DIFFRACTION AND PRECISE QCD MEASUREMENTS AT HERA

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Results are reported on precision measurements of jet and diffractive cross sections in *ep* deep-inelastic scattering (DIS) and photoproduction at HERA. The inclusive jet and multi-jet cross sections are used in QCD calculations at next-to-leading order (NLO) to determine the strong coupling α_s. The cross section measurements for diffractive inclusive DIS processes with a leading proton in the final state are combined for the H1 and ZEUS experiments to improve the precision and extend the kinematic range. The dijet cross sections are measured in diffractive DIS with a leading proton and compared with QCD predictions based on diffractive parton densities in the proton. The cross sections for heavy vector meson photoproduction processes are studied in terms of the momentum transfer at the proton vertex and of the photon-proton centre of mass energy.

1 Jets in DIS and photoproduction

Processes of inclusive *ep* DIS, described at leading order (LO) by quark-parton model (QPM), are sensitive to valence and see quark parton distribution functions (PDF) in the proton. At next-to-leading order (NLO) inclusive DIS processes become sensitive to the gluon PDF and strong coupling α_s via scaling violations. But these quantities extracted from a NLO QCD fit to inclusive DIS data are strongly correlated. Jets with large P_T produced in DIS in the Breit frame are sensitive to the gluon density and α_s already in LO via boson-gluon fusion (BGF). BGF process dominates at low and medium values of photon virtuality, Q^2 (up to $Q^2 \sim 10^3\mathrm{GeV}^2$). The QCD-Compton process dominates at higher values of Q^2 and provides sensitivity to α_s and the quark density. Contrary to BGF and QCD-Compton, processes described by QPM generate no jets with large P_T in the Breit frame. Therefore, the inclusion of inclusive jet data into a NLO QCD fit disentangle α_s and the gluon density.

The H1 Collaboration measured inclusive-jet, 2-jet and 3-jet production in the Breit frame at high Q^2 ($150 < Q^2 < 15000$ GeV^2) [1] using DIS data, which correspond to the integrated luminosity of 351 pb^{-1}. The ultimate 1% jet energy scale uncertainty is achieved to minimise the experimental uncertainty of α_s extracted from a NLO QCD analysis. The double-differential 3-jet cross section measured as a function of the averaged P_T of jets in bins of Q^2 is shown in Fig. 1(left). The data are well described by a NLO calculation with the hard scale defined as $\mu_r^2 = (Q^2 + < P_T >^2)/2$. The value of the strong coupling evaluated at the mass of Z^0 from a NLO QCD fit to the 3-jet cross sections is:

$$\alpha_s(M_Z) = 0.1196 \pm 0.0016(\mathrm{exp}) \pm 0.0010(\mathrm{pdf}) \pm^{0.0055}_{0.0039} (\mathrm{theory}), \qquad (1)$$

where the theory uncertainty due to missing higher orders in the NLO calculation dominates over the experimental uncertainty and the uncertainty of the proton PDF parameterisation.

In photoproduction processes ($Q^2 \sim 0$ GeV^2) a hard scale is provided by E_T of the hardest jet in the laboratory frame. These processes are directly sensitive to α_s, the gluon and photon PDFs. The cross section for direct photoproduction of n-jets, where photon interacts as a point-like object, is proportional in LO to α_s^{n-1}. In resolved photoproduction process, where photon interacts by its constituents, the cross section for n-jet production is proportional in LO to α_s^n.

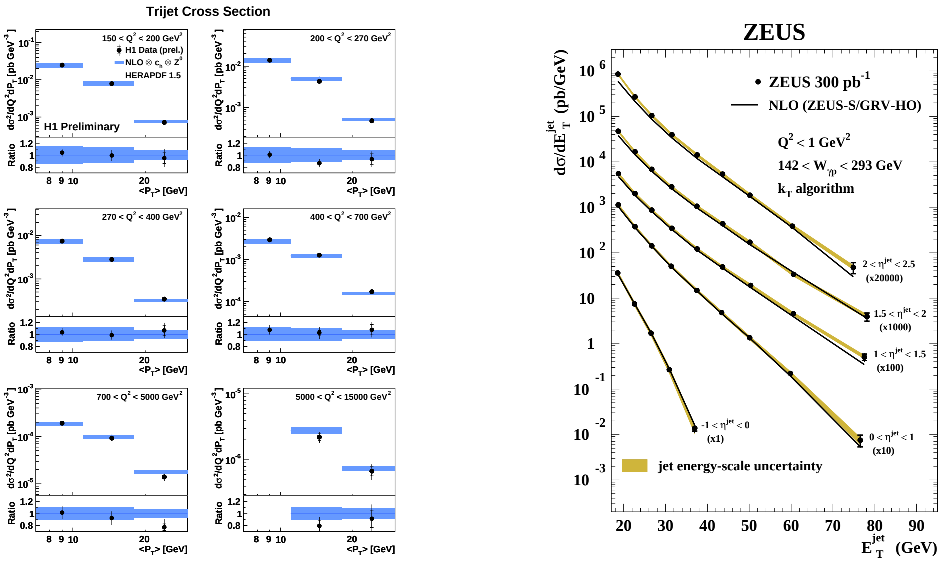

Figure 1: Differential 3-jet cross section by H1, shown as a function of jet $< P_T >$ in Q^2 bins (left). The differential cross section for inclusive jet photoproduction by ZEUS, shown as a function of jet E_T in η bins (right).

The ZEUS Collaboration measured inclusive-jet photoproduction [2] using data based on luminosity of 300 pb^{-1}. The differential cross sections on the jet E_T are measured in bins of pseudo-rapidity η, as it is shown in Fig. 1(right). The 1% jet energy scale uncertainty is achieved. The value of $\alpha_s(M_Z)$ is extracted using a NLO calculation performed in the range $21 < E_T < 70$ GeV, where non-perturbative effects from multiple-interactions are small. The result is:

$$\alpha_s(M_Z) = 0.1206 \pm^{0.0023}_{0.0022} \text{ (exp)} \pm 0.0030\text{(pdf)} \pm^{0.0042}_{0.0033} \text{ (theory)}, \quad (2)$$

where the uncertainties due to the proton and photon PDFs are added in quadrature. The uncertainties due to PDFs and missing orders in the NLO calculation dominate over the experimental uncertainty.

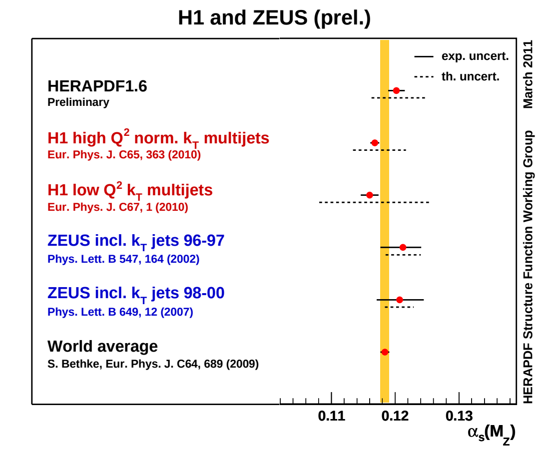

Figure 2: Recent $\alpha_s(M_Z)$ values obtained from the NLO QCD fit HERAPDF1.6 and from the H1 and ZEUS jet measurements.

A NLO QCD fit to inclusive DIS data alone with $\alpha_s(M_Z)$ treated as a free fit parameter leads to a very large uncertainty on the gluon density. Combined H1 and ZEUS inclusive NC and CC cross sections together with inclusive jet DIS cross sections are used in the NLO QCD fit HERAPDF1.6 [3] for the simultaneous determination of the proton PDF and $\alpha_s(M_Z)$. The addition of jet data into the fit significantly reduces the correlation between the gluon density and $\alpha_s(M_Z)$ compared to the fit without jet data. The uncertainty of the gluon density at low fractional momenta is considerably decreased and an unbiased evaluation of $\alpha_s(M_Z)$ is achieved. The results on $\alpha_s(M_Z)$ obtained from the HERAPDF1.6 fit and from the jet cross sections measured by H1 and ZEUS in DIS are shown in Fig. 2. The values are consistent with each other and with the world average.

2 Diffraction at HERA

Diffractive processes such as $ep \to eXp$ constitute about $\sim 10\%$ of the DIS cross section measured at low Bjorken x at HERA. The photon virtuality Q^2 provides a hard scale for perturbative QCD to be applicable, so that diffractive DIS events can be viewed as processes in which the photon probes a net colour singlet combination of exchanged partons. In processes of diffractive production of jets and heavy vector mesons (VM), the P_T of jets and the mass of heavy quarks provide a hard scale for perturbative calculations.

Diffractive processes are characterised by the absence of hadron activity in the rapidity interval between the central rapidity range and the leading proton (or the proton dissociation system). Therefore, diffractive events are selected at HERA by the requirement of a large rapidity gap between the leading proton and hadrons in the central rapidity range (LRG method) or by the measurement of the leading proton using the forward proton spectrometers (PS method). The LRG method is limited by the systematics related to the missing leading proton and the proton dissociation contribution. The PS method is limited by the low acceptance and proton tagging systematics. The diffractive DIS variables are the momentum fraction of the proton carried by the diffractive exchange ($x_{I\!P}$), the momentum fraction of the diffractive exchange carried by the struck quark ($\beta = x/x_{I\!P}$) and the squared 4-momentum transfer at the proton vertex t.

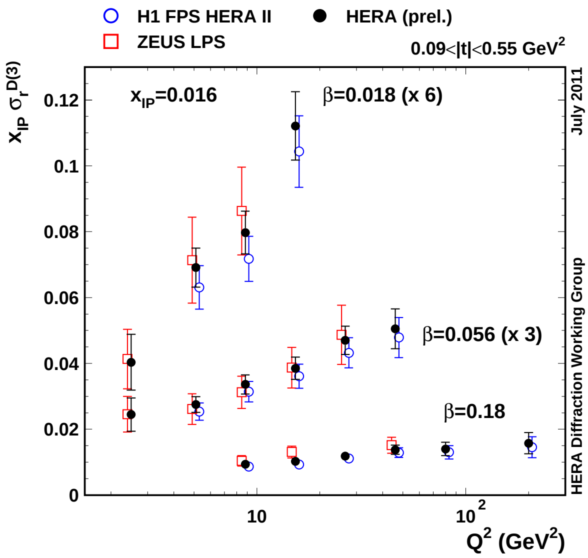

Figure 3: Diffractive reduced cross section σ_r^D, shown as a function of Q^2 for selected values of $x_{I\!P}$ and β. The H1, ZEUS and combined cross sections are presented.

The H1 and ZEUS Collaborations performed the first combination of the diffractive DIS cross sections measured using their proton spectrometers in the range $0.09 < |t| < 0.55$ GeV^2 [4]. The diffractive reduced cross sections are presented in Fig. 3 as a function of Q^2 for selected values of β and $x_{I\!P}$. A reasonable agreement is found between the H1 and ZEUS data in the shape and normalisation taking into account that the H1 and ZEUS normalisation uncertainties are 4.5% and 7%, respectively. The H1 and ZEUS diffractive DIS cross sections are combined to extend the phase space in $x_{I\!P}$ and Q^2 and reduce the uncertainties compared to those for one experiment. The combination method [5] uses the iterative χ^2 minimisation and takes into account correlations of systematic errors of the data points. The two experiments calibrate each other resulting in the reduction of systematic uncertainties. The combined data have $\sim 27\%$ smaller total uncertainties with respect to the most precise H1 data set.

In recent H1 analyses [6,7], dijets are selected in events with a leading proton measured in the forward and very forward proton spectrometers. The measurements cover new regions of the phase space in which there are jets at rapidity beyond the LRG range. These dijet data are reasonably described by NLO QCD predictions based on the diffractive PDF sets H1 Jets and H1 FitB [8,9] supporting the universality of the diffractive PDFs.

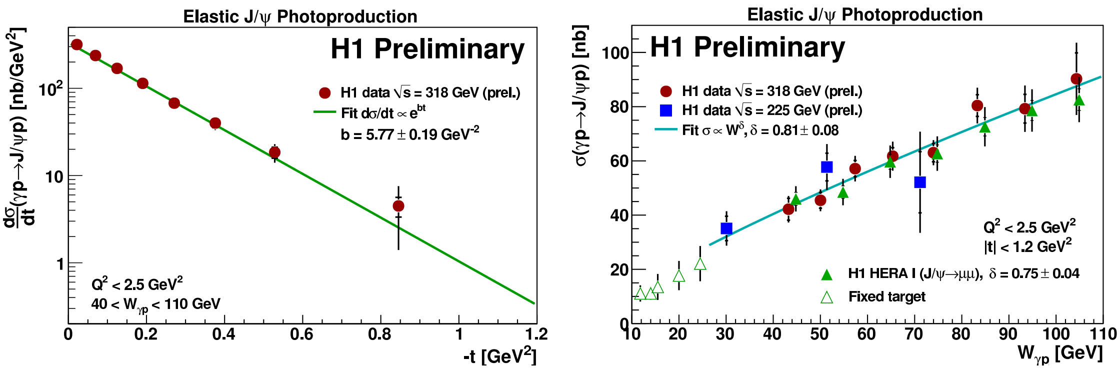

Figure 4: Cross section for J/ψ photoproduction by H1, shown as a function of t (left) and γp centre of mass energy (right).

The H1 Collaboration performed a simultaneous measurement of J/ψ photoproduction in elastic and proton dissociation processes[10] using the LRG method. The cross section is measured as a function of t and the γp centre of mass energy, $W_{\gamma p}$. The measurement is also performed at the reduced proton energy to extend the kinematic range to lower $W_{\gamma p}$ values. The cross sections for elastic J/ψ photoproduction are presented in Fig. 4.

In a colour dipole approach the exclusive VM is produced at leading order via a 2-gluon colour-singlet exchange between the $\gamma \to q\bar{q}$ dipole and the proton. The cross section is proportional to the square of the gluon density in the proton. The J/ψ photoproduction cross section rises steeply with W as $\propto W^{\delta}$ with $\delta \sim 0.8$. This can be explained by the rapid increase of the gluon density with decreasing of the fractional momentum x, where $x \propto 1/W^2$.

In an optical model approach the exponential slope b of the t-dependence of the exclusive VM production is related to the sum of the squared radii of the $\gamma \to q\bar{q}$ dipole and that of the proton. At high values of the VM mass M_V or photon virtuality Q^2 the $q\bar{q}$ contribution decreases as $b_{q\bar{q}} \propto 1/(Q^2 + M_V^2)$ and the slope of the t-dependence saturates at $b \sim 5$ GeV^{-2}, which corresponds to the gluonic radii of the proton. The H1 results on the t-dependence of the J/ψ photoproduction and the recently published ZEUS results on the $\Upsilon(1S)$ photoproduction [11] are consistent with this approach.

References

1. H1 Collaboration, `H1-preliminary-11-032`.
2. ZEUS Collaboration, H.Abramowicz *et al.*, DESY-12-045.
3. H1 and ZEUS Collaborations, HERAPDF1.6,
   `H1-preliminary-11-034, ZEUS-preliminary-11-001`.
4. H1 and ZEUS Collaborations, `H1-preliminary-11-111, ZEUS-preliminary-11-011`.
5. A. Glazov, AIP Conf.Proc 792 (2005) 237.
6. H1 Collaboration, F.D.Aron *et al*, DESY 11-166 [arXiv:1111.0584].
7. H1 Collaboration, `H1prelim-11-013`.
8. H1 Collaboration, A. Aktas *et al.*, EPJC **48**, 715 (2006) [hep-ex/0606004].
9. H1 Collaboration, A. Aktas *et al.*, JHEP 0710:042 (2007) [arXiv:0708.3217].
10. H1 Collaboration, `H1prelim-11-011`.
11. ZEUS Collaboration, H.Abramowicz *et al.*, *Phys. Lett.* B **708**, 14 (2012).