QCD Measurements at HERA*

Armen Bunyatyan[1,2]

[1] *Max-Planck-Institut für Kernphysik, Heidelberg, Germany*
[2] *Yerevan Physics Institute, Armenia*

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Abstract

A review is presented of recent results in QCD from the H1 and ZEUS experiments at HERA. The summary comprises new results on the quark and gluon structure of the proton, on the strong coupling α_s, on the production of jets, charm and beauty and on hard diffractive scattering.

1 Introduction

HERA was the world's first lepton–proton collider, in which the electrons or positrons of 27.6 GeV energy collided with 920 GeV protons. The total center-of-mass energy of *ep* collision at HERA was about 320 GeV, equivalent to a fixed target experiment of 54 TeV electron energy. HERA was finally shutdown on June 30, 2007, after 15 years of operation.

The data provided by HERA are ideally suitable for detailed studies of perturbative Quantum Chromodynamics (QCD) and for testing new QCD predictions. This report briefly describes the recent physics results on QCD obtained by H1 and ZEUS experiments.

2 Deep Inelastic Scattering and Proton Structure

Neutral current Deep Inelastic Scattering (NC DIS) processes proceed via exchange of photons and Z^0 bosons. The reaction is seen as a hard collision between the exchanged boson and a parton within the proton carrying a fraction x of the proton's momentum. The negative squared four-momentum transfer carried by the exchanged boson is denoted as Q^2. The differential cross section of NC DIS is given by

$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}[Y_+F_2(x,Q^2) - y^2F_L(x,Q^2) \mp Y_-xF_3(x,Q^2)],$$

where y is the inelasticity variable and $Y_\pm = 1 \pm (1-y)^2$. The structure functions F_2, F_L and F_3 are interpreted in terms of the quark and gluon parton structure at a given (x, Q^2) as: $F_2 \sim \sum x(q+\bar{q})$, $F_3 \sim \sum x(q-\bar{q})$ and $F_L \sim xg$. F_2 has a dominant contribution to cross section. Contribution of F_L is typically only few percents at the highest y, and F_3 is essential only at high Q^2. Thus measurement of the DIS rates gives direct sensitivity to quark distributions but only indirect sensitivity to gluons. Gluons in the proton are accessed via the Q^2 evolution ($g \sim dF_2/dlnQ^2$). The precision measurement of structure functions is interesting in its own right, and also provides the input needed for the calculations of every hard process at the LHC.

The H1 and ZEUS experiments measure the inelastic scattering of electrons or positrons off protons over the range $0.00005 < x < 1$, $0.35 < Q^2 < 30000$ GeV^2. The experiments recently combined the data collected in the HERA I phase (1992-2000) [1]. The obtained results for the NC reduced cross

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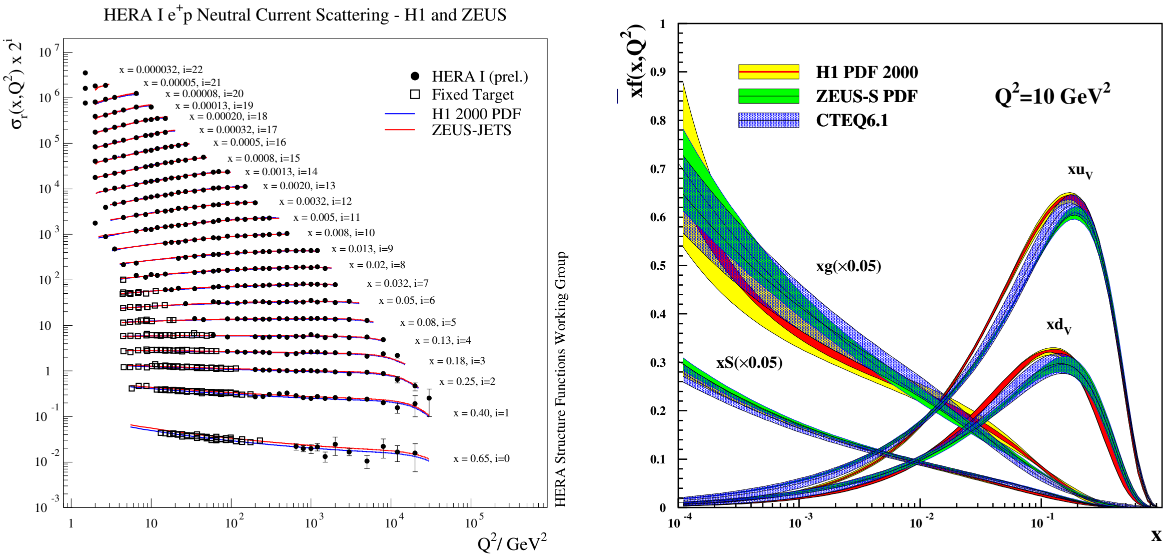

Figure 1: **(left)**H1 and ZEUS combined neutral current e^+p reduced cross sections. The curves are NLO QCD fits as performed by H1 and ZEUS to their own data. **(right)** Parton distribution functions (PDFs) obtained by H1 and ZEUS Collaborations from the NLO QCD fits to F_2 measurements.

section, defined as $\sigma_r(x,Q^2) = (d^2\sigma/dx\,dQ^2)(xQ^4/2\pi\alpha^2 Y_+)$, are shown in Fig.1, together with fixed target data and the previously obtained QCD fits. The measurements confirm Q^2 evolution of F_2 predicted by perturbative QCD over five orders of magnitude in Q^2 and x. At low and medium Q^2 precision of F_2 reaches 2% while at higher Q^2 it is statistically limited.

The H1 and ZEUS Collaborations have performed QCD fits to extract parton densities using various combinations of HERA and other data [2]. The fits are based on the evolution of the PDFs with Q^2 using DGLAP equations in next-to-leading order (NLO). The quark densities can be obtained directly from F_2, while gluon densities are obtained from the scaling violation of F_2. The PDFs are shown in Fig.1(right) for $Q^2 = 10$ GeV^2. The gluon contribution dominates at $x \lesssim 0.1$, however the uncertainties on gluon densities are rather large at low x. Additional constrains and the reduction of uncertainties on gluon PDFs can be obtained from the complementary measurements which are directly sensitive to gluons, as jet and heavy flavour production and the longitudinal structure function F_L.

The new measurements of inclusive ep cross sections at the large values of y, above ~ 0.6, have been recently presented by H1 and ZEUS [3]. Here the quarks in the proton with a given momentum fraction x are probed at the highest available resolution scale Q^2. Furthermore, these data are sensitive to F_L, whose contribution to the NC cross section becomes essential only at high y. The H1 and ZEUS results are shown in Fig.2 as function of Q^2 and y. The NLO QCD described well the measurements (right plot), but the uncertainties on predictions, indicated by error band, increase at high y values. These measurements can thus help to reduce the theoretical uncertainties in this region.

3 Jet Physics at HERA

Measurements of jets are traditionally used to test the concepts of perturbative QCD. In addition, jet measurements in DIS allow precise determination of the strong coupling α_s and are a valuable input to global fits of PDFs. Jet production is dominated over a large range in x by the boson gluon fusion process and thus provides direct access to the proton gluon density. A wealth of new jet measurements is available from HERA experiments, in both the DIS and photoproduction regimes.

Figure 3 shows the measured inclusive jet cross-sections at Q^2 between 5 and 100 GeV^2 [4]. QCD calculation up to second order in the strong coupling α_s is compared with the data. The NLO pQCD

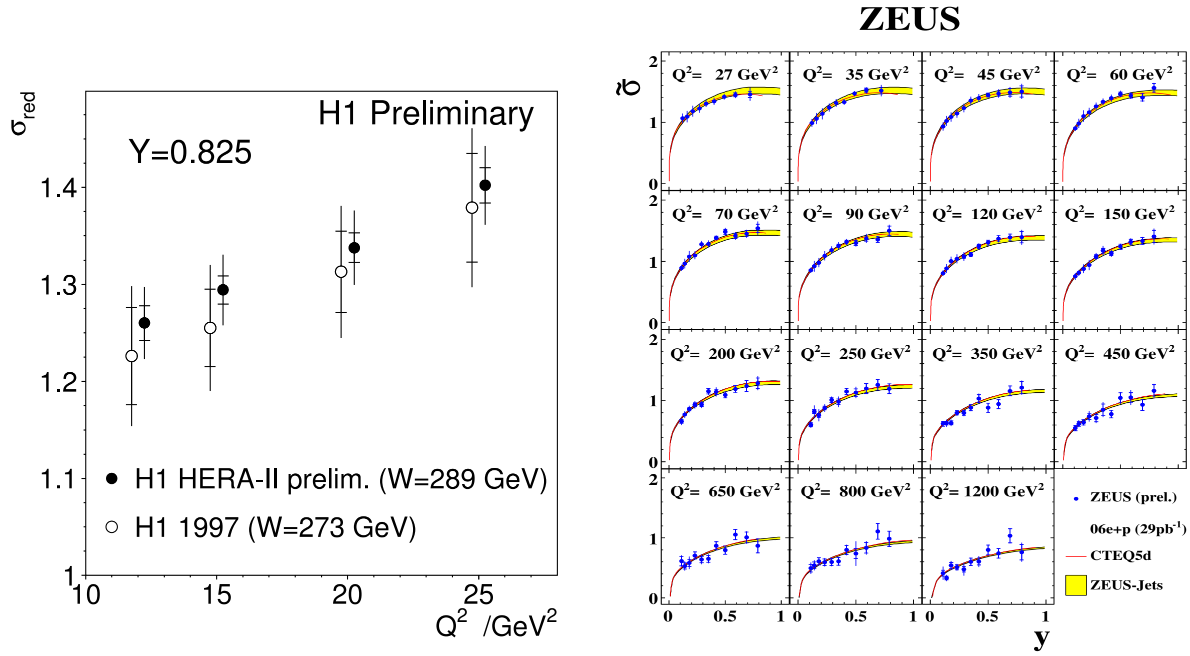

Figure 2: Neutral Current DIS reduced cross sections at high inelasticities y.

calculations corrected for hadronization provide quite a reasonable description of the inclusive jet cross sections for relatively high $Q^2 \gtrsim 10$ GeV^2 and E_T of the jet above 10 GeV. At lower Q^2, the comparison indicates the need for higher order QCD corrections.

Figure 4 shows the new measurements at high Q^2 ($125 < Q^2 < 5000$ GeV^2) [5]. The data is well described by the NLO QCD and can provide further constrain of the proton gluon density.

The strong coupling, α_s, is one of the fundamental parameters of QCD. However its value is not predicted by theory and has to be determined experimentally. At HERA, several determinations of α_s have been provided from a variety of observables based on jets and structure functions. A new precise determination of α_s was performed applying simultaneous fit to the H1 and ZEUS jet measurements in DIS [6]. The HERA combined value of $\alpha_s(M_Z)$ is $\alpha_s(M_Z) = 0.1198 \pm 0.0019(exp.) \pm 0.0026(theor.)$ [7]. This result is shown in Fig.5 (left) together with the individual values obtained by both collaborations, the previous measurements and the "World average" [8]. The measurements are consistent with each other. The HERA 2007 combined α_s has smaller uncertainties and is competitive with the recent results from LEP [9]. Figure 5 (right) shows the dependence of α_s from the energy-scale E_T^{jet}. The running of α_s, i.e. decrease of α_s with the scale, as predicted by QCD, is observed from HERA jet data alone.

4 Charm and Beauty Production

Charm and beauty quarks are produced at HERA mainly in the boson-gluon fusion process $\gamma^* g \rightarrow c\bar{c}$ (or $b\bar{b}$), where a pair of heavy quarks is formed in the collision of a photon emitted by the electron and a gluon out of the proton. Therefore this process is directly sensitive to the gluons and can provide additional constrain of the proton gluon density. Charm and beauty production NC cross sections are used to define structure functions as follows

$$\frac{d^2\sigma^{c\bar{c},b\bar{b}}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}[Y_+ F_2^{c\bar{c},b\bar{b}}(x,Q^2) - y^2 F_L^{c\bar{c},b\bar{b}}(x,Q^2)].$$

Figure 6 shows a compilation of the HERA $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ results [10]. These data provide an important consistency check of the global QCD fits to the HERA inclusive data. Scaling violation is large, as expected for gluon driven process. In Fig.6 (left), two QCD calculations of $F_2^{c\bar{c}}$ are shown which differ

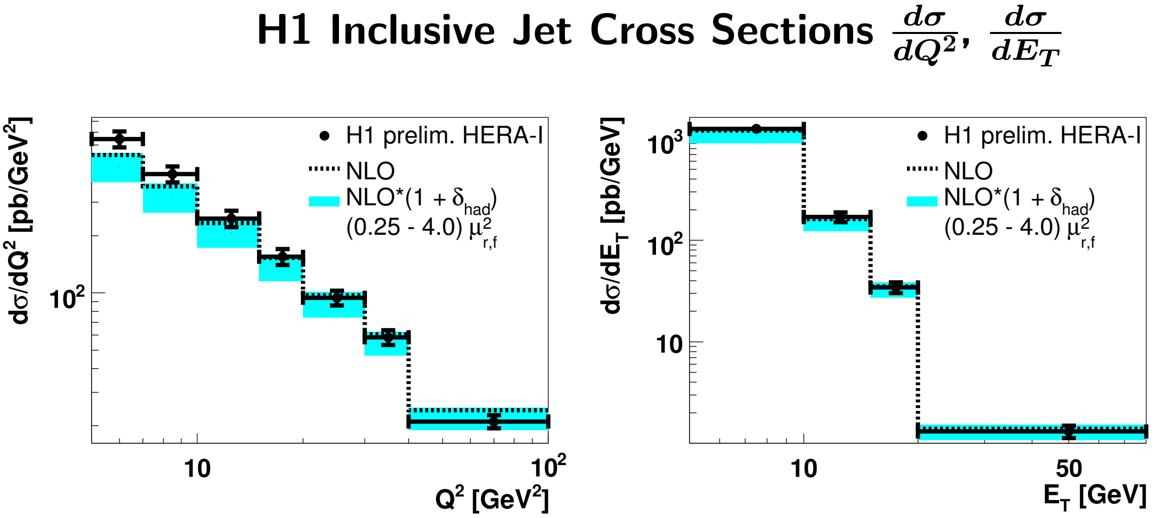

Figure 3: The inclusive cross sections of jet production at $5 < Q^2 < 100$ GeV^2 as function of Q^2 and transverse energy of the jet E_T.

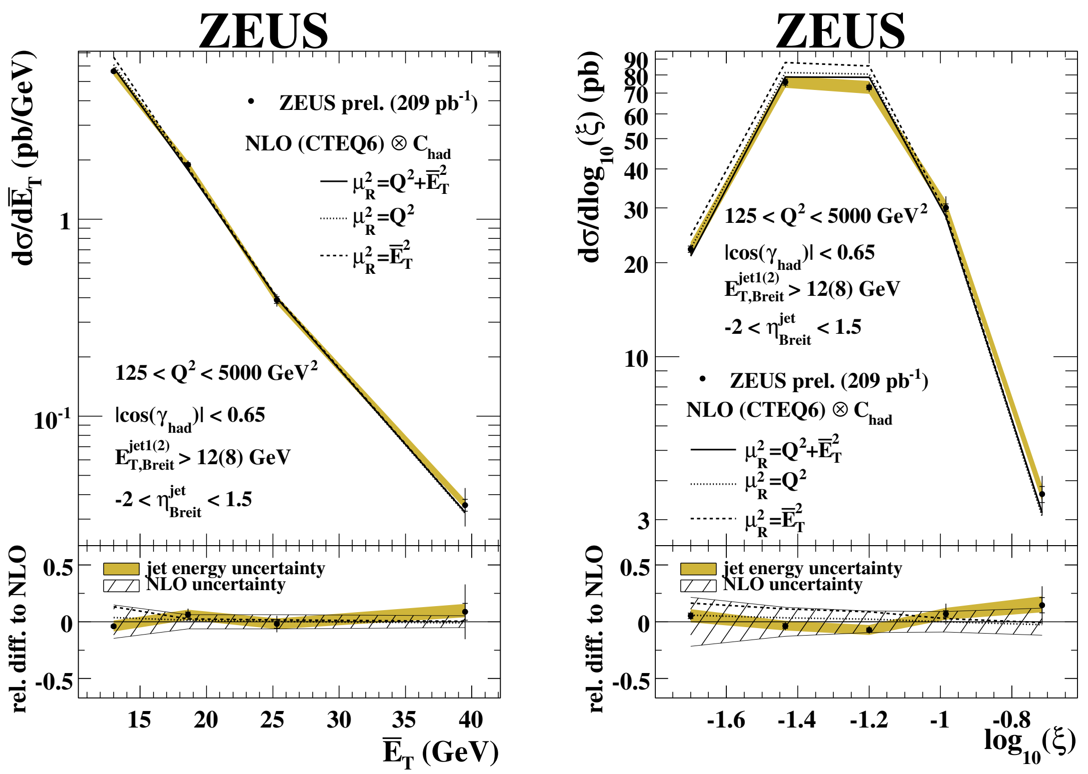

Figure 4: The differential cross sections for dijet production at $125 < Q^2 < 5000$ GeV^2 as function of the mean transverse energy of the jets $\bar{E}_T$ and the momentum fraction of the proton carried by the interacting parton ξ.

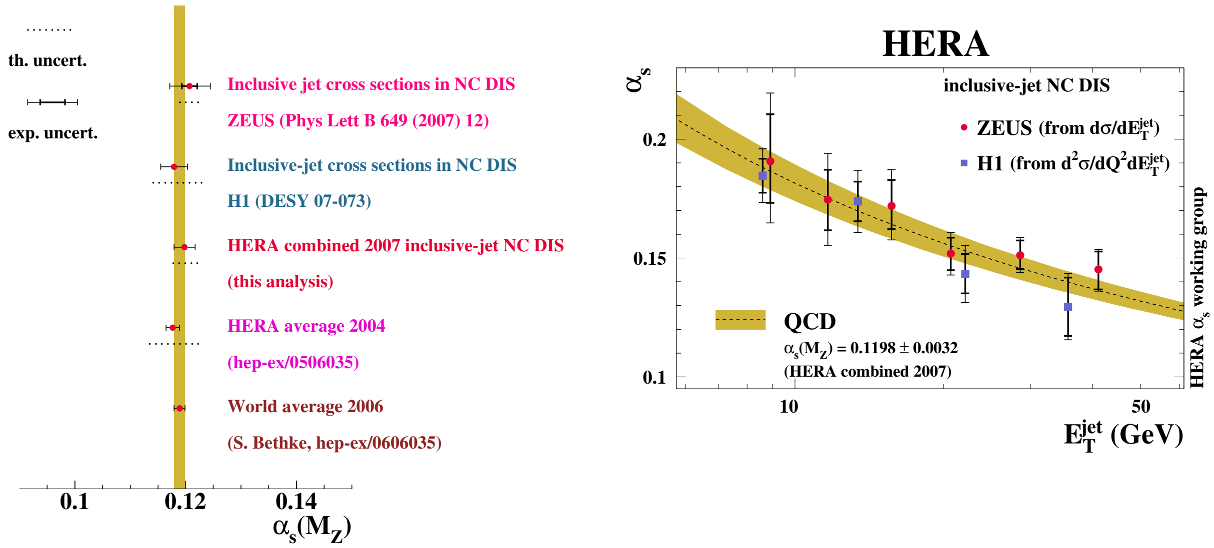

Figure 5: **(left)** $\alpha_s(M_Z)$ determinations from the H1 and ZEUS Collaborations shown together with the "World average" value; **(right)** α_s determinations from the H1 and ZEUS Collaborations as a function of the energy scale E_T^{jet}.

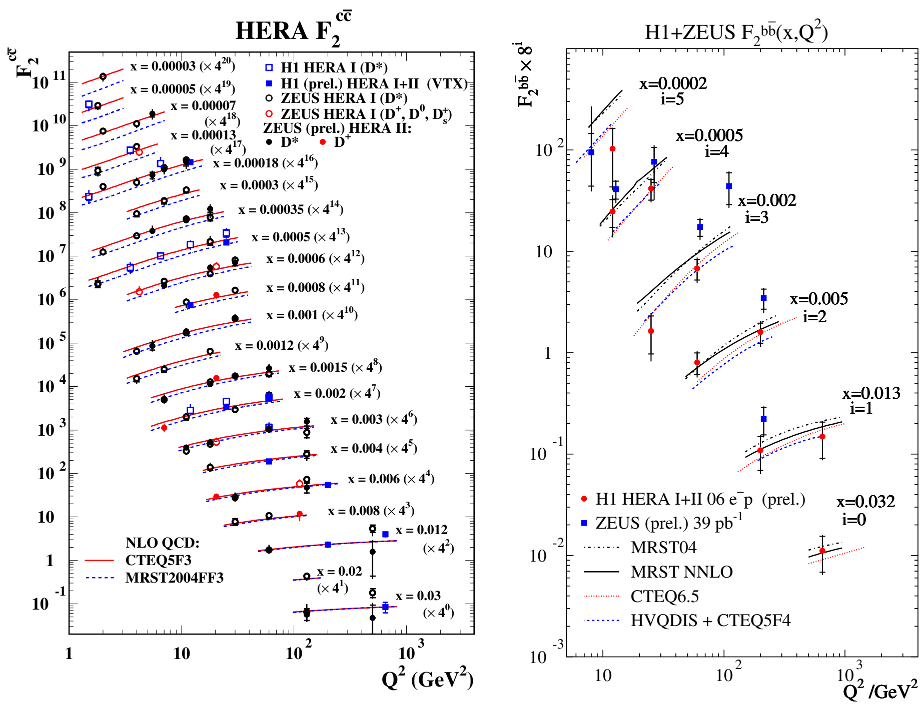

Figure 6: Compilation of the available HERA results for the contributions from charm and beauty events to F_2, the observables $F_2^{c\bar{c}}$ (left) and $F_2^{b\bar{b}}$ (right). The H1 and ZEUS data are compared to QCD model predictions.

in the used gluon density parameterisation and thus diverge toward small x and Q^2. For $F_2^{b\bar{b}}$ the theoretical predictions for NLO and NNLO differ by a factor of two but the data errors are sufficiently large not to discriminate between them. The large uncertainties of the present measurements will be hopefully reduced after inclusion of all available HERA data.

5 Diffractive PDFs from HERA

The study of hard diffractive processes at HERA offers an important inside on the diffraction and the "Pomeron" structure. Hard diffractive processes– inclusive DIS, jet and charmed quark production– can be well described by factorizing the cross sections into a diffractive parton distribution function and a hard QCD scattering process with a parton from the diffractive exchange. The diffractive parton densities (DPDF) were determined in DGLAP QCD analysis of the inclusive diffractive HERA data [11] and have been found to be dominated by the gluon distribution.

Diffractive dijet production is directly sensitive to the gluon component of the diffractive exchange, and for DIS it is in reasonable agreement with the QCD fits to the inclusive diffractive DIS data [12, 13]. The H1 Collaboration has performed a combined NLO QCD fit to the inclusive diffractive structure functions and the differential dijet cross sections in DIS (H1 2007 Jets DPDF) [13]. The diffractive gluon and quark singlet distributions are shown in Fig.7 (left) for two hard scales $\mu_r^2 = 25\ GeV^2$ and $\mu_r^2 = 90\ GeV^2$. The combined fit constrains both the diffractive quark and gluon densities well in the range $0.05 < z_{I\!P} < 0.9$. The NLO QCD prediction which use the combined DPDF fit are in good agreement with the measured dijet cross sections (Fig.7 (right)). Thus a consistent NLO QCD prediction is possible by a suitable choice of the diffractive parton distribution.

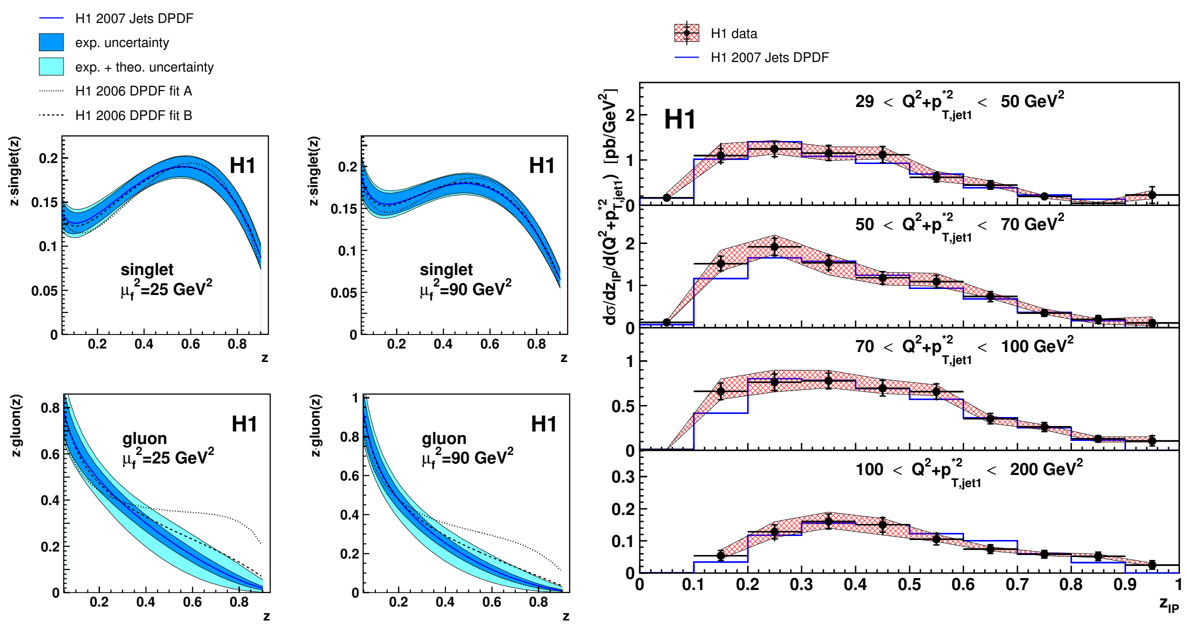

Figure 7: **(left)** The diffractive gluon and singlet quark density from combined jet and inclusive DIS DPDF fit (H1 2007 Jets DPDF) for two values of the hard scale (μ_r^2 = 25 GeV^2 and 90 GeV^2) as function of $z_{I\!P}$. $z_{I\!P}$ is a longitudinal momentum fraction of a parton entering hard sub-process with respect to diffractive exchange. The two dashed lines show the predictions of the H1 2006 DPDF fit [11] for comparison. **(right)** Cross section of diffractive dijets doubly differential in $z_{I\!P}$ and the scale $Q^2 + p_{T,jet}^2$. Also shown is the NLO QCD prediction based on the combined fit.

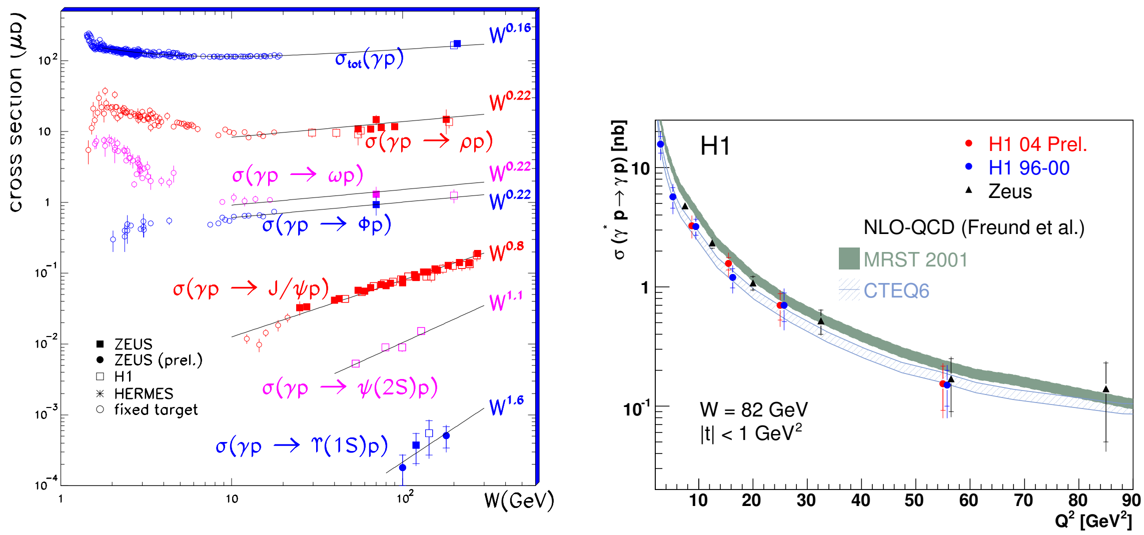

Figure 8: **(left)** The cross section for diffractive vector meson production in the photoproduction kinematic regime ($Q^2 > 0$ GeV^2). The results for various vector mesons are shown as a function of the total energy of photon-proton system W, together with fits of the form W^δ. **(right)** The DVCS cross section as function of Q^2. The NLO QCD predictions using two different sets of proton PDF are compared to the measurements.

6 Diffractive Vector Meson Production and DVCS

Diffractive production of vector mesons (VM) or real photons at HERA $\gamma^* p \to Vp$ (with $V = \rho^0$,ω,ϕ, $J/\psi, \Psi', \Upsilon$) have been extensively studied at HERA. The exclusive VM production at HERA spans the whole range from "soft" diffraction, described by Regge phenomenology, to "hard" diffraction, where the hard scales are involved and where the pQCD calculations can be applied. The transition from the soft to the hard QCD regime is seen in the energy dependence of VM photoproduction cross sections (Fig.8(left)) [14]. For inclusive γp scattering and for light VM production a soft rise of the cross section with the total energy of the photon-proton system, W, is observed. The larger the mass of the VM, the steeper the cross section rises with W: this rise reflects the increase of the gluon density towards small x which becomes steeper for larger scales set by the mass of the VM.

The QCD description of the diffractive process involves the exchange of several partons, e.g. a colour-singlet pair of gluons. While the PDFs extracted from the inclusive scattering process do not contain information about correlations between partons, the elastic VM production offers the possibility to learn more about these correlations, which are encoded in the generalized parton distributions. In particular the Deep Virtual Compton scattering (DVCS), $ep \to ep\gamma$, where a real photon is produced in diffractive scattering, is ideal for this study since it has no complications due to presence of the VM wave function in the final state description. The cross section of DVCS process is shown in Fig.8(right) as a function of Q^2[15]. NLO pQCD calculation provides good description of the measurements, although the predictions are sensitive to the choice of PDF.

7 Conclusions

Presented here is a subjective selection taken from the wealth of new measurements of deep inelastic and hard hadronic scattering processes delivered by H1 and ZEUS experiments at HERA collider. Much progress has been made over recent years, in the type of studies that can be performed, the precision achieved and in theoretical understanding. The final analyses of the full data samples will significantly improve our understanding of the QCD and the proton structure.

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