Inclusive jet and dijet production at HERA

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Abstract.
The inclusive jet cross section in deep-inelastic scattering (DIS) and dijet cross-section in photo-production and DIS have been measured at $\sqrt{s} = 320$ GeV at the electron-proton collider HERA by the H1 and ZEUS collaborations using data taken in 1998-2000 (HERA I) and in 2004-2007 (HERA II). Cross-sections are presented as a function of relevant kinematical variables such as boson virtuality $Q^2$, proton (photon) momentum fraction carried by the interacting parton $x_p$ ($x_\gamma$) or transverse energy $E_T$ of the jets. The data are compared to perturbative QCD (pQCD) predictions at next-to-leading order (NLO) and are in general in good agreement within the estimated theory error which exceeds the typical experimental uncertainty in most regions of phase-space. The sensitivity of these high-precision jet observables to QCD parameters such as the strong coupling $\alpha_S$ and parameterisations of the parton density functions (PDF) of the proton and the photon are discussed.

1. Jet production at HERA

Jet production in electron-proton scattering is an ideal ground for testing the strong interaction and measuring QCD parameters. According to the virtuality $Q^2$ of the exchanged boson, one distinguishes two processes, DIS and photo-production. In DIS a highly virtual boson ($Q^2 > 1$ GeV$^2$) interacts with a parton carrying a momentum fraction $x_p$. At low $x_p$ in particular, DIS is sensitive to the gluon content of the proton.

In direct photo-production the quasi-real photon ($Q^2 < 1$ GeV$^2$) interacts with a parton from the proton. In resolved photo-production the photon behaves as a hadron and a parton from the photon, carrying a fraction $x_\gamma$ of its momentum enters the hard scattering with the proton and gives rise to jet production. This resolved process allows the structure of the photon to probed. Moreover, jet production in both processes is highly sensitive to the coupling constant of the strong interaction $\alpha_S$.

In the analyses presented here jets are defined using the $k_T$ clustering algorithm [9]. The associated jet cross-sections are collinear and infrared safe and therefore well suited for comparison with predictions from fixed order perturbative QCD calculations. For DIS, the jet algorithm is applied in the Breit frame, and for photo-production in the photon-proton collinear frame (laboratory frame). Particles in the hadronic final state are iteratively merged...
according to the $p_T$ recombination scheme when their distance defined in the azimuthal angle ($\phi$) – pseudorapidity ($\eta$) – plane is smaller than the jet radius.

The ZEUS collaboration has studied jet production in DIS for different values of the radius parameter $R$ [1]. Figure 1 shows the variation by more than three orders of magnitude of the jet cross-section as the transverse momentum of the jets varies from 8 to 50 GeV. This fall-off is equally well described for smaller values of $R$ (0.5, 0.7) and for the conventional choice $R = 1$.

2. Inclusive dijet photo-production measurement

Photo-production is defined by H1 (ZEUS) by $Q^2 < 1$ GeV$^2$ and inelasticity $0.1 < y < 0.9$. At least two jets are required with transverse energy $E_T$ above 25 GeV (20 GeV) for the first jet and 15 GeV for the second jet. Furthermore, the jet pseudorapidity $\eta$ is required to lie between $-0.5$ and 2.75 ($-1.0 < \eta < 3.0$) [2, 3].

The measured cross-sections are corrected bin-by-bin for detector acceptance using leading-order Monte-Carlo (LO-MC) event generators (PYTHIA and HERWIG) followed by a detailed detector simulation. The overall experimental systematic error of typically 10–15% is dominated by the uncertainty on the absolute energy scale of the hadronic calorimeters and the model dependence of data correction.

Relevant photo-production kinematic variables such as the parton momentum fraction of the photon $x_\gamma$ and of the proton $x_p$, average jet transverse momentum $\langle E_T \rangle$ and pseudorapidity $\langle \eta \rangle$ are calculated using leading jet momenta. Figure 2(a) shows the strong rise of differential dijet cross-sections with $x_\gamma$ from a low $x_\gamma$ tail dominated by the resolved process to a spike at $x_\gamma \approx 1$ containing mainly the direct process. The different behaviour of the cross-section as a function of $x_p$ in these two regimes is shown in Figure 2b (resolved) and 2c (direct).
3. Inclusive jet and dijet production in DIS measurement

High $Q^2$ DIS is defined in the H1 (ZEUS) analysis in the kinematical region $Q^2 > 150$ GeV$^2$ ($Q^2 > 125$ GeV$^2$) and $0.2 < y < 0.7$ (\(|\cos \gamma_h| < 0.65\) where $\gamma_h$ is the angle of scattered quark in quark-parton model). Measurement of the inclusive jet cross-section in DIS was recently extended to the low $Q^2$ region ($5 - 100$ GeV$^2$) by H1 [8].

In the dijet analysis [5] events with at least two jets enter the cross-section measurement with equal weight, whereas in the inclusive jet analyses [1, 4, 6, 7] jets are counted individually. Dijet cross-sections with asymmetric cuts on $E_{T,B}$ and inclusive jet cross-sections are infrared and collinear safe observables and therefore suitable for comparison with pQCD predictions.

The jets are required by H1 (ZEUS) to have a transverse momentum in the Breit frame $E_{T,B}$ greater than 7 GeV (8 GeV) with a pseudo-rapidity in the HERA laboratory frame (in the Breit frame) in the range $-1 < \eta_L < 2$ ($-2 < \eta_B < 1.5$). Additionally, the ZEUS dijet analysis imposes a higher cut on of $E_{T,B} > 12$ GeV on the hardest jet.

Detector acceptance and QED-radiation effects are corrected for by using the LO MC programs LEPTO and ARIADNE interfaced to HERACLES. The correction factors differ from unity by typically 10% with an uncertainty due to the MC model dependence which amounts typically to 3%, but can reach 10% in some phase-space regions.

Figure 3(a) shows the inclusive dijet cross-section as a function of the fraction $\xi$ of the proton momentum carried by incoming parton in different $Q^2$ bins. This preliminary results from ZEUS [5] benefit from an integrated luminosity of 209 pb$^{-1}$ including new HERA II data and therefore have reduced statistical error and improved jet energy calibration which contribute half the experimental error estimated to be around 7% for most of bins.

Average jet multiplicities as obtained in H1 by normalizing the inclusive jet rate by the DIS event rate are shown in fig. 3 [7]. Jet rates increase with $Q^2$ as available phase-space opens, especially at high $E_{T,B}$ where their spectrum becomes harder as soon as $Q$ exceeds $E_{T,B}$. This measurement includes the full HERA II data set (320 pb$^{-1}$). The ensuing reduction of...
experimental errors is particularly visible at high $Q^2$ and high $E_{T,B}$. Moreover, the normalized inclusive jet cross-section benefits from the cancellation of some experimental (e.g. luminosity measurement) and theoretical (e.g. dependence on PDFs) systematic errors. The resulting overall experimental uncertainty is reduced typically from 7% to 6% in most of bins.

4. NLO QCD calculations

Predictions by QCD at NLO for the jet cross-sections in photo-production are obtained from [10], whereas those in DIS are calculated using the DISENT and NLOJET++ programs. Jet observables at parton level given by these calculations are corrected for hadronisation using the the Lund string fragmentation model as implemented in the above mentioned LO MC generators.

The theoretical uncertainty due to the missing higher orders in the perturbative expansion is estimated by varying the renormalization $\mu_r$ and factorisation $\mu_f$ scales around the central value of $Q^2$ or $E_{T,B}$. This scale dependence typically amounts to 5 − 15% and is generally the dominating source of systematic theoretical error, although in DIS at high $x_p > 0.1$ or for $E_{T,B} > 30\text{GeV}$ it is outweighed by the uncertainty on the parameterisation of the proton PDF.

In general, the jet cross-sections in photo-production and in DIS are well described by NLO pQCD calculations, with notable exception of low $Q^2$ inclusive jet data where NNLO calculations are clearly necessary especially for $Q^2 < 10\text{ GeV}^2$.

5. Probing QCD parameters

Inclusive dijet photo-production data provides a handle on the internal structure of photon as can be seen from fig. 2(a) where the measured cross-section is compared to NLO QCD calculations using six different photon PDF parametrisations. The accuracy of the data permits a good discrimination between these parametrisations at low $x_\gamma$.

Conversely, high precision jet cross-sections in direct photo-production where the dependance on the photon PDF is small, and naturally in DIS, help to improve the knowledge of the proton’s structure at intermediate and high parton momentum fraction $x_p$ (ξ for di-jets in DIS) where the proton PDF sensitivity dominates the renormalisation scale uncertainty. In fig. 2b and 2c dijet photo-production data are compared to the LO MC PYTHIA (scaled ad hoc by a factor of 1.2) and to NLO QCD predictions (proton PDF CTEQ5L, photon PDF GRV-LO). Both describe the data well except at very high $x_p > 0.5$. Dijet DIS data are also well described by NLO QCD predictions using the CTEQ6 proton PDF as can be seen in fig. 3(a).

Since the probability of each jet emission is roughly proportional to the strong coupling constant $\alpha_S(\mu)$, where $\mu$ is the relevant energy scale of the event ($Q^2$ or $E_{T,R}$), jet observables and inclusive jet cross-sections in particular are highly sensitive to its value and can be exploited to test the running of $\alpha_S(\mu)$ and to measure $\alpha_S(M_Z)$ accurately [6, 1]. The most precise measurement in DIS has been achieved by fitting $\alpha_S$ to the jet multiplicities resulting in a 40% lower experimental uncertainty compared to fits to the unnormalized inclusive jet cross-section.

References

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