REVIEW OF JET RESULTS FROM HERA*

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Some of the most recent results on jet production at HERA are reviewed. The measurements are confronted with predictions from next-to-leading order Quantum Chromodynamics. In regions where uncertainties are small, the strong coupling, $\alpha_{\rm s}$, has been extracted. Other topics of current interest are also highlighted.

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1. Introduction

The HERA collider is a unique laboratory for the study of the hadronic final state. In particular, the study of jets provides a precise tool to aid understanding of the underlying parton dynamics.

The large luminosity accumulated at HERA allows very precise measurements to be made in both Deep Inelastic Scattering (DIS) and photoproduction, thereby enabling meaningful comparisons with next-to-leading order (NLO) QCD predictions. Issues relevant to the description of the QCD hard subprocess, such as the potential size of higher order corrections, and the most appropriate choice of scale, can now be addressed. Furthermore, in regions of phase space where the description of the data by NLO QCD is sufficiently good, extraction of the strong coupling, $\alpha_{\rm s}$, is possible.

Measurements of inclusive charged-current (CC) and neutral-current (NC) DIS cross sections at HERA have already placed strong constraints on the quark densities in the proton. However, jet cross sections are directly sensitive to both the quark *and* the gluon distributions and, hence, may provide

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complementary information on the gluon density. Furthermore, in the photoproduction region ($Q^2 \sim 0$ GeV^2), the photon can behave hadronically and jet cross sections provide constraints on the quark and gluon densities in the photon.

Presented here is a brief summary of some of the most recent results from the large number of precision jet measurements available from HERA. A number of topics of current interest are highlighted.

2. Jet production in neutral current deep inelastic scattering

The NC DIS process proceeds via the exchange of a γ^* or a Z^0. The lowest order (LO) non-trivial contributions are the $\mathcal{O}(\alpha\alpha_s)$ QCD Compton and Boson–Gluon Fusion processes. The high virtuality of the exchanged boson ($Q^2 \gg 0$ GeV^2) provides the hard scale for the interaction.

2.1. Inclusive jet production

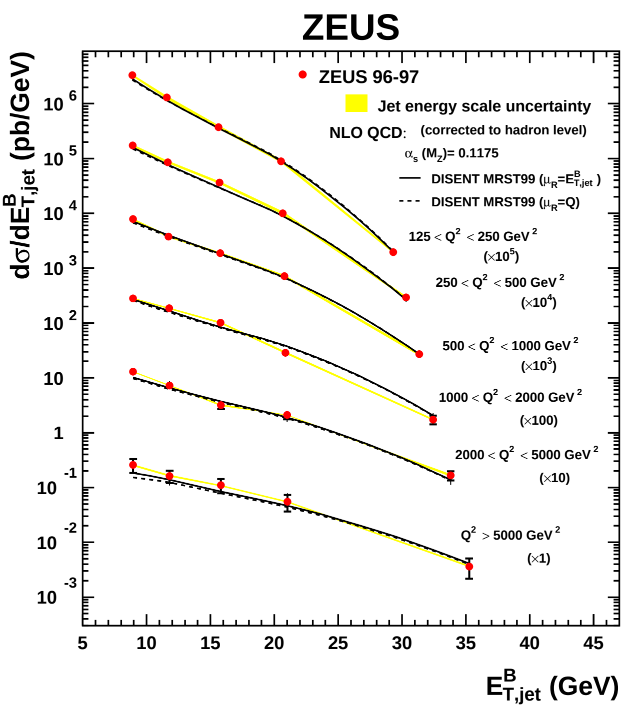

Fig. 1. Inclusive jet production in the Breit frame from ZEUS [1].

The inclusive production of jets in the Breit frame is an intrinsically $\mathcal{O}(\alpha\alpha_s)$ process and is directly sensitive to the QCD subprocess and the gluon density in the proton.

The cross section for inclusive jet production in NC DIS, for virtualities $Q^2 > 125$ GeV^2, is shown in Fig. 1. Jets are required to satisfy $E_T^B > 8$ GeV and $-2 < \eta^B < 1.8$. The data are compared to the NLO QCD predictions of DISENT [2], evaluated with renormalisation scales of $\mu_R = E_T^B$ (solid curve) and $\mu_R = Q$ (dashed curve). The renormalisation scale uncertainty, estimated by varying μ_R by a factor of 1/2 and 2, is relatively small and the calculations at both scales are in reasonable agreement with the data. At low Q^2 and E_T^B, there is an indication that the data lie above the NLO QCD prediction. However, this is also the region where the theoretical uncertainties are largest, precluding any strong conclusions regarding this point.

Given the good overall agreement between data and NLO QCD, it is possible to extract the value of α_s. Figure 2 shows the results for the HERA NC DIS jet data. The results show a clear running of α_s with the scale, μ.

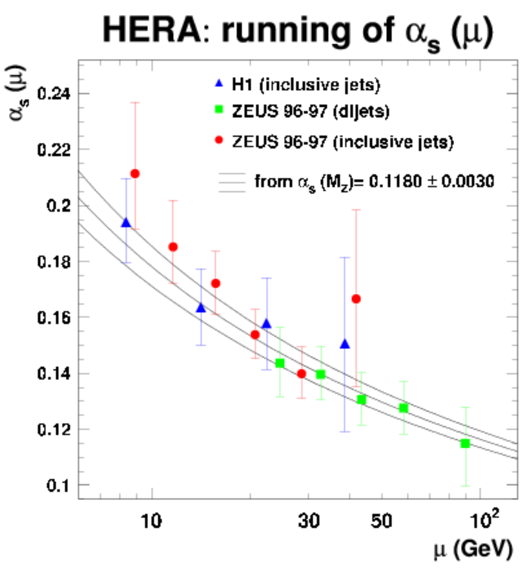

Fig. 2. The strong coupling extracted from HERA inclusive and two-jet NC DIS data.

The value of $\alpha_s(M_Z)$ extracted by H1, for bosons with virtualities in the range $150 < Q^2 < 5000$ GeV^2, is

$$\alpha_s(M_Z) = 0.1186 \pm 0.0030(\text{exp.})^{+0.0039}_{-0.0045}(\text{theory})^{+0.0033}_{-0.0023}(\text{PDF})$$

while that from ZEUS, for $Q^2 > 500$ GeV^2, is

$$\alpha_s(M_Z) = 0.1212 \pm 0.0017(\text{exp.})^{+0.0023}_{-0.0031}(\text{syst.})^{+0.0028}_{-0.0027}(\text{theory}).$$

These results are consistent with the world average and are of competitive precision [3]. The largest single uncertainty is from the renormalisation scale dependence.

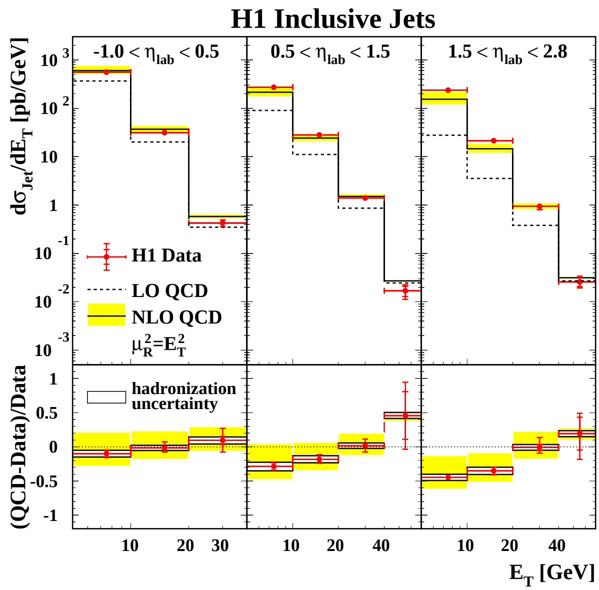

Fig. 3. Inclusive jet production in NC DIS at lower Q^2 [4].

The cross section for inclusive jet production in the Breit frame for the lower Q^2 region, $5 < Q^2 < 100$ GeV^2, is shown in Fig. 3. The data are well described by the NLO QCD calculation for $-1.0 < \eta_{\text{lab}} < 1.5$. However, in the forward region ($\eta_{\text{lab}} > 1.5$) the theory lies significantly below the data for low E_T^{jet}. Further measurements in the forward region, differential in Q^2, have shown that the discrepancy between data and NLO QCD is largest when Q^2 is also low. In this region, the DGLAP evolution of the parton distributions might break-down and we may expect to observe the onset of BFKL. However, the large uncertainties in the DGLAP predictions in this region of phase space preclude any further conclusions on the need for BFKL effects in these data.

2.2. Virtual photon structure

If $E_T \gg Q$, logarithms in E_T/Q can be large. However, these logarithms can be re-summed by defining parton distribution functions (PDFs) for a virtual photon in a similar fashion to the proton. This means that the photon can either interact directly, or it may fluctuate into a hadronic state and interact via a parton carrying some fraction $x_\gamma < 1$ of the photon's total longitudinal momentum.

Figure 4 shows the ratio of the cross section for resolved-enhanced ($x_\gamma < 0.75$) and direct-enhanced ($x_\gamma > 0.75$) two-jet events as a function of Q^2. The data are compared to the predictions of DISASTER [6] (which includes no resolved virtual photon) with renormalisation scales of $\mu_{\rm R} = Q$ and $\mu_{\rm R} = (Q^2 + E_{\rm T}^2)^{1/2}$. The predictions at both scales fail to describe the data for $Q^2 < \bar{E}_{\rm T}^2$, where the resolved component would be larger.

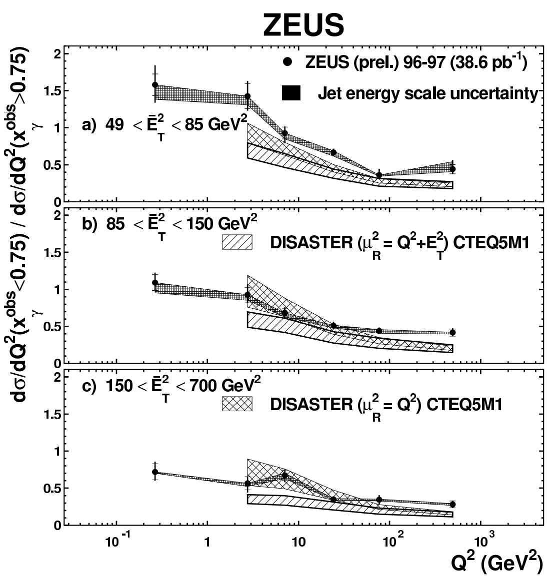

Fig. 4. The ratio of resolved-enhanced to direct-enhanced two-jet production from ZEUS [5].

An alternative picture is available using $k_{\rm T}$ unordered parton evolution schemes, such as CCFM. These allow the two highest transverse energy partons to come from anywhere along the gluon ladder between the photon and proton. This provides a qualitatively simple picture without the need for any explicit photon structure. Results from H1, shown in Fig. 5, suggest that predictions from CASCADE [8], which uses CCFM evolution, are in reasonable agreement with the data. However, predictions from the LO Monte Carlo HERWIG [9], including a simulation of a resolved virtual photon, also give a reasonable description of the data.

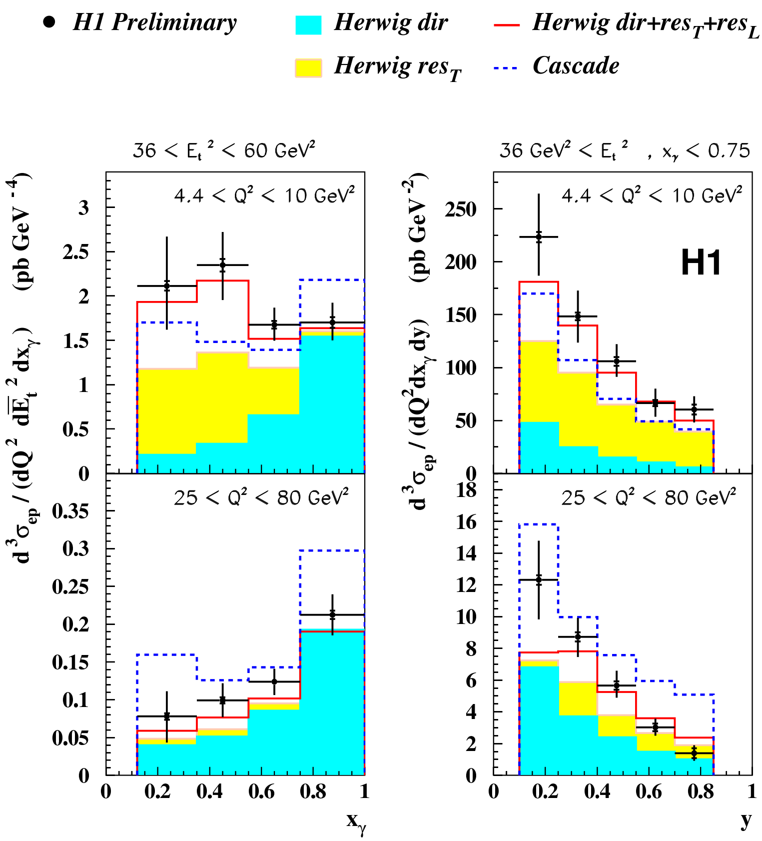

Fig. 5. Two-jet cross sections as functions of x_γ and y from H1 [7].

2.3. Three-jet production

At LO, three-jet production is an $\mathcal{O}(\alpha\alpha_s^2)$ process. A NLO[1] prediction [10] is available and so the study of three-jet events provides sensitive tests of QCD predictions at intrinsically higher orders in α_s.

Figure 6 shows the measured three-jet cross section as a function of Q^2 (left), together with the ratio of the three-jet to two-jet cross section, $R_{3/2}$ (right). Compared to the data are the predictions of LO and NLO QCD. The results show that, while LO QCD is unable to describe the data over the full measured Q^2 range, the NLO prediction gives a reasonable description of the data. In the ratio, both experimental systematic and theoretical uncertainties are reduced relative to the absolute cross sections, and the dependence on the dynamics of jet production is reduced. This ratio may prove a useful variable for the extraction of α_s.

[1] For three-jet events, the next-to-leading order process is $\mathcal{O}(\alpha\alpha_s^3)$.

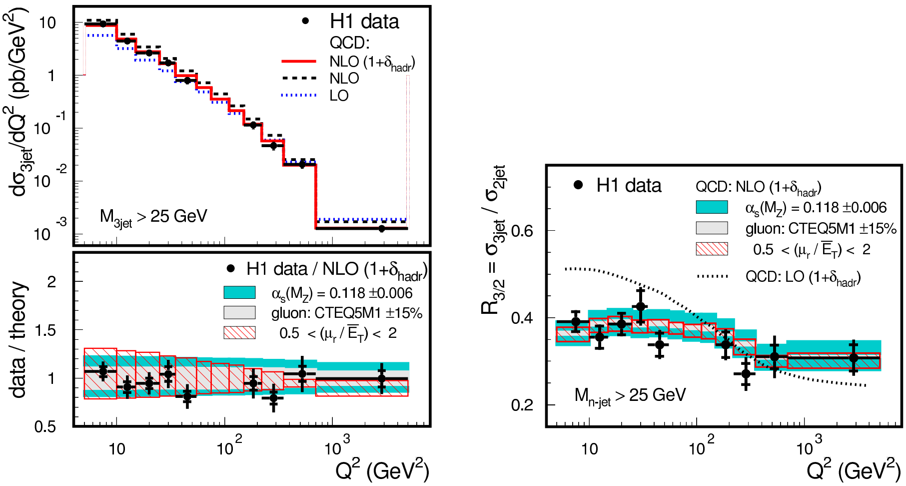

Fig. 6. Three-jet production in Neutral Current DIS from H1 [11].

3. Jets in photoproduction

In photoproduction processes, the exchanged boson is a very low virtuality photon ($Q^2 \sim 0$ GeV^2) and $E_{\rm T}^{\rm jet}$ is used as the hard scale in the interaction. At $\mathcal{O}(\alpha\alpha_{\rm s})$, both direct and resolved photon processes contribute to the total cross section.

3.1. Inclusive jets in photoproduction

Inclusive jet photoproduction is directly sensitive to the quark and gluon distributions in the photon. Figure 7 shows the inclusive cross section, requiring at least one jet satisfying $E_{\rm T}^{\rm jet} > 21$ GeV. The NLO QCD prediction using the GRV-HO [13] and CTEQ5M [14] PDFs agrees reasonably well with the data. However, predictions using other parton distribution sets are also shown to give an adequate description within the large theoretical uncertainties. More stringent constraints on the photon parton densities will rely primarily on improvements to the theoretical calculations.

The inclusive jet measurement [15] from ZEUS has been used to extract a value for $\alpha_{\rm s}$. This is the first extraction of the strong coupling from photoproduction data. The value at the Z^0 mass was determined to be $\alpha_{\rm s}(M_Z) = 0.1224 \pm 0.0001({\rm stat.})^{+0.0022}_{-0.0019}({\rm syst.})^{+0.0054}_{-0.0044}({\rm theory})$, consistent with the world average. The theoretical error dominates the overall uncertainty.

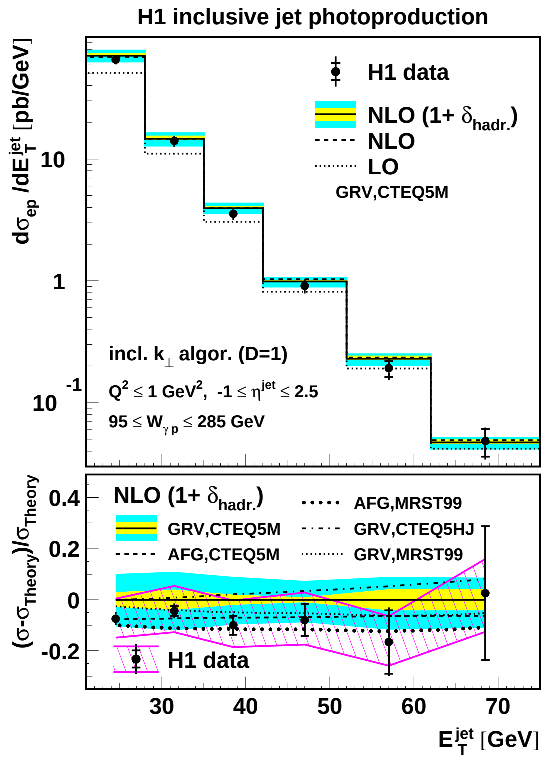

Fig. 7. Inclusive jet cross section, as a function of $E_{\mathrm{T}}^{\mathrm{jet}}$, from H1 [12].

3.2. Two-jet cross sections in photoproduction at high tranverse energy

Recent measurements of two-jet photoproduction cross sections at high transverse energy has highlighted an apparent discrepancy between the analyses of H1 and ZEUS. While H1 find that the data is well described by NLO predictions, the ZEUS analysis indicates that the data lie above NLO calculations at low x_γ. The main difference in the cross section definitions between the two analyses is in the constraints imposed on the minimum transverse energies of the jets (*i.e.* $E_{\mathrm{T}}^{\mathrm{jet1,2}} > 25, 15$ GeV for H1 and $E_{\mathrm{T}}^{\mathrm{jet1,2}} > 14, 11$ GeV for ZEUS).

The dependence of the cross sections as a function of the cut on the second highest transverse energy jet is shown in Fig. 8. The data are compared to the prediction of HERWIG, which uses the LO matrix element combined with parton showering. In addition, comparisons with NLO QCD, with two choices of photon PDF, are shown. The results show that the cross section exhibits a strong dependence on $E_{\mathrm{T}}^{\mathrm{jet2;cut}}$, which is well described by the

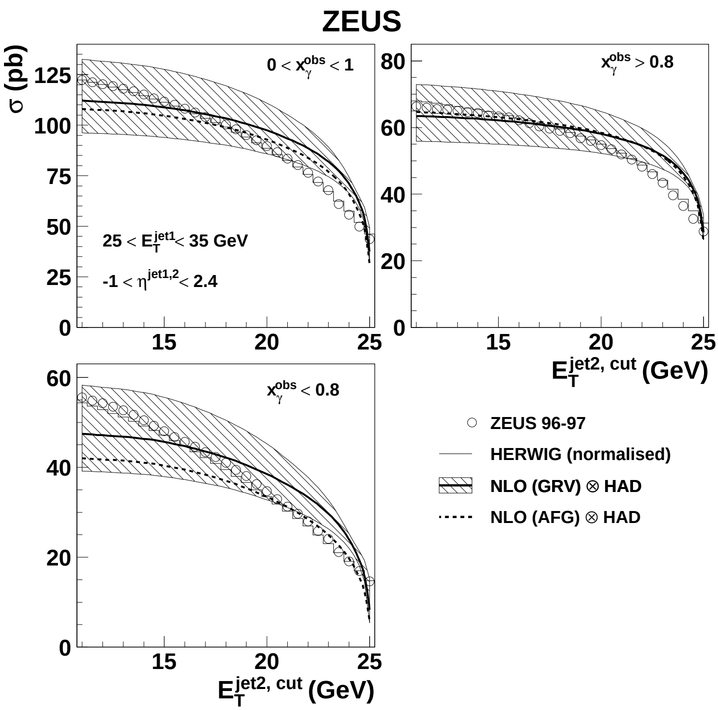

Fig. 8. Dependence of the two-jet cross section on $E_{\mathrm{T}}^{\mathrm{jet2;cut}}$ from ZEUS [16].

parton shower model. However, the NLO QCD calculations are unable to describe the cross section dependence with either choice of photon PDF. At the value of $E_{\mathrm{T}}^{\mathrm{jet2;cut}} = 15$ GeV used by H1, the description of the total cross section is reasonable, while at the value of $E_{\mathrm{T}}^{\mathrm{jet2;cut}} = 11$ GeV chosen by ZEUS, the cross section is underestimated. This accounts for the apparent discrepancy between the two analyses. A full understanding of jet production at low Q^2 will require further theoretical developments.

4. Conclusions

The large luminosity accumulated at HERA has allowed very precise measurements in both DIS and photoproduction. This paper has summarised a small sample of the most recent results from H1 and ZEUS. The measured cross sections have been compared to the predictions of NLO QCD. At high Q^2, the data are well described by the calculations, representing a significant triumph of our understanding of QCD. At lower Q^2, theoretical uncertainties dominate and some discrepancy between data and NLO QCD exits, most notably at low $E_{\mathrm{T}}^{\mathrm{jet}}$ in the forward region. A full understand will require further developments in the theoretical community.

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