Structure Functions and PDF determination at HERA

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Latest results on the measurements of the deep inelastic scattering (DIS) processes at HERA published by the H1 and ZEUS collaborations are presented in this report. The parton distribution functions (PDFs) of the proton extracted from the HERA data and the open source QCD framework for PDF determination, `HERAFitter`, are discussed here as well.

1 DIS ata HERA and recent measurements

The HERA (Hadron Elektron Ring Anlage) is the world's only *ep* collider operated in the years 1992-2007, with centre-of-mass energies $\sqrt{s} = 225 - 318$ GeV. Two different deep inelastic *ep* scattering processes are measured at HERA: neutral current (NC), $ep \rightarrow eX$, and charged current (CC), $ep \rightarrow \nu X$. NC reactions are mediated by the photon or a Z boson while in the CC scattering a $W^{\pm}$ boson is exchanged. The NC (and similarly CC) cross section can be expressed in terms of structure functions:

$$\frac{d^2\sigma_{NC}^{e^{\pm}p}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}[Y_+\tilde{F}_2^{\pm} \mp Y_- x\tilde{F}_3^{\pm} - y^2\tilde{F}_L^{\pm}],$$

where $Y_{\pm} = 1 \pm (1-y)^2$ with y being the inelasticity. The structure function $\tilde{F}_2$ is the dominant contribution to the cross section, $x\tilde{F}_3$ is important at high Q^2 and $\tilde{F}_L$ is sizable only at high y. In the framework of perturbative quantum chromodynamics (QCD) the structure functions are directly related to the parton distribution functions, i.e. in leading order (LO) F_2 is the momentum sum of quark and anti-quark distributions, $F_2 \approx x\sum e_q^2(q+\overline{q})$, xF_3 is related to their difference, $xF_3 \approx x\sum 2e_q a_q(q-\overline{q})$. At higher orders, terms related to the gluon density distribution ($\alpha_s g$) appear.
In analogy to neutral currents, the inclusive CC *ep* cross section can be expressed in terms of structure functions. In LO the CC e^+p and e^-p cross sections are sensitive to different quark densities, i.e. $\tilde{\sigma}_{CC}^{e^+p} \approx x[\overline{u}+\overline{c}] + (1-y)^2 x[d+s]$ and $\tilde{\sigma}_{CC}^{e^-p} \approx x[u+c] + (1-y)^2 x[\overline{d}+\overline{s}]$.

Two collider experiments at HERA, H1 and ZEUS, have recently published their final measurements of the inclusive DIS data. Inclusive $e^{\pm}p$ single and double differential cross sections for NC and CC scattering processes are measured by the H1 experiment [1] using data with centre-of-mass energy of $\sqrt{s} = 319$ GeV and a total integrated luminosity of 333.7 pb^{-1} corresponding to the full second data taking period at HERA with longitudinal lepton polarisation (HERA II). The differential cross sections are measured in the range of negative four momentum transfer squared, Q^2, between 60 and 50 000 GeV^2, and Bjorken x between 0.0008 and 0.65. The measurements are combined with earlier published unpolarised H1 data and, among other things,

are used to determine the structure function $xF_3^{\gamma Z}$. The NC parity violating structure function $F_2^{\gamma Z}$ is measured for the first time and is show in figure 1 (left). The polarisation dependence of the charged current total cross section is also measured. The H1 measurements are well described by a next-to-leading order (NLO) QCD fit based on all published H1 inclusive cross section data which are used to extract the parton distribution functions of the proton.
The ZEUS collaboration has published the measurement of the NC cross sections for e^+p data collected in 2006-2007 years [2]. Together with the single and double differential NC cross sections, the structure functions $\tilde{F}_3$ and $F_3^{\gamma Z}$ (figure 1 right) were determined. This is the final ZEUS measurement of the inclusive cross sections from the HERA II period.

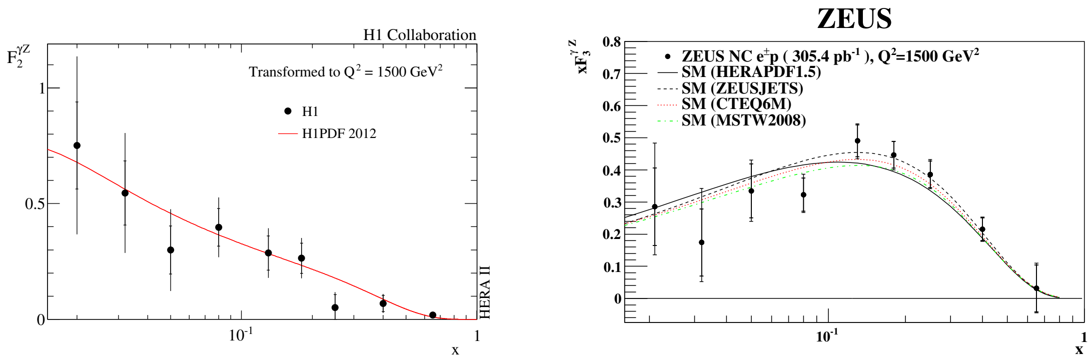

Figure 1: Left: structure function $F_2^{\gamma Z}$ transformed to $Q^2 = 1500$ GeV^2 for H1 data (solid points) and the expectation from the prediction obtained with H1PDF 2012 (solid curve). Right: structure function $xF_3^{\gamma Z}$ determined from ZEUS NC data and compared to the predictions using various PDFs.

2 HERA PDFs

A precise knowledge of the PDFs of the proton is essential in order to make predictions for basically any scattering processes at hadron colliders. This knowledge mainly comes from DIS at HERA, fixed target experiments and from TEVATRON while precise data from LHC also becomes increasingly important. The HERAPDFs are based only on HERA DIS data which allows the usage of the conventional χ^2 tolerance of $\Delta\chi^2 = 1$. Since this analysis is solely based on *ep* data, the PDFs do not depend on the approach for nuclear corrections needed for fixed target data.
In the HERAPDF1.0 fit [3], the combined set on NC and CC *ep* inclusive cross-sections for the first running period of HERA (HERA I) is used. A large fraction of the full statistics of the HERA inclusive CC and NC data are used for NLO and NNLO QCD fits resulting in HERA-PDF1.5 [4]. Currently, the recently published H1 and ZEUS data presented in previous section are in the process of combination and will be used in the determination of new HERA PDF set (HERAPDF2.0).

For HERA PDFs the QCD predictions for the structure functions are obtained by solving the DGLAP evolution equations [5] at NLO (or NNLO) in the $\overline{MS}$ scheme with the renormalisation and factorisation scales chosen to be Q^2. PDFs are parametrised as a functions of x at the input scale Q_0^2 (chosen to be below the charm mass threshold) and for higher Q^2 are obtained through the DGLAP evolution equations. For the PDF parametrisation the generic form $xf(x) = Ax^B(1-x)^C(1+\ Ex^2\ )$ is used. The parametrised PDFs are the gluon distribution xg, the valence quarks xu_v, xd_v, and the u-type and d-type anti-quark distributions $x\bar{U}$, $x\bar{D}$ which at the starting scale are $x\bar{U} = x\bar{u}$ and $x\bar{D} = x\bar{d} + x\bar{s}$. The normalisation parameters A are constrained by the quark number sum-rules and momentum sum-rule, extra constrains for small-x behaviour of $d-$ and $u-$type quarks $B_{u_v} = B_{d_v}$, $B_{\bar{U}} = B_{\bar{D}}$ and $A_{\bar{U}} = A_{\bar{D}}(1-f_s)$ (f_s is the strange quark distribution) which ensures that $x\bar{u} \to x\bar{d}$ as $x \to 0$.

The break-up of the HERAPDF1.0 and HERAPDF1.5 into different flavours is illustrated in figure 2. Model uncertainties (shown as yellow bands) are evaluated by varying the input assumptions on Q^2_{min}, f_s, mass of heavy quarks m_C and m_B. Parametrisation uncertainties (green band) are formed by an envelope of the maximal deviation from the central fit varying parametrisation assumptions and therefore has an asymmetric shape. As it can be seen from the figure 2, the uncertainty bands in HERAPDF1.5 are smaller than in HERAPDF1.0 due to the inclusion of the more precise HERA II data.

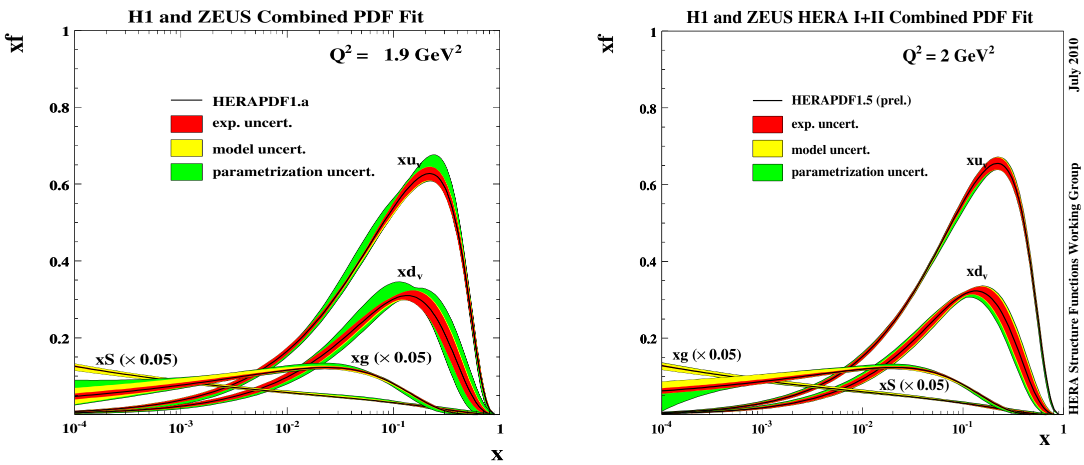

Figure 2: The parton distribution functions from HERAPDF1.0 (left) and HERAPDF1.5 (right) shown for $xu_v, xd_v, xS = 2x(\bar{U} + \bar{D}), x_g$ at $Q^2 = 1.9$ GeV^2. The gluon and sea distributions are scaled down by a factor 20. The different colour bands represent experimental, model and parametrisation uncertainties, respectively.

The effect of including the HERA charm production data in the PDF fits is studied and published in [6]. In this study, several implementations of the variable flavour number schemes (VFNS), which have different treatment of heavy quark mass terms in pQCD, are investigated. The different treatments can have different impact on the charm contribution to the sea quark and therefore affect the composition of $x\overline{U}(x)$ from the $x\overline{u}(x)$ and the $x\overline{c}(x)$ contributions. A combined NLO QCD analysis is performed using the charm production and the inclusive DIS data repeatedly for each VFN scheme with different values of the charm quark mass parameter, M_c. Figure 3 (left) shows the results of the M_c scan for all schemes considered. It is interesting to observe that first, different schemes have different optimal charm quark mass parameter M_c, and second, the χ^2 minimum values are comparable for all schemes despite of different optimal values of M_c.
The implications of this result on the NLO predictions for $W^\pm$ and Z production cross sections at the LHC are investigated by calculating the boson cross sections with PDF sets produced for each scheme at its optimal M_c. As an example, the W^+ cross section as a function of M_c is shown in figure 3. Good agreement between different predictions is observed at optimal M_c which results in a reduction of the uncertainties due to the heavy flavour treatment to below 2.0%.
The QCD analysis is also performed in the fixed-flavour-number-scheme at NLO and the running charm quark mass is determined: $m_c(m_c) = 1.26 \pm 0.05_{exp} \pm 0.03_{mod} \pm 0.02_{param} \pm 0.02_{\alpha_s}$ GeV.

The impact of the HERA inclusive jet data on PDFs (HERAPDF1.6 [7]) and inclusive DIS, jet, charm and low energy data together (HERAPDF1.7 [8]) were also studied but not discussed here.

HERAFitter project

`HERAFitter` project is an open source QCD fit framework designed for the extraction of PDFs and the fast assessment of the impact of the new data. The framework includes various modules and interfaces enabling a large number of theoretical and methodological options, as well as a large number of relevant data sets like inclusive cross sections from HERA DIS and fixed

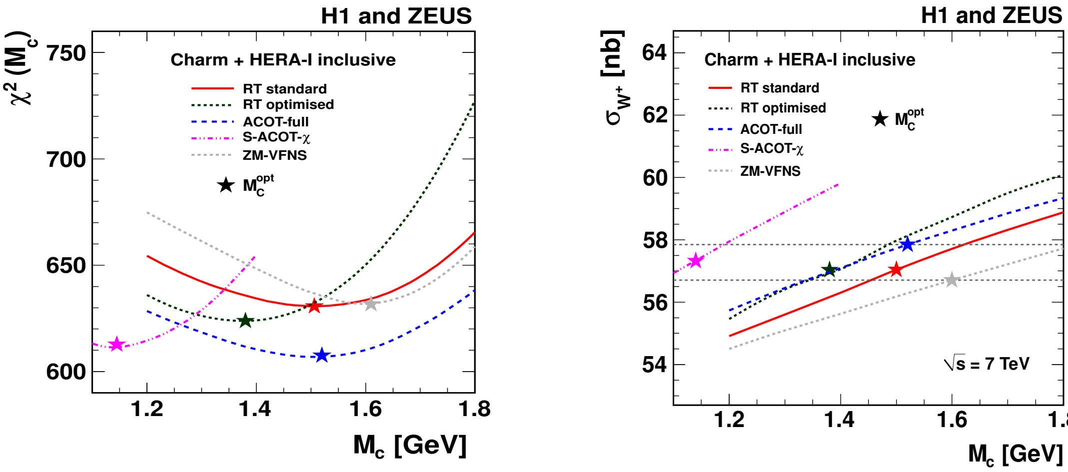

Figure 3: Left: Comparison of the χ^2 obtained by NLO fits to the inclusive HERA I and the preliminary combined charm data in different VFN schemes represented as lines of different styles. Right: W^+ production cross section σ_{W^+} at the LHC for $\sqrt{s} = 7$ TeV as a function of M_c. Lines represent different schemes and the stars show the positions of the corresponding optimal M_c values obtained for each scheme.

target experiments, Drell-Yan, jet production data (ep, pp and $p\bar{p}$) and heavy quark structure functions. The structure functions may be computed in a variety of heavy quark schemes as well as the fixed flavour scheme. For the systematic uncertainty treatment of the experimental data there are several methods provided (Hessian, covariance matrix, Monte Carlo replicas).
The package is interfaced to different tools like FastNLO [9] and APPLGRID [10] for the fast input of NLO jet and Drell-Yan cross sections and HATHOR [11] for the calculation of the top cross sections. HERAFitter is under continues development and includes many useful additions. Basic plots are provided together with the fit result and the resulting PDFs are supported by the LHAPDF standards. This framework is actively used by LHC experiments.
In summary, HERAFitter contains all necessary ingredients to study the proton PDFs, it incorporates variety of different data processes and theory calculations, contains many useful tools and is an optimal platform for various benchmarking studies. More information and the package downloads can be found on the web site `http://herafitter.org`.

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