Proton Structure from HERA

Voica A. Radescu
Ruprecht-Karls-Universität
Heidelberg Physikalisches Institut
Work: +49 (0)40 8998-3212 E-mail: **voica@mail.desy.de**

Precision measurements at HERA enable accurate proton structure determination which is essential for the interpretation of the LHC results. A QCD fit analysis to the combined HERA-I inclusive deep inelastic cross sections measured by the H1 and ZEUS collaborations for $e^{\pm}p$ scattering is presented. The HERA predictions are compared to $p\bar{p}$ processes at Tevatron, and also used for predictions of the pp processes at the LHC.

1 Introduction

The Standard Model (SM), developed in the 1970s describes concisely the electromagnetic, weak, and strong interactions of particles, as well as it explains the large variety of experimental observations. In this model, the elementary particles are grouped into gauge bosons and fermions. Bosons are carriers of forces which mediate the electromagnetic (photon), strong (gluon), and weak interactions (Z and $W^{\pm}$). Fermions are the primary constituents of matter, which are divided further into two groups, quarks and leptons. To complete the picture of the SM, the Higgs mechanism is invoked to generate masses to elementary particles, while it is the dynamics of the gluon interactions, which generates the mass of ordinary matter, as of the proton.

Although the SM provides a solid framework to explain the building blocks of matter, there are still many questions that remain unanswered. A key question so far unanswered is whether the Higgs mechanism indeed leads to the existence of the Higgs boson in its simplest, conventional form. The SM may be embedded in a new theory truely unifying the interactions and possibly introducing higher (”super”) symmetries or additional (”extra”) space-time dimensions. Therefore, continued active experimental investigation is crucial to deepen our knowledge in this field and the next big step to achieving this is with recently launched Large Hadron Collider (LHC), a proton-proton collider. However, the interpretation of the LHC results will deeply depend on a detailed understanding of the highly complex structure of proton. Measurements at HERA, the only ep collider in the world, have been crucial to the exploration of proton structure and quark-gluon interaction dynamics as prescribed by perturbative Quantum Chromodynamics (QCD) and these results are presented here.

2 Deep Inelastic scattering and Experimental Settings at HERA

The information on the structure function comes mainly from the Deep Inelastic Scattering (DIS) experiments, where a lepton is scattered off the constituents of the proton by a virtual exchange of neutral (NC) or charged (CC) boson producing a hadronic shower and a scattered lepton in the final state. The DIS experiments are carried either on fixed targets or at the collider facillities using electrons, muons or neutrinos to probe the proton. The kinematic variables of a DIS process are the negative squared four-momentum of the exchange boson, Q^2, the scaling variable x, which can be related in the parton model to the fraction of momentum carried by the struck quark, and the inelasticity parameter y, which is the fraction of the energy transfered to the hadronic vertex. These variables are related through the invariant centre of mass energy, $s = Q^2/xy$.

Measurements at HERA go well beyond the phase space accessible by fixed target experiments, with an extended kinematic range of $0.045 < Q^2 < 30\,000$ GeV^2 and $6 \times 10^{-5} < x < 0.65$, as shown in Fig. 1. Running of HERA proceeded in two phases, HERA I, from 1992 to 2000, and HERA II, from 2003 to 2007. The results presented in these proceedings are based on data taken by both experiments during the HERA I period. During that time, HERA operated with an electron beam, $E_e = 27.5$ GeV and a proton beam, E_p, of 820 GeV until 1997 and of 920 GeV afterwards. The luminosity collected by each of the collider experiments at HERA, H1 and ZEUS, in unpolarised $e^{\pm}p$ scattering during first phase of running was approximately 115 pb^{-1}.

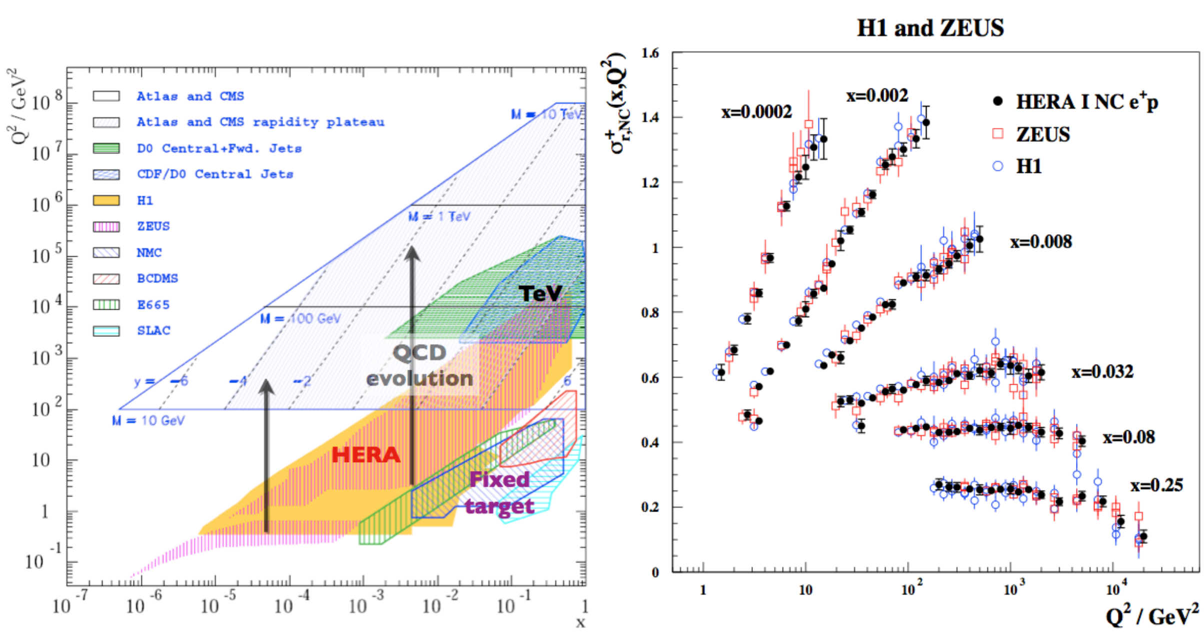

Figure 1: On the left hand side is it shown the kinematic span in x and Q^2 of experiments from DIS fixed target and HERA ep colider, $p\bar{p}$ at Tevatron, pp at the LHC. On the right hand side the combined HERA NC DIS ep data (black filled circles) are compared to the separate H1 (blue open circles) and ZEUS (red open square) measurements for six representatitve values of x.

The DIS $e^{\pm}p$ scattering cross section is given by a linear combination of generalised structure functions, shown here for the NC process (and it is similarly for CC),

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

where the electromagnetic coupling constant α, the photon propagator and a helicity factor are absorbed in the definition of the reduced cross section $\sigma^{\pm}_{r,NC}$ and $Y_{\pm} = 1 \pm (1-y)^2$. The structure functions depend on the electroweak parameters and are linearly related to the quark, anti-quark and gluon momentum distributions in the proton, called parton distribution functions (PDFs).

To further benefit from the precision of the measurements, the H1 and ZEUS cross sections are combined resulting in a most consistent and precise DIS inclusive double differential cross-section measurement of neutral and charged current $e^{\pm}p$ scattering to date [1]. The combination is based on χ^2 minimisation method with a coherent treatment of the systematic uncertainties as described in [2].The gain of this procedure is not only statistical, as both experiments accumulated similar amount of data, but also systematic uncertainties are reduced by exploiting the differences between experiments. Figure 1 shows the combined NC e^+p reduced cross section compared to the separate H1 and ZEUS data input to the averaging procedure.

3 QCD Analysis Strategy

The main features of the QCD theory are the confinement (at short ranges the quarks are strongly bound inside protons) and asymptotic freedom (at large scales the coupling constant of strong force decreases and quarks become quasi-free partons). Therefore, factorisation theorem exploits these features by separating the short and long distances processes, so that structure funcions can be written as a convolution product between calculable parts (hard scattering coefficients) and non-calculable parts, which are therefore parametrised (PDFs) and determined from data. Hence, the proton PDFs are extracted from the QCD fits by a measure of agreement between data described in the previous section and theory models. To restrain to the region where perturbative QCD is valid, only data above $Q^2_{min} = 3.5$ GeV^2 is used in the central fit. The HERA data have a minimum invariant mass of the hadronic system, W, of 15 GeV, such that they are in a kinematic region where there is no sensitivity to non-perturbative effects common to fixed target data.

The fit procedure consists first in parametrising PDFs at a starting scale $Q^2_0 = 1.9$ GeV^2, chosen to be below the charm mass threshold. The parametrised PDFs at HERA are the valence distributions xu_v and xd_v, the gluon distribution xg, and the u-type and d-type $x\bar{U}$, $x\bar{D}$, where $x\bar{U} = x\bar{u}$, $x\bar{D} = x\bar{d} + x\bar{s}$. The following standard functional form is used to parametrise them

$$xf(x) = Ax^B(1-x)^C(1 + Dx + Ex^2), \quad (2)$$

where the normalisation parameters, A_{uv}, A_{dv}, A_g, are constrained by the QCD sum-rules, such that the counting and momentum conservation are preserved. The B parameters $B_{\bar{U}}$ and $B_{\bar{D}}$ are set equal, $B_{\bar{U}} = B_{\bar{D}}$, such that there is a single B parameter for the sea distributions. The strange quark distribution is already present at the starting scale and it is assumed here that $x\bar{s} = f_s x\bar{D}$ at Q^2_0. The strange fraction is chosen to be $f_s = 0.31$ which is consistent with determinations of this fraction using neutrino induced di-muon production. In addition, to ensure that $x\bar{u} \to x\bar{d}$ as $x \to 0$, $A_{\bar{U}} = A_{\bar{D}}(1 - f_s)$. The D and E are introduced one by one until no further improvement in χ^2 is found. The best fit results in a total of 10 free parameters.

The PDFs are then evolved using DGLAP evolution equations [3-7] at next-to-leading-order in perturbative series in the $\overline{MS}$ scheme with the renormalisation and factorisation scales set to Q^2 [a]. The QCD predictions for the structure functions are obtained by convoluting these parametrised PDFs with the calculable coefficient functions taking into account mass effect for the heavy quarks based on the general mass variable flavour scheme [9].

The uncertainties at HERA are classified in three categories: experimental, model, and parametrisation uncertainties. Consistency of the input data ensures that the experimental uncertainty of the HERA PDFs set can be determined using rigorous statistical methods. The form of the χ^2 is consistent with the one used for the combination of the data sets.

[a] The QCDNUM package is used [10].

The model uncertainties are evaluated by varying the input assumptions, which are the variation of the starting scale and of the Q^2_{min}, the variations of the heavy quark masses which are set to the standard values of $m_c = 1.4$ GeV and $m_b = 4.75$ GeV for the central fit, and the variation of f_s. The parametrisation uncertainty is estimated as an envelope which is formed as a maximal deviation at each x value from the central fit of 10 parameter fits with D and E non-zero from Equation 2.

4 Results and Comparisons

The QCD fit analysis based on the combined HERA I data and NLO calculations results into HERAPDF1.0 and are shown in Fig. 2. The resulting χ^2 per degree of freedom for the central fit is found to be 574/582. As expected, the resulting HERAPDFs, determined by using HERA data as a sole input in the QCD fit, has greatly reduced experimental uncertainties, as compared to the separate analyses of the ZEUS and H1 experiments. The PDF parametrisation uncertainty dominates, especially in the high x region. In addition, the precision of gluon PDF is very good in the low x region, especially at the scale relevant to the LHC [11].

The HERAPDF1.0 is a competitive PDF set which is compared to other PDFs extracted from the global fit analyses, such as MSTW08 (as shown in Fig. 2), CTEQ6.6, ABKM09, NNPDF2.0, GJR. The main advantage of the global fit analyses is the use of more available data which bring additional constraining power over the PDFs, however there are still open issues of data compatibility, understanding of corrections needed for the fixed target data. Therefore, HERAPDF provides an alternative approach free of these uncertainties and a check of PDF universality for other processes. The predictions based on HERAPDFs from the DIS process

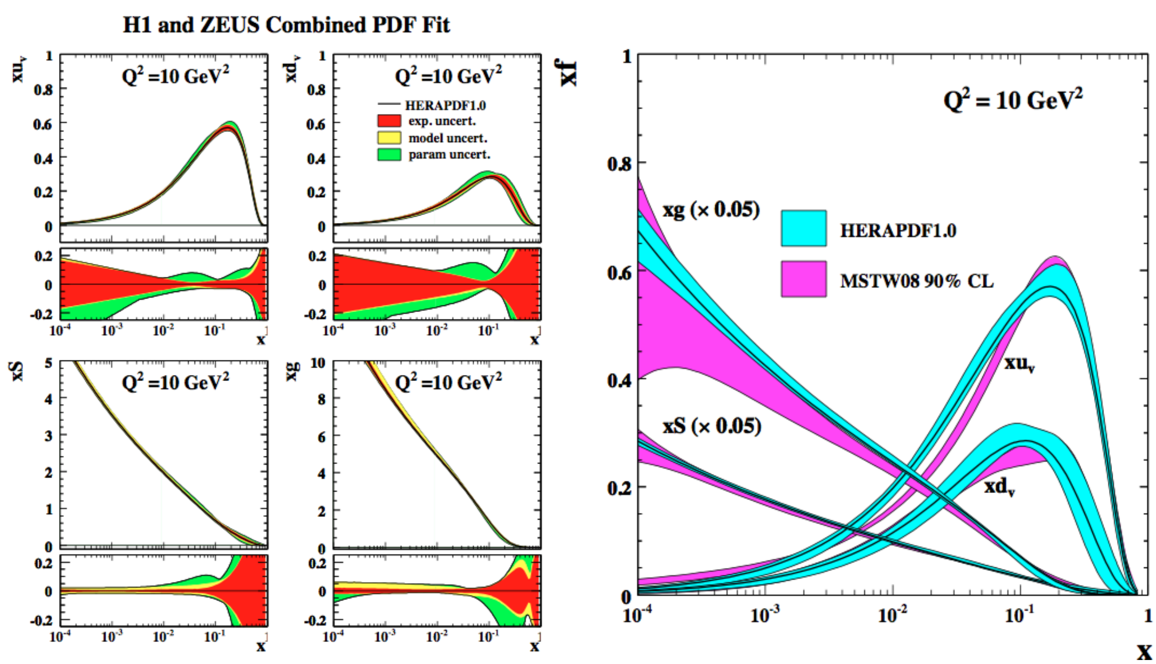

Figure 2: On the left hand side, the parton distribution functions from HERAPDF1.0, xu_v, xd_v, $xS = 2x(\bar{U} + \bar{D})$, xg, at $Q^2 = 10$ GeV^2 are shown separately with the experimental, model and parametrisation uncertainties and the fractional uncertainty bands below each PDF. HERAPDF1.0 with its total uncertainty (blue) is compared on the right to MSTW08 (magenta).

agree well with the Tevatron jet production, Z and W cross sections from the $p\bar{p}$ process and provide a competitive prediction for the LHC pp processes, which are now confronted with the upcoming data as shown in Fig. 3.

5 Summary

It these proceedings the combination of the published HERA I H1 and ZEUS cross section measurements was presented followed by a NLO QCD fit analysis to extract HERA PDFs. The consistent treatment of uncertainties in the joint data set ensures that experimental uncertainties on the PDFs can be calculated using statistical robust methods. Model uncertainties and PDF parametrisation dependencies have also been carefully considered and included in the total uncertainty estimate. The predictions based on HERA PDFs from *ep* collider agree well with the Tevatron jet production, Z and W cross sections from the $p\bar{p}$ process and provide a competitive prediction for the LHC *pp* processes which are now confronted with upcoming data.

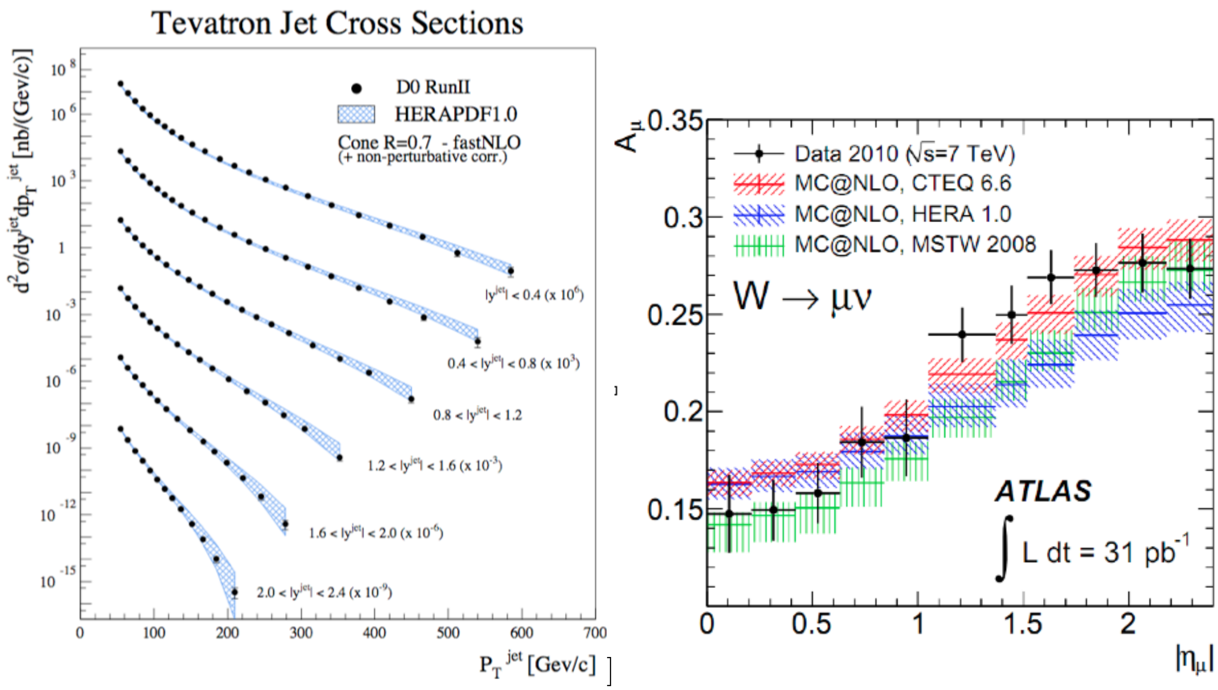

Figure 3: The predictions from HERAPDF1.0 are in good agreement with D0 jet data from Tevatron (left) and to W charge asymmetry from ATLAS at the LHC (right).

References

1. H1 Collaboration, ZEUS Collaboration, F. Aaron *et al.*, JHEP 1001, 109 (2010)
2. H1 Collaboration, F. Aaron *et al.*, [arXiv:0904.0929].
3. V. N. Gribov and L. N. Lipatov, Sov. J. Nucl. Phys. 15, 438 (1972).
4. V. N. Gribov and L. N. Lipatov, Sov. J. Nucl. Phys. 15, 675 (1972).
5. L. N. Lipatov, Sov. J. Nucl. Phys. 20, 94 (1975).
6. Y. L. Dokshitzer, Sov. Phys. JETP 46, 641 (1977).
7. G. Altarelli and G. Parisi, Nucl. Phys. B 126, 298 (1977).
8. C. Amsler *et al.* (Particle Data Group), Phys. Lett. **B667,** (2008).
9. R. S. Thorne code, revised in 2008.
10. QCDNUM package, M. Botje, (2010), arXiv:1005.1481
11. V. Radescu, TES2010 Slides located at `http://events.lal.in2p3.fr/TESchool10/Profs-Presentations/V-Radescu.pdf`