Low x Dynamics with Final States

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Recent results obtained from the analysis of deep-inelastic scattering data in the regime at low x are presented. Final states with jets are used to access regions of phase space where the evolution schemes of QCD predictions are investigated.

The HERA collider has extended the available kinematic space for deep-inelastic scattering (DIS) to regions of large values of the four momentum transfer Q^2 ($\leq 10^5$) and small Bjorken scaling variable x ($x \approx 10^{-5}$). The large $\gamma^* p$ center of mass energy available at small x gives rise to a large phase space for additional gluon cascades exchanged between the proton and the photon. In perturbative QCD such multiparton emissions are described only in approximation. At large Q^2 the initial state radiation is described by standard DGLAP evolution equations [2] 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 of emitted partons. At asymptotically high energies and thus in the region of very small x, it is believed that the theoretically correct description is given by the BFKL equation [3]. 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 momenta, while the transverse momenta perform a random walk in the tranverse momentum space. The DGLAP and BFKL approaches are examples of two *extreme* choices in how the transverse momenta of the radiated gluons are ordered. The CCFM evolution [4] 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. A parton chain without transverse momentum ordering is also provided by allowing the virtual photon to have a partonic structure. In this process 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.

The measurements at HERA are 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 adopt various QCD approaches to modeling the parton cascade, while fixed order QCD calculations implement DGLAP evolution scheme. 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 BFKL or CCFM evolution to describe all HERA data at low x. A closely related problem is to what extent HERA data constrain the unintegrated parton density function (uPDF) required by BFKL&CCFM evolution schemes. The general strategy to answer these questions is to study hadronic final states which reflect the kinematic

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structure of gluon emissions. The H1 measurements we quote are ordered by increasing level of exclusivity, increasing parton kinematics control and decreasing phase space for gluon radiation. The data are compared with calculations performed using RAPGAP [7] (LO matrix element matched to DGLAP based parton showers, in addition resolved photon interactions), ARIADNE [8] (implementation of the Color Dipole Model (CDM) [9], transverse momenta of emitted gluons perform a random walk simulating BFKL-like behavior), CASCADE [10] (gluon emissions based on the CCFM equation employs an unintegrated gluon density fitted to describe the inclusive DIS cross section) NLOJET++ [12](calculates cross sections for two- and three-jet production in DIS i.e. up to NLO(α_S^3) accuracy and includes some $ln(1/x)$ terms of the perturbative expansion). The figure 1 shows azimutal

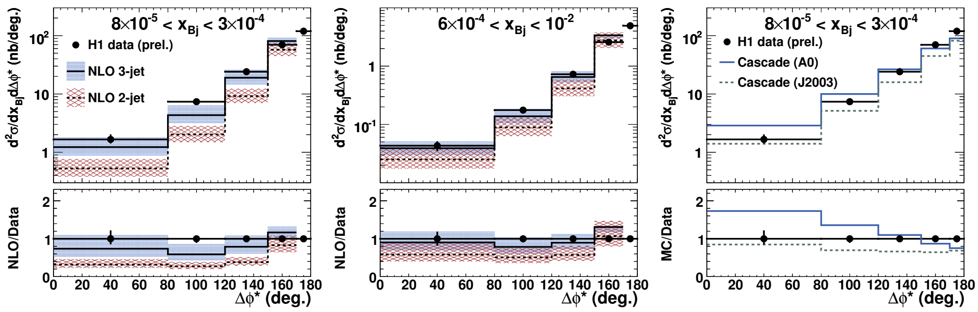

Figure 1: Differential cross section for inclusive dijet production as a function of the azimuthal jet separation in the center of $\gamma^* p$ system in two bins of x. The data are compared with 2-jet and 3-jet NLO calculation (left and central) and CASCADE model (right).Gray and hatched bands mark the scale uncertainty

jet separation of the two leading jets in the inclusive sample of dijet events in the DIS region $2 < Q^2 < 100$ GeV^2; $0.1 < y < 0.7$. The jets have transverse momentum $E_T > 5$ GeV and their azimutal separation $\Delta\Phi^*$ is measured in the center of mass of the $\gamma^* p$ system. Figure 1 (left) shows $\Delta\Phi^*$ distribution in $8 \times 10^{-5} < x < 3 \times 10^{4}$ bin. It can be seen that one parton radiation (NLO 2-jet calculation in NLOjet++) does not describe the data. Two parton radiation (NLO 3-jet calculation) is still systematically low at low x while for larger x (Fig.1 center) the data description is excellent. We conclude that calculations based on BFKL or CCFM approximations seem to be more practical in the region of very small values of x. The figure 1 (right) proves that HERA data do constrain uPDF: the $\Delta\Phi^*$ distribution is very sensitive to its choice.

The figure 2 presents differential cross section for inclusive production of *forward jets* in the DIS region $2 < Q^2 < 85$ GeV^2; $10^{-4} < x < 4 \times 10^{-3}$. The *forward jets* are searched for in the Breit frame, have a laboratory transverse momenta $p_T > 5$ GeV, carry a fraction of the protons momentum $x_{jet} > 0.035$ and their agular distance from proton momentum in laboratory frame is small ($7^\circ < \Theta_{jet} < 20^\circ$). In addition the *forward jets* are required to fulfill condition $0.5 < p_T^2/Q^2 < 5.0$. The *forward jet* selection follows strategy proposed by Mueller [5] : suppress DGLAP evolution ($p_T^2 \approx Q^2$) and at the same time enhance phase space for BFKL evolution ($x_{jet} >> x$). The prediction of the 2-jet NLO DGLAP calculation is well below the data points, however it appears that DGLAP based calculation with resolved photon shown in Fig. 2c provides a much better description. In the resolved

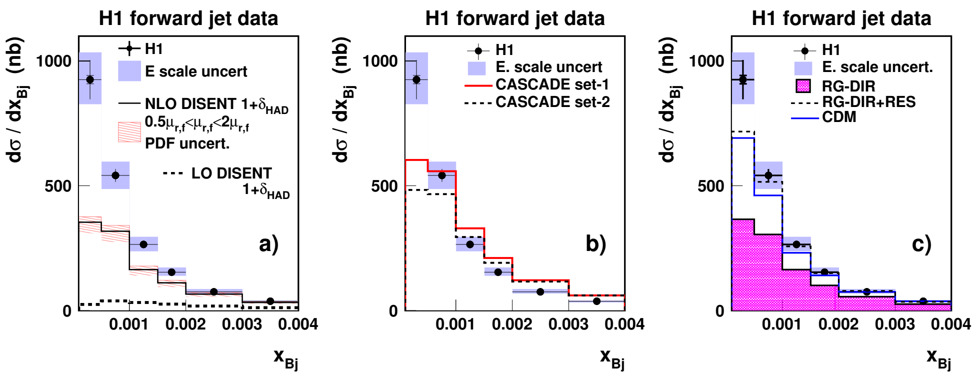

Figure 2: The hadron level cross section for inclusive forward jet production as a function of x compared to NLO 2-jet calculation (a) and to QCD Monte Carlo Models (b and c). The shaded band around the data points shows the errors from uncertainties in the calorimetric energy scale. The hatched band around the NLO calculations illustrates the uncertainties in theoretical calculations.

photon process (RAPGAP) DGLAP cascade develops from both photon and proton sides, so that the hard parton produced in LO process can emerge in the region of *forward jet*. In this sense the inclusive *forward jet* cross section is not a very sensitive test for non-DGLAP parton dynamics. Color Dipole Model predictions are similar to direct+resolved RAPGAP. CASCADE does not describe neither normalization nor slope of the data points. It is interesting to note that the BFKL calculation presented at this conference [17] predicts the correct shape of the inclusive forward cross section.

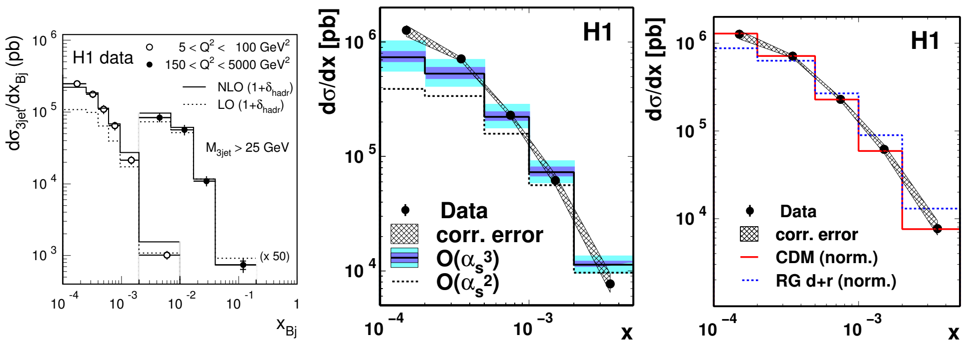

Figure 3: The inclusive three-jet cross section measured as a function of x with (left) and without (center and right) cut on 3-jet invariant mass $M_{3jet} < 25$ GeV. The data are compared the predictions of 3-jet LO and NLO QCD calculations (left and central) and QCD models RAPGAP and CDM calculations

Final states with three jets seem to be an ideal tool to investigate low x dynamics. In contrast to inclusive jets and dijets, in these final states the radiation of at least one hard gluon is required, in addition to the $q\bar{q}$ pair from dominating hard boson gluon fusion scattering process $\gamma^* g \to q\bar{q}$. However it appears that that this advantage is to some extent canceled by decreased phase space for additional emissions. In figure 3 we present inclusive cross section for production of three jets in two slightly different phase space regions. The event sample corresponding to open circles in figure 3(left) [15] is selected in the DIS region $2 < Q^2 < 100$ GeV^2; $0.2 < y < 0.6$, the jets have Breit frame transverse momentum $p_T^* > 5$ GeV and their invariant mass $M_{3jet} > 25$ GeV. The samples corresponding to data in central and right histograms of figure 3 [16] are selected in very similar DIS region ($2 < Q^2 < 80$ GeV^2; $0.1 < y < 0.7$) but the jet phase space is slightly larger: $p_T^* > 4$ GeV and no cut on M_{3jet} is applied. The data in figure 3(left) are very well described by 3-jet NLO calculation in the whole range of x. Opening of the phase space for the jet production results in discrepancy between data and 3-jet NLO calculation in the lowest bin of x as seen in figure 3(center). Comparison of three-jet cross section with QCD models now allows to distinguish between DGLAP and non-DGLAP approaches : CDM contrary to RAPGAP (direct + resolved) provides excellent description of the data.

We conclude that QCD calculations based on DGLAP evolution with transverse momentum ordered cascades fail to describe many aspects of HERA small-x data, such as azimuthal decorrelation for inclusive dijets, inclusive cross section for production of forward jets and 3-jet inclusive cross section at very small x. The need for full resummation of $ln(1/x)$ terms has not been proven, nevertheless BFKL(CCFM) calculation may appear to be most practical tool for the description of small-x data, with potential to determine uPDF.We note also, that Color Dipole Model based on quasi-classical radiation of color dipoles describes most of the small-x data and seems to contain all salient features of QCD evolution in many-parton processes.

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