Forward Jets and Particles at HERA and Dynamics of Partons

J. Turnau [a]

[a]Institute of Nuclear Physics,
31-142 Kraków, Radzikowskiego 152, Poland

Jet and particle production at small angles with respect to the proton remnant (the forward region) in deeply inelastic ep interactions at low values of Bjorken-x is discussed. Hadronic final state calculations based on QCD models implementing different parton evolution schemes (DGLAP direct and resolved, BFKL and CCFM) are confronted with the data.

1. Introduction

One of the long standing questions in high energy collisions is whether significant deviations from the successful DGLAP [1] evolution equation can be observed at HERA. In deep inelastic scattering processes (DIS) at low values of Bjorken x the struck parton usually results from a long cascade of parton branchings. Field theory requires that the lifetimes of subsequent branchings are ordered . Such ordering can be realized as parton branching process

- with ordered transverse momenta p_T (DGLAP approximation, resums leading $\log(Q^2)$ terms and ignores $\log(1/x)$ terms)
- with ordered longitudinal momenta, no transverse momentum ordering (BFKL [2], resums $\log(1/x)$ terms)
- with ordered angles (CCFM [3], interpolates between DGLAP and BFKL)

At sufficiently low values of x the DGLAP approximation should fail while the BFKL and CCFM approximations should be applicable. However, without knowledge of higher order terms it is difficult to decide where exactly DGLAP calculations break down. For this reason, choice of the relevant perturbative expansion is a matter that must be decided by both theory and experiment.

Calculations of inclusive quantities like the structure function $F_2(x, Q^2)$ at HERA, performed in NLO DGLAP, are in very good agreement [4] with the measurements. However the interplay of nonperturbative ($F_2(x, Q_0^2)$) and perturbative (NLO DGLAP evolution) elements in this calculation makes it impossible to decide if parton cascades with strongly ordered transverse momenta are the dominant mechanism leading to scaling violations. In addition, when exclusive quantities like jet or heavy quark production are investigated, the agreement between NLO coefficient functions convoluted with NLO DGLAP parton densities and the data is less satisfactory. One example is b-quark production at the TEVATRON [5], [6] and HERA [7], [8]. Another example is the recent confrontation of the inclusive ep jet cross section with NLO DGLAP calculations [9], which revealed a gradual deterioration of the theoretical description as the jet approaches the proton beam direction (forward region). However we can not decide yet if this is due to breakdown of the DGLAP approximation or rather to the lack of the higher order terms in the perturbative series.

Several measurements of highly energetic jets ($x_{jet} = E_{jet}/E_p >> x$) at large pseudorapidities [1] η_{lab} with transverse energies squared $E_{T,jet}$ of the order of Q^2 have been made by both the H1 [10], [11] and the ZEUS collaborations [13]. This kind of measurement, originally proposed by Mueller (so called forward jets [15]) is so designed,

[1]The pseudorapidity η_{lab} is defined as $\eta_{lab} = -\ln\tan(\theta/2)$, with polar angle θ being measured with respect to positive z-axis, which is given by the proton beam (or forward) direction

that DGLAP evolution in transverse momentum space is suppressed ($E_{T,jet} \approx Q$) while BFKL evolution in x-space ($x_{jet} >> x$) is enhanced. The measurements showed large discrepancies between data and DGLAP NLO calculations at low values of Bjorken-x, which might be an indication of the breakdown of the DGLAP approximation and the onset of BFKL effects. However, it was shown [14] that a good description of the data can be obtained by considering the partonic structure of the virtual photon, which is expected to be important for $E^2_{T,jet} > Q^2$ and Q^2 not too large. In this approach we are back to the classic DGLAP approximation, with simultaneous evolution in transverse momentum space from both the photon and the proton sides towards the hard scatter. H1 [16], [17] also measured single particles (π^0) as opposed to jets, allowing the study of angles closer to the proton direction and smaller Bjorken-x, at the price of a stronger dependence the fragmentation process. Studies of the inclusive cross section for the production of forward particles led essentially to the same conclusions as the study of forward jets.

Studies of transverse energy flow provide a complementary means of investigating QCD processes. Compared with jet and leading particle studies, measurements of transverse energy production are sensitive to parton emissions of lower transverse momentum and the modeling of both the perturbative QCD evolution and the soft hadronisation process. In a recent H1 [17] publication both types of measurement (forward jet and energy flow) have been merged. The transverse energy flow measured for events with forward π^0 reveals the range over which the transverse momentum of the forward parton is compensated. We may expect that different models of parton evolution lead to different radiation patterns.

This paper presents a review of recent results concerning low x DIS interactions in which high transverse momentum jets or π^0's are produced in the forward region. The data are confronted with various QCD-based models.

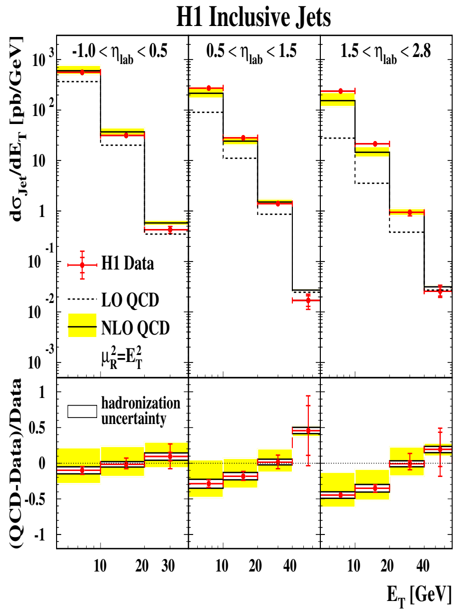

Figure 1. Inclusive jet cross section $d\sigma_{Jet}/dE_T$ in different ranges of η_{lab} ,integrated over the region $5 < Q^2 < 100$ GeV^2 and $0.2 < y < 0.6$. Top, the data are compared to DISENT NLO (solid line) and LO (dashed line). The hatched band around the NLO prediction stems from variation of the renormalization scale by factors of 2 and 1/2. Bottom, the ratio (QCD-Data)/Data is shown. Here "QCD" denotes NLO QCD corrected for hadronization effects.

1.1. Inclusive jet cross section vs. NLO DGLAP approximation

Before coming to the main subject of the present paper i.e. jets and particles in the forward region in DIS, let us briefly recall the general status of NLO QCD calculation of inclusive jet cross sections at HERA. There exists several programs for the numerical NLO calculation of jet observables at the parton level. They are known to give comparable results. All of them calculate the direct photon contributions to the cross sections. Only the JetVip program [18] provides the additional possibility to calculate a cross section consisting of both direct and resolved photon contributions, however in the DIS case conceptual difficulties are encountered [19] which lead to ambiguous results.

In a recent H1 paper [9], NLO calculations of the inclusive jet cross sections made using the DISENT program [20] were confronted with high statistics data (H1 detector, years 1996-1997, 27.5 GeV positrons + 820 GeV protons, 21.1 pb^{-1}). The kinematic range considered in this analysis was constrained by the conditions $5 < Q^2 < 100$ GeV^2 and $0.2 < y < 0.6$ (the latter condition leads to a reduction of photoproduction background). Jets are defined using the inclusive $k_\perp$ cluster algorithm in Breit frame [2] and selected by the requirement $E^2_{T,jet} > 5$ GeV^2 . The choice of the Breit frame ensures that the jet transverse energies are closely related to those of the partons emerging from the hard scattering.

Figure 1 shows the inclusive jet cross section as a function of the transverse jet energy $E_{T,jet}$ in different regions of the pseudorapidity η_{lab}: in the backward region $-1 < \eta_{lab} < 0.5$, the central region $0.5 < \eta_{lab} < 1.5$ and the forward region $1.5 < \eta_{lab} < 2.8$. The measured cross sections, which extend over four orders of magnitude, are compared to the QCD calculations using the renormalisation scale $\mu_R = E_{T,jet}$. While there is good agreement between the data and the NLO QCD calculation in the backward region for all $E_{T,jet}$ values, discrepancies are observed for more forward jets with low $E_{T,jet}$. In the lowest $E_{T,jet}$ range $5 < E_{T,jet} < 20$ GeV, for $\eta_{lab} > 1.5$, the assumed renormalisation scale uncertainty ($E_{T,jet}/2 < \mu_R < 2E_{T,jet}$) does not cover the large difference between the data and the QCD calculation. Figure 1 shows that the discrepancies are accompanied by large NLO correction (i.e. difference between LO and NLO calculations). The NLO predictions are up to a factor of 5 larger than the LO ones. Furthermore, the effect of a variation of the renormalization scale, which are indicated by the hatched band, are largest for these low $E_{T,jet}$ jets in the forward region.

The correlation of large NLO/LO corrections and high sensitivity to renormalization scale variations with poor agreement between data and QCD predictions strongly suggests that inclusion of higher order (e.g. NNLO or resolved photon component) terms in the QCD calculations is necessary in order to describe the data. The above statement has to be kept in mind when discussing possible breakdown of the DGLAP approximation in DIS at small Bjorken-x.

[2]The Breit frame is defined by $2x\vec{p} + \vec{q} = 0$,where x is Bjorken scaling variable, and $\vec{p}$ and $\vec{q}$ are the proton and the virtual photon momenta, respectively

1.2. Forward jets in DIS

Recently the H1 Collaboration has measured [11] the cross section for a class of DIS events ($5 < Q^2 < 75$ GeV^2) with a jet with $E_{T,jet} > 3.5$ GeV close to the proton direction ($7° < \theta_{jet} < 20°$) and carrying a large fraction of the proton's momentum, $x_{jet} = E_{jet}/E_p > 0.035$. In addition, $0.5 < E^2_{T,jet}/Q^2 < 2$ is required to suppress contributions from DGLAP type evolution, while the phase space for BFKL type evolution in Bjorken-x is enhanced due to the large ratio of x_{jet}/x. This cross section for forward jet production as a function of x is shown in figure 2. The measurements are up to a factor of two larger than the prediction based on $\mathcal{O}(\alpha_s)$ (and also $\mathcal{O}(\alpha_s^2)$) QCD calculations in DGLAP approach. Such parton level calculations were presented in older forward jet papers e.g. [10], [13]. Here instead we show comparison of the data with hadron level Monte Carlo calculations implementing various QCD models. To perform the hadronisation step, both models use string fragmentation as implemented in JETSET7.4 [26].

RAPGAP [24] matches exact first-order QCD matrix elements to DGLAP-based leading-log parton showers. In addition to the direct photon processes RAPGAP simulates resolved photon interactions in which the virtual photon is assumed to have structure. This allows a reasonable description of the forward jet data. It should be noted however, that the predictions of the model are sensitive to the renormalization and factorization scales. The RAPGAP package allows a choice of renormalisation and factorisation scales, and for the predictions presented in figure 2, these are set to $p_T^2 + Q^2$, where p_T is the transverse momentum of the partons taking part in the hard scattering process. The errors (mainly systematic) are large and reasonable agreement

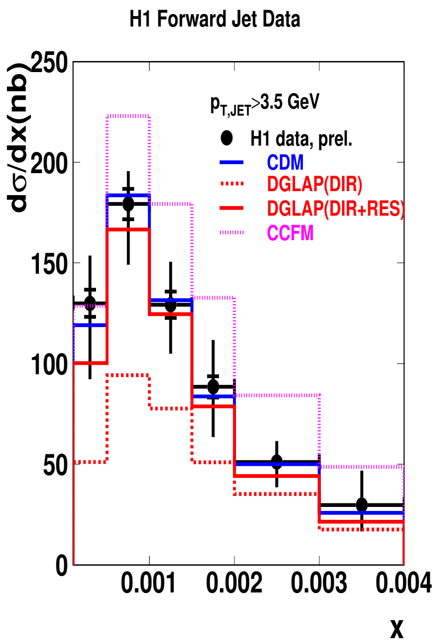

Figure 2. The cross section for forward jet production at the hadron level, as a function of x for $E_{T,jet} > 3.5$ GeV. Also shown are the predictions from various Monte Carlo calculations.

with the data would still be achieved for a scale of $4p_T^2 + Q^2$.

In CASCADE [25], QCD matrix elements are supplemented with parton emissions based on the CCFM equation using a backward evolution approach. An unintegrated gluon density which fits the F_2 structure function measurements of H1 is used as input to this model. The above version of CASCADE predicts a rate of forward jet events which is too high, however slightly modified generator [12] produces the correct cross section. . For all other distributions e.g. $\mathrm{d}\sigma/\mathrm{d}p_{T,jet}$ the pattern of agreement/disagreement is similar. Before closing this section we would like to mention that the problem of the forward jet cross section was also studied using the BFKL formalism [2]. In particular Kwiecinski, Martin and Outhwaite (KMO) in ref. [27] used a modified LO BFKL equation, supplemented by a consistency constraint which mimics higher orders of the perturbative expansion, to describe the inclusive forward jet cross section. The KMO model describes the data well, however the predicted cross section is very sensitive to the input parameters in particular the infrared cut-off and the scale of α_s. In a sense the model does not really describe the forward jet cross section but rather the shape of the distribution in Bjorken-x. We will come back to the KMO calculation in the next section.

1.3. Forward π^0 mesons

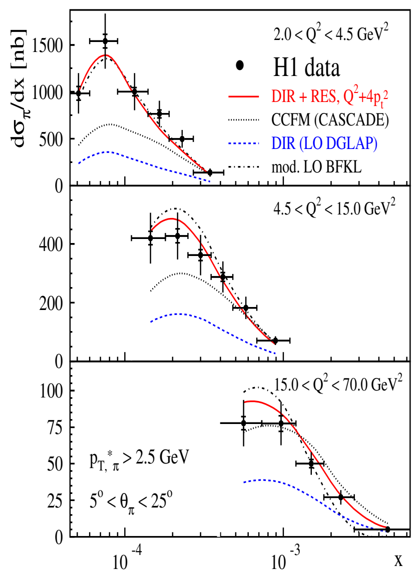

Figure 3. The cross section for forward π^0 production as a function of x for $p^\star_{T,\pi^0} > 2.5$ GeV. Also shown are the predictions from various Monte Carlo calculations.

H1 recently measured single forward π^0 meson production [17]. This new measurement triples the number of π^0's in comparison to previously published data [16], allowing the measurement of more differential distributions and additional final state observables. The analysis is restricted to the kinematic range $2 < Q^2 < 70$ GeV^2, $5° <$

$\theta_\pi < 25°$, $x_\pi = E_\pi/E_p > 0.01$ (lab. system) and $p^\star_{T,\pi} > 2.5$ (hadronic center of mass system). The differential cross section as a function of Bjorken-x for different regions in Q^2 is shown in figure 3. It should be noted that this measurement covers a range in x down to $4*10^{-5}$. The prediction of a DGLAP based Monte Carlo (RAPGAP direct) is well below the data, whereas a reasonable description is obtained when the resolved virtual photon contribution is added (RAPGAP resolved). It should be noted however, that a rather large renormalisation scale $4p_t^2+Q^2$ has to be used in this case. Surprisingly, CASCADE falls below the data at small x values despite the reasonable description it provides for the forward jet data. At present we do not understand why RAPGAP is able to provide a consistent description of both forward jets and forward particles while this is not the case for CASCADE. It should be stressed however, that there is no direct contradiction in the data: discrepancies in the π^0 cross section arise in the region of x which is mostly beyond the reach of the forward jet measurement. It is interesting to note that the previously mentioned BFKL calculation of the forward jet cross section [27] is consistent with the forward π^0 mesons measurement (dotted curve). The BFKL prediction for π^0 cross section was obtained by the convolution of the parton distribution with the KKP fragmentation function [28].

We expect that different cascade dynamics should lead to different radiation patterns and therefore to the different transverse energy flow. The transverse energy flow in the hadronic center of mass system, $\frac{1}{N}\mathrm{d}E^\star_T/\mathrm{d}(\eta^\star - \eta^\star_\pi)$, in events containing at least one forward π^0 is presented in figure 4. The flow, which includes the contribution from the forward π^0, is plotted as a function of the distance in pseudorapidity $\Delta\eta^\star = \eta^\star - \eta^\star_\pi$ from the forward π^0. The spectra are presented in three intervals of π^0 pseudorapidity: $-1.25 < \eta^\star_\pi < -0.25$ (closest to proton direction) , $-0.25 < \eta^\star_\pi < 0.25$ and $0.25 < \eta^\star_\pi < 2.0$ (farthest from proton direction).

The QCD-based approaches all describe the transverse energy flow around the π^0 but give different predictions in the current region. The resolved photon picture gives a reasonable description of the spectra whilst the CCFM approach overestimates the transverse energy flow when the forward π^0 is closest to the proton direction (top left). The direct photon model gives the worst description of the data. It predicts a transverse energy flow which rises strongly with increasing $\Delta\eta^\star$ and shows a peak at large values of pseudorapidity difference. This effect becomes less pronounced with increasing pseudorapidity of the forward π^0. The differences between the models can be qualitatively understood as a consequence of the presence or otherwise of k_T ordering in the parton cascade algorithms implemented in various Monte Carlo generators.

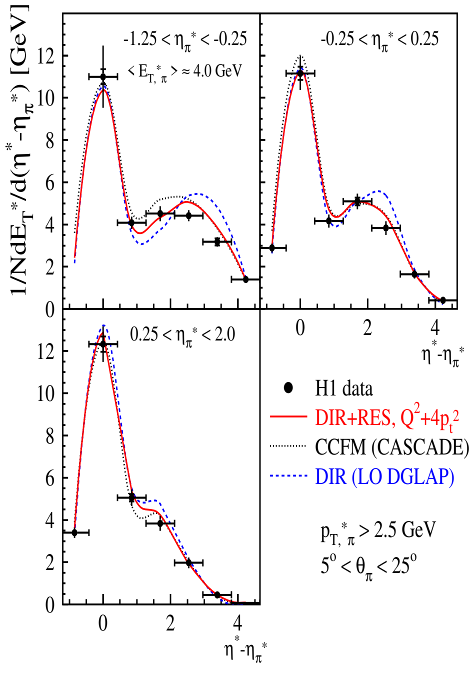

Figure 4. The distribution of transverse energy as a function of pseudorapidity difference in different intervals of π^0 pseudorapidity. Predictions of three QCD-based models are shown.

1.4. Conclusions

The measurements of forward jets and particles are sensitive to the dynamics of parton evolution. Several QCD-based approaches were confronted with the data. It has been shown that NLO DGLAP calculations fall well below forward jet data. The forward jet cross section is well described by a DGLAP based Monte Carlo which includes a resolved photon component. Similarly, results obtained using the BFKL and CCFM evolution schemes are compatible with the data. The measurement of the forward π^0 cross section leads essentially to the same conclusions for the region of Bjorken-x covered by the forward jet measurements. For the lowest values of x i.e. those beyond the reach of the forward jet measurements, the CCFM approach fails to describe the data. The comparison of results from various models seems to indicate some sensitivity to the fragmentation method used to connect the parton and hadron levels. Study of the transverse energy flow associated with forward π^0's seems to favor the DGLAP direct + resolved approach. However, after almost 10 years of investigation of forward jets we still do not have a firm answer to the question formulated in the Introduction: can significant deviations from the successful DGLAP [1] evolution equation be observed at HERA?

REFERENCES

1. Yu. L. Dokshitzer, Sov. Phys. JETP **46** (1977) 641;
   V. N. Gribov and L. N. Lipatov, Sov. J. Nucl. Phys. **15** (1972) 438 and 675;
   G. Altarelli and G. Parisi, Nucl. Phys. **126** (297) 1977.
2. E. A. Kuraev, L. N. Lipatov and V. S. Fadin, Sov. Phys. JETP **45** (1972) 199;
   Y. Y. Balitsky and L. N. Lipatov, Sov. J. Nucl. Phys. **28** (1978) 822.
3. M. Ciafaloni, Nucl. Phys. **B 296** (249) 1987;
   S. Catani, F. Fiorani and G. Marchesini, Phys. Lett. **B 234** (339) 1990, Nucl. Phys. **B 336** (18) 1990.
4. C. Adloff et al. hep-ex/0304003 Submitted to Eur. Phys. J.
5. F. Abe et al. Phys. Rev. **D 55** (2546) 1997.
6. B. Abbot et al. Phys. Lett. **B 487** (264) 2000.
7. C. Adloff et al. Phys. Lett. **B 467** (156) 1999.
8. J.Breitweg Eur. Phys. J. **C 18** (625) 2001.
9. C. Adloff Phys. Lett. **B 542** (193) 2002.
10. C. Adloff et al. Nucl. Phys. **B 538** (3) 1999.
11. H1 Collaboration, C. Adloff et al., Forward Jet Production at HERA, 2002, contributed paper to ICHEP 2002.
12. H. Jung, Dijet production at low Q^2 and virtual photon structure, Proceedings of DIS 2003, 23-27 April 2003, St.Petersburg, Russia
13. J. Breitweg et al., Eur. Phys. J. C **6** (239) 1999;
    J. Breitweg et al., Phys. Lett. **B 474** (223) 2000.
14. H. Jung, L. Jönsson and H. Kuester, Eur. Phys. J. **C 9** (383) 1999.
15. A.H. Mueller, Nucl. Phys. Proc. Suppl. **18** (125) 1991.
16. C. Adloff et al., Nucl. Phys. **B 538** (3) 1999.
17. H1 Collaboration, Forward π^0 meson production, contributed paper to DIS 2002, April 2002.
18. B. Pötter, Comput. Phys. Commun. **119**(1999)45.
    G. Kramer and B. Pötter, Eur. Phys. J. **C 5** (665) 1998.
19. B. Pötter, J.Phys.G **28**(2002)871.
20. S. Catani and M.H. Seymour Nucl. Phys. **B 485** (291) 1997.
21. CTEQ Collaboration, Phys. Rev. **D 55** (1280) 1997.
22. H. Plothow-Besch, PDFLIB Version 7.09, User's Manual, W5051 1997.07.2 CERN-PPE, 1997.
23. G. Schuler and T. Sjöstrand, Phys. Lett. **B 376** (193) 1996.
24. H. Jung, Comp. Phys. Commun. **86** (147) 1995.
25. H. Jung, Nucl. Phys. Proc. Suppl. **79** (429) 1999.
26. T. Sjöstrand, Comp. Phys. Comm. **82** (1994) 74.
27. J. Kwiecinski, A.D. Martin, J.J. Outhwaite Eur. Phys. J. **C 611** (1999) .
28. B.A. Kniehl, G. Kramer and B. Pötter, Nucl. Phys. **B 597** (337) 2001.