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Dijets at low x and low Q^2 at HERA

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Dijet production in deep inelastic $e^{\pm}p$ scattering is investigated in the region of low values of the Bjorken-variable x and low photon virtualities Q^2. The measured dijet cross sections are compared with perturbative QCD calculations in next-to-leading order. For most dijet variables studied, these calculations can provide a reasonable description of the data over the full phase space region covered, including the region of very low x. However, large discrepancies are observed for events with small separation in azimuth between the two highest transverse momentum jets. This region of phase space is described better by predictions based on the CCFM evolution equation, which incorporates k_t factorized unintegrated parton distributions. A reasonable description is also obtained using the Color Dipole Model or models incorporating virtual photon structure.

Also triple differential dijet cross sections in the $\gamma^* p$ centre-of-mass frame are compared with NLO QCD calculations and LO Monte Carlo programs with and without a resolved virtual photon contribution. NLO QCD calculations fail to describe the region of low Q^2 and low jet transverse energies, in contrast to a LO Monte Carlo generator which includes direct and resolved photon interactions with both transversely and longitudinally polarised photons. Initial and final state parton showers are tested as a mechanism for including higher order QCD effects in low E_T jet production.

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1. Introduction

Dijet production in deep inelastic lepton-proton scattering (DIS) provides an important testing ground for Quantum Chromodynamics (QCD). HERA dijet data may be used to gain insight into the dynamics of the parton cascade exchanged in low-x lepton-proton interactions. Since in this region of phase space photon-gluon fusion is the dominant underlying process for dijet production, such measurements also open the possibility of studying the unintegrated gluon distribution. In leading order (LO), i.e. $O(\alpha_s)$, dijet production in DIS is described by the boson-gluon fusion and QCD-Compton processes. The evolution of the parton density functions (PDFs) with the factorization scale, μ_f^2, is generally described by the DGLAP equations. To leading logarithmic accuracy, this is equivalent to the exchange of a parton cascade, with the exchanged partons strongly ordered in virtuality up to Q^2 . For low fractional momentum x this becomes approximately an ordering in k_t , the transverse momentum of the partons in the cascade. The DGLAP approximation, which only resums leading logarithms in Q^2, is expected to break down at low x, where contributions from $\ln(1/x)$ terms become large. At very low values of x, it is believed that the theoretically most appropriate description is given by the BFKL evolution equations. These resum large logarithms of $1/x$ up to all orders and impose no restriction on the ordering of the transverse momenta within the parton cascade. A promising approach to parton evolution at both small and large values of x is given by the CCFM evolution equation, which, by means of angular-ordered parton emission, is equivalent to the BFKL ansatz for $x \to 0$, whilst reproducing the DGLAP equations at large x. An alternative approach to modelling additional contributions due to non-k_t-ordered parton cascades is given by the concept of virtual photon structure. This approach mimics higher order QCD effects at low x by introducing a second k_t-ordered parton cascade on the resolved photon side, evolving according to the DGLAP formalism.

2. Experimental Results and Comparison with Models

In [1] inclusive dijet production in deep inelastic ep scattering is measured in the kinematic range $5 < Q^2 < 100$ GeV^2 , $10^{-4} < x < 10^{-2}$ and $0.1 < y < 0.7$. Multi-differential cross section data are compared with NLO QCD predictions and no significant deviations are observed within the experimental and theoretical uncertainties. In the kinematic range studied, the next-to-leading order DGLAP approach provides an adequate theory for predicting ep dijet cross sections as a function of Bjorken- x, Q^2 , $E^*_{\mathrm{T,max}}$ and $|\Delta^*_\eta|$ (as measured in the hadronic center-of-mass system).

More insight into small-x dynamics can be gained from the dijet data by studying the behaviour of events with a small azimuthal separation, $\Delta\phi$, between the two highest transverse momentum jets. Partons entering the hard scattering process with negligible transverse momentum, as assumed in the DGLAP formalism, lead at leading order of QCD to a back-to-back configuration of the two outgoing jets with $\Delta\phi = 180^o$. Azimuthal jet separations different from 180^o occur due to higher order QCD effects. However, in models which predict a significant proportion of partons entering the hard process with large transverse momentum, the number of events with small $\Delta\phi$ also increases. In order to search for such effects, the ratio of the number of events N_{dijet} with an azimuthal jet separation of $\Delta\phi = 120^o$ relative to all dijet events, $S = \int_0^{120^o} N_{\mathrm{dijet}}(\Delta\phi^*, x, Q^2) d\Delta\phi^* / \int_0^{180^o} N_{\mathrm{dijet}}(\Delta\phi^*, x, Q^2) d\Delta\phi^*$, is shown as a function of x for dif-

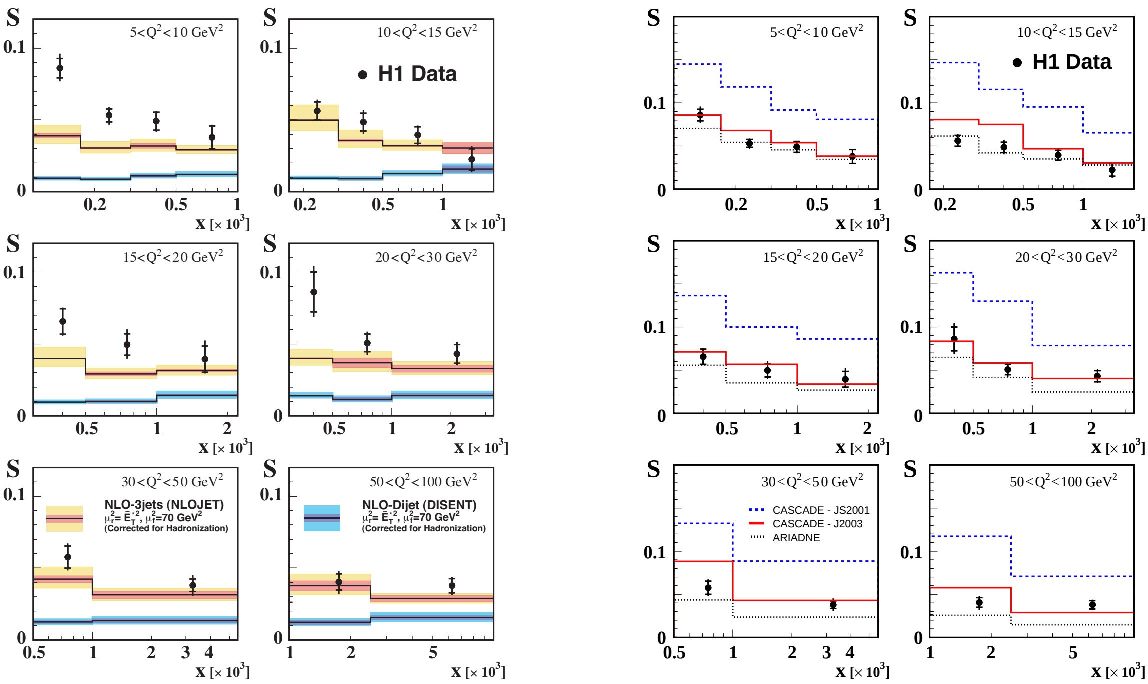

Figure 1: Ratio S as a function of Bjorken-x and Q^2. The data are compared with LO and NLO QCD predictions using the CTEQ6M parton distribution functions (left) and with predictions from CASCADE using two different k_t-unintegrated gluon distributions and predictions from ARIADNE, which is based on the color dipole model (right).

ferent regions in Q^2 in fig. 1. The fraction of jets with an azimuthal separation $\Delta\phi = 120^o$ increases with decreasing x. This rise is most prominent in the lowest Q^2 interval, where the smallest values of x are reached. The NLO dijet QCD calculations predict S values of only $\sim$1% and show no rise towards small x. The data are also compared with an NLO calculation for 3-jet production, corresponding to an extra order in the strong coupling constant α_s for the perturbative calculation. The 3-jet calculation is closer to the data and shows the correct qualitative features. However, it is still insufficient to describe the magnitude of S at the lowest x and Q^2 values, suggesting that further improvements to the theory are required. In fig. 1 right the data are also compared with the predictions of the CASCADE Monte Carlo program, which includes CCFM evolution and unintegrated parton densities. The predictions are found to be highly sensitive to the choice of unintegrated gluon density, with different parameterisations that describe the proton structure function F_2 yielding rather different predictions for S. The quantity S therefore offers significant potential to constrain the unintegrated parton densities.

In another study [2] triple differential dijet cross sections in $e^{\pm}p$ interactions are measured in a slightly different region of phase space and are compared with NLO and LO calculations, with and without resolved photon contributions or parton showers, as well as with a calculation based on k_T factorisation and an unintegrated PDF of the proton (see fig. 2). A sizable and systematic excess of the data over NLO calculations which do not include a resolved virtual photon contribution is observed for $Q^2 < 10$ GeV^2 , small jet transverse energies, E_T^* , and small x_{jets} , or equivalently, large jet pseudorapidities, η^* . The excess observed for $x_{\text{jets}} < 0.75$ decreases with increasing Q^2. NLO QCD calculations incorporating a resolved virtual photon, as implemented in JETVIP, bring

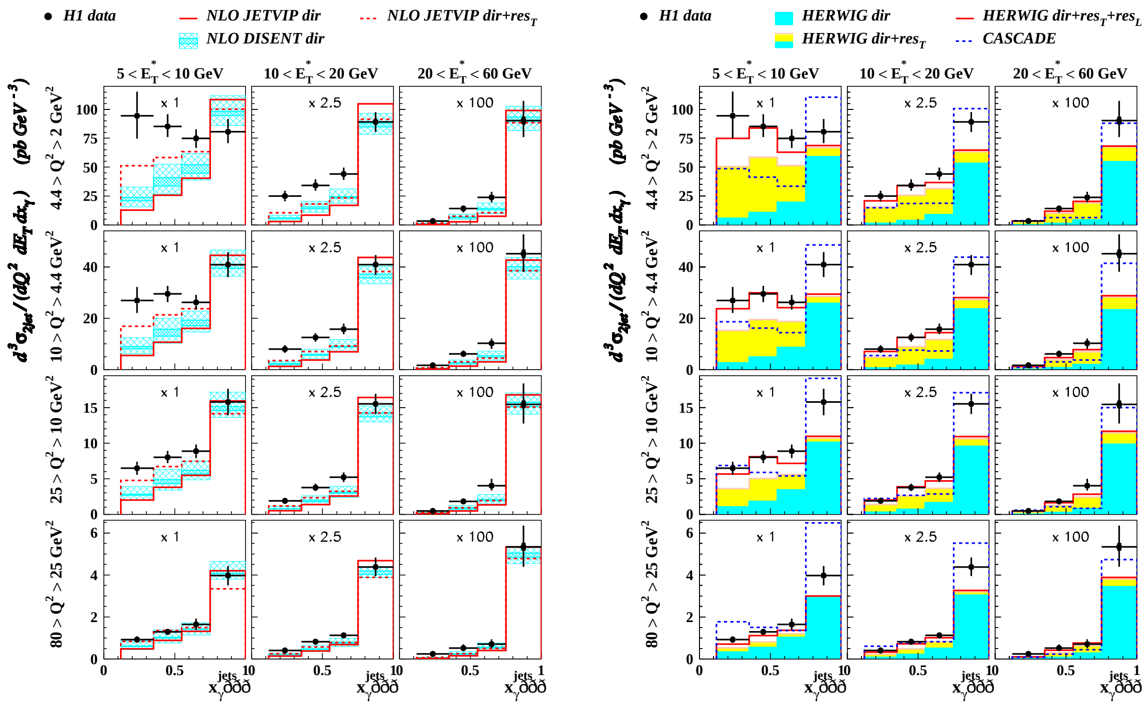

Figure 2: Triple differential cross section $d^3\sigma_{2\text{jet}}/dQ^2dE_T^*dx_\gamma^{\text{jets}}$ compared to NLO predictions from JETVIP and DISENT (left) and to calculations from the LO program HERWIG and from CASCADE (right).

the QCD predictions closer to the data, though there is still a deficit at low x_{jets} for low Q^2 . The inclusion of QCD parton showers in the HERWIG LO Monte Carlo model leads to a considerable improvement in the description (not shown here), though a discrepancy remains in the region of high x_{jets}. Within this model, the best agreement with the data is obtained when both transversely and longitudinally polarised resolved virtual photons are included (see fig. 2 right). CASCADE, which is based on the CCFM evolution scheme, does not involve the concept of virtual photon structure. The CASCADE description of the data is best in the region of moderate Q^2 between 10 and 25 GeV^2 . The Q^2 dependence of the cross section is less steep than in the data.

In conclusion, measurements of azimuthal jet separation and of triple differential cross sections at medium Q^2 have been used to establish clear evidence for effects that go beyond fixed-order NLO QCD. The NLO calculations do not provide satisfactory agreement at small values of Q^2 and x or Q^2, E_T^*, and x_γ. LO Monte Carlo predictions give a reasonable description if they are supplemented with parton showers and if transversely and longitudinally polarised resolved photon contributions are included. CASCADE, which is based on the CCFM evolution equation qualitatively describes the main features of the data.

References

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[2] A. Aktas *et al.* [H1 Collaboration], *Measurement of Dijet Production at Low Q^2 at HERA*, *Eur. Phys. J.* **C37** (2004) 141-159 [hep-ex/0401010].