QCD DYNAMICS FROM FORWARD HADRON AND JET MEASUREMENTS

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Recent measurements of deep inelastic events containing jets and π° mesons, produced close to the proton remnant in the laboratory frame, are discussed. The data are used to discriminate between QCD models with different parton evolution approximations.

1. Introduction

The HERA collider has extended the available kinematic region for deep-inelastic scattering (DIS) to regions of small Bjorken-x ($x_{B_j} \approx 10^{-5}$) at moderate four momentum transfers Q^2 of a few GeV^2. The large $\gamma^* p$ centre of mass energy available at small x_{B_j} gives rise to a large phase space for gluon cascades exchanged between the proton and the photon. The fast rise of the gluon density with decreasing x_{B_j} suggests that at some point the gluon density will be so large that non-linear recombination effects leading to saturation phenomena may become important.

In perturbative QCD multiparton emissions are described only in approximation and in different regions of Q^2 and x_{B_j} different QCD-based prescriptions are expected to describe the radiation of partons. At large Q^2 the initial state radiation is described by standard DGLAP evolution equations[1] which at leading order resum $(\alpha_S \ln Q^2)^n$ terms. In this approach the struck quark originates from a parton cascade ordered in virtuality what is reflected by a strong ordering in transverse momenta k_T of subsequent gluon emissions. It is believed that at asymptotically high energies the theoretically correct description in the region of very small x_{B_J}

*Representing the H1 and ZEUS collaborations is given by the BFKL equation[2]. In this approximation the evolution is dominated by large leading $\alpha_S \ln(1/x)$ terms which are resummed to all orders. Here the cascade is ordered strongly in fractional longitudinal momenta, while there is no ordering in transverse momentum of the partons along the ladder. The DGLAP and BFKL approaches are examples of two "extreme" choices for the transverse momentum ordering of the radiated gluons. The CCFM evolution[3] is an attempt to unify these two approaches. In the limit of asymptotic energies the CCFM evolution equation is almost equivalent to BFKL and for large x and high Q^2 it behaves like the DGLAP approximation. This behaviour follows from the fact that the CCFM evolution resums in addition to large logarithms of $(\alpha_s \ln(1/x))^n$ also terms $(\alpha_s \ln(1/(1-x))^n$. Furthermore, this approach introduces angular ordering of emissions to correctly treat gluon coherence effects.

A partially unordered parton chain can be also realized within DGLAP evolution scheme by allowing the exchanged virtual photon to have a partonic structure. In this approach two k_T-ordered DGLAP cascades are initiated: one from the proton and one from the photon. Resolved photon processes may become important in the region in which the k_T^2 of the parton at the photon end of the parton cascade is greater than the photon virtuality Q^2.

One of the important questions in high energy collisions at HERA is whether deviations from DGLAP type predictions can be observed and whether there is a need for small-x effects. At low x_{B_j} there is a lot of gluon radiation and to make a reliable comparison of measurements with theoretical predictions it is essential to calculate higher order terms in the relevant perturbative expansion.

Different measurements of DIS at low x_{B_j} have been performed to study the QCD parton dynamics in this region. Measurements of the proton structure function $F_2(x, Q^2)$ in a wide range of x and Q^2, and in particular the strong rise of F_2 with decreasing x_{B_j}, are well described by NLO DGLAP calculation. However, in this calculation there is an interplay of perturbative (NLO DGLAP evolution) and non-perturbative effects, coming from the input form of the parton distribution functions of the proton, which may obscure the underlying dynamics effects at low x_{B_j}. The observable F_2 is too inclusive to distinguish between the different alternatives. The hadronic final state observables which reflect the kinematic structure of gluon emissions are expected to be able to discriminate between different evolution approximations.

Studies of DIS events accompanied by an energetic jet of high transverse momentum close to the proton remnant are considered to be especially sensitive to the QCD dynamics at low x. These measurements, inspired by the proposal of Mueller[4], are restricted to the phase space region where transverse momentum of the jet is approximately equal to the photon virtuality, $k^2_{T,jet} \approx Q^2$, to suppress DGLAP evolution in Q^2. Sufficiently large values of transverse momentum also minimize the k_T diffusion into the infrared region[5]. In addition, the ratio x_{jet}/x_{B_j}, where $x_{jet} = E_{jet}/E_p$, should be large to enhance the phase space for BFKL effects[a]. The selected jets are close to the proton remnant direction in the laboratory frame, the so-called forward region.

Studies of single forward particles are complementary to measurements of forward jet production. An advantage of studying single particles as opposed to jets is the easier experimental identification without the dependence on the jet-finding algorithm and the potential to reach angles closer to the proton remnant direction. A disadvantage is that the cross section for the process is suppressed in comparison to forward jet production, and that the fragmentation effects are more significant.

In this analysis we present recent results of the H1 and ZEUS Collaborations on high tranverse momentum forward jet and π°-mesons produced in DIS at low x_{B_j}. The data are confronted with various QCD-based models.

2. Monte Carlo Programs and Theoretical Calculations

Presented measurements will be compared either with predictions of Monte Carlo (MC) programs which model higher order terms by leading logarithm parton showers, or with parton level fixed order QCD calculations. Different MC event generators which adopt various QCD approaches to modelling the parton cascade are used.

LEPTO[6] and RAPGAP[7] match LO QCD matrix elements for direct photon processes to DGLAP based parton showers with strong k_T ordering. In addition to the direct photon processes, RAPGAP simulates resolved photon interactions. The RAPGAP description of the hadronic final state is very similar to that of LEPTO when only direct photon interactions are considered.

ARIADNE[8] is an implementation of the Color Dipole Model (CDM)[9] in which all radiation is assumed to come from the dipole formed by the struck quark and the proton remnant. Subsequent parton emissions come

[a] $E_{jet}(E_P)$ denotes the energy of the forward jet(proton) in the laboratory system.

from a chain of independently radiated dipoles formed by emitted gluons. In consequence, transverse momenta of emitted gluons perform a random walk and in this sense ARIADNE is a BFKL-like program.

CASCADE[10] uses off-shell QCD matrix elements, supplemented with parton emissions based on the CCFM equation. An unintegrated gluon density, obtained using CCFM evolution and fitted to describe the inclusive DIS cross section is used as input to this model. Two different sets of unintegrated gluon density are used: one with only singular terms of the gluon splitting function and another one including also non-singular terms.

Studied data samples with selected forward jets are multijet events and are compared to fixed order QCD predictions of following programs:

DISENT[11], which provides calculations at LO(α_S) and NLO(α_S^2) accuracy for dijet production in DIS via direct photon interactions;

NLOJET++[12], which calculates cross sections for three-jet production in DIS at NLO(α_S^3) accuracy. This program is the only NLO generator for three-jet configuration and is used in the description of the class of events with the forward jet accompanied by two additional jets.

Recently, three independent NLO calculations of the cross section for the production of high transverse momentum hadrons in DIS interactions have been made[13–15], which describe measurements of forward π° production. A large part of the cross section is generated by higher order contributions which correspond to lowest order BFKL and resolved photon processes. In the analysis of Aurenche et al.[13] also higher order corrections to the resolved photon processes are included. NLO calculations of high p_T hadrons are discussed in more detail in Ref. 16.

Analytical calculations based on LO BFKL effects with a consistency constraint which effectively includes part of higher order BFKL effects have been discussed in Ref. 17 for DIS events containing a forward jet or π°. These predictions are very sensitive to the choice of the scale for α_S and the infra-red cut-off.

3. Measurements of Forward Jets

Recently the ZEUS Collaboration has published results on inclusive forward jet measurements in the region $Q^2 > 25$ GeV^2 and $y > 0.04$ [18] based on a data sample corresponding to an integrated luminosity of 38.7 pb^{-1}. Jets are reconstructed using the inclusive k_T algorithm in the laboratory frame and then special conditions are applied to define the BFKL phase space region. The hadronic angle corresponding to the polar angle of the massless struck quark in the Quark-Parton Model (QPM) is required to be in the backward direction ($cos\gamma_h < 0$) and at least one jet with $p_{T,jet} > 6$ GeV is found in the forward region of the detector ($0 < \eta_{jet} < 3$). These conditions suppress QPM-type events with single jets and enhance kinematic region for multijet production. In addition, the requirement $0.5 < E_T^2/Q^2 < 2$ restricts the jet kinematics to the region where the DGLAP effects are suppressed and the BFKL effects are expected to be large.

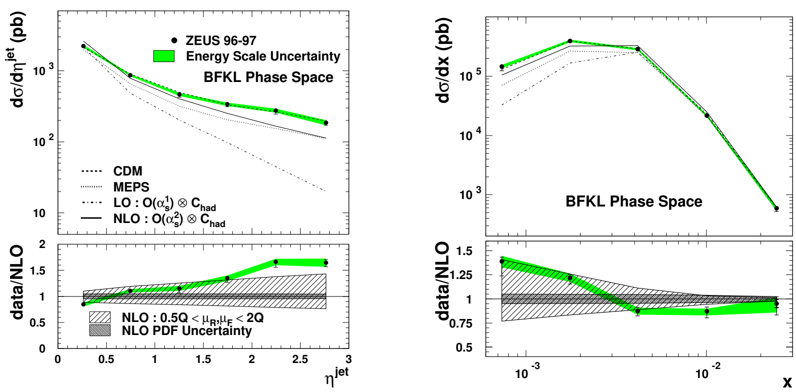

Figure 1. The forward jet cross section measurements of ZEUS as a function of η_{jet} and x_{B_j} compared with the predictions of CDM, LEPTO(MEPS) and DISENT.

In Fig. 1 the inclusive forward jet cross section is shown as a function of η_{jet} and x_{B_j}. The data are compared with LO(α_S^1) and NLO(α_S^2) predictions provided by DISENT with the renormalisation scale set to Q. The lower part of each plot shows the ratio of data to the QCD calculations and the theoretical uncertainties. The theoretical uncertainty is estimated in the conventional way by varying renormalisation or factorisation scales by a factor of two up and down. NLO calculations give a reasonable description of the data except for the forward region ($\eta_{jet} > 1$) and for low x_{B_j}. In these regions NLO corrections are large and the ratio NLO/LO reaches values as large as five for $\eta_{jet} \approx 3$. The large NLO/LO factors at low x_{B_j} and large η_{jet} are associated with the contribution from t-channel gluon exchange diagrams. Large scale variation uncertainties, related mainly with the renormalisation scale, suggest that higher order terms are needed to improve the description of the data. Predictions of the BFKL-like model

CDM are also shown in Fig. 1 and describe the data well.

Further new measurements of forward jet production are available from both H1[19] and ZEUS[20] Collaborations. In both analyses jets are identified using the inclusive k_T-algorithm in the Breit frame and therefore QPM type events with single jets are kinematically forbidden. The kinematical cuts and jet selection criteria are summarized in Table 1.

Table 1. Selection cuts of forward jets by H1 and ZEUS.

$exp.$	$Q^2[GeV^2]$	x	E_T^2/Q^2	η_{jet}	$p_{T,jet}[GeV]$	x_{jet}
$H1$ 13.7 pb^{-1}	5-85	0.0001-0.004	0.5-5.0	1.7-2.8	> 3.5	> 0.035
$ZEUS$ 82 pb^{-1}	20-100	0.0004-0.005	0.5-2.0	2.0-3.5	> 5.0	> 0.036

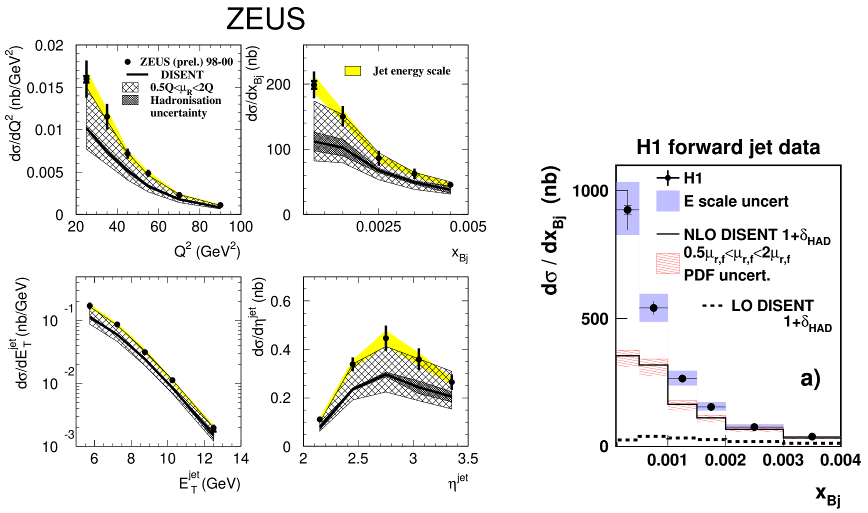

Figure 2. The forward jet cross section measurements of ZEUS (left) and H1 (right) compared with LO and NLO predictions of DISENT.

The H1 analysis reaches lower x_{B_j} values as it covers the phase space region at lower Q^2. The requirement on E_T^2/Q^2 is more restrictive in the ZEUS measurement. ZEUS also extends the measurements to the more forward region up to $\eta_{jet} = 3.5$. Fig. 2 shows the forward jet cross sections as a function of Q^2, x_{B_j}, $E_{T,jet}$ and η_{jet} obtained by ZEUS. The results are compared with NLO(α_S^2) predictions of DISENT with the choice of the renormalisation scale $\mu_R = Q$. The NLO QCD predictions are below the data but within theoretical uncertainties except for the region of low x_{B_j}. The large renormalisation scale uncertainty indicates the importance of higher order terms in this analysis.

The new H1 forward jet measurements are also shown in Fig. 2. The forward jet cross section as a function of x_{B_j} is compared with LO(α_S^1) and NLO(α_S^2) calculations from DISENT with the renormalisation scale defined by the average p_T^2 of the dijets from the matrix element $\mu_R^2 =< p_{T,dijets}^2 >$. The scale uncertainty in this analysis is estimated by simultaneously changing the renormalisation and factorisation scales. The NLO calculation is closer to the data than the LO contribution and at low x_{B_j} there is one order of magnitude difference between LO and NLO predictions. This reflects the fact that at LO the forward jet production is suppressed by kinematics. However, the NLO predictions are still a factor two below the data at low x_{B_j}.

Conclusions from measurements of the forward jet cross section by H1 and ZEUS seem to be contradictory. However, the main difference in the NLO(α_S^2) description comes from different choice of the renormalisation scale which leads to a significantly different estimate of the theoretical uncertainty.

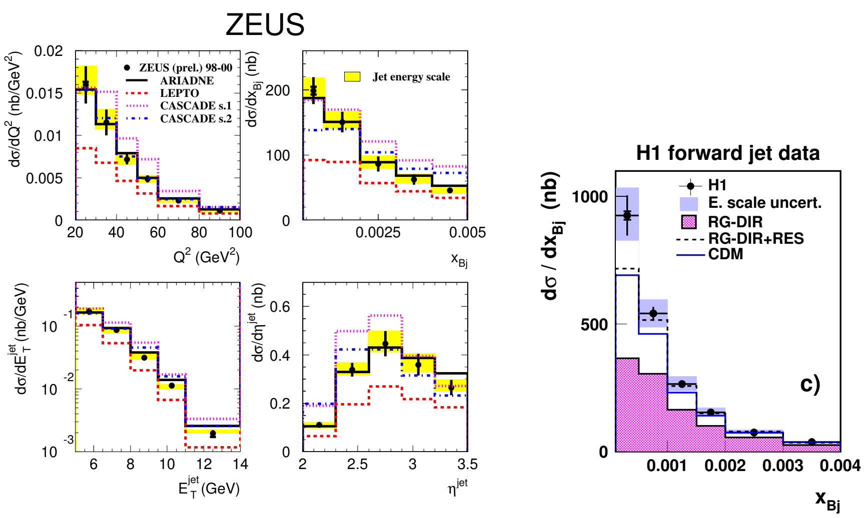

Figure 3. The forward jet cross section measurements of ZEUS (left) and H1 (right) compared with different Monte Carlo models.

Experimental results presented in Fig. 2 are again shown in Fig. 3, now in a comparison with different MC models. Predictions of DGLAP-based models with only the direct photon processes included, marked LEPTO or RG-DIR, are well below the data. The addition of resolved photon contribution, as shown for the H1 data (RG-DIR+RES), significantly improves the description. However, there is still a discrepancy in the lowest bin of x_{Bj}. A similar good description is given by the CDM model with emissions non-ordered in transverse momentum. The ZEUS results are best described by the CDM model as given by ARIADNE. Predictions of the CCFM model as implemented in CASCADE with two different parametrizations of the unintegrated gluon density fail to describe the shape of the distributions in x_{Bj} and η_{jet}. This might be caused by the parametrization of the unintegrated gluon density and/or missing contributions from quark induced cascades and gluon splittings into quark pairs.

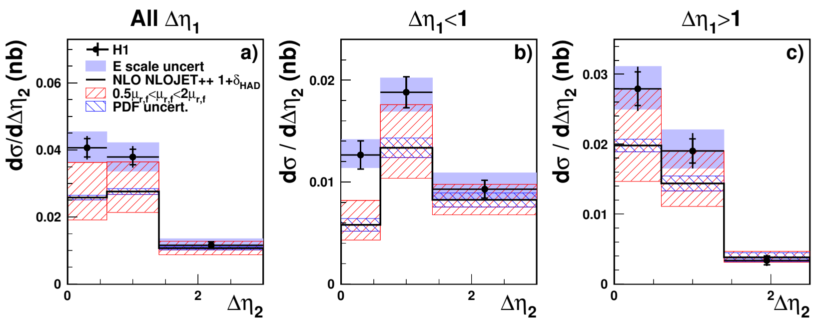

Figure 4. The cross section for events with "forward jet + 2 additional jets" as a function of the rapidity separation $\Delta_{\eta 2}$ (see text) compared with NLO predictions.

The H1 Collaboration has also performed a more exclusive analysis of events with the forward jet accompanied by two additional jets. All jets have transverse momenta larger than 6 GeV and are ordered in rapidity according to $\eta_{fwdjet} > \eta_{jet2} > \eta_{jet1} > \eta_e$, where η_e is the rapidity of the scattered electron. The cross section is measured in two bins of $\Delta\eta_1$ as a function of $\Delta\eta_2$, where $\Delta\eta_1 = \eta_{jet2} - \eta_{jet1}$ is defined as a difference in rapidity between two additional jets and $\Delta\eta_2 = \eta_{fwdjet} - \eta_{jet2}$ is a separation in rapidity between the forward jet and the closer additional jet. The direction of the forward jet is restricted in space as being close to the proton axis and the directions of additional jets are selected through $\Delta\eta$ requirements. In general, by choosing different $\Delta\eta$ values one can select different event topologies and test the breaking of the k_t ordering at different location along the ladder between the virtual photon and the forward jet. Fig. 4 shows a comparison of the data with NLO(α_S^3) predictions of the NLOJET++ program. Good agreement with the data is observed if additional jets are produced in the central region (large $\Delta\eta_2$). NLO QCD calculations deviate from the data if both values $\Delta\eta_1$ and $\Delta\eta_2$ are small i.e. when all three jets are in the forward region. This configuration is suppressed in NLOJET++.

In Fig. 5 we show that the more exclusive measurement of "forward jet + 2 additional jets" is able to differentiate different QCD models. The data are best described by the CDM model. The DGLAP-based model with only direct as well with resolved photon processes is below the data. The conclusion is that different type of the k_T-order breaking is needed than that provided by the resolved photon model.

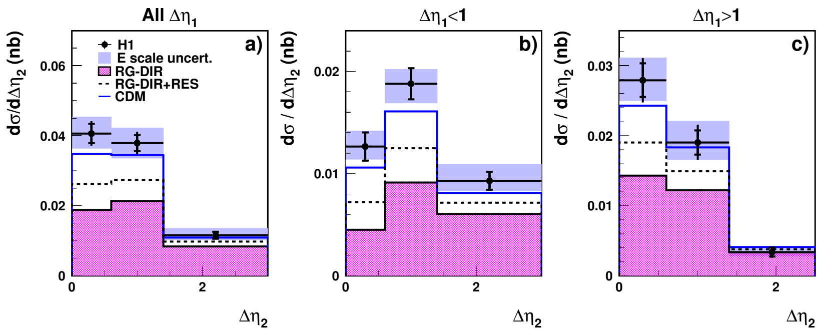

Figure 5. The cross section for events with "forward jet + 2 additional jets" compared with predictions of CDM and RAPGAP with direct and resolved processes .

4. Inclusive Forward π° Cross Sections and Transverse Energy Flow

Measurements of forward π° mesons[21] in the H1 detector are restricted in the kinematic range $2 < Q^2 < 70$ GeV^2, $0.1 < y < 0.6$, $5^\circ < \theta_\pi < 25^\circ$, $x_\pi = E_\pi/E_p > 0.01$ and $p^*_{T,\pi} > 2.5$ or 3.5 GeV, where $E_\pi(E_P)$ denotes the energy of the forward π(proton) in LAB and $p^*_{T,\pi}$ is defined in the photon-proton centre-of-mass system (CMS). The resulting range in Bjorken-x extends down to $x \approx 4 \cdot 10^{-5}$.

Inclusive forward π° cross sections as a function of x_{B_j} for $p^*_{T,\pi} > 2.5$

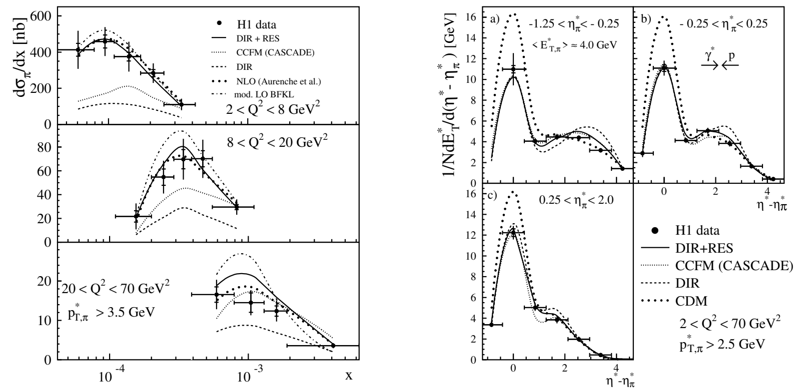

Figure 6. Inclusive forward π° cross section as a function of x_{Bj} in three regions of Q^2 for $p^*_{t,\pi} > 3.5$ GeV (left) and transverse energy flow relative to the π° in various ranges of η^*_π (right).

GeV in comparison with MC calculations which implement various QCD models have been discussed in Ref. 22. The conclusions are similar as those for the forward jet analysis. In Fig. 6 of this paper we show results for $p^*_{T,\pi} > 3.5$ GeV which are also compared with recent NLO DGLAP calculations[13]. The NLO prediction describe the data well, however large NLO/LO factors and large theoretical uncertainties indicate that a NNLO analysis would be required for a reliable prediction.

Studies of transverse energy flow provide a complementary means of investigating QCD processes. The transverse energy flow in the CMS, $\frac{1}{N}dE^*_T/d(\eta^* - \eta^*_\pi)$, in events containing at least one forward π° is shown in Fig. 6. The energy flow, which includes the contribution from the forward π°, is plotted as a function of the distance in pseudorapidity $\Delta\eta^* = (\eta^* - \eta^*_\pi)$ from the forward π°. The spectra are presented in three intervals of the π° pseudorapidity ranging from close (Fig. 6a) to far (Fig. 6c) from the proton direction. The QCD-based models except CDM all describe the transverse energy flow around the π° but give different predictions in the current region. The differences between the models can be qualitatively understood as a consequence of the ordering or otherwise of the transverse momentum in the parton cascades implemented within MC models. The CDM predicts too much transverse energy in the vicinity of the π°, which is a consequence of the too hard π° transverse momentum distribution predicted by this model.

5. Future Studies

At HERA II one expects about 700 pb^{-1} of ep data until the end of data taking in 2007, which would exceed the luminosity of HERA I by a factor of 5. With increased statistics further improvements in the precision of the forward region measurements can be gained by selecting forward jets with higher transverse momentum and higher jet energy. The investigation of the dependence on additional variables like p_T^2/Q^2, x_{B_j}/x_{jet}, $cos\gamma_h$ may help to differentiate various QCD models.

The interpretation of the forward production data indicates the importance of resolved photon processes. Therefore in addition to the primary hard scattering additional interactions between the remnants of the proton and the photon could contribute in the reaction. A better understanding of multiple interactions could help in precision studies of the forward jet and particle production.

Continuation of the studies of multijet production with different forward jet configurations, the jet shape analysis of forward jets and measurements of azimuthal correlation between the scattered electron and the forward jet will provide additional information about the QCD dynamics at low x_{B_J}.

Another possibility is to perform a measurement of forward photon production in DIS[23]. In this process there is no dependence on the hadronization mechanism, however the rate for this reaction is low and background from neutral pions may turn out to be large.

6. Conclusions

A new kinematic regime of low values of x_{B_j} provided by HERA for DIS measurements allows for tests of the QCD dynamics in this region. The production of forward jets and hadrons is especially sensitive to the dynamics of parton evolution and has been studied by the H1 and ZEUS Collaborations for the last ten years.

The measured cross sections show deviations from the LO DGLAP predictions. The inclusion of resolved photon processes improves the overall description. In some regions of phase space NLO DGLAP predictions give reasonable agreement with the data, however higher order calculations would be needed to improve the agreement and to reduce theoretical uncertainties. The CCFM evolution as implemented in the MC program CASCADE does not describe the data. The BFKL-like CDM model describe the data in most of the phase space region. Summarizing, existing theoretical approaches do not explain all features of forward jet and particle production. Recently important progress in measurements and theoretical calculations has been achieved, however the correct interpretation of the low x_{B_j} data at HERA is still a challenge.

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