FORWARD JETS AND PARTICLES AT HERA*

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It is possible to study the low x behavior of the proton structure at HERA for x values as low as $\sim 10^{-5}$. One of the most interesting aspects of low x proton structure is the study of QCD dynamics — the evolution of partons between kinematic regimes. In *ep* DIS, this can be studied inclusively by measuring the proton structure functions — F_2, $F_{\rm L}$, *etc.*, or exclusively by studying processes in the target region of the proton — forward going jets and particles. In this paper, various measurements made at HERA by the H1 and ZEUS experiments are presented and compared to MC models and fixed-order QCD calculations. While DGLAP-based evolution is able to describe the inclusive, *i.e.* F_2, data over the whole HERA kinematic region, a consistent picture of deviations from DGLAP models and fixed-order calculations in exclusive measurements is emerging. MC models and calculations based on BFKL or BFKL-like x-dependent parton evolution are able to describe most of the exclusive results.

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1. Introduction

Very early in the HERA program a steep rise of F_2 with increasingly lower x was observed, much steeper than predicted by the pre-HERA data and the existing parton density functions. Since the rise of F_2 was so steep, the onset of unitarity — the cross section limit for a proton saturated with partons — was closer than previously imagined. Also, since the pre-HERA predictions were obtained assuming only DGLAP parton evolution (evolution with Q^2), it was anticipated that at low x additional parton evolution could occur directly with x (BFKL parton evolution), contributing to the observed steeper rise.

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After 10 years of HERA data, we now know that a DGLAP-based NLO QCD fit is able to describe the F_2 data over the whole kinematic range of $\sim 1 < Q^2 < 50000$ and $\sim 5\times 10^{-5} < x < 0.5$. In addition, the x-dependence of the F_2 data can be fit with a constant slope parameter — no indication of saturation effects (parton–parton interactions change the linear evolution equations to non-linear ones) are seen.

2. Small x parton evolution

The proton structure can be defined in terms of two kinematic variables — most commonly chosen are the 4-momentum transfer variable Q^2 and the fraction of proton momentum carried by the interacting parton, x. Traditionally, only evolution of the parton densities with Q^2, as described by the DGLAP equations, has been used to determine the change in proton structure functions when moving from one kinematic region to another. However, parton evolution can also occur with x, defined by the BFKL equations, which should dominate at very low values of x. The DGLAP equations are characterized by strong ordering of angles, momentum fraction, and transverse momentum in the evolution chain. Forward partons far from the struck quark are characterized by small k_{T}, small angles, and large momentum fraction. These partons have very little effect on those close to the hard scattering vertex, so dijets in DGLAP models are approximately back-to-back. In the BFKL picture, angular and x ordering are preserved, but there is no requirement for k_{T} ordering. This results in the possibility of extreme forward partons having k_{T} values as large as that of the struck quark (Q). Therefore, in the BFKL picture, high E_{T} jets can be found in the forward region and these jets can have a large effect on the E_{T} balance of dijets at the interaction vertex.

At HERA, forward jets can be used to study the physics of the target region of the proton, investigate parton densities and evolution mechanisms at small x, and search for local density fluctuations where saturation effects might begin to occur.

3. Inclusive jets

Inclusive jet data can be compared to the DGLAP-based NLO QCD calculation which describes the F_2 data so well. Figure 1 shows inclusive jet cross sections in DIS *versus* jet pseudorapidity and *versus* x compared to the NLO QCD calculation and two Monte Carlo models: a DGLAP-based model (MEPS) and a BFKL-like model (CDM).

The data is described by CDM but not by MEPS or the NLO QCD calculation in the forward pseudorapidity region and at the lowest x values. It is clear that forward jets in DIS events at low x cannot be described by the same theory that adequately describes the F_2 data.

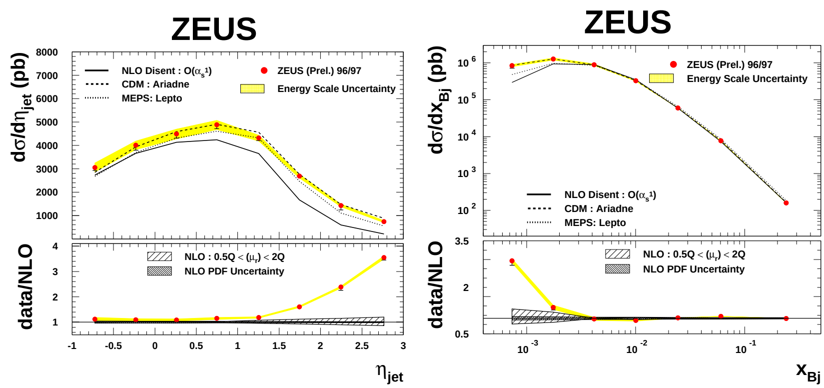


Fig. 1. Inclusive jet cross sections *versus* (a) pseudorapidity, and (b) x.

4. Forward jets

Focusing on jets in the forward region, selection cuts can be made to suppress the DGLAP contribution to the cross section. First, only target region jets are kept for analysis — directly in the Breit frame including only the target region, or indirectly by imposing large η cuts in the Lab frame. Kinematic cuts for the DIS events are made keeping x as small as possible for Q^2 values of at least 10 GeV^2. Figure 2 shows some of the properties of selected forward jets in DIS, particular cuts for this ZEUS analysis indicated by the shaded regions.

A jet E_{T} minimum of 4–5 GeV is required and a value for x_{jet}, the momentum fraction of the proton carried by the forward jet, of at least 0.025 is imposed. This cut forces the forward jet to be far from the current jet ($\ln x_{\mathrm{jet}}/x$ is large). In addition, by requiring that the ratio of $E_{\mathrm{T}}^{\mathrm{jet}}/Q \sim 1$, the forward jet is forced to have increasingly higher E_{T} as Q^2 increases. The cross section for jets with high E_{T} far from the current jet is very small for DGLAP evolution — an excess in the cross section may be the signal for an alternate form of parton evolution. The description of the data by various MC models indicates that the BFKL-like CDM model adequately describes the data, while the DGLAP-based models, LEPTO and HERWIG, are in much worse agreement.

Figure 3 shows the forward jet cross section *versus* x. Once again, only the CDM model comes close to describing the data, but there is an excess in the data at the lowest x values. The DGLAP NLO QCD calculation cross section is far too low, compared to the CDM model, while a LO BFKL calculation appears to overshoot the CDM model even more than the data. A similar analysis by H1 also shows that the DGLAP NLO QCD calculation of the cross section is too small, but the CASCADE MC model (based on the CCFM equation which has BFKL evolution in the small x limit) is able to describe the data.

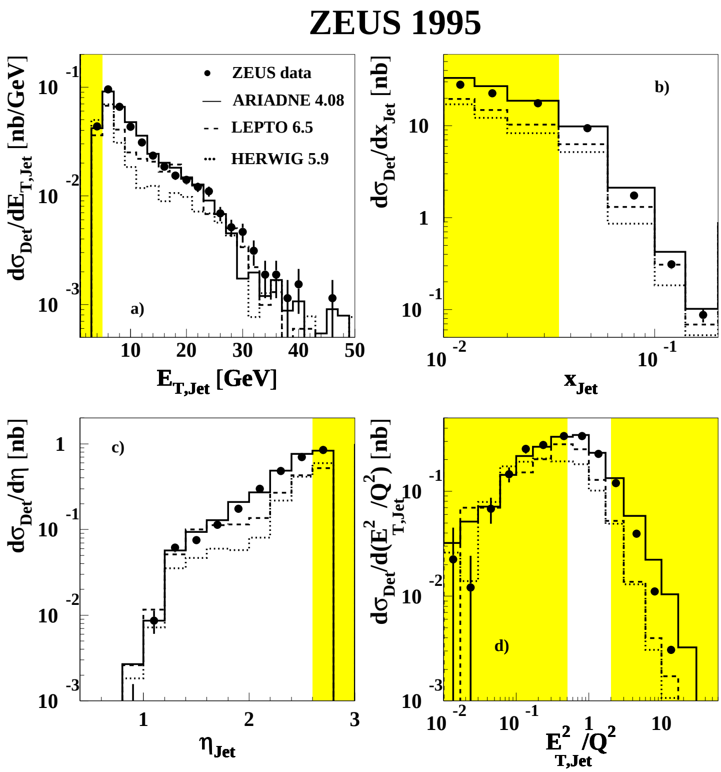


Fig. 2. Forward jet cross sections *versus* (a) jet E_{T}, (b) x_{jet}, (c) jet η, and (d) jet E_{T}^2/Q^2.

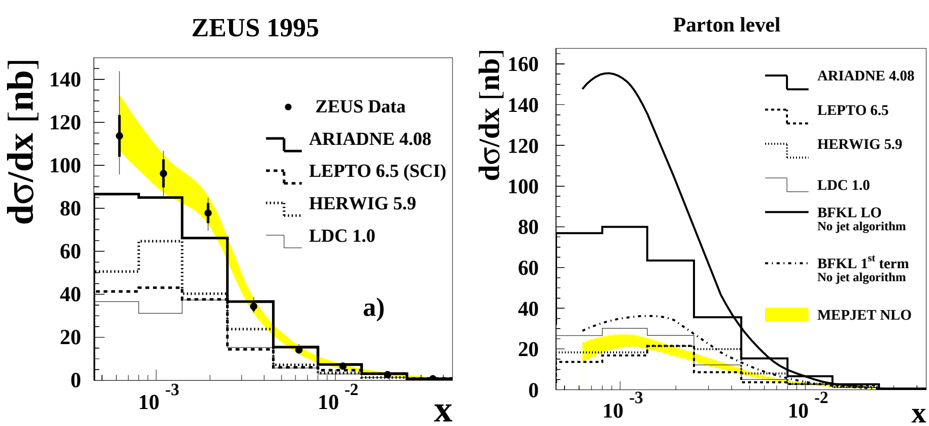


Fig. 3. Forward jet cross sections *versus* x; (a) data (corrected for detector effects) compared to MC, and (b) MC (parton level) compared to QCD calculations.

5. Forward particles

Some factors that must be understood for jets in forward region — separation of a jet from the proton remnant and model-dependent hadronization, can result in large corrections. However, leading particles, *i.e.*, π^0 in the forward region, are less sensitive to these effects. Figure 4 shows the cross section for forward π^0 production *versus* x in Q^2 bins. The results are con-

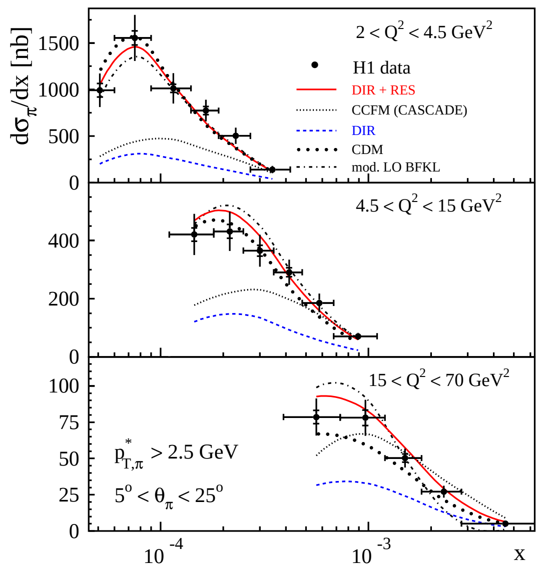
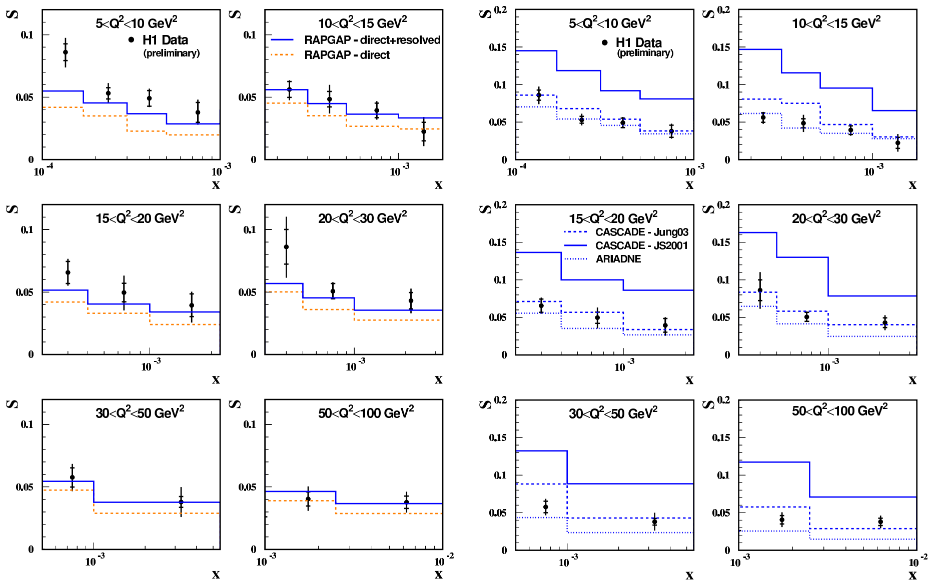


Fig. 4. Forward π^0 cross sections *versus* x for (top) low Q^2, (middle) medium Q^2, and (bottom) high Q^2.

sistent with the forward jets, comparisons with MC models showing again that DGLAP-based MC models can not describe the data. A modified LO BFKL calculation is able to describe the data along with the CDM model. In addition, the RAPGAP DGLAP-based MC model but with a resolved component of the exchanged virtual photon is also able to describe the data. The resolved virtual photon adds a kink in the parton ladder which allows extra $k_{\rm T}$ to appear far from the current region.

6. Azimuthal decorrelation of dijets

Finally, the $\Delta\phi$ distribution of the two hardest ($E_{\rm T}$) jets in an event can reveal features of the evolution of these jets. A hard component in the evolution chain from the high x to low x jets would show up as recoil momentum, forcing the two jets to not be emitted back-to-back. A variable S has been constructed which compares the tails of the $\Delta\phi$ distribution to the central peak. Figure 5 shows the ratio S *versus* x. The ratio S rises as x decreases, especially in the lowest Q^2 bins. Again, BFKL-like models (CDM and CASCADE) are able to describe the data as well as RAPGAP with a resolved virtual photon. DGLAP NLO QCD calculations are unable to describe this data.



(a) (b)

Fig. 5. Forward jet cross sections *versus* x; (a) data (corrected for detector effects) compared to MC, and (b) MC (parton level) compared to QCD calculations.

7. Summary

HERA is contributing to our understanding of the proton structure and to the dynamics of parton evolution as well. A consistent picture is emerging of deviations from traditional DGLAP evolution with Q^2 towards a more complete picture involving a significant contribution from BFKL or x-dependent parton evolution. This is evident in many exclusive measurements as shown in this paper. Still to come are measurements that should be sensitive to saturation effects — the onset of parton–parton interactions that eventually slow the steep rise of the proton structure function F_2.