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LOW-x DYNAMICS THROUGH JET STUDIES

JOZEF FERENCEI
(on behalf of the H1 and ZEUS collaborations)

Institute of Experimental Physics, Slovak Academy of Sciences, Watsonova 47, 04001 Košice, Slovakia

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One of the most challenging aspects of low x proton structure is the study of QCD dynamics - the evolution of partons between different kinematic regimes. In electron-proton deep-inelastic scattering, this can be investigated by studying processes in the target region of the proton - forward going jets. In this paper various measurements made at HERA by the H1 and ZEUS experiments are presented and compared to Monte Carlo models and fixed-order QCD calculations.

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1. Introduction

The HERA collider has extended the available kinematic region for deep-inelastic scattering (DIS) to regions of small Bjorken-x ($x_{\rm Bj} \approx 10^{-5}$) at moderate four-momentum transfers Q^2 of a few GeV^2. At the low $x_{\rm Bj}$ regime, a different evolution of the parton cascades other than the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) equation [1] should become important. Whereas DGLAP re-sums terms of $(\alpha_S \log Q^2)^n$, the Balitskij-Fadin-Kuraev-Lipatov (BFKL) evolution [2] takes into account terms $\alpha_S \log (1/x_{\rm Bj})$ and neglects $\log Q^2$ terms. One consequence of the different description of the parton dynamics is that for BFKL the strong ordering in transverse momentum, k_T, for the partons of the so-called gluon ladder between proton remnant and photon vertex no longer exists. This leads to signatures of the BFKL dynamics in DIS that can be discovered experimentally. For jets one can find a kinematic region where the phase space of the DGLAP evolution is suppressed compared to BFKL. This is the case when transverse jet momentum, $p^2_{T,{\rm jet}}$, is in the order of the momentum transfer, Q^2, and the longitudinal momentum fraction of the jet, $x_{\rm jet} = p_{z,{\rm jet}}/p_{\rm proton}$, is much larger than the Bjorken-x, $x_{\rm Bj}$. The cross section for jets at low $x_{\rm Bj}$ in the forward direction, i.e. in the direction of the incoming proton, would thus be increased due to BFKL dynamics [3].

2. *Multijet production*

Multijet production in DIS is an ideal environment for investigating different approaches to parton dynamics at low Bjorken-x, $x_{\rm Bj}$. An understanding of this regime is of particular relevance in view of the startup of the LHC, where many of the Standard Model processes, such as the production of electroweak gauge bosons or the Higgs particle, involve the collision of partons with a low fraction of the proton momentum.

ZEUS collaboration studied dijet and trijet production in DIS at low-$x_{\rm Bj}$ based on 82 pb^{-1} of data collected during 1998 and 2000 [4]. The kinematic range is $10 < Q^2 < 100$ GeV^2 and $10^{-4} < x_{\rm Bj} < 10^{-2}$. Multi-differential cross sections, as functions of the jet correlations in transverse momenta, azimuthal angles and pseudorapidity, have been measured for dijet and trijet production in the hadronic center-of-mass (HCM) frame. DGLAP-based calculations from NLOJET [5] at $\mathcal{O}(\alpha_s^2)$ and $\mathcal{O}(\alpha_s^3)$ were compared to the measurements. The data were found to be well described by the NLOJET calculations at $\mathcal{O}(\alpha_s^3)$, while calculations at $\mathcal{O}(\alpha_s^2)$ do not describe data, in particular at low $x_{\rm Bj}$. It was shown that these measurements are very sensitive to the QCD higher-order effects which can be enhanced by up to a factor ten at the lowest $x_{\rm Bj}$. The importance of higher-order terms at low $x_{\rm Bj}$ is seen especially when measuring the double-differential cross sections in Q^2 and $x_{\rm Bj}$ for events with $\Delta\Phi^{\rm jet1,2}_{\rm HCM} < 120°$, where $\Delta\Phi^{\rm jet1,2}_{\rm HCM}$ is the azimuthal separation of the two jets with the highest transverse energy. At low $x_{\rm Bj}$, the NLOJET calculations at $\mathcal{O}(\alpha_s^3)$ are up to about one order of magnitude larger than the $\mathcal{O}(\alpha_s^2)$ calculations and are consistent with the data, as seen in Fig. 1. The NLOJET calculations at $\mathcal{O}(\alpha_s^3)$ also provide a

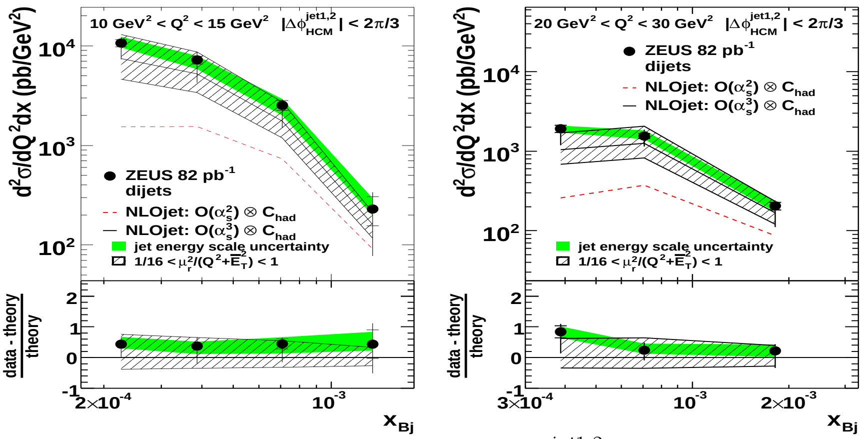

Fig. 1. The dijet cross sections for events with $|\Delta\Phi^{jet1,2}_{HCM}| < 2\pi/3$ as functions of $x_{\rm Bj}$ in two different Q^2-bins. The NLOJET calculations at $\mathcal{O}(\alpha_s^2)$ ($\mathcal{O}(\alpha_s^3)$) are shown as dashed (solid) lines. The lower parts of the plots show the relative difference between the data and the $\mathcal{O}(\alpha_s^3)$ predictions. The shaded band indicates the jet energy scale uncertainty. The hatched band represents the renormalisation-scale uncertainty of the QCD calculations.

reasonable description of the trijet measurements, with the description improving at higher $x_{\rm Bj}$.

The H1 study of trijet cross sections and correlations is based on 44 pb^{-1} of data collected in 1999 and 2000 [6]. The kinematic range of the measurement is focused on the low-$x_{\rm Bj}$ domain, $x_{\rm Bj} < 10^{-2}$ with $5 < Q^2 < 80$ GeV^2. Cross sections were measured as functions of $x_{\rm Bj}$, jet pseudorapidity, scaled jet energies, and correlations in the jet angles Θ' and ψ'. The variable Θ' is defined as the angle between the proton beam and the jet with the highest transverse energy, while ψ' is defined as the angle between the plane defined by the proton beam and the highest E_T jet, and the plane defined by the two jets with the highest E_T. A comparison of the inclusive trijet sample shows that $\mathcal{O}(\alpha_s^2)$ calculations undershoot the data while $\mathcal{O}(\alpha_s^3)$ predictions are marginally consistent, although within a large scale uncertainty. Yet the data tend to be higher compared to the $\mathcal{O}(\alpha_s^3)$ prediction for the smallest $x_{\rm Bj}$ and the largest pseudorapidity. To investigate this kinematic domain in more detail, the trijet sample was split in sub-samples with one or two jets in the forward direction. A significant discrepancy was observed for the sample with two forward jets for $x_{\rm Bj} \approx 10^{-4}$ (see Fig. 2. This discrepancy may indicate an enhancement of gluon radiation compared to NLO QCD evolution, but also higher-order QCD calculations for the hard scattering may improve the data description.

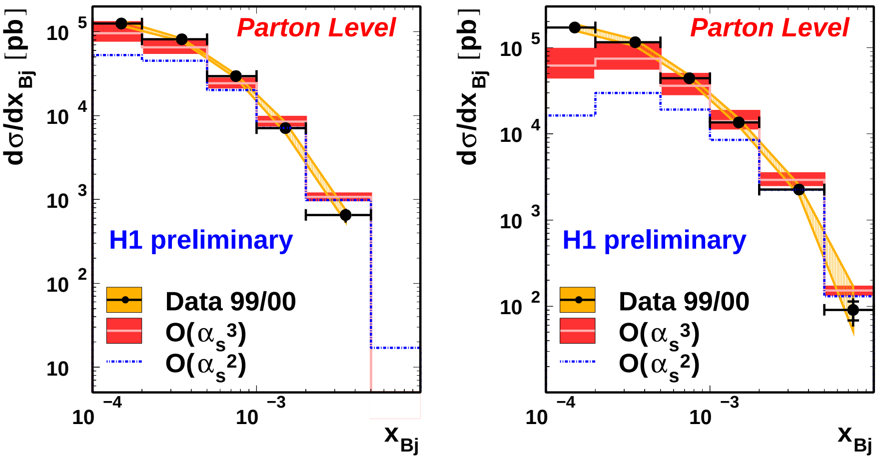

Fig. 2. Differential cross sections in the Bjorken scaling variable $x_{\rm Bj}$ for the samples with one forward and two central jets (left) and two forward and one central jet (right). The hatched error bands show the estimate of the correlated systematic uncertainties. The dark shaded (inner) error band shows the NLO $\mathcal{O}(\alpha_s^3)$ prediction with the uncertainty due to hadronisation corrections, the light shaded (outer) band includes the scale uncertainty added in quadrature.

Two LO Monte Carlo (MC) programs have been used to compare the data to RAPGAP [9] which includes standard k_T ordered parton showers and a resolved photon component and to DJANGOH which creates gluon radiation not ordered in k_T using color dipole model (CDM). The cross sections for the inclusive trijet sample are better described by CDM predictions, but both the CDM and RAPGAP predictions are inconsistent for the jet correlation angles Θ' and ψ'; the RAPGAP predictions fail to describe the Θ' distributions, and the CDM predictions fail to describe the ψ' cross sections.

3. Dijet azimuthal correlations

Dijet cross sections were investigated by the H1 Collaboration [7] as a function of the separation azimuthal angle $\Delta\Phi^*$ between the two jets (closest to the scattered electron in pseudorapidity, η) in bins of $x_{\rm Bj}$ and Q^2 in HCM frame. The measurements of $\Delta\Phi^*$ are reasonably well described by NLOJET calculations at $\mathcal{O}(\alpha_s^3)$, although within large theoretical uncertainties. Normalising the cross section to the visible cross section, the scale uncertainties of the NLO calculations partially cancel, such that both NLO calculations are unable to describe the data (Fig. 3 left). A sensitivity to the unintegrated gluon density is observed (Fig. 3 right). Hence, the data can be used to gain further information about the k_T-dependence of the unintegrated gluon densities.

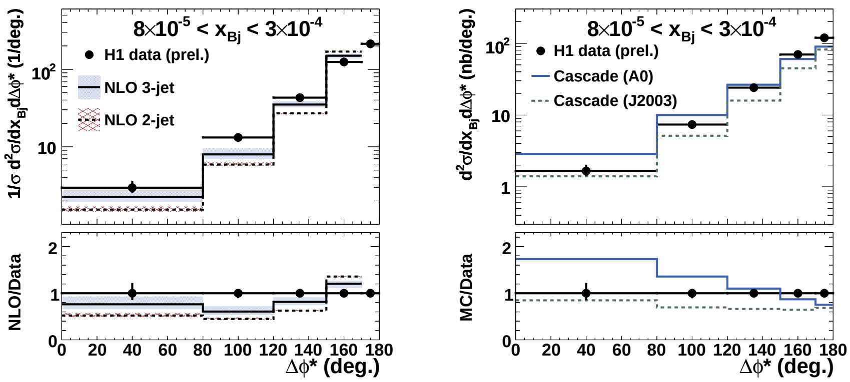

Fig. 3. Dijet cross sections as a function of $\Delta\Phi^*$ in lowest $x_{\rm Bj}$ bin and normalised to the visible cross section between $0° < \Delta\Phi^* < 170°$ in each $x_{\rm Bj}$ bin (left). Data are compared to NLO trijet (full line) and NLO dijet (dashed line) calculations obtained using the NLOJET program. The error band represent the scale uncertainty. Dijet cross sections as a function of $\Delta\ \Phi^*$ in lowest $x_{\rm Bj}$ bin compared to the predictions of CASCADE [10] using two different unintegrated gluon parton distribution functions (right).

4. Forward jet production

A new measurement of forward jet production in DIS with a significant extension in forward region up to pseudorapidities of $\eta^{\rm jet} < 4.3$ were made by ZEUS Collaboration using an integrated luminosity of 81.8 pb^{-1} [8]. This measurement is expected to highlight the differences between predictions of the BFKL and DGLAP formalism with BFKL resulting in a larger fraction of small-$x_{\rm Bj}$ events with forward jets than typically present in DGLAP evolution to NLO in QCD. Inclusive forward jets as well as forward jet accompanied by a dijet system were studied. The measurements were compared to the predictions of NLO QCD calculations, which were found to be below the data, in certain regions by as much as a factor of two. The best overall description of the inclusive forward jet cross sections (Fig. 4) was obtained by the newly tuned CDM model ARIADNE [11]. The predictions of the LEPTO [12] MC are found to be in agreement with the data in shape for all distributions, however the absolute normalisation is below the measurements by a factor of two. However, the CASCADE MC with the J2003 set-1 and set-2 unintegrated gluon densities failed to describe the data, suggesting that a further adjustment of the input parameters of the CASCADE model is necessary.

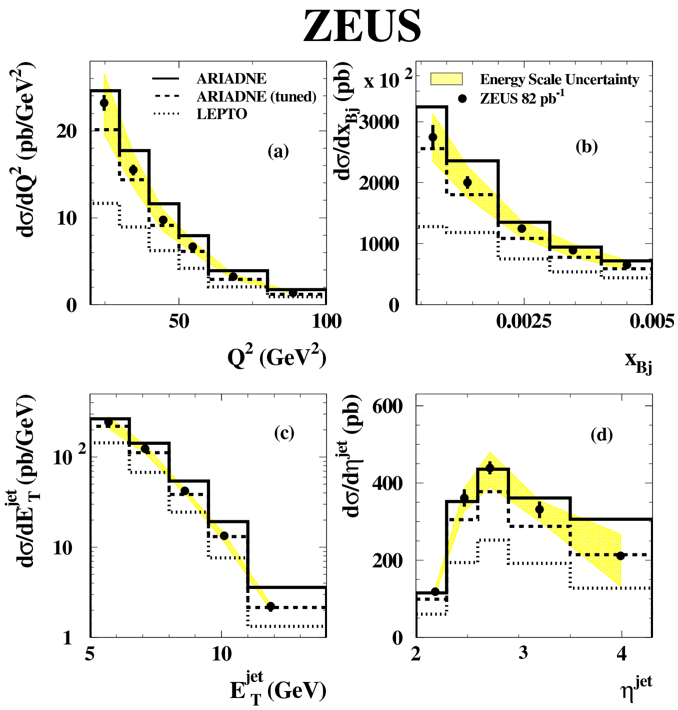

Fig. 4. Measured differential cross sections as a function of Q^2 (left) and $x_{\rm Bj}$ (right) for inclusive jet production (dots) compared with the ARIADNE (solid histogram), ARIADNE with new tuning (dashed histogram) and LEPTO (dotted histogram) predictions. The shaded area shows the uncertainty after varying the energy scales.

5. *Summary*

Parton dynamics at low $x_{\rm Bj}$ ($10^{-4} < x_{\rm Bj} < 10^{-2}$) has been investigated at HERA by the H1 and ZEUS collaborations. A LO MC with addition of non k_T-

ordered gluon radiation as implemented in CDM describes the data in most of the phase space region. The addition of the diagrams, which allows two gluons to be radiated, improves the agreement between data and the fixed order QCD prediction significantly and closes most of the gap between the measured cross sections and $\mathcal{O}(\alpha_s^2)$ prediction. Remaining discrepancies are concentrated at $x_{\rm Bj}$ values below 10^{-3} and events where two jets are going forward. This is a topology which is expected to be most sensitive to gluon radiation. CASCADE predictions are highly sensitive to the unintegrated gluon parton distribution functions used and do not describe the data consistently.

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MLAZOVI U PROUČAVANJU DINAMIKE ZA MALE x

Među najspornijim izazovima protonske strukture za male x je proučavanje QCD dinamike razvoja partona pri prijelazu među različitim kinematičkim uvjetima. To je moguće proučavanjem procesa u području protonske mete u duboko-neelastičnom raspršenju elektrona s protonima preko mlazova pod malim kutom. Predstavljamo više mjerenja suradnje H1 i ZEUS na HERI i uspoređujemo ih s Monte Carlo modelima i QCD računima određenog reda.