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PDF Fits at HERA

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The HERAPDF1.0 PDF set, which was an NLO QCD analysis based on H1 and ZEUS combined inclusive cross section data from HERA-I, has been updated to HERAPDF1.5 by including preliminary inclusive cross section data from HERA-II running. Studies have also been made by adding various other HERA data sets: combined charm data, combined low energy run data and H1 and ZEUS jet data. These data give information on the treatment of charm and the charm quark mass and on the value of $\alpha_s(M_Z)$. The PDF analysis has also been extended to NNLO. The PDFs give a good description of Tevatron and early LHC data.

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1. Introduction

The HERAPDF1.0 NLO parton distribution functions (PDFs) were extracted using the combined inclusive cross section data from the H1 and ZEUS collaborations taken at the HERA collider during the HERA-I running period 1992-1997 [1]. These data come from neutral and charged current interactions from both e^+p and e^-p scattering. The combination of the H1 and ZEUS data sets takes into account the full correlated systematic uncertainties of the individual experiments such that the total uncertainty of the combined measurement is typically smaller than 2%, for $3 < Q^2 < 500$ GeV^2, and reaches 1%, for $20 < Q^2 < 100$ GeV^2. Additional preliminary HERA data has been added to the HERAPDF1.0 NLO QCD analysis: HERA combined charm data have been added [2]; combined data from low energy running have been added [3]; further combined inclusive cross-section data from the HERA-II running period 2003-2007 have been added (HERAPDF1.5) [5]; H1 and ZEUS jet data have been added (HERAPDF1.6) [6]; finally a fit which comprises all these data sets has been made (HERAPDF1.7). The NLO fits have also been extended to NNLO for both HERAPDF1.0 and 1.5 [7] and the NLO and NNLO PDFs have been confronted with Tevatron and LHC data

2. Results

The combined $F_2^{c\bar{c}}$ data can help to reduce the uncertainty on PDFs coming from the choice of heavy-quark-scheme and the value of the charm mass input to these schemes. Fig. 1 compares the χ^2, as a function of the charm mass, for a fit which includes charm data (top right) to that for the HERAPDF1.0 fit (top left) when using the Thorne-Roberts (RT) variable-flavour-number (VFN) scheme. However, this scheme is not unique, specific choices are made for threshold behaviour. In Fig. 1 (bottom left) the χ^2 profiles for the standard and the optimized versions (optimized for smooth threshold behaviour) of this scheme are compared. The same figure also compares the alternative ACOT VFN schemes and the Zero-Mass VFN scheme. Each of these schemes favours a different value for the charm quark mass, and the fit to the data is good for all the heavy-quark-mass schemes excepting the zero-mass scheme. Each of these schemes can also be used to predict W and Z production for the LHC and their predictions for W^+ are shown in Fig. 1 as a function of the charm quark mass (bottom right). If a particular value of the charm mass is chosen then the spread of predictions is as large as $\sim 7\%$. However this spread is considerably reduced $\sim 1\%$ if each heavy quark scheme is used at its own favoured value of the charm quark-mass. Furher details of this study are given in ref. [2].

The HERA-II data have been combined with the HERA-I data to yield an inclusive data set wih improved accuracy at high Q^2 and high x [4]. This new data set is used as the sole input to a PDF fit called HERAPDF1.5 [5] which uses the same formalism and assumptions as the HERAPDF1.0 fit. Fig. 2 (left) shows the combined data for $NC\ e^{\pm}p$ cross-sections with the HERAPDF1.5 fit superimposed. The parton distribution functions from HERAPDF1.0 and HERAPDF1.5 are compared in Fig. 2 (right). The improvement in precision at high x is clearly visible.

The HERAPDF1.5 analysis has been extended to include HERA inclusive jet data. The new PDF set which results is called HERAPDF1.6 [6]. The gluon PDF contributes only indirectly to the inclusive DIS cross sections. However, measurements of jet cross sections can provide a direct

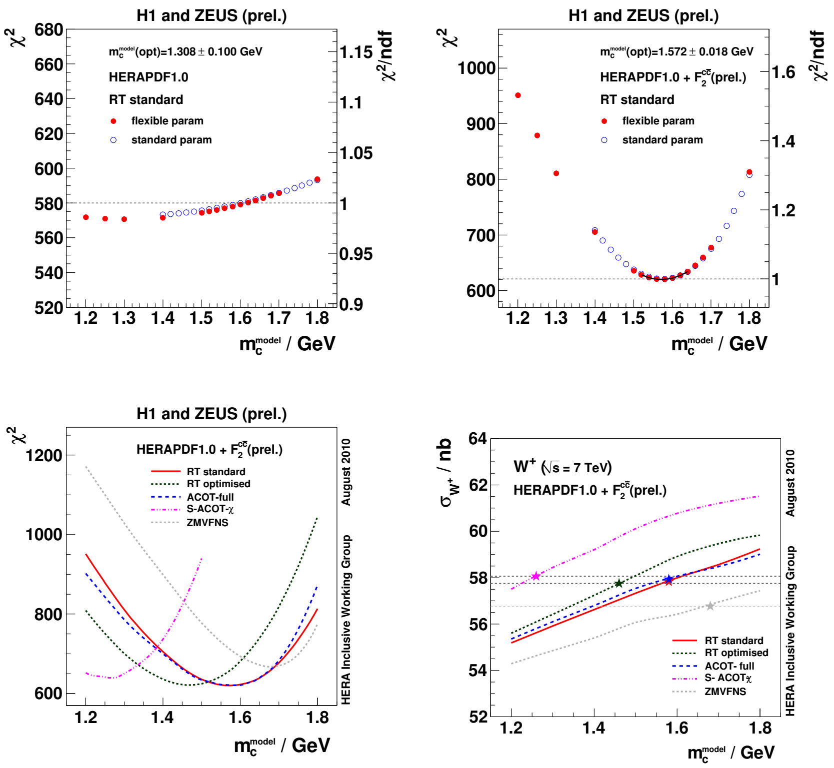


Figure 1: The χ^2 of the HERAPDF fit as a function of the charm mass parameter m_c^{model}. Top left; using the RT-standard heavy-quark-mass scheme, when only inclusive DIS data are included in the fit. Top right; using the RT-standard heavy-quark-mass scheme, when the data for $F_2^{c\bar{c}}$ are also included in the fit. Bottom left; using various heavy-quark-mass schemes, when the data for $F_2^{c\bar{c}}$ are also included in the fit. Bottom right: predictions for the W^+ cross-sections at the LHC, as a function of the charm mass parameter m_c^{model}, for various heavy-quark-mass schemes.

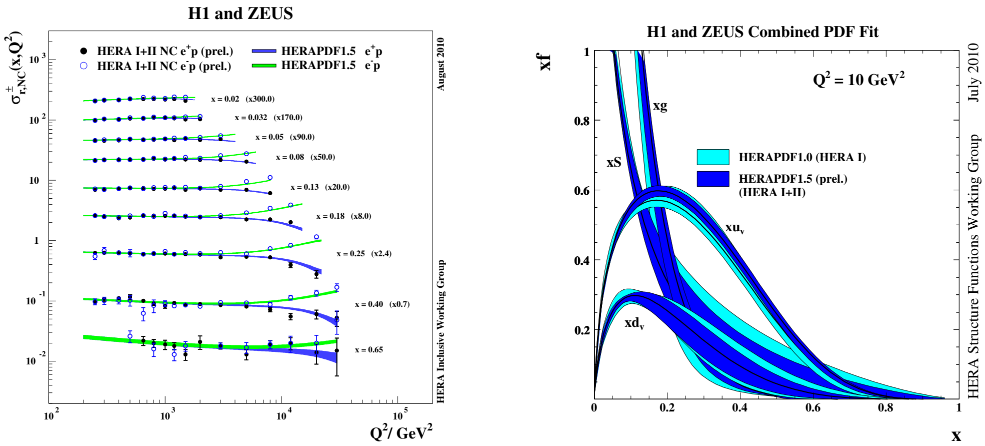


Figure 2: Left: HERA combined data points for the NC $e^{\pm}p$ cross-sections as a function of Q^2 in bins of x, for data from the HERA-I and II run periods. The HERAPDF1.5 fit to these data is also shown on the plot. Right: Parton distribution functions from HERAPDF1.0 and HERAPDF1.5; xu_v, xd_v,$xS = 2x(\bar{U}+\bar{D})$ and xg at $Q^2 = 10$ GeV^2.

determination of the gluon density. For these fits the HERAPDF1.5 parametrisation of the gluon distribution xg is extended to include a term such that the NLO gluon may become negative at low x and low Q^2 (however it does not do so in the kinematic region of the HERA data). Furthermore, the low-x slopes of u and d valence PDFs are no longer required to be equal. This more flexible parametrisation is called HERAPDF1.5f. The extra flexibility does not change the NLO PDFs central values significantly, and the uncertainties are not much increased- the largest increase is in the low-x gluon uncertainty, which increases from $\sim 8\%$ to $\sim 10\%$ at $Q^2 = 10$ GeV^2, $x = 10^{-4}$ - since HERAPDF always evaluated parametrisation uncertainties and model uncertainties as well as purely experimental uncertaintes on the PDFs. When the jet data are added the HERAPDF1.6 PDFs are also similar, there is no tension between the jet data and the inclusive data. The impact of the jet data is seen when $\alpha_S(M_Z)$ is allowed to be a free parameter of the fit. Fig. 3 shows the PDFs for HERAPDF1.5f and HERAPDF1.6, each with $\alpha_S(M_Z)$ left free in the fit. It can be seen that without jet data the uncertainty on the gluon PDF at low x is large. This is because there is a strong correlation between the low-x shape of the gluon PDF and $\alpha_S(M_Z)$. However once jet data are included the extra information on gluon induced processes reduces this correlation and the resulting uncertainty on the gluon PDF is not much larger than it is for fits with $\alpha_S(M_Z)$ fixed. The

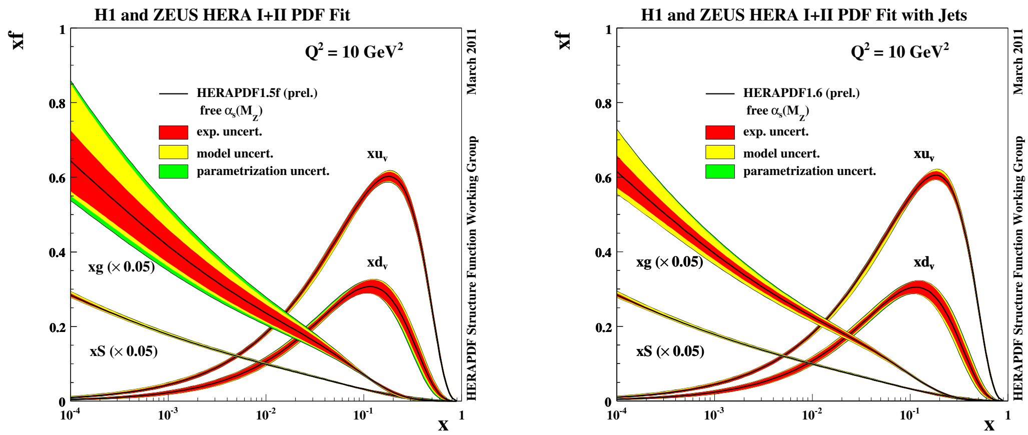


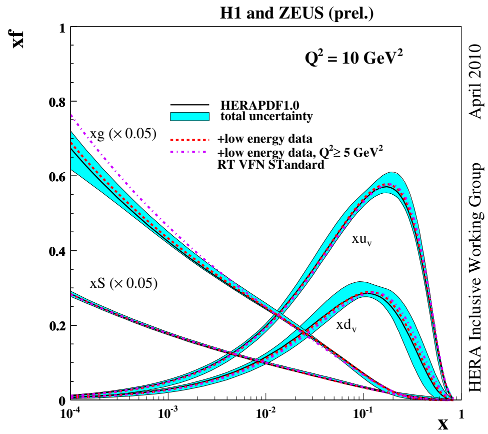
Figure 3: The parton distribution functions $xu_v, xd_v, xS = 2x(\bar{U} + \bar{D}), xg$, at $Q^2 = 10$ GeV^2, from HERA-PDF1.5f and HERAPDf1.6, both with $\alpha_S(M_Z)$ treated as a free parameter of the fit. The experimental, model and parametrisation uncertainties are shown separately. The gluon and sea distributions are scaled down by a factor 20.

value of $\alpha_s(M_Z)$ extracted from the HERAPDF1.6 fit is:

$$\alpha_S(M_Z) = 0.1202 \pm 0.0013(exp) \pm 0.0007(model/param) \pm 0.0012(had) + 0.0045/-0.0036(scale)$$

Model and parametrisation uncertainties on $\alpha_S(M_Z)$ are estimated in the same way as for the PDFs and the uncertainties on the hadronisation corrections applied to the jets are also evaluated. The scale uncertainties are estimated by varying the renormalisation and factorisation scales chosen in the jet publications by a factor of two up and down. The dominant contribution to the uncertainty comes from the jet renormalisation scale variation.

In 2007 NCe^+p data were taken at two lower values of the proton beam energy in order to determine the longitudinal structure function F_L. Some of the data sets from H1 and ZEUS have been combined and used as input to the PDF fits together with the HERA-I data. The resulting



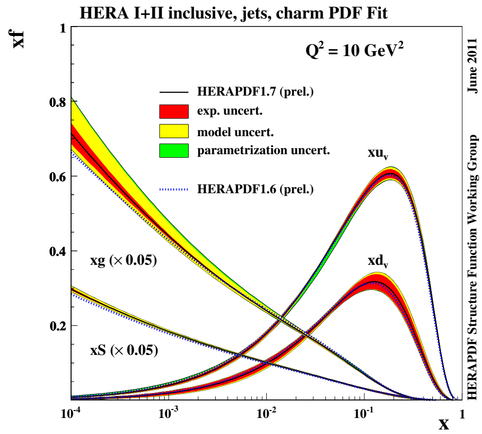


Figure 4: Left: PDFs from fit to HERA-1 data plus combined low energy data, for two values of the minimum Q^2 cut, compared to HERAPDF1.0. Right: PDFs from HERAPDF1.7, which includes charm data, jet data and low energy data as well as the HERA-I and II high energy inclusive data.

PDFs are compared with HERAPDF1.0 in Fig. 4. The low energy data are sensitive to the choice of the minimum Q^2 of data entering the fit (standard cut $Q^2 > 3.5$ GeV^2). If this cut is raised to $Q^2 > 5$ GeV^2 a steeper gluon results. This sensitivity is also seen if a x cut ($x > 0.0005$) or a saturation inspired cut $Q^2 > 0.5x^{-0.3}$ is made. However, these variations are comparable to the uncertainty at low-x which is covered by the HERAPDF1.5f flexible parametrisation. This parametrisation has been used for a fit which includes all inclusive HERA data from HERA-I and II, charm data, low energy data and jet data. For this fit the central settings of the HERAPDF1.5f(6) fits are modified such that $\alpha_S(M_Z) = 0.119$ and $m_c = 1.5$ is used together with the RT-optimized heavy quark scheme following the preferences of the jet and charm data. This fit, called HERAPDF1.7, is illustrated on the right hand side of Fig. 4

A preliminary NNLO extraction HERAPDF1.0 NNLO was presented in 2010 but this has been updated to HERAPDF1.5NNLO [7], with full accounting for experimental, model and parametrisation uncertainties, and using the extended form of the parametrisation. Fig. 5 compares the HERAPDF1.5NNLO with HERAPDF1.0 NNLO for $\alpha_s(M_Z) = 0.1176$, which is our recommended value for $\alpha_S(M_Z)$ at NNLO. The HERAPDF1.5 NNLO fit has a signficantly harder high-x gluon.

Finally the HERAPDFs have been successfully confronted with both Tevatron and LHC data on W,Z and jet production. Fig. 6 show comparisons of the HERAPDF1.5 NLO predictions to the early LHC data on the W asymmetry from CMS and comparisons of various PDFs to the ATLAS inclusive jet data.

3. Summary

The addition of new data sets to HERAPDF1.0 has given new information. The addition of inclusive data from HERA-II running, as used for the HERAPDF1.5, has improved the precision of PDFs at high x and Q^2. The addition of charm data helps to fix the charm mass and the heavy quark scheme. The addition of jet data, as used for HERAPDF1.6, yields a competitive measurement of $\alpha_s(M_Z)$. The PDF analysis has been extended from NLO to NNLO. The HERAPDF

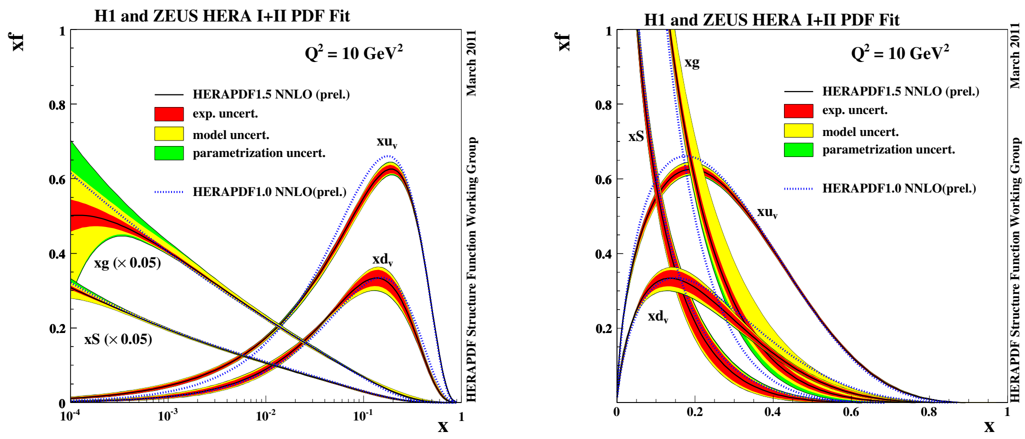


Figure 5: HERAPDF1.5NNLO PDFs compared to HERAPDF1.0NNLO PDFS on log and linear x scales.

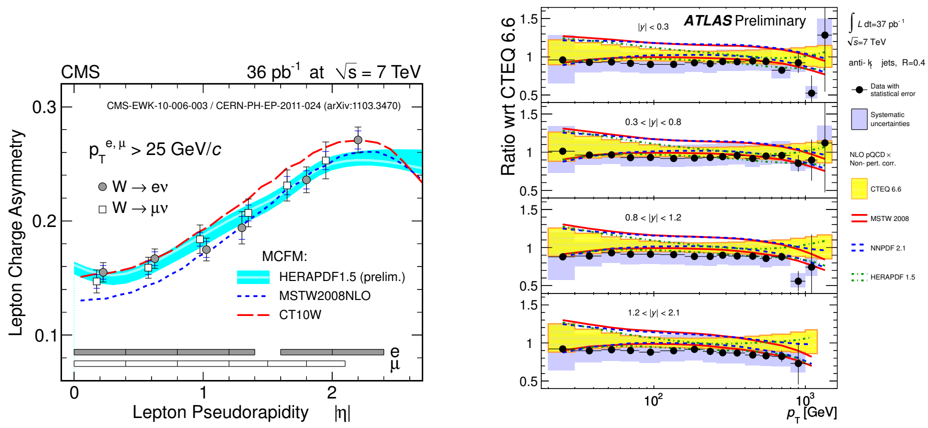


Figure 6: Left: HERAPDF1.5 predictions for LHC W-lepton asymmetry data from CMS. Right: ATLAS jet data in the central region in ratio to the predictions of CTEQ6.6 and compared to other PDF predictions.

has been successfully confronted with Tevatron and LHC data on W,Z production and jet production. The HERAPDF1.5 NLO and NNLO PDFs are available on LHAPDF (LHAPDFv6.8.6, http:projects.hepforge.org/lhapdf).

References

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