Jet Production at HERA

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This article reviews recent jet physics results from HERA.

1. Introduction

Jet production allows precise tests of perturbative QCD. At the electron-proton collider HERA the production of jets is investigated in inelastic electron (positron) proton scattering over a wide range of photon virtualities $Q^2$, from photoproduction ($Q^2 \approx 0$ GeV$^2$) to deep inelastic scattering (DIS). This article presents recent measurements of jet cross sections and jet shapes and their comparison to perturbative QCD (pQCD) calculations. These calculations are performed up to next-to-leading order (NLO) for all measurements presented. Jet cross sections at HERA are calculated by convoluting the short distance sub-process cross sections with parton density functions (pdfs) of the proton. At very small $Q^2$ (photoproduction) the photon may fluctuate into partons before the hard scatter. This is parametrised by the pdfs of the photon.

The standard choice since about 5 years at HERA is to define jets according to the theoretically preferred invariant $k_\perp$ algorithm as proposed by Ellis and Soper[1]. ZEUS and H1 have reduced their energy scale uncertainty for high transverse energy ($E_T$) jets to 1%, respectively 2%, which significantly improves the data precision.

The data at high $Q^2$ and high $E_T$ allows quantitative tests of pQCD and extractions of $\alpha_s$ and the proton pdfs. Photoproduction data at high $E_T$ are, in addition, sensitive to the photon pdfs. At moderate $Q^2$ and $E_T$ the limits of NLO pQCD are exploited. These measurements provide additional and complementary information to $p\bar{p}$ and $e^+e^-$ data.

2. Jets at moderate and high $Q^2$ DIS

Jet production in deep inelastic scattering events has been investigated over a wide range in $Q^2$. A recent H1 measurement [2] of inclusive jet production is performed for the medium $Q^2$ range between 5 and 100 GeV$^2$. The data are compared to LO and NLO pQCD calculations using $E_T$ as renormalization scale. The agreement is good, although NLO pQCD fails to describe the data in the forward region ($\eta_{lab} > 1.5$), when both $E_T$ and $Q^2$ are small. This region corresponds to the largest NLO/LO corrections. Figure 1 shows the inclusive jet cross section $d\sigma/dE_T$ for $1.5 < \eta_{lab} < 2.8$ as a function of the transverse energy in the Breit frame $E_T$, in different regions of $Q^2$.

Especially at $5 < E_T < 20$ GeV and $5 < Q^2 < 10$ GeV$^2$ the renormalization scale uncertainties do not cover the uncertainties of the data. These theory uncertainties are estimated by a variation of the scale by a factor of 2 (0.5).

Both the large differences between NLO and LO calculations and the poor agreement between data and NLO shows the necessity of further theoretical progress.

As an example of the many jet measurements at high $Q^2$ a new ZEUS measurement of inclusive jet cross sections [3] for photon virtualities $Q^2 > 125$ GeV$^2$ is discussed. A good agreement between data and NLO calculations is found at high $Q^2$. Figure 2 shows the differential cross section $d\sigma/dQ^2$ as a function of $Q^2$ for inclusive jet production requiring $E_T > 8$ GeV in the Breit frame. Since there is good agreement between data and the NLO calculation the measured cross sections were used to determine $\alpha_s(M_Z)$. The
QCD fit to H1 and ZEUS high $Q^2$ jet data yield $\alpha_s$ values in good agreement with the world average and of similar precision to that obtained by other experiments.

3. Internal jet structure

Observables which give insight into the internal jet structure are the mean subjet multiplicity and the integrated jet shape. At high $E_T$, where fragmentation effects are small, these observables are calculable in pQCD. The subjet multiplicity $< n_{\text{subjet}} >$, for instance, is derived by repeating the $k_T$ jet algorithm with a smaller resolution scale $y_{\text{cut}}$ considering particles lying within a jet and counting the number of subjets found inside it. ZEUS has compared new measurements [6] of these observables to QCD calculations at NLO. The jets are found in the laboratory frame. Figure 3 shows the mean subjet multiplicity as a function of $y_{\text{cut}}$ for $E_T > 15$ GeV and $Q^2 > 125$ GeV$^2$. The NLO pQCD prediction reproduces the data well. This shows, for the first time, the ability of NLO pQCD in describing the internal jet structure. A QCD fit of these data were used to derive $\alpha_s$ values, consistent with the world average.
4. Jets in photoproduction

Dijet photoproduction has been investigated by the H1 and ZEUS experiments \[4,5\]. Both analyses present dijet cross sections as functions of various jet observables. Asymmetric cuts on the $E_T$ of the two jets are applied in order to avoid regions of phase space which are infrared sensitive in NLO calculations. Thus the H1 (ZEUS) analysis requires $E_T$ for the first and second jet of 25 and 15 GeV (14 and 11 GeV). In both analyses the ratio of the measured cross sections to the theoretical prediction varies at small $x_\gamma$ by $\pm$10-15% when the cut on $E_T$ of the second jet is varied by $\pm$5 GeV. This effect is covered by the NLO scale uncertainty at low $x_\gamma$ of $\approx 15 - 20\%$.

Figure 4 shows the dijet cross section, as measured by ZEUS, as a function of $x_\gamma$, which is an estimator of the momentum fraction carried by partons out of the photon.

Although the shape of the data for different $E_T$ is not perfectly modelled by the NLO prediction, strong conclusions can’t be drawn, because of the size of the theoretical uncertainties. These data are nevertheless sensitive enough to constrain the photon pdfs (quarks and gluon). Once more further theoretical understanding would be helpful in the interpretation of the data.

In Figure 5 the H1 dijet cross section as a function of the mean transverse energy of the two jets $d\sigma/dE_{T,\text{mean}}$ and of the transverse energy of the leading jet $d\sigma/dE_{T,\text{max}}$ is shown. The data are well described up to $E_T \approx 70$ GeV by the NLO calculation. The NLO scale uncertainty is not reduced significantly with increasing $E_{T,\text{max}}$, but decreases from $\pm 20\%$ for the first bins to less than $\pm 5\%$ for increasing $E_{T,\text{mean}}$. This shows the sensitivity to the choice of dijet $E_T$ cuts.

The momentum fraction carried by partons out of the proton is termed $x_P$. Figure 6 shows the cross section $d\sigma/dx_P$ as a function of $x_P$ for two different $x_\gamma$ regions.

Even at the highest $x_P$ the measured cross sections agree well with the QCD predictions. In this part of the phase space about 40% of the cross section is attributed to processes induced by gluons in the proton. The recent data could be used to further constrain the existing proton pdfs, particularly at medium $x_P$.

5. Summary

Recent HERA jet data show that NLO QCD calculations and current pdf parameterisations are mostly compatible with high $E_T$ and high $Q^2$ jet data, which allows precise determinations of $\alpha_s(MZ)$ and pdfs. The increasing precision of the data shows that a deeper understanding of jet physics will require theoretical progress.

REFERENCES

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Figure 5. Differential $ep$ cross section for dijet photoproduction as a function of $E_{T,\text{max}}$ (upper Figure) and $E_{T,\text{mean}}$ (lower Figure).

Figure 6. Differential $ep$ cross section for dijet photoproduction as a function of $x_p$ for two regions of $x_\gamma$.

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