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LOW-x DYNAMICS PROBED BY MULTIJETS AT HERA*

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Recent results on forward jet and multijet production at low Bjorken x at HERA are reviewed. The measured cross sections and jet correlations are compared to predictions from DGLAP-based fixed order calculations. Further comparisons are made to DGLAP-based and CCFM-based leading-order Monte Carlo (MC) predictions as well as to colour dipole model (CDM) predictions. Recent results on multijet production in photoproduction are also presented.

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1. Introduction

Jet production in *ep* deep inelastic scattering is an ideal tool for investigating the different approaches to parton dynamics at low Bjorken x. The study of this kinematic region is of particular relevance in view of the startup of the LHC, where many of the Standard Model processes such as electroweak gauge boson or Higgs production involve the collision of partons with a low fraction of the beam-proton momentum.

In the usual collinear QCD factorisation framework, cross sections are obtained as the convolution of perturbative matrix elements and parton densities evolved according to the DGLAP evolution equations. In these equations all orders proportional to $\alpha_{\rm s} \ln Q^2$ and terms with double logarithm ln $Q^2 \ln 1/x$ are resummed. An excess of forward jets compared to DGLAP-based predictions and jets produced in the hard scattering that are not strongly correlated in transverse momentum may indicate the need for higher-order calculation or the breakdown of DGLAP dynamics at low x. In the latter case a better description may be provided by the BFKL approach, which resums terms proportional to $\ln 1/x$, or from CCFM, where strong angular ordering and unintegrated gluon densities are used.

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2. Azimuthal correlations in dijet events

Dijet azimuthal correlations have been investigated by the H1 Collaboration [1] by measuring the deep inelastic scattering ($Q^2 > 4\,\mathrm{GeV}^2$) cross-sections $d^2\sigma/dxd\Delta\phi^*_{\mathrm{HCM}}$, where $\Delta\phi^*_{\mathrm{HCM}}$ is the azimuthal separation in the hadronic centre-of-mass frame between the two jets selected as the closest to the scattered electron in pseudorapidity, η. The measurements of $\Delta\phi^*$ are reasonably well described by NLOjet calculations at $\mathcal{O}(\alpha_s^3)$, albeit within large theoretical uncertainties. To reduce the theoretical uncertainties, the measurements were normalised to the visible cross section for $\Delta\phi^* < 170°$. With a reduced theoretical uncertainty, the calculations predict a narrower $\Delta\phi^*$ spectrum than that measured, especially at very low x, as shown in Fig. 1. The measurements have been also compared to different Monte Carlo models including the CCFM-based *cascade* program. Although all models fail to describe $\Delta\phi^*$, a sensitivity to the unintegrated gluon densities is observed.

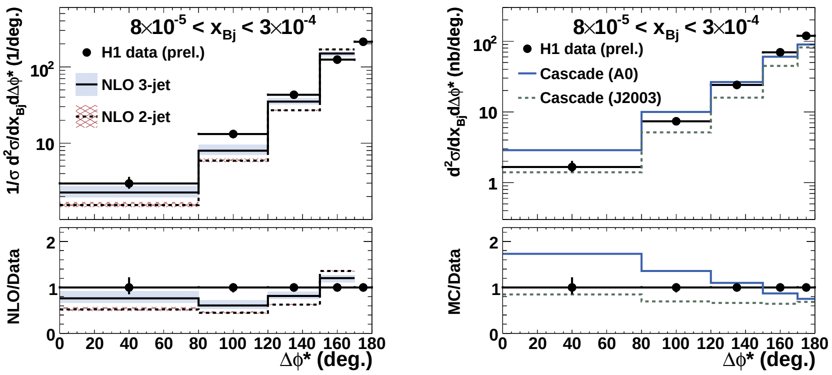

Fig. 1. Double-differential normalised cross sections as a function of $\Delta\phi^*$ as measured by H1 compared to NLOjet calculations for $\mathcal{O}(\alpha_s^2)$ and $\mathcal{O}(\alpha_s^3)$ (left) and to the Monte Carlo *cascade* program with different input gluon densities (right).

3. Forward jet production

To investigate the sensitivity of parton evolution to forward jet production, the ZEUS collaboration has studied jet production [2] in an extended pseudorapidity range up to $\eta^{\mathrm{jet}}_{\mathrm{LAB}} = 4.3$ covered by the Forward Plug Calorimeter. Measurements of cross sections as functions of Q^2, x, $E^{\mathrm{jet}}_{\mathrm{T,LAB}}$, and $\eta^{\mathrm{jet}}_{\mathrm{LAB}}$ are reasonably well described by DGLAP-based calculations from *Disent*, with large theoretical uncertainties at both low x and high $\eta^{\mathrm{jet}}_{\mathrm{LAB}}$. Predictions from *lepto* (DGLAP) and *ariadne* (CDM) were also compared to the measurements. Overall, as shown in Fig. 2(a), (b), *ariadne* provides the best description of the measured cross sections.

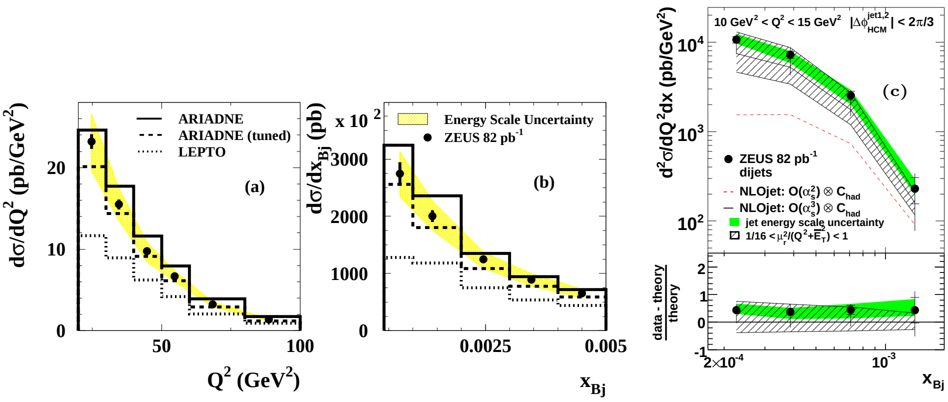

Fig. 2. (a), (b) Forward-jets differential cross sections as functions of x and Q^2 compared to predictions from *ariadne* and *lepto*. (c) ZEUS dijet cross sections in x and Q^2 as a function of x with $\Delta\phi^{\mathrm{jet1,2}}_{\mathrm{HCM}} < 120°$.

4. Multijet production and correlations

ZEUS has measured dijet and three-jet production in the phase-space region $10 < Q^2 < 100\,\mathrm{GeV}^2$ and $10^{-4} < x < 10^{-2}$ using an integrated luminosity of $82\,\mathrm{pb}^{-1}$ [3]. The dependence of dijet and three-jet production on the kinematic variables Q^2 and x and on jet variables is well described by perturbative QCD calculations which include NLO corrections. To further investigate possible deviations with respect to the collinear factorisation approximation dijet events with low azimuthal separation are selected. As shown in Fig. 2(c), the agreement between data and the fixed order QCD calculations is satisfactory provided that higher-order terms $O(\alpha_s^3)$ are taken into account. Such terms increase the predictions of pQCD calculations by up to one order of magnitude at low x when the two jets with the energy are not balanced in transverse momentum.

H1 has presented a new measurement of three- and four-jet production in deep-inelastic ep scattering at low x and Q^2 using an integrated luminosity of 44.2 pb^{-1} [4]. Several phase-space regions are selected for the three-jet analysis in order to study the underlying parton dynamics from global topologies to the more restrictive regions of forward jets close to the proton direction. The measurements of cross sections for events with at least three jets are compared to fixed order QCD predictions in which higher order effects are approximated by parton showers. A good overall description is provided by the $\mathcal{O}(\alpha_{\mathrm{s}}^3)$ calculation. Too few events are predicted at the lowest x, especially for topologies with two forward jets as shown in Fig. 3. This hints to large contributions at low x from initial state radiation of gluons close to the proton direction and unordered in transverse momentum.

The Monte Carlo program in which gluon radiation is generated by the colour dipole model gives a good description of both the three- and the four-jet data in absolute normalisation and shape.

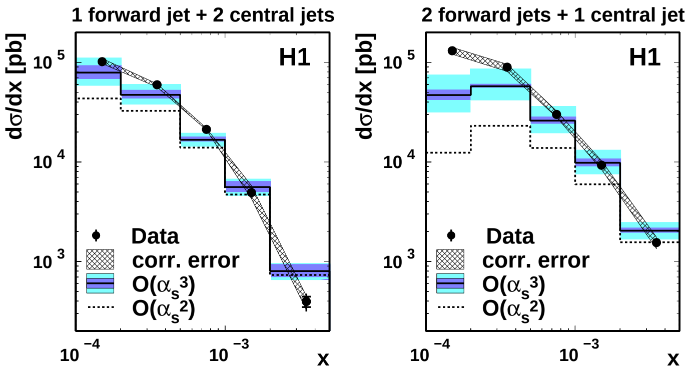

Fig. 3. H1 three-jet cross sections as a function of x for events with two forward jets compared to NLOjet calculations at $\mathcal{O}(\alpha_s^2)$ and $\mathcal{O}(\alpha_s^3)$.

5. Multijets in photoproduction

Three- and four-jet states in photoproduction at HERA, have been recently measured by ZEUS [5] in two multijet mass regions $25 \leq M_{nj} < 50$ GeV and $M_{nj} \geq 50$ GeV. While in the high mass region, the shape of the three- and four-jet cross sections are reasonably well described in by the *pythia* and *herwig* Monte Carlos, in the low-mass region, as shown in Fig. 4, the Monte Carlo models underestimate the data when normalised to the measured high-mass cross section suggesting the need for contributions from

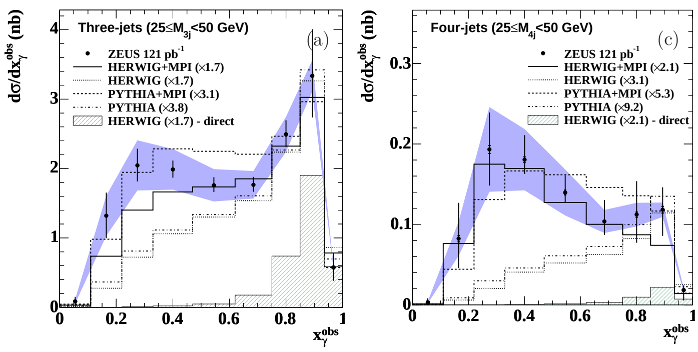

Fig. 4. Measured three- and four-jet cross section as a function of x_γ^{obs}, the fraction of momentum of the parton in the photon participating to the hard process in the mass region $25 < M_{nj} < 50\,\text{GeV}$.

multi particle interactions (MPI). Once these are added to the MC simulations, the agreement between the models and data is generally improved. Although the data have large uncertainties, the measured cross sections are potentially useful in the testing and tuning of MPI and underlying event models.

6. Conclusions

A wide spectrum of measurements to study the parton dynamics at low x has been performed by H1 and ZEUS. While LO calculations are not consistent with the data, NLO calculations provide a good description for most measurements. Nevertheless BFKL-enhanced forward jet data at low x, not described by NLO QCD, indicate the need of NNLO calculations. The colour dipole model as implemented in *ariadne* provides a consistent description of most dataset, while *cascade* (CCFM) with currently used sets of unintegrated gluon densities fails to describe the shape of most distributions; these data could be used to determine the unintegrated gluon distributions. Multijet photoproduction data are better described adding Multi Particle Interactions to LO Monte Carlos. Measurements using the full HERA luminosity, that for the two experiments H1 and ZEUS together is of $1\,\mathrm{pb}^{-1}$, will provide additional constraints to the theory.

I would like to thank all the people involved in the conference preparation for the perfect organization and the warm atmosphere during the whole workshop.

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