PRECISION QCD MEASUREMENTS AT HERA*

Jacek Turnau

for H1 and ZEUS collaborations

The H. Niewodniczański Institute for Nuclear Physics, PAN
Radzikowskiego 152, 31-342 Kraków, Poland

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Recent high precision measurements of inclusive jets, dijet and trijet production in deep inelastic scattering and photoproduction at HERA are reviewed. The data are compared to NLO QCD predictions. The value of the strong coupling is extracted from jet cross section measurements.

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1. Introduction

The HERA electron–proton collider is an ideal machine to study jet production in a clean environment and to test QCD in hadron–induced reactions (as opposed to e^+e^- at LEP). In contrast to hadron–hadron collisions at TeVatron and LHC, in Deep Inelastic Scattering (DIS) complications from pile-up and multiple parton interactions are absent and only a minimal amount of modeling of non-perturbative effects is needed.

Jet measurements at HERA recently reached a new level of precision due to the large data samples available and excellent control of experimental uncertainties. After 15 years of successful operation, the two colliding beam experiments H1 and ZEUS each have collected about 0.5 fb^{-1} of ep scattering data. Since the HERA shutdown in year 2007, a lot of efforts have been invested in improving the detector calibrations and reconstruction algorithms. At present, the experimental precision of the electron and jet energy measurement is of the order of 1% for both experiments. At HERA, jet production can be studied in two regimes of the exchanged photon virtuality Q^2: DIS, with $Q^2 > 1$ GeV^2 and photoproduction with $Q^2 < 1$ GeV^2. In

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this document, the most recent precision jet measurements in both regimes are reviewed, together with QCD analyzes and extractions of the strong coupling constant $\alpha_s(M_Z)$.

2. Multijet production in DIS

Jet production in neutral current (NC) DIS is ideal for studies of Quantum Chromodynamics (QCD) and for extracting of the strong coupling α_s in particular. While inclusive DIS cross section measurements only provide indirect information on α_s through scaling violations of the proton structure functions, the production of jets provides a more direct probe of α_s. The Born level contribution to DIS generates no transverse momentum in the Breit frame, where the virtual boson and the proton collide head on. Significant transverse momentum p_T in this frame is produced at leading order (LO) in α_s by the QCD Compton (QCDC) and boson–gluon fusion (BGF) processes. For $Q^2 < 1000$ GeV^2, where BGF dominates, there is a strong correlation between the gluon density and α_s. Only at high Q^2 above 1000 GeV^2, where QCDC processes are dominant, the jet cross section becomes sensitive to the valence quark distributions and the α_s-to-gluon density correlation is reduced. A further reduction of this correlation can be achieved by measurements of trijet cross section, α_s^2 process in LO. The importance of jet measurements for determination of α_s is illustrated in Fig. 1 [1], where $\alpha_s(M_Z)$ dependence of QCD fits on DIS cross sections is studied. The fits are repeated two times, once with and once without the inclusion of jet cross section data. The jet data drastically increase the sensitivity of the fit to the value of α_s.

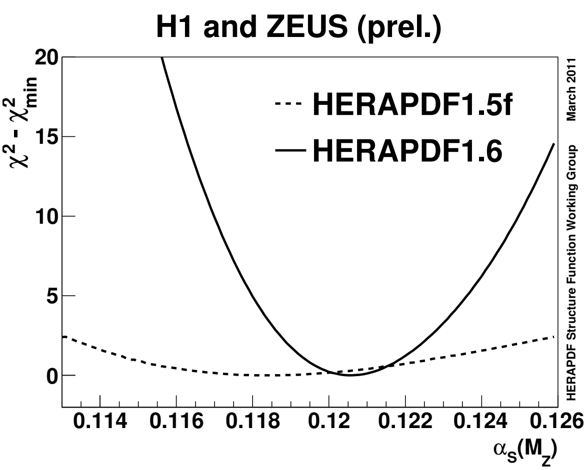

Fig. 1. $\Delta\chi^2$ distribution as a function of the value of $\alpha_s(M_Z)$ in global NC+CC DIS fits of PDF without (dashed line) and with (solid line) inclusive jet data.

The measurement of normalized jet cross sections in DIS presented here [2] is based on data with an integrated luminosity of 361 pb^{-1} collected in the years 2003–2007 with the H1 detector. The normalization is performed with respect to the NC DIS cross section. In comparison with another recent H1 publication on multijet measurement [3] based on full sample of H1 data (1999–2007), improvements on the reconstruction are applied. The correction of detector effects to determine the particle level cross section is performed using a regularized unfolding procedure [4].

The NC DIS events are selected by requiring an identified scattered electron, a virtuality of the exchanged boson (γ/Z^0) of $150 < Q^2 < 15000\ \mathrm{GeV}^2$ and an inelasticity of the interaction of $0.2 < y < 0.7$. The jet finding is performed in the Breit frame of reference, where the exchanged boson is completely space-like and aligned with the incoming proton. Particle candidates of the hadronic final state are clustered into jets using the inclusive k_T algorithm with a distance parameter $R_0 = 1$, as implemented in the FastJet package. The jets are required to be in the pseudorapidity range $-1 < \eta_\mathrm{lab} < 2.5$ measured in the laboratory frame. The jet transverse momentum in the Breit frame P_T is required to be $7 < P_\mathrm{T} < 50$ GeV. Events with at least two (three) jets with transverse momentum larger than 5 GeV are considered as dijet (trijet) events if the two leading jets of the measured observables have an invariant mass M_jj exceeding 16 GeV.

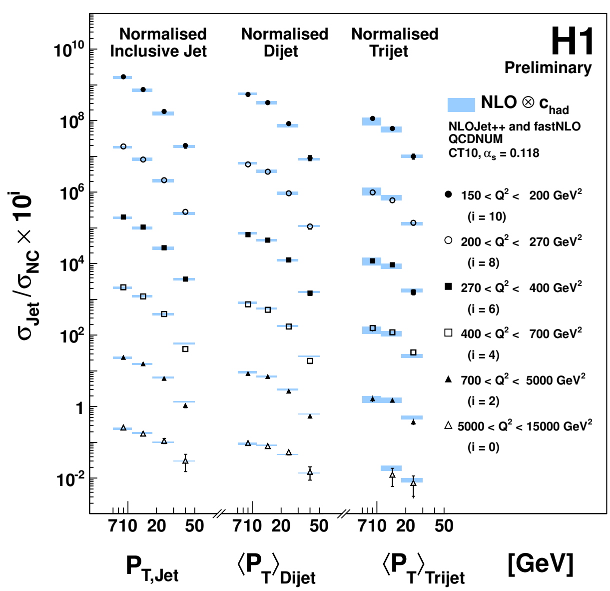

Fig. 2. Normalized inclusive jet, dijet and trijets measurements in bins of virtuality and average transverse momentum of the leading jets in Breit frame $\langle P_\mathrm{T} \rangle$. The measurements are compared to NLO calculations.

The normalized inclusive jet, dijet and trijet measurements are shown in Fig. 2, where they are compared to pQCD predictions made with NLO-JET++ program. NLO calculation (LO for trijets) provides very good description of the data. With the exception of the highest Q^2 bin, the experimental uncertainties are smaller than the theoretical ones.

3. Inclusive jet photoproduction

In photoproduction measurements at HERA, selected events are restricted to photon virtualities $Q^2 < 1$ GeV^2. In contrast to DIS, there is only one hard scale: the jet transverse momentum $p_{\rm T}$. For this reason, the jet photoproduction seems to be theoretically more attractive than DIS data for a precise extraction of $\alpha_{\rm s}$, because the scale choice in DIS is not

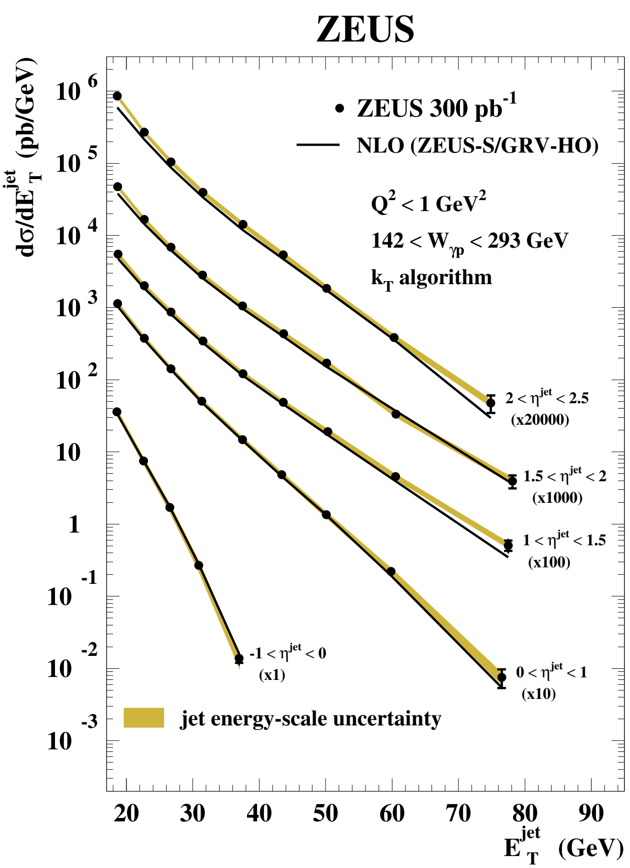

Fig. 3. The inclusive jet photoproduction cross section $d\sigma/dE_{\rm T}^{\rm jet}$ measured in different regions of jet pseudorapidity $\eta^{\rm jet}$. The data are compared to NLO calculations.

unique. However, since at $Q^2 < 1$ GeV^2 the photon shows a significant hadronic structure, multiple parton interactions and insufficient knowledge of the photon structure (γPDF) represent additional sources of uncertainty.

The ZEUS Collaboration measured inclusive jet photoproduction [5], using the full sample of the data collected in years 2003–2007. In this analysis, the selected events are restricted to $\gamma^* p$ center-of-mass energies in the range of $142 < W_{\gamma^* p} < 293$ GeV. The selected jets are required to have $p_{\rm T} > 17$ GeV and $-1 < \eta_{\rm lab} < 2.5$. In Fig. 3, the data are compared to QCD NLO ($\mathcal{O}(\alpha_{\rm s}^2)$) calculations using the program [6], corrected for hadronization effects with help of the PYTHIA and HERWIG event generators. Disagreements of up to 40% between the data and the NLO can be found at large values of pseudorapidity, $\eta_{\rm lab} > 2$, and small values of jet transverse momenta, $p_{\rm T} < 30$ GeV. In this region, the resolved photon is expected to give a large contribution to the cross section and in addition multiple interactions may occur.

4. Extraction of strong coupling $\alpha_{\rm s}(M_Z)$

The H1 and ZEUS collaborations adopted different methods of extracting the strong coupling $\alpha_{\rm s}(M_Z)$ from jet cross sections. The H1 approach is to search for a value $\alpha_{\rm s}(M_Z)$ which provides the best description of the data. The function $\chi^2(\alpha_{\rm s}(M_Z))$ which is minimized, takes into account statistical and systematic (correlated and uncorrelated) uncertainties. The theoretical uncertainties due to missing higher orders in the NLO calculations, hadronization corrections and the PDF uncertainties are determined with the offset method. Theoretical predictions are recalculated with varied input parameters according to their uncertainties and χ^2 minimization is repeated.

In ZEUS analysis, the dependence of theoretical cross section on $\alpha_{\rm s}(M_Z)$ is parametrized using several PDF sets at different $\alpha_{\rm s}(M_Z)$, then the data are projected on parametrization. In this method, the correlation between $\alpha_{\rm s}$ and gluon density is correctly taken into account.

5. Comparison of the extracted $\alpha_{\rm s}(M_Z)$ values and conclusions

$\alpha_{\rm s}(M_Z)$ determined from simultaneous fit to data points of normalized inclusive jet, dijet and trijet cross sections is

$$\alpha_{\rm s}(M_Z) = 0.1168 \pm 0.0007({\rm exp.}) \pm 0.0016({\rm pdf})^{+0.0046}_{-0.0030}({\rm theor.})\,.$$

$\alpha_{\rm s}(M_Z)$ extracted from measured inclusive jet photoproduction cross section for 21 GeV $< E_{\rm T}^{\rm jet} <$ 71 GeV is

$$\alpha_{\rm s}(M_Z) = 0.1206^{+0.0023}_{-0.0022}({\rm exp.}) \pm 0.0030({\rm pdf})^{+0.0042}_{-0.0033}({\rm theor.})\,.$$

Comparing these two measurements, one observes that the PDF uncertainties are significantly larger in photoproduction due to the large spread of the resolved photon PDF.

In Fig. 4, a comparison of $\alpha_s(M_Z)$ extracted from various measurements is presented. In general, experimental uncertainties are small and in most cases are much smaller than theoretical uncertainties, which are dominated by the renormalization scale dependence due to missing higher orders in the QCD calculation. All measurements, within uncertainties, are compatible with each other and with the world average. The NNLO calculations for jet cross sections are required to fully exploit the potential of precise jet measurements at HERA.

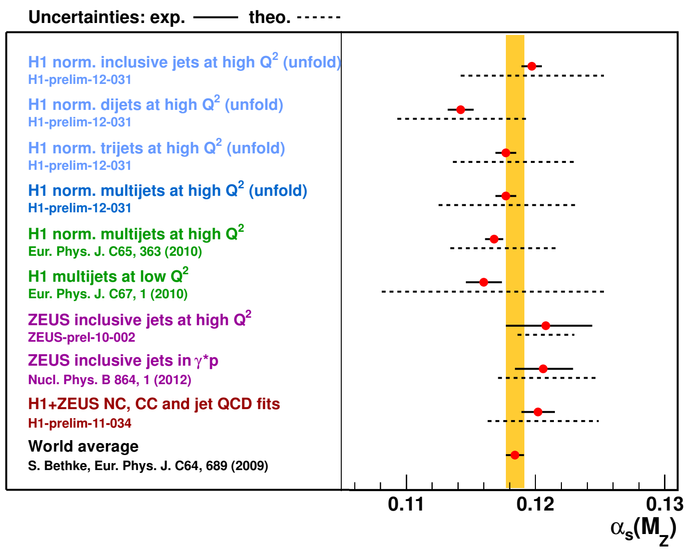

Fig. 4. Comparison of values of $\alpha_s(M_Z)$ extracted from various measurements.

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