Precision measurements with jets and particles at HERA

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Abstract

Inclusive jet and multijet cross sections as measured in ep collisions in different kinematical regions by the H1 and ZEUS experiments are shown. The measurements are used to extract the strong coupling α_s as a function of the scale and at the mass of the Z-boson. Results from prompt photon production in comparison with calculations, are shown in photoproduction and deep-inelastic scattering. Further topics address scaled momentum distributions of charged particles, a measurement of the transverse momenta of charged particles which is sensitive to parton dynamics beyond DGLAP and the first measurement of the charge asymmetry at HERA.

Keywords: Jets, α_s, fragmentation, prompt photons, parton dynamics, charge asymmetry

1. Introduction

The HERA ep-collider operated with electrons or positrons of 27.6 GeV and protons of 920 GeV. Each of the two experiments H1 and ZEUS collected roughly 0.5 fb^{-1} in fifteen years of running. At HERA, two kinematical regimes are distinguished, deep-inelastic scattering (DIS) with photon virtualities $Q^2 \geq 5\,\mathrm{GeV}^2$ and photoproduction (γp) with a quasi real photon, $Q^2 \simeq 0\,\mathrm{GeV}^2$, which is the dominating process. The large statistics of the HERA data allows detailed tests of perturbative QCD (pQCD) by cross section measurements with jets or prompt photons. In DIS there are two relevant hard scales, Q and the transverse momentum P_T of the jet or the photon, while in γp there is only P_T. Jet measurements are conveniently carried out in the Breit frame. Here, the leading order process with only one jet has no transverse momentum, only higher orders generate jets with high transverse momenta in the Breit frame. When comparing jet measurements to QCD calculations, the k_t algorithm is used which is collinear and infrared safe.

2. Jet production

Jet production in ep scattering provides stringent tests of QCD and an independent assessment of the gluon contribution to the parton density functions. It further allows the extraction of the strong coupling α_s as a function of the scale and at the mass of the Z-boson.

In five recent analyses jet production is measured in the Breit frame at HERA in various kinematical regions. ZEUS measured the inclusive jet cross section in γp [1] ($Q^2 < 1\,\mathrm{GeV}^2$, $P_{T,jet} > 17\,\mathrm{GeV}$) and high Q^2 DIS [2] ($Q^2 > 125\,\mathrm{GeV}^2$, $P_{T,jet} > 8\,\mathrm{GeV}$). Both measurements provide a determination of α_s, furthermore the 2-jet cross section is measured for the high Q^2 [3] region ($125 < Q^2 < 20000\,\mathrm{GeV}^2$, $P_{T,jet} > 8\,\mathrm{GeV}$), here the invariant mass of the two jets is required to be $M_{j,j} > 20\,\mathrm{GeV}$. The 2-jet cross section has a high sensitivity to the gluon contribution of the PDFs in kinematical regions where its uncertainty is contributing significantly to the theoretical error. H1 measured inclusive, 2-jet and 3-jet cross sections as well as the ratio of the 2-jet to 3-jet cross sections for low [4] ($5 < Q^2 < 100\,\mathrm{GeV}^2$, $5 < P_{T,jet} < 80\,\mathrm{GeV}$, $M_{j,j} > 18\,\mathrm{GeV}$) and high Q^2 [5] ($150 < Q^2 < 15000\,\mathrm{GeV}^2$, $7 < P_{T,jet} < 50\,\mathrm{GeV}$, $M_{j,j} > 16\,\mathrm{GeV}$). For the latter the jet cross sections are normalised to the inclusive DIS cross section, which significantly reduces the experimental and theoretical errors.

Fig. 1 shows the inclusive jet cross section as a function of the transverse energy of the jet for the ZEUS measurement in γp and high Q^2 DIS. For both kinematical regions the cross section falls steeply. The data are very precise, the dominant experimental error being the uncertainty of the energy scale of the jets, which is 1(3)% for jet energies above (below) 10 GeV. The measurement is compared to NLO QCD predictions which

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describe the measurement very well, the theoretical and experimental errors are of comparable size. The theoretical errors are dominated by the renormalisation scale uncertainty.

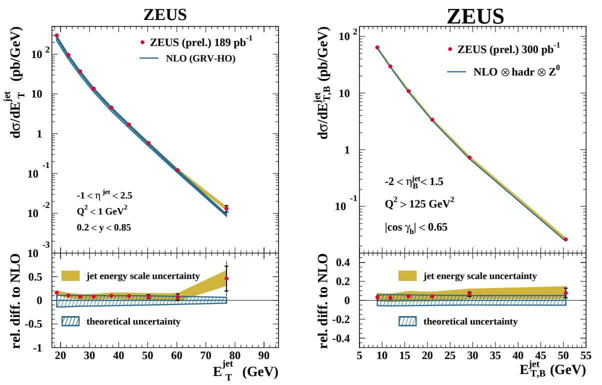

Figure 1: Differential cross section for inclusive jet production in photoproduction (left) with $Q^2 < 1\,\mathrm{GeV}^2$ and NC DIS (right) with $(125 < Q^2 < 20000\,\mathrm{GeV}^2)$. Jets are found with the longitudinally inclusive k_T algorithm in the Breit frame.

Similar results are obtained for the multijet cross sections. Overall the description by the NLO calculations is very good in all kinematical regions, though the low Q^2 analysis suffers from high theoretical uncertainties of up to 30%.

2.1. *Extraction of running α_s and $\alpha_s(M_Z)$*

The jet cross sections discussed above are used to extract the strong coupling α_s at different values of the renormalisation scale μ_r and at the Z-boson mass. Statistical, systematic and correlated uncertainties are taken into account. The dominant theory uncertainty is estimated by varying the renormalisation and factorisation scales by a factor 0.5 and 2. The running of α_s as a function of the renormalisation scale is shown in Fig. 2. The values are extracted from the H1 data at low and high Q^2. In the low Q^2 region the values and experimental uncertainties are found to be in good agreement with the QCD expectation which is based on the extracted value of $\alpha_s(M_Z)$ of the high Q^2 measurement.

Fig. 3 shows a summary of recent α_s measurements using jets at HERA together with the most precise determination of α_s from LEP [6] and from TEVATRON [7]. All measurements of α_s are in good agreement with each other in different kinematical regions (γp, low and high Q^2) and with the world average. Further measurements using different jet algorithms (anti-k_T and SISCone [8]) lead to similar results. For many of the precise HERA results the theoretical uncertainties dominate the error. Higher order calculations are expected to improve the results.

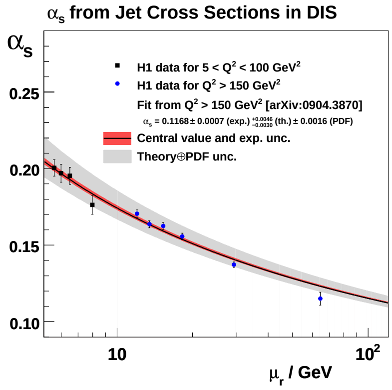

Figure 2: α_s as a function of the scale $\mu_r = \sqrt{(Q^2 + P_{T,jet}^2)/2}$ from jet cross sections at low and high Q^2.

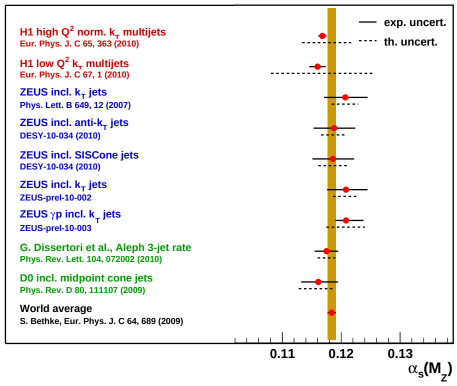

Figure 3: Recent values of α_s from HERA, LEP and TEVATRON.

3. Prompt Photon Production

Events with an isolated photon emerging from the hard subprocess $ep \to e\gamma X$ - so called prompt photons - offer an alternative access to study the hard interactions. Recent results have been published by H1 on prompt photon production in γp [9] for transverse energies of the photon $6 < E_T^\gamma < 15\,\mathrm{GeV}$ and in DIS [10] $(4 < E_T^\gamma < 15\,\mathrm{GeV})$by ZEUS. Both experiments use the shower shapes of the electromagnetic cluster to discriminate the signal of single photons from multiple photons of decays of neutral hadrons. As already observed in previous publications, the new results show that the available calculations are not able to describe all the measured distributions well. In photoproduction it is found that the NLO calculations underestimate the inclusive prompt photon cross section, while there is reasonable agreement for events with a prompt photon and a jet. However, their transverse correlation, which is sensitive to higher order processes, is not well described. In DIS the cross section receives contributions from radiation off the electron (LL) and also off the quark (QQ). The differential cross section as a function of Q^2 is shown in Fig. 4. The order α^3 QCD prediction (GGP) significantly underestimates the data at low Q^2. Also included in the figure is the prediction of MRST for the LL part of the cross section, this calculation is based on QED contributions to the PDFs which increases the LL contribution. MRST together with the QQ contribution from GGP shows similar deficits at low Q^2.

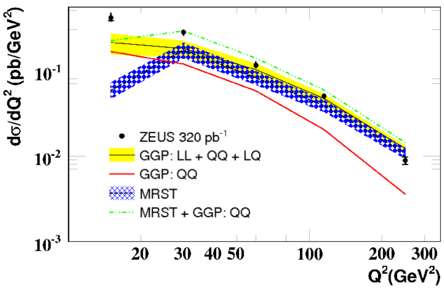

Figure 4: Isolated photon differential cross section $d\sigma/dQ^2$. The data is compared to a order α^3 calculation (GGP) as well as to a calculation with an increased contribution of the LL part (MRST).

4. Charged Particle Production

4.1. Rapidity spectra of charged particles

HERA experiments are able to access very small Bjorken x, a kinematic region where it is expected that the parton shower differs from the description by the DGLAP evolution equations. The latter imply a strong ordering of the transverse momenta k_T in the parton cascade from the proton to the virtual photon. Measurements of the hadronic final state are sensitive to the dynamics of the parton shower. Fig. 5 shows the η^* spectra of charged particles with a transverse momentum in the hadronic centre of mass system $p_T^* > 1\,\text{GeV}$ in different bins of x and Q^2 as measured by H1 in low Q^2 DIS events [11]. The data are compared to two MC predictions. RAPGAP is based on the DGLAP evolution equations for the parton dynamics, whereas DJANGOH follows the Color Dipole Model, in which parton radiation is not ordered in p_T. At small x and Q^2 and in the forward (proton) direction the RAPGAP predictions are significantly below the data, whereas the data are described reasobanly well over the full kinematic range by the approach based on the Color Dipole Model.

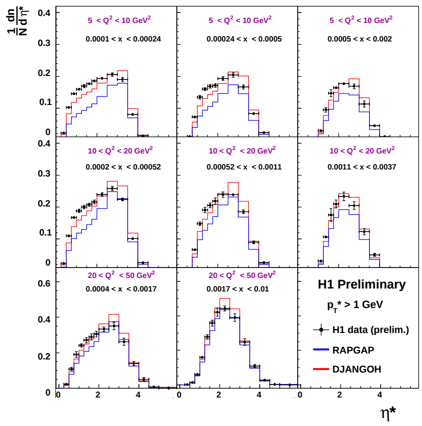

Figure 5: Rapidity spectra of charged particle with $p_T^* > 1\,\text{GeV}$ for different bins of Q^2 and x.

4.2. Scaled momentum distributions

Quark fragmentation may be studied at HERA by using the scaled momentum x_p in the current region of the Breit frame as observable. Here, $x_p = 2P_{Breit}/Q$ with P_{Breit} the momentum of a hadron. Scaled momentum distributions are measured by ZEUS for $10 < Q^2 < 41000\,\text{GeV}^2$ for tracks with a transverse momentum larger than 0.15 GeV. Fig. 6 shows the density of charged particles per unit of x_p as a function of Q in bins of x_p. As the energy scale Q increases, the phase space for soft gluon emission increases, leading to a rise of the number of particles with small x_p, which is clearly seen in Fig. 6. In this figure the data from HERA are shown together with data from e^+e^- which were scaled to half of the centre-of-mass energy. The overall agreement between the different datasets supports the concept of fragmentation universality. NLO calculations predict too weak scaling violation and also Monte Carlo predictions are not able to describe the data in the full kinematic range.

4.3. Hadronic charge asymmetry

The hadronic charge asymmetry is measured in the Breit frame by H1 [12]. Fig. 7 shows the event normalised distribution of the scaled momentum for all, positively and negatively charged particles. There are significantly more particles produced at low x_p than at high x_p. At low x_p the distribution is very similar for negative and positive particles. This is expected since low x_p particles are predominantly produced in fragmentation. Fig. 7c) illustrates that the original asymmetry observed on quark level is not visible anymore on hadron level at low x_p. At high x_p there is an overshoot of positively charged particles reflecting the charge asymmetry

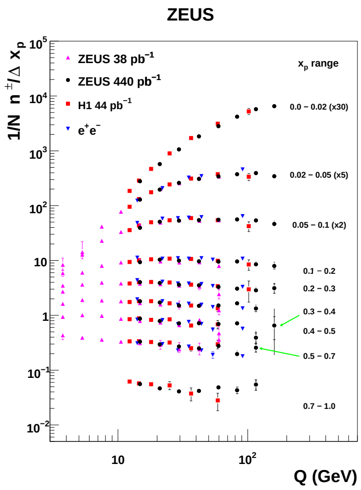

Figure 6: n^{*} distribution in the hadronic centre of mass system of charged particles with $p_T^{*} > 1\,\mathrm{GeV}$.

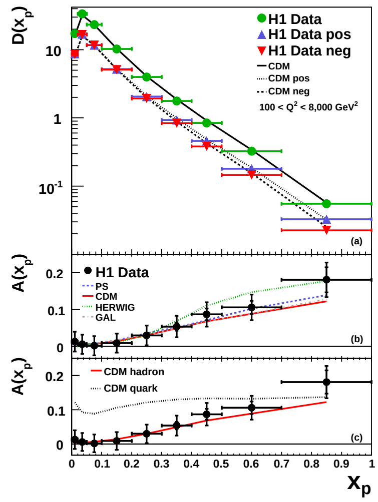

Figure 7: Normalised distribution of the scaled momentum $D = 1/N dn/dx_p$ (a) for all, positively charged and negatively charged particles and charge asymmetry $A(x_p)$ as a function of x_p. The data is compared to Monte Carlo predictions with different parton cascade and hadronisation processes and to the parton level before the hadronisation.

of the proton. The asymmetry is reproduced by various models. The data are expected to further constrain the valence quark distributions in the proton and to provide useful information on the fragmentation functions.

5. Conclusions

Several results of inclusive jets and multijets in different kinematical regions have been presented. The accurate measurements are well described by NLO calculations and allow the extraction of the strong coupling α_s as a function of the scale and at M_Z with small experimental errors.

Results of prompt photon production in photoproduction and DIS both reveal problems in some kinematical regions when compared to theoretical predictions. In general the predictions underestimate the data, most significantly at low Q^2 in DIS.

Measurements of the hadronic final states are used to study the parton dynamics and fragmentation processes. The charged particle spectra at low Q^2 and low x are sensitive to the parton dynamics and comparisons to models hint at dynamics beyond the conventional DGLAP evolution equations. The scaled momentum spectra have been measured in DIS. Large scaling violations are observed. Comparing the data to e^+e^- results supports the concept of quark-fragmentation universality. The hadronic charge asymmetry was measured and found to be largest at large scaled momenta x_p and increasing with the scale Q. The results are consistent with the expectation that at high x_p the asymmetry is directly related to the quark content of the proton.

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