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PROTON STRUCTURE FUNCTIONS AT HIGH Q^2 AND HIGH x AT HERA

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Proton structure measurements at high Q^2 and high x, performed by the H1 and ZEUS collaborations at the HERA collider, are reviewed. Neutral and charged current deep inelastic scattering cross sections and structure functions are presented. The review also discusses improvements to the parton density measurements using jet cross section data and recent high Q^2 inclusive cross section measurements. The projected parton density uncertainties using the entire HERA data set are also presented.

1 Introduction

Precise measurements of the proton parton density functions (PDFs) are crucial for understanding the structure of the proton. This is of particular importance with the imminent start of the LHC proton-proton collider. Unpolarised lepton beams were used before the luminosity upgrade in 2000 (HERA-I), whereas the post-upgrade collider (HERA-II) has delivered polarised leptons beams. This paper reviews the latest measurements at high Q^2 and high x performed by the ZEUS and H1 collaborations at HERA.

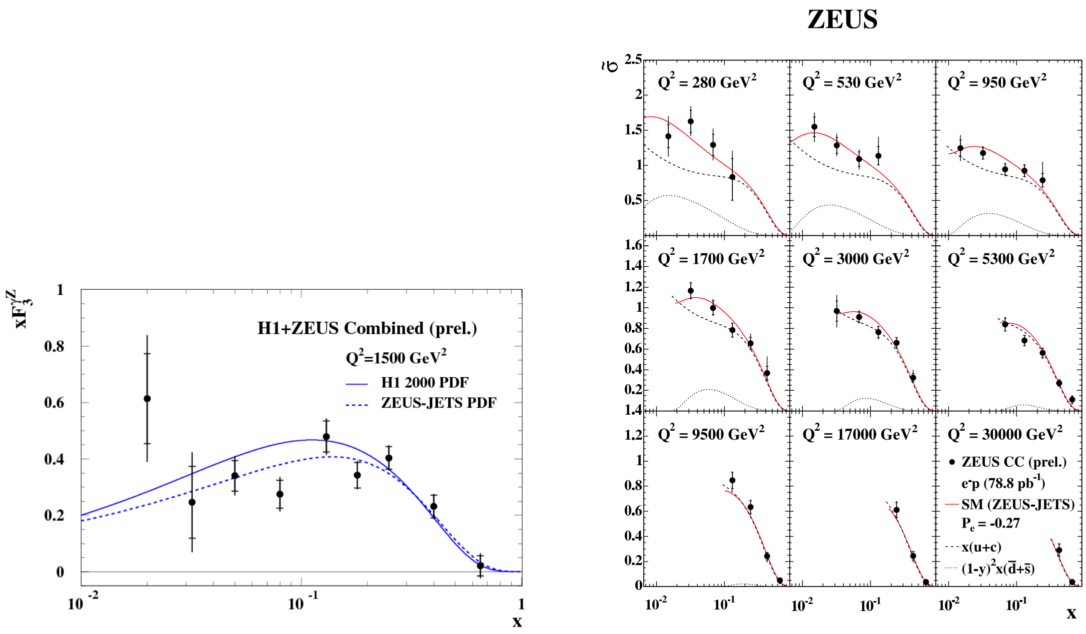
The PDFs are determined in global fits at next-to-leading order (NLO) in QCD using data from deep inelastic scattering (DIS) experiments. The kinematic range covered by HERA has allowed the determination of PDFs across a wide range of phase space spanned by the fractional proton momentum of the struck quark, Bjorken-x, and the negative squared four-momentum transfer, Q^2, of approximately $10^{-6} < x < 1$ and $0 < Q^2 < 10^5\,\mathrm{GeV}^2$.

2 Cross Section Measurements and Structure Functions

The Born-level reduced cross section for the $e^{\pm}p$ neutral current (NC) interaction with polarised lepton beams can be written as [1],

$$\tilde{\sigma}^{e^{\pm}p} = \frac{xQ^4}{2\pi\alpha^2}\frac{1}{Y_+}\frac{d^2\sigma(e^{\pm}p)}{dxdQ^2} = F_2^{\pm}(x,Q^2) \mp \frac{Y_-}{Y_+}xF_3^{\pm}(x,Q^2) - \frac{y^2}{Y_+}F_L^{\pm}(x,Q^2), \tag{1}$$

where α is the fine-structure constant, $Y_{\pm} \equiv 1 \pm (1-y)^2$ and y is related to the centre-of-mass energy, $\sqrt{s}$, via $Q^2 = sxy$. The longitudinal structure function, F_L, is small in the kinematic region considered and can be ignored. The structure functions, F_2 and xF_3, contain the sum and difference of the quark and anti-quark PDFs and can be separated into contributions from pure γ exchange, the interference of γ and Z boson exchange and from pure Z exchange. These



(a) (b)

Figure 1: Graph (a) shows the combined measurement of the structure function $xF_3^{\gamma Z}$ versus x at $Q^2 = 1500\,\mathrm{GeV}^2$ from the H1 and ZEUS collaborations using $e^{\pm}p$ NC DIS data. The curves represent the SM prediction from the H1 2000 and ZEUS-JETS PDFs. The plots shown in (b) present the CC $e^{-}p$ reduced cross section as a function of x in fixed bins of Q^2. The SM prediction using the ZEUS-JETS PDF is shown in red and dashed lines indicate the contributions from terms involving up type quarks and down type anti-quarks.

terms depend on the lepton beam charge, the longitudinal polarisation of the lepton beam, P_e, the mass of the Z and W bosons, M_Z and M_W, and the weak-mixing angle, θ, to give the following[2],

$$F_2^{\pm} = F_2^{\gamma} + k(-v_e \mp P_e a_e)F_2^{\gamma Z} + k^2(v_e^2 + a_e^2 \pm 2P_e v_e a_e)F_2^{Z}, \tag{2}$$

$$xF_3^{\pm} = k(-a_e \mp P_e v_e)xF_3^{\gamma Z} + k^2(2v_e a_e \pm P_e(v_e^2 + a_e^2))xF_3^{Z}, \tag{3}$$

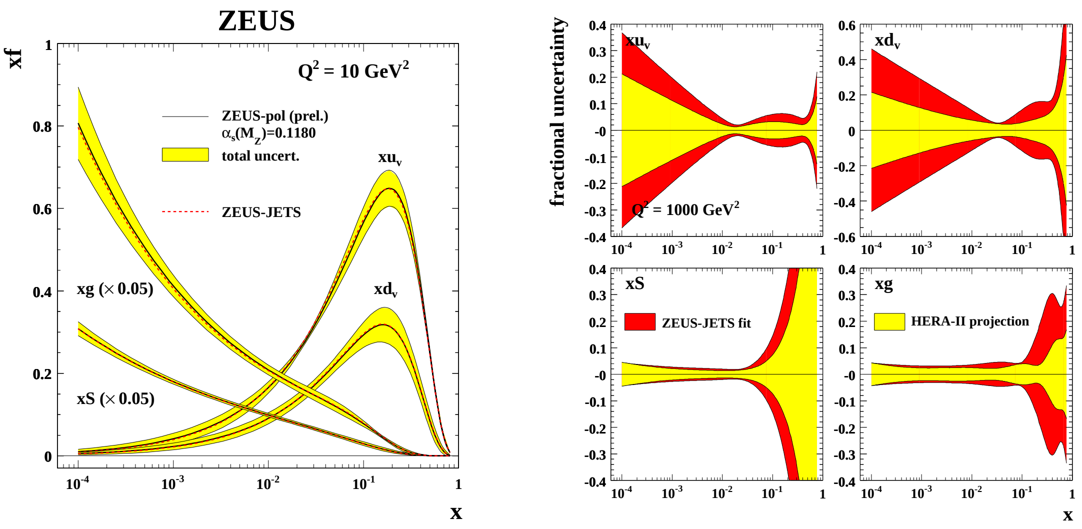
where $k = \frac{1}{4\sin^2\theta\cos^2\theta}\frac{Q^2}{Q^2+M_Z^2}$ and the vector and axial-vector coupling of the electron to the Z boson are $v_e = -1/2 + 2\sin^2\theta$ and $a_e = -1/2$ respectively. By taking the difference $\tilde{\sigma}^{e^-p} - \tilde{\sigma}^{e^+p}$ one can extract xF_3 using unpolarised HERA-I data and net unpolarised data from HERA-II. As the polarisation dependence is removed, xF_3 can be written as,

$$xF_3 = -a_e k xF_3^{\gamma Z} + 2v_e a_e k^2 xF_3^{Z}. \tag{4}$$

Since the coupling v_e is small and $k < 1$, the interference term dominates xF_3. In leading order (LO) perturbative QCD the interference structure function can be explicitly written in terms of the valence quark distributions, u_v and d_v,

$$xF_3^{\gamma Z} = \frac{x}{3}(2u_v + d_v + \Delta), \tag{5}$$

where $\Delta = 2(u_{sea} - \bar{u} + c - \bar{c}) + (d_{sea} - \bar{d} + s - \bar{s})$. Therefore $xF_3^{\gamma Z}$ is determined by the valence quark distribution if the Δ term is ignored, and is only weakly dependent on Q^2. To minimise statistical errors, the $xF_3^{\gamma Z}$ measurements can be extrapolated in Q^2 and averaged in x. Results from the ZEUS and H1 collaborations are shown in Fig. 1(a).



(a) (b)

Figure 2: The ZEUS-pol PDFs for the valence (u_v, d_v), sea (S), and gluons (g) are shown in figure (a) compared with the ZEUS-JETS PDFs central values. Figure (b) shows the uncertainties for the ZEUS-JETS PDFs in red and the HERA-II projected uncertainties in yellow.

The Born level charged current (CC) $e^{\pm}p$ cross section with polarised leptons can be expressed at LO in QCD as [1],

$$\frac{d^2\sigma_{CC}(e^-p)}{dxdQ^2} = (1-P_e)\frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 [u + c + (1-y)^2(\bar{d}+\bar{s})], \tag{6}$$

$$\frac{d^2\sigma_{CC}(e^+p)}{dxdQ^2} = (1+P_e)\frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 [\bar{u} + \bar{c} + (1-y)^2(d+s)], \tag{7}$$

where G_F is the Fermi coupling constant and u, c, d, s are the respective quark densities. The flavour selecting nature of the CC interaction is apparent as u quark content is revealed through e^-p DIS, whereas d quark constraints are possible through e^+p scattering. This can be illustrated in the e^-p CC DIS reduced cross section measurements [4] shown in Fig. 1(b), where the SM prediction describes the data well and is dominated by the u quark density.

3 PDF Fits Using Only HERA Data and the Inclusion of Jet Data

The PDFs are usually determined in global fits using data from many different experiments. However, the high precision and wide kinematic coverage of existing HERA data allow precise extractions of the proton PDFs using only HERA data. The use of HERA data alone eliminates the uncertainty from heavy-target corrections and also avoids difficulties that can sometimes arise from combining data sets from several different experiments.

The high statistics HERA NC data is used to determine the low x sea and gluon distributions while information on the valence quarks is provided by the higher-Q^2 NC and CC data. The gluon density contributes indirectly to the inclusive DIS cross sections, however it makes a direct contribution to the jet cross sections through boson-gluon fusion. The ZEUS collaboration has performed a combined NLO QCD fit (ZEUS-JETS PDF [5]) to inclusive NC and CC DIS data as well as high precision jet data in DIS and γp scattering.

The ZEUS-JETS PDFs agree well with the previous ZEUS-S PDF global fits and are also compatible with the MRST [6] and CTEQ [7] PDFs. The shapes of the PDFs are not changed significantly by including jet data but the decrease in the uncertainty on the gluon distribution is significant, approximately halved, in the mid-x region over the full Q^2 range.

4 Inclusion of New Data in PDFs and Future Projections from HERA

The PDF uncertainties from current global fits are, in general, limited by irreducible experimental systematics. In contrast, the fits to HERA data alone are largely limited by the statistical precision of existing measurements. Since 2003, HERA has delivered a substantial amount of luminosity with polarised lepton beams. Figure 2(a) shows a new PDF fit named ZEUS-pol [8] which includes HERA-II e^-p NC and CC inclusive cross section data with a total integrated luminosity of $121.5\,\mathrm{pb}^{-1}$. This leads to an improvement in PDF uncertainties at high x, especially for the u valence quark.

As new HERA data is analysed, a significant impact on the gluon uncertainties could be made by future jet cross section measurements in kinematic regions optimised for PDF sensitivity. The effect on the PDF uncertainties using the entire HERA data set has been estimated in the HERA-II projection fit [9]. A total integrated luminosity of $700\,\mathrm{pb}^{-1}$ was assumed for the high Q^2 inclusive data, and $500\,\mathrm{pb}^{-1}$ was assumed for the jet measurements with central values and systematic uncertainties taken from the published data in each case. A set of optimised jet cross sections were included for forward γp collisions assuming a luminosity of $500\,\mathrm{pb}^{-1}$.

The increased statistical precision of the assumed amount of high Q^2 data gives a significant improvement in the valence quark uncertainties over the whole range of x. A significant improvement at high x is seen for the sea quarks, however the low x sea and low x gluons are not significantly impacted as the data constraining this region tends to be at lower Q^2 and so already systematically limited. Much improvement is seen in the mid-to-high x gluon which is constrained by jet data. Approximately half of the projected reduction in the gluon uncertainties is due to the inclusion of optimised jet cross sections.

Accurate proton PDFs are of great importance, especially for the LHC proton-proton collider which is planning to deliver high energy collisions in 2008. With HERA shutting down in July 2007, the projected improvements to the PDF uncertainties using solely HERA data will be particularly relevant to future physics at the LHC.

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