the factorization assumption in Eq. (5) is modified see [20].

For the NLO resolved virtual photon predictions, we have used the PDFs SaS1D [21] and transformed them from the DIS to the \( \overline{\text{MS}} \) scheme as in [15]. If not stated otherwise, the renormalization and factorization scales at the pomeron and the photon vertex are equal and fixed to \( p_T^* = p_{T,jet}^* \). We include four flavours, *i.e.* \( n_f = 4 \) in the formula for \( \alpha_s \) and in the PDFs of the pomeron and the photon. The SaS-type PDFs for the virtual photon are chosen, since in their parametrization the scale dependence following from the evolution is given separately for the hadronic part and the point-like part, which is called the anomalous part in [21].

With these assumptions we have calculated the same cross section as in our previous work [12]. First we investigated how the cross section \( d\sigma/dQ^2 \) depends on the factorization scheme of the PDFs for the virtual photon, *i.e.* \( d\sigma/dQ^2 \) is calculated for the choice SaS1D and SaS1M. Here \( d\sigma/dQ^2 \) is the full cross section (sum of direct and resolved) integrated over the momentum and rapidity ranges referred to above. The results are shown in Fig. 2, where \( d\sigma/dQ^2 \) with SaS1D (full line) is compared to \( d\sigma/dQ^2 \) with SaS1M (dashed line). The theoretical cross sections are integrated over the same \( Q^2 \) bins as the experimental ones. In this figure and in all the following ones, except Fig. 4 where we study the explicit \( M_\gamma \)-dependence, both predictions are obtained with suppressed resolved cross section and the additional suppression of DIR as described above with suppression factor \( R = 0.34 \). As we can see in Fig. 2, the choice of the factorization scheme of the virtual photon PDFs has negligible influence on \( d\sigma/dQ^2 \) for all considered \( Q^2 \). The predictions agree reasonably well with the preliminary H1 data [14]. Comparing with our previous results [12] we notice that the cross sections in Fig. 2 are somewhat smaller than the corresponding ones in Fig. 2 of [12]. This is, however, not the effect of the additional suppression of a NLO term in the direct cross section. The difference comes instead from a different choice of the overall scales in [12] which was fixed to the average \( \langle p_T^* \rangle = \sqrt{40} \) GeV. Another check on the effect of a different choice of the factorization scheme is shown in Fig. 3 where the dependence of the cross section \( d\sigma/dz_F \) as a function of \( z_F \) is plotted for various ranges of \( Q^2 + p_T^2 \). From this plot we see that the scheme dependence is again very small for all \( Q^2 + p_T^2 \) ranges and
Figure 2. Dependence of the diffractive dijet cross section at HERA on the squared photon virtuality $Q^2$. Preliminary H1 data [14] are compared with theoretical NLO predictions including resolved virtual photon and direct contributions with a suppression factor of $R = 0.34$ for the resolved and for the DIR$_{IS}$ term using virtual photon PDFs SaS1D (full) and SaS1M (dashed) from [21].

for all $z_{\gamma'} \in [0; 1]$. Except for the lowest $z_{\gamma'}$ bin and for the two highest $z_{\gamma'}$ bins in the two upper $Q^2 + p_T^2$ ranges, we observe reasonable agreement with the data. The agreement is best for the smallest $Q^2 + p_T^2 \in [20; 35] \text{ GeV}^2$ region and $z_{\gamma'} \geq 0.2$.

We now turn to the $M_\gamma$-dependence of the cross section with a suppression factor for DIR$_{IS}$, which is the main part of this paper. To show this dependence for the two suppression mechanisms, (i) suppression of the resolved cross section only and (ii) additional suppression of the DIR$_{IS}$ term as defined in Eq. (4) in the NLO correction of
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$ep \rightarrow e' + 2\text{jets} + X + Y$

$Q^2 + p_T^2 > 60 \text{ GeV}^2$

$Q^2 + p_T^2 \in [45, 60] \text{ GeV}^2$

$Q^2 + p_T^2 \in [35, 45] \text{ GeV}^2$

$Q^2 + p_T^2 \in [20, 35] \text{ GeV}^2$

**Figure 3.** Dependence of the diffractive dijet cross section at HERA on the parton momentum fraction in the pomeron $z_{IP}$ for different ranges of $Q^2 + p_T^2$. Preliminary H1 data [14] are compared with two theoretical predictions (as in Fig. 2) using SaS1D (full) and SaS1M (dashed) virtual photon PDFs [21].

the direct cross section, we consider $d\sigma/dQ^2$ for the lowest $Q^2$-bin, $Q^2 \in [4, 6] \text{ GeV}^2$. In Fig. 4, this cross section is plotted as a function of $\xi = M_\gamma/p_T^*$ in the range $\xi \in [0.25, 4]$ for the cases (i) (light full curve) and (ii) (full curve). We see that the cross section for case (i) has an appreciable $\xi$-dependence in the considered $\xi$ range of the order of 40%, which is caused by the suppression of the resolved contribution only. With the additional suppression of the DIRIS term in the direct NLO correction, the $\xi$-dependence of $d\sigma/dQ^2$ is reduced to approximately less than 20%, if we compare the maximal and the minimal value of $d\sigma/dQ^2$ in the considered $\xi$ range. The remaining $\xi$-dependence is
caused by the NLO corrections to the suppressed resolved cross section and the evolution of the virtual photon PDFs. How the compensation of the $M_\gamma$-dependence between the suppressed resolved contribution and the suppressed direct NLO term works in detail is exhibited by the dotted and dashed-dotted curves in Fig. 4. The suppressed resolved term increases and the suppressed direct NLO term decreases by approximately the same amount with increasing $\xi$. In addition we show also $d\sigma/dQ^2$ in the DIS theory, i.e. without subtraction of any $\ln Q^2$ terms (dashed line). Of course, this cross section must be independent of $\xi$. This prediction agrees very well with the experimental point,
whereas the result for the subtracted and suppressed theory (full curve) lies slightly below. We notice, that for $M_\gamma = p_T^*/4$ the additional suppression of DIR$_{IS}$ has only a small effect. It increases $d\sigma/dQ^2$ by 5% only.

In order to get an idea about the $M_\gamma$ scale dependence of $d\sigma/dQ^2$ for the other $Q^2$ bins and for $d\sigma/dz_p$ in the $Q^2 + p_T^2$ ranges as in Fig. 4, we have computed these two cross sections for two choices of $M_\gamma$, namely $M_\gamma = p_T^*/4$ and $M_\gamma = 4p_T^*$ corresponding to the lowest and highest $\xi$ in Fig. 4. The result for the $d\sigma/dQ^2$ is shown in Fig. 5. We see that the $M_\gamma$-dependence in the considered range decreases with increasing $Q^2$. This is to be expected since the resolved contribution diminishes with increasing $Q^2$, so that the NLO
corrections to the resolved cross section and the effect of the evolution of the photon PDF diminish as well. Similar conclusions can be drawn from Fig. 6 where we plotted $d\sigma/dz_{IP}$ in the four $Q^2 + p_T^2$-ranges. For all four ranges the dependence on $M_\gamma$ is small if $z_{IP} \geq 0.4$. Only for the two lowest $Q^2 + p_T^2$-ranges this cross section depends on $M_\gamma$ for the two lowest $z_{IP}$-bins and is strongest for $z_{IP} \in [0; 0.2]$ and $Q^2 + p_T^2 \in [20; 35]$ GeV$^2$.

As is well known the photon PDFs consist of a point-like or anomalous part, the hadron-like part and the gluon part. The compensation of the $M_\gamma$-dependence between the NLO direct and the LO resolved cross section occurs via the anomalous part. This means that this part of the PDFs is closely related to the direct cross section. If one
assumes that the direct part obeys factorization, i.e. has no suppression factor, it was suggested in [9], that one possibility to avoid the non-compensation of the $M_{\gamma}$-dependence between the suppressed resolved cross section and the unsuppressed direct cross section would be to suppress only the hadron-like and the gluon part of the PDFs. Fortunately, in the SaS-type photon PDFs the hadron-like and the anomalous part and the effect of their evolution are presented separately, so that the effect of the suppression of the hadron-like part can be investigated for all scales. It turns out, however, that the hadron-like part contributes only a very small fraction to the total resolved cross section. For $Q^2 = 5 \text{ GeV}^2$, this fraction is $3 \cdot 10^{-3}$, and it decreases strongly with increasing $Q^2$. This means that the anomalous component dominates the total resolved cross section and a suppression of the hadron-like part alone would not be sufficient to account for the experimental data at low $Q^2$. Although in the case of photoproduction ($Q^2 \simeq 0$) the hadron-like part is supposed to be larger, it would be quite artificial to have two different mechanisms for the $M_{\gamma}$-scale compensation depending on whether $Q^2 > 0$ or $Q^2 \simeq 0$. For this reason we prefer the mechanism with the suppression in the DIR$\text{IS}$ contribution to the NLO corrections of the direct cross section, which works for all $Q^2$.

3. Conclusions

In summary, we propose in this paper a new factorization scheme for diffractive production of jets in low-$Q^2$ deep inelastic scattering. By suppressing not only the resolved photon contribution, but also the unresummed logarithm as well as scheme-dependent finite terms in the NLO direct initial state correction, factorization scheme and scale invariance is restored up to higher order effects, while at the same time the cut-off invariance required in phase space slicing methods is preserved.

For pedagogical reasons, we have chosen in this paper the kinematical region of finite, but low photon virtuality $Q^2$, which exposes and regularizes a logarithmic virtual photon initial state singularity. We do, however, not rely on the finiteness of $Q^2$, but rather separate suppressed and unsuppressed terms using the hard transverse momentum scale $p_T^*$, so that our scheme is equally valid for real photoproduction. Furthermore, due to the universality of the initial state singularity, our new factorization scheme should apply to any other diffractive photon-induced process with a second hard scale, such as inclusive hadron-production at large $p_T^*$ or heavy quark and quarkonium production.

The scheme- and scale invariance has been demonstrated numerically using the kinematics of a recent H1 analysis, differential in $Q^2$ and parton momentum fraction in the pomeron $z_p$. Very good stability with respect to scheme- and scale variations and good agreement with the experimental data has been found.

Individual studies of the anomalous and hadronic component of the resolved
virtual photon show that the parton densities in the virtual photon are dominated by the resummed pointlike component, as expected from non-diffractive deep inelastic scattering. While suppressing only the hadronic component in the photon PDFs would also be scheme- and scale-invariant and therefore be theoretically consistent, our numerical study shows that this alternative is thus phenomenologically not viable.

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