Jet production at HERA

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Abstract. I review the status of perturbative QCD calculations for jet production in eP-scattering at HERA. I will discuss possibilities of combining fixed order, especially higher order, calculations and parton showers.

1. Introduction

Jet production in high-energy scattering is a classical testing ground for QCD. Not only can one measure typical QCD quantities, such as the strong coupling α_s or the parton distributions functions (PDF's), but also one has a handle to test perturbative QCD, including the factorization theorems. Furthermore jet production processes can provide important backgrounds for the search of new physics. Therefore jet production has received much attention in theoretical calculations and impressive progress has been made in the last decade to describe jet production in the framework of perturbative QCD.

Most available calculations have been performed in next-to-leading order (NLO) accuracy. There are several reasons to perform these NLO calculations. First, the theoretical uncertainties due to unphysical renormalization and factorization scale dependences are reduced. Second, due to the emission of additional particles in the initial and final state, one becomes sensitve to jet algorithms, which is certainly the case in the experimental results. Third, for the same reason, calculations become more sensitve to detector limitations. Finally, the presence of infrared (IR) logarithms is clearly seen and regions where resummation is needed can be identified.

In the following I will review the state-of-the-art for perturbative calculations for eP-scattering which can be tested at HERA. Jet production in eP-scattering involves large transverse energies E_T or photon virtualities Q^2. The presence of a large scale ensures that perturbative calculations can be performed and one can hope that hadronization corrections and theoretical uncertainties are small.‖ In the following I will not present many experimental results, since these have been reviewed nicely in this workshop by M. Wing [1].

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‖ In looking at theoretical errors, one should keep in mind also the selection of a stable jet algorithm to obtain reliable results [2].

Presently the limiting factor for higher precision measurements of QCD parameters are the systematic and theoretical uncertainties. Therefore, theoretical advances are in urge, such as NNLO calculations or NLO Monte Carlo programs (MC's) including parton showers and hadronization corrections. Therefore, I will also discuss possibilities of combining fixed order calculations and parton showers (PS), especially the problem of incorporating higher order corrections in the fixed order part of the MC's.

2. Jet cross sections at next-to-leading order

I start by summarizing the procedure for the numerical evaluation of an inclusive n-jet cross section in NLO QCD. The first step is to select a jet algorithm, which defines how partons are recombined to give jets. In the following we take for definiteness the invariant mass s_{ij} of two partons i and j and define the n-jet region such that $s_{ij} < s_{\min}$, with some kind of minimum mass $s_{\min}$, and likewise the $(n+1)$-jet region such that $s_{ij} > s_{\min}$ for all i, j. The LO process for the production of n jets consists of n final state partons and obviously does not depend on the jet definition. This dependence only comes in at NLO. The $\mathcal{O}(\alpha_s)$ corrections to this process are given by the ultraviolet (UV) and infrared (IR) divergent one-loop contributions to the n-parton configuration, which are the virtual corrections, and the NLO tree level matrix elements with $(n+1)$ partons, the real corrections. The tree-level matrix elements have to be integrated over the phase space of the additional parton, which gives rise to collinear and soft singularities. After renormalization, the singularities in the virtual and soft/collinear contributions cancel and remaining poles are absorbed into parton distribution functions. One wants to integrate most of the phase space of the real corrections numerically, but one needs to find a procedure to calculate the soft/collinear contributions analytically as to explicitly cancel the poles from the virtual corrections. The two basic methods to perform these integrations are the subtraction method [3, 4, 5] and the phase-space slicing (PSS) method [6, 7, 8, 9] (see also [10] for a review).

In the following we will make use of the PSS method and therefore discuss this method further. To illustrate the method, we rely on the classical example given by Kunszt and Soper [4]. We label the LO Born contribution as $\sigma^{\mathrm{LO}} = \sigma^B$. The NLO cross section is given by the sum of the Born cross section and the virtual and real corrections, σ^V and σ^R:

$$\sigma^{\mathrm{NLO}} = \sigma^B + \sigma^V + \sigma^R = \sigma^B + C_V - \lim_{\epsilon \to 0} \frac{1}{\epsilon} F(0) + \int_0^1 \frac{dx}{x} F(x) \; . \tag{1}$$

Here, $F(x)$ is the known, but complicated function representing the $(n+1)$-parton matrix elements. The variable x represents an angle between two partons or the energy of a gluon, the integral represents the phase-space intergation that has to be performed over the additional parton. The singularity of the real corrections at $x \to 0$ is compensated by the virtual corrections, given by the pole term and some constant, C_V. In the PSS method, the integral over the real corrections is divided into two parts, $0 < x < \delta$ and $\delta < x < 1$. We note that the technical cut-off δ should lie within the n jet region, i.e.,

if we define $y_{\rm cut} = s_{\rm min}/Q^2$, then we should have $\delta < y_{\rm cut}$. If the cut-off parameter is sufficiently small, $\delta \ll y_{\rm cut} < 1$, one can write

$$\begin{aligned}\sigma^R &= \int_0^1 \frac{dx}{x} F(x) \simeq \lim_{\epsilon\to 0}\left\{\int_\delta^1 \frac{dx}{x} x^\epsilon F(x) + F(0)\int_0^\delta \frac{dx}{x} x^\epsilon\right\} \\ &\simeq \int_\delta^1 \frac{dx}{x} F(x) + F(0)\ln(\delta) + \lim_{\epsilon\to 0}\frac{1}{\epsilon} F(0)\ , \end{aligned} \tag{2}$$

where the integral has been regularized by the term x^ϵ, as suggested by dimensional regularization. The pole is now explicit and the NLO cross section $\sigma^{\rm NLO}$ is finite:

$$\sigma^{\rm NLO} \simeq \sigma^B + C_V + \int_\delta^1 \frac{dx}{x} F(x) + F(0)\ln(\delta)\ . \tag{3}$$

Clearly, the real corrections σ^R should not depend on δ, and the logarithmic δ dependence of the last term in eqn (3) should be canceled by the integral, which sometimes is numerically difficult for very small parameters δ. However, an improvement of the above solution is possible by using a hybrid of the PSS and the subtraction methods, suggested by Glover and Sutton [11]. In this method, one adds and subtracts only the universal soft/collinear approximations for $x < \delta$, such that

$$\begin{aligned}\sigma^R &= \lim_{\epsilon\to 0}\left\{\int_0^1 \frac{dx}{x} x^\epsilon F(x) - F(0)\int_0^\delta \frac{dx}{x} x^\epsilon + F(0)\int_0^\delta \frac{dx}{x} x^\epsilon\right\} \\ &\simeq \int_\delta^1 \frac{dx}{x} F(x) + \int_0^\delta \frac{dx}{x}\Big[F(x) - F(0)\Big] + F(0)\ln(\delta) + \lim_{\epsilon\to 0}\frac{1}{\epsilon} F(0)\ . \end{aligned} \tag{4}$$

A cancellation between the analytical and numerical terms still occurs, however only the phase space is approximated, so that this method is valid at larger values of δ. In the case where the phase-space is not approximated for small x the hybrid method becomes independent from δ.

3. Jet production in eP-scattering

In eP-scattering, the interaction of the electron with the proton is mediated by a gauge boson ($\gamma, Z^0, W^\pm$) with virtuality $Q^2 \geq 0$. The region from $Q^2 = 0$ (photoproduction) up to the highest $Q^2 > 10^4$ GeV^2 (deep-inelastic scattering, DIS) is covered by the HERA collider. In the DIS region there are four available programs, namely `DISENT` [12], `DISASTER++` [13], `MEPJET` [14] and `JetViP` [15, 16], based on the calculations in [17]. The programs are summarized in Table 1 (taken from [18]). So far, only MEPJET incorporates contributions from Z^0 and $W^\pm$ exchange in NLO, which become important at virtualities above $Q^2 > 2500$ GeV^2. Therefore, a detailed comparison of the existing fixed order MC's is necessary to see whether these contributions are reliably predicted (see [16, 18]).

One of the main features of `JetViP` is the possibility to include a resolved virtual photon component in NLO. In this way the photoproduction limit can be taken. There are several calculations available for photoproduction [19, 20, 21]. The NLO corrections to the direct process in DIS become singular in the limit $Q^2 \to 0$ in the initial state

	MEPJET	DISENT	DISASTER++	JETVIP
version	2.2	0.1	1.0.1	2.1
method	PS slicing	subtraction	subtraction	PS slicing
1+1,2+1	NLO	NLO	NLO	NLO
3+1	LO	LO	LO	LO
4+1	LO	—	—	—
full event record	✓	✓	✓	✓
flavour dependence	switch	switch	full	switch
Quark Masses	LO	—	—	—
Resolved γ	—	—	—	NLO
Electroweak	NLO	—	—	—
Polarized e/P	NLO	—	—	—

Table 1. Summary of $eP \to$ jets fixed order computer programs in DIS.

on the real photon side. For $Q^2 = 0$ these photon initial state singularities are usually evaluated with the dimensional regularization method. Then the singular contributions appear as poles in $\epsilon = (4-d)/2$ with the form $-\frac{1}{\epsilon}P_{q\gamma}$ multiplied with the LO matrix elements for quark-parton scattering. These singular contributions are absorbed into PDF's $f_{a/\gamma}(x)$ of the real photon. For $Q^2 \neq 0$ the corresponding contributions are replaced by [17].

$$-\frac{1}{\epsilon}P_{q\gamma} \to -\ln(s/Q^2)P_{q\gamma} \tag{5}$$

where $\sqrt{s}$ is the c.m. energy of the photon-parton subprocess. These terms are finite as long as $Q^2 \neq 0$ and can be evaluated with $d = 4$ dimensions, but become large for small Q^2, which suggests to absorb them as terms proportional to $\ln(M_\gamma^2/Q^2)$ in the PDF of the virtual photon. Parametrizations of the virtual photon have been provided by several groups [22]. By this absorption the PDF of the virtual photon becomes dependent on M_γ, which is the factorization scale of the virtual photon, in analogy to the real photon case. Of course, this absorption of large terms is necessary only for $Q^2 \ll M_\gamma^2$. In all other cases the direct cross section can be calculated without the subtraction and the additional resolved contribution. M_γ^2 will be of the order of E_T^2. But also when $Q^2 \simeq M_\gamma^2$, one can perform this subtraction. Then the subtracted term will be added again in the resolved contribution, so that the sum of the two cross sections remains unchanged. In this way also the dependence of the cross section on M_γ^2 must cancel, as long as the resolved contribution is calculated in LO only.

4. Jet cross sections at low Q^2

In this section I will focus on a region of Q^2 which is not yet well understood, i.e. the intermediate region between photoproduction and DIS. This region involves photon virtualities roughly in the range $1 < Q^2 < 100$ GeV^2.

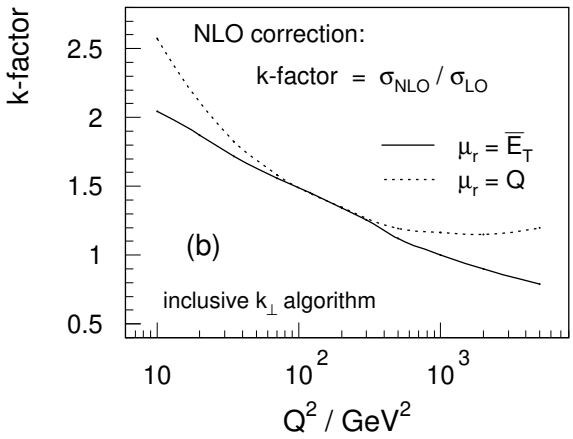

Figure 1. The predictions of the next-to-leading order corrections to the dijet cross section as a function of Q^2 for the inclusive $k_\perp$ algorithm using two different renormalization scales μ_r.

In [23] a study was made of the scale dependence for the NLO corrections to the dijet cross section employing the inclusive $k_\perp$ algorithm. The size of the scale variation is an indication of the possible size of perturbative higher-order contributions. This study is displayed in Fig. 1. Shown is the k-factor, defined as the ratio of the NLO and the LO predictions, for two different choices of the renormalization scale ($\mu_r = \overline{E}_T, Q$). Towards low Q^2 the NLO corrections become large, especially for the choice $\mu_r = Q$. Reasonably small k-factors ($k < 1.4$) are only seen roughly at $Q^2 > 150$ GeV^2 where Q^2 and E_T^2 are of similar size such that terms $\propto \ln(E_T^2/Q^2)$ are small. The renormalization scale dependence is seen to be correlated with the NLO correction i.e. large at small Q^2. The factorization scale dependence was found to be below 2% over the whole phase

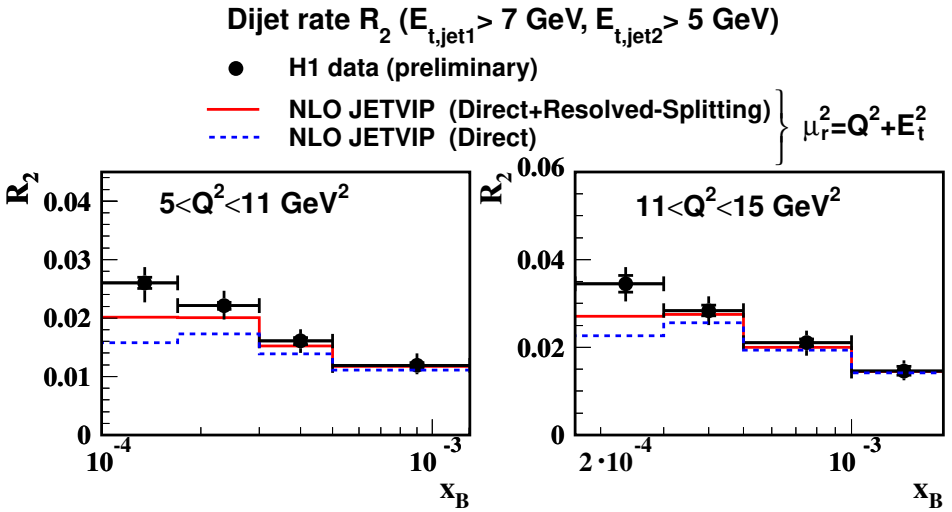

Figure 2. Ratio of cross sections for dijet and inclusive production as a function of x_{B}. The data are shown as the points with statistical errors (inner bars) and statistical and systematic uncertainties added in quadrature (outer bars). The NLO calculation is shown with (solid line) and without (dashed line) a resolved component.

space.

This study indicates that higher order (i.e. NNLO) corrections may be important in the region of $Q^2 < 100$ GeV^2. One way of incorporating these higher order contributions might be to include the resolved virtual photon contribution. This is clearly a justified approach for small Q^2 around 1 GeV^2, since here the photoproduction regime starts. In photoproduction it is well established that the resolved photon contribution is an important part of the jet cross sections. The inclusion of a resolved photon into the calculation compared to data from dijet production in the region $5 < Q^2 < 15$ GeV^2 and at least two jets, such that again $E_T^2 \gg Q^2$, is shown in Fig. 2 (taken from [1]). It can be seen that the calculation lies below the data at low x_{B} and that the description improves with the inclusion of a resolved photon. The effect is larger at the lower range in Q^2, but is not enough to completely describe the data.

Another region of phase space where resolved virtual photon contributions has been discussed to give important contributions is that of the forward jet cross sections. The H1 and ZEUS collaborations have measured forward jet cross sections at small x for rather similar kinematical conditions [24, 25]. The jet selection criteria and kinematical cuts are summarized in Tab. 1. In [26] we have performed a NLO calculation including the virtual resolved photon for the forward jet region with the help of `JetViP`.

The results for the ZEUS kinematical conditions are shown in Fig. 3 a,b. In Fig. 3 a we plotted the full $\mathcal{O}(\alpha_s^2)$ inclusive two-jet cross section (DIS) as a function of x for three different scales $\mu^2 = \mu_R^2 = 3M^2{+}Q^2, M^2{+}Q^2$ and $M^2/3{+}Q^2$ with a fixed $M^2 = 50$ GeV^2 related to the mean E_T^2 of the forward jet and compared them with the measured points from ZEUS [24]. The choice $\mu_F^2 > Q^2$ is mandatory if we want to include a resolved contribution. Similar to the results obtained with MEPJET and DISENT, the NLO direct cross section is by a factor 2 to 4 too small compared to the data. The variation inside the assumed range of scales is small, so that also with a reasonable change of scales we can not get agreement with the data. In Fig. 3 b we show the corresponding forward jet cross sections with the NLO resolved contribution included, labeled DIR$_S$+RES,

Table 2. Forward jet selection criteria by H1 and ZEUS

H1 cuts	ZEUS cuts
$E'_e > 11$ GeV	$E'_e > 10$ GeV
$y_e > 0.1$	$y_e > 0.1$
$E_{T,jet} > 3.5$ (5) GeV	$E_{T,jet} > 5$ GeV
$1.7 < \eta_{jet} < 2.8$	$\eta_{jet} < 2.6$
$0.5 < E_{T,jet}^2/Q^2 < 2$	$0.5 < E_{T,jet}^2/Q^2 < 2$
$x_{jet} > 0.035$	$x_{jet} > 0.036$

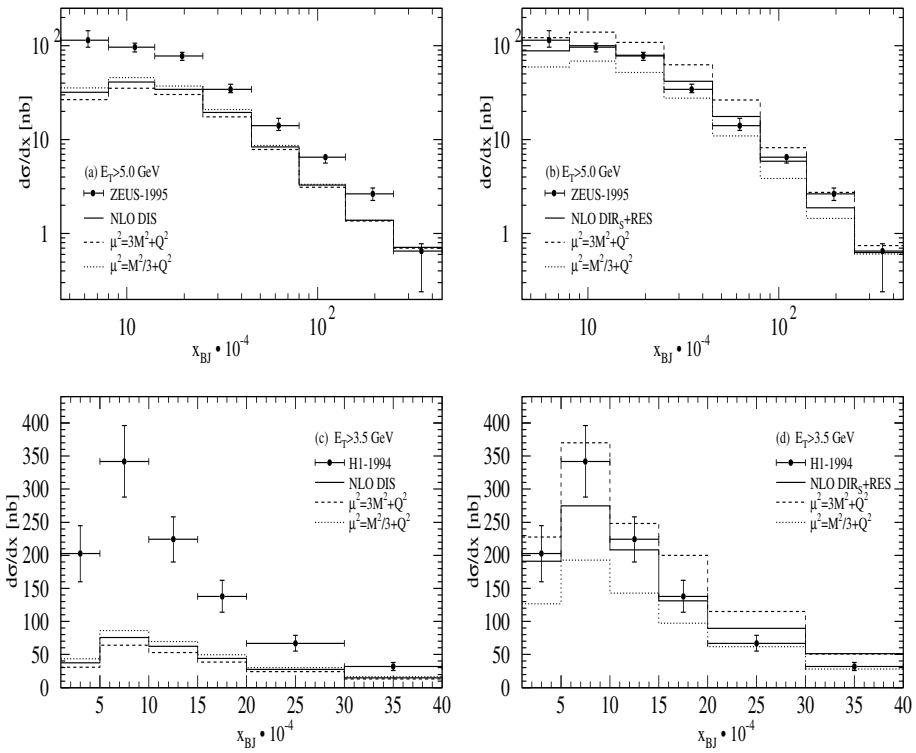

Figure 3. Dijet cross section in the forward region compared to HERA data: (a) and (b) ZEUS; (c) and (d) H1. (a) NLO DIS, $E_T > 5$ GeV; (b) NLO DIR$_S$+RES, $E_T > 5$ GeV; (c) NLO DIS, $E_T > 3.5$ GeV; (d) NLO DIR$_S$+RES, $E_T > 3.5$ GeV.

again for the three different scales μ as in Fig. 3 a. Now we find good agreement with the ZEUS data. The scale dependence is not so large that we must fear our results not to be trustworthy.

In Fig. 3 c,d we show the results compared to the H1 data [25] obtained with $E_T > 3.5$ GeV in the HERA system. In the plot on the left the data are compared with the pure NLO direct prediction, which turns out to be too small by a similar factor as observed in the comparison with the ZEUS data. In Fig. 3 d the forward jet cross section is plotted with the NLO resolved contribution included in the way described above. We find good agreement with the H1 data inside the scale variation window $M^2/3 + Q^2 < \mu^2 < 3M^2 + Q^2$. We have also compared the predictions with the data from the larger E_T cut, namely $E_T > 5.0$ GeV, and found similar good agreement [26]. The enhancement of the NLO direct cross section through inclusion of resolved processes in NLO is mainly due to the convolution of the point-like term in the photon PDF with the NLO resolved matrix elements, which gives an approximation to the NNLO direct cross section without resolved contributions. One can therefore speculate that the forward jet cross section could be described within a fixed NNLO calculation, using only direct photons. In summary, the NLO theory with a resolved virtual photon contribution as an approximation of the NNLO DIS cross section, which is presently

not available, gives a good description of the forward jet data.

These results indicate that the resolved virtual photon approach might give some higher order contributions. However, the concepts of factorization and of the virtual photon structure function itself are not well defined for too large photon virtualities (i.e. certainly for $Q^2 > 10$ GeV^2) due to $k_\perp$ and mass effects. This is a problem to be clearified in the future.

5. Combining NLO QCD calculations and parton showers

There are two approaches to the problem of simulating high-energy physics processes. First, one can employ fixed order QCD calculations which deliver the partonic final state of a single event and which currently are available up to next-to-leading order (NLO) for the case of inclusive jet production at HERA. This approach has been discussed so far. Second, Monte Carlo models are widely used which implement phenomenological descriptions of the parton cascades in the initial and final states, like for example parton shower (PS) algorithms in which a resummation of leading $\log Q^2$ terms to all orders and a natural matching to hadronisation models lead to a good description of small-angle phenomena (see [27] for a summary of programs in eP-scattering).

The technical realisation of parton shower models has several shortcomings: A beforehand-calculation of the total cross-section is required to get a correct normaliztion of the cross sections, which might be difficult for any other physics scenario than the one-jet case. The cross-section predictions in the 'soft' parton shower region as well as in the 'hard' region are only in leading order (LO). Going to NLO, which is necessary in order to increase the predictive power of the event generators, is however made difficult by negative cross-section contributions which lead to numerical stability problems when being combined with the probabilistic Sudakov approach to parton showers. In order to improve on the predictive power of the simulations, we have developed [28] and implemented [29] a method with which negative weights are avoided during the NLO calculation such that one easily arrives at the correct NLO weight in the PS region. For other approaches for combining PS and fixed order calculations, see [30].

The Born term σ^B and the virtual corrections σ^V to the NLO cross-section are easily evaluated analytically; the real corrections σ^R can be written as an integral from 0 to R_{tech} over a function $F(z)$ which is basically the matrix element without the propagator (beyond R_{tech} the hard region begins). One can then split the real corrections integral by some arbitrary parameter δ. Choosing this parameter δ such that the Born term, the virtual corrections and the soft/collinear part of the real corrections (the two-body parts) exactly cancel we are left only with an integral over the finite part of the real corrections (three-body contributions) which gives the complete NLO cross-section in the parton shower region. The corresponding value of δ, which depends on x and Q^2 and the renormalisation and factorisation scales, is denoted by $\tilde{\delta}$:

$$\sigma_{PS}^{NLO} = \sigma^B + \sigma^V + \sigma^R \simeq \int_{\tilde{\delta}}^{R_{tech}} \frac{dz}{z} F(z) > 0. \tag{6}$$

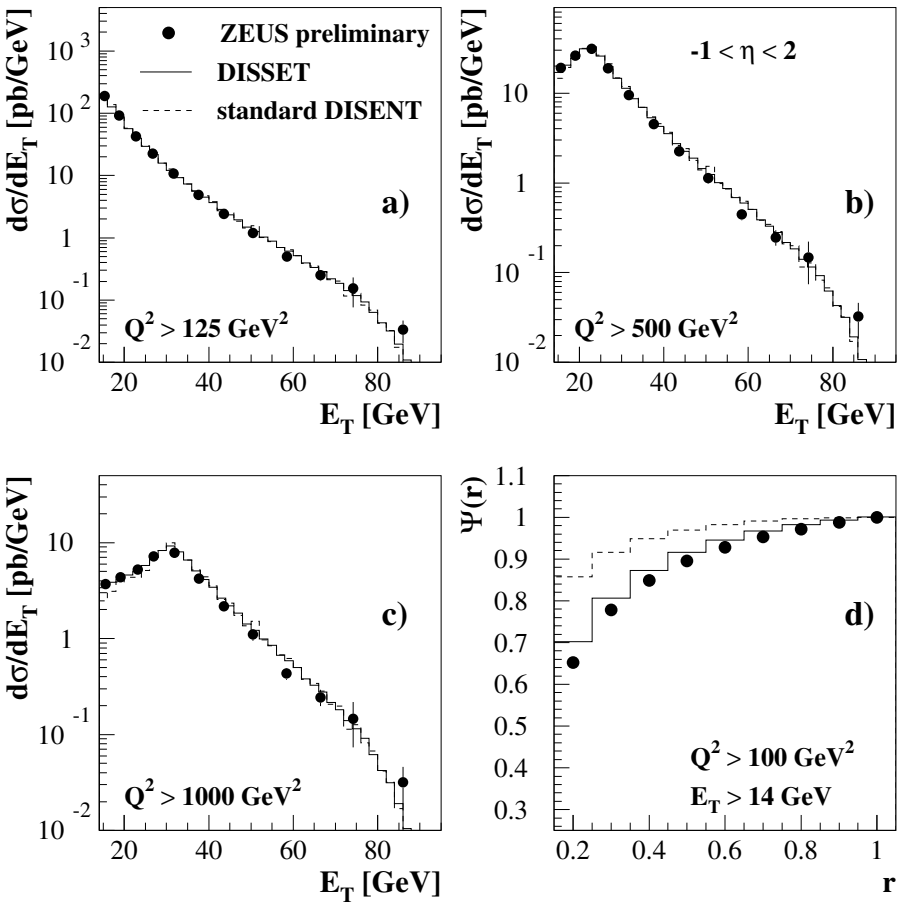

Figure 4. E_T distributions in different bins of Q^2 (a-c) and integrated jet shape (d). Shown are ZEUS data, standard `DISENT` NLO results and results of our calculation called `DISSET`.

For the inclusive one-jet cross-section calculations we implemented [29] the analytically derived function $\tilde{\delta}$ in the NLO QCD program `DISENT` [12] and combined the NLO cross-sections thus obtained for the PS region with the final state parton shower from `PYTHIA` [31]. Events where $2p_ip_j < \tilde{\delta}Q^2$ for any pair of partons i, j are rejected (this is the soft/collinear emission region). The hard region is described by $\mathcal{O}(\alpha_s)$ matrix elements. PS emissions into the hard region are vetoed in order to avoid double-counting. The parameter R_{tech} is typically of the order of 1. We have checked that our results are reasonably stable against a variation of R_{tech} by a factor of 2.

The ZEUS collaboration at HERA has published jet spectra [32] and jet shape data [33] for the case of inclusive jet production in the laboratory frame. For the spectra, events with Q^2 >125 GeV^2, $y < 0.95$ and an energy of the scattered electron of more than 10 GeV were selected. The jets which were reconstructed using a $k_\perp$ algorithm were required to have transverse energies E_T >14 GeV and a pseudorapidity -1< η <2. For the jet shape analysis, an iterative cone jet algorithm was used, and Q^2 >100GeV^2 was required.

In Fig. 4 we show comparisons of ZEUS inclusive jet E_T spectra in three bins of Q^2 (a-c) and of the integrated jet shape for the full Q^2 and E_T ranges (d) with a standard `DISENT` NLO calculation and with our results (called `DISSET`). Good agreement between the data, our result and `DISENT` can be observed for the inclusive spectra. For the jet shapes the `DISENT` result, which is only LO, fails. Our result however is much closer to the data since we describe the soft region by the parton shower. The remaining difference between the data and our predictions can be accounted for by hadronisation effects as we checked using the `LEPTO` event generator[34]. These results show that we correctly combine the NLO cross-section normalisation with the parton shower which describes the details of the hadronic final such as the jet shapes.

Currently, we are investigating the technically much more complicated case of dijet production in the Breit frame. In principle the method described above works also for this physically more relevant case. However it turns out that the analytical solution of equation (6) is not straight forward. The relevant equation to be solved for $\tilde{\delta}$ becomes

$$0 = \sum_{i=0}^{2} \ln(\tilde{\delta})^i \cdot A_i + A_3 \cdot \ln(1 + f(s,t,u,\xi)/\tilde{\delta}) + A_4 \cdot \ln(1 + g(s,t,u,\xi)/\tilde{\delta}) \quad (7)$$

with analytical expressions for coefficients A_i. We decided for a numerical evaluation of this equation using Newton's method which after 4 to 5 iterations gives stable results, such that this way of estimating the cut-off is applicable in a MC enviroment, where many events have to be generated.

6. Summary

We have described the status of next-to-leading order calculations for jet production in eP-scattering at HERA. We discussed the photoproduction, DIS and intermediate regimes and found that especially the range of intermediate photon virtualities $1 < Q^2 < 100$ GeV^2 to be not well described by present NLO calculations. We finally described progress made for the problem of including higher order corrections into MC models, that include PS and hadronization.

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