Study of HERA data at low Q^2 and low x

A M Cooper-Sarkar[*][†]

Oxford University, UK

E-mail: `amanda.sarkar@cern.ch`

In the HERAPDF2.0 PDF analysis it was noted that the fit χ^2 worsens significantly at low Q^2 for both NLO and NNLO fits. The turn over of the reduced cross section at low-x and low Q^2 due to the contribution of the longitudinal cross section F_L is also not very well described. In this paper the prediction for F_L is highlighted and the corresponding extraction of F_2 from the data is further investigated, showing discrepancies with description of HERAPDF2.0 at low x and Q^2. The effect of adding a simple higher twist term of the form $F_L * A/Q^2$ to the description of F_L is investigated. This results in a significantly better description of the reduced cross-sections, F_2 and F_L at low x, Q^2 and a significantly lower χ^2 for the NNLO fit as compared to the NLO fit. This is not the case if the higher twist term is added to F_2

---

[*]Speaker.

[†]With thanks to I Abt, B Foster, M Wing, V Myronenko, K Wichmann
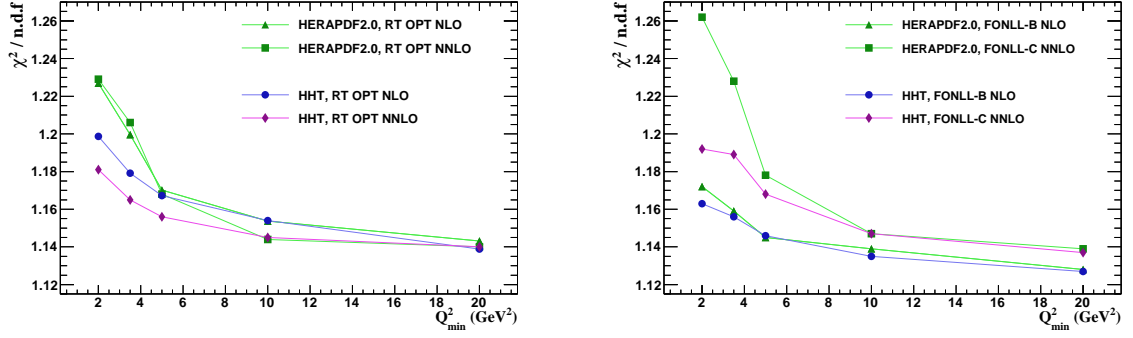
Figure 1: The χ^2 per degree of freedom vs the minimum Q^2 of data entering the HERAPDF2.0 NLO and NNLO fits and the corresponding HHT fits which include a higher twist term in F_L. Left: using the default RTOPT heavy flavour scheme. Right: using the FONLL heavy flavour scheme.

HERA data may shed light on low-x physics and the transition to the non-perturbative regime at low Q^2. Ever since the rise of F_2 at low-x was observed it has been speculated that there may be a need for QCD resummations beyond the conventional DGLAP equations, whether these be $ln(1/x)$ resummations a la BFKL or the need for non-linear evolution equations which take account of gluon recombination and the possibilty of gluon saturation. The final combined data on NC and CC e^+p and e^-p inclusive cross sections from H1 and ZEUS are now published [1]. These data were used as the input for next-to-leading order (NLO) and next-to next to leading order (NNLO) QCD PDF fits resulting in a PDF set called HERAPDF2.0. The HERAPDF2.0 analysis used the RTOPT heavy flavour scheme [4] as default and the fits described in the present contribution are done in this scheme unless otherwise stated. It has been observed that the χ^2 of the QCD fits in the DGLAP formalism is worse at low Q^2. The kinematic reach of HERA is such that low Q^2 is also low x. It has been suggested that in this kinematic region diagrams with two, three and four gluons in the t-channel could give rise to higher twist terms which contribute to the longitudinal structure function F_L while cancelling between the longitudinal and transverse components in F_2 [2]. The NC e^+p data includes data at different centre-of-mass energies such that different values of y are accessed at the same x, Q^2. This gives information on the longitudinal structure function F_L. The present contribution looks at the QCD fits concentrating on the role of the longitudinal structure function F_L. Further details are given in Ref. [3]

The dependence of the χ^2 on the Q^2 cut applied to the data was investigated in the HERA-PDF2.0 analysis, and the results are shown in Fig. 1 which shows χ^2 per degree of freedom vs the minimum Q^2_{min} of data used in the fit, for the HERAPDF2.0 NLO and NNLO QCD fits. It is interesting to see whether the situation can be improved by modification of the leading twist QCD predictions for F_L by a simple higher twist term such that $F_L(HT) = F_L * (1 + A/Q^2)$. The fits of the HERAPDF2.0 analysis are repeated using this modified F_L with A as a free parameter. All the other conditions are set as for HERAPDF2.0. These fits are called the HHT QCD fits. One can see a very significant decrease in χ^2 particularly at NNLO, such that the NNLO fit is now significantly better than the NLO fit. The values of A extracted are quite high: $A = 4.2 \pm 0.7$ GeV^2 for NLO and $A = 5.5 \pm 0.6$ GeV^2 for NNLO fits. Details of the χ^2 are given in Table. 1

| Type of fit $Q^2_{min} = 3.5\,\text{GeV}^2$	HERAPDF2.0	HHT	A_{HT}
NNLO χ^2/ndof	1363/1131	1316/1130	5.5 ± 0.6
χ^2/ndp for NCe^+p:$Q^2 > Q^2_{min}$	451/377	422/377	
χ^2/ndp for NCe^+p: $2.0\,\text{GeV}^2 < Q^2 < Q^2_{min}$	41/25	32/25	
NLO χ^2/ndof	1356/1145	1329/1145	4.2 ± 0.7
χ^2/ndp for NCe^+p:$Q^2 > Q^2_{min}$	447/377	431/377	
χ^2/ndp for NCe^+p: $2.0\,\text{GeV}^2 < Q^2 < Q^2_{min}$	46/25	46/25	

Table 1: Table of χ^2 per degree of freedom (ndof) for HERAPDF2.0 and HHT fits both with $Q^2_{min} = 3.5\,\text{GeV}^2$. Also given are the χ^2 per number of data points (ndp) for the high precision NC e^+p data at $\sqrt{s} = 318$ GeV for $Q^2 > Q^2_{min}$. The final row in each category represents the χ^2 per number of data points for predictions of the fits below the fitted region, from $Q^2 = 3.5$ to $Q^2 = 2.0$. In addition the values of the higher twist parameter A are given for the HHT fits.
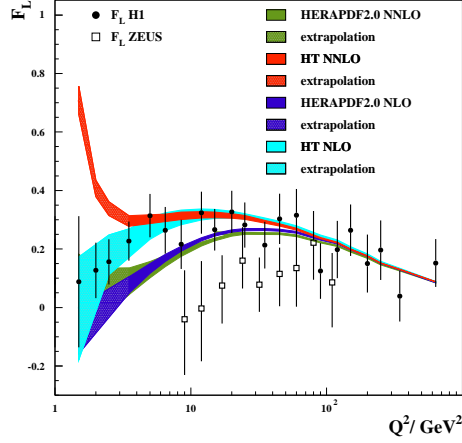

Figure 2: The separate H1 and ZEUS measurements of F_L compared to the HERAPDF2.0 NLO and NNLO QCD fit predictions and to the corresponding predictions of the HHT fits which include a modified higher twist term in F_L.

In the default RTOPT heavy flavour scheme F_L is calculated to O(α_s^2) at NLO and at O(α_s^3) at NNLO. The behaviour of the χ^2 as Q^2_{min} is raised can differ somewhat according to the heavy flavour scheme used [1]. In particular the χ^2 for low Q^2 data is lower for schemes in which F_L is calculated to O(α_s). The HERAPDF2.0 and HHT fits have also been performed in the FONLL [5] schemes B and C in which F_L is calculated respectively to O(α_s) at NLO and at O(α_s^2) at NNLO. The results are also shown in Fig. 1. The NNLO fit behaves in much the same way as the fits in the RTOPT scheme, with a much decreased χ^2 for the HHT fit. The NLO fit does not need a large higher twist term essentially because an F_L calculation at O(α_s) already produces a larger F_L. However as soon as F_L is calculated to O(α_s^2) or higher the need for a higher twist term appears.

Fig. 2 shows the HERAPDF2.0 and HHT predictions for F_L superimposed on the separate H1 and ZEUS measurements. The corresponding predictions for the reduced cross-section, $\sigma_{red} =$
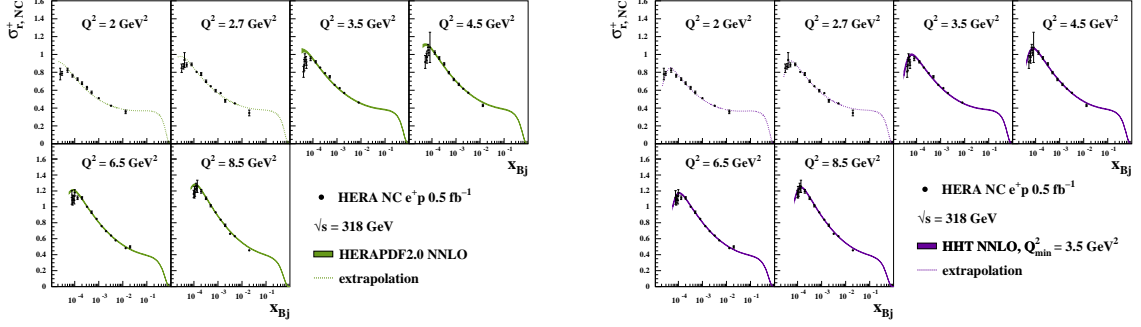
Figure 3: The combined HERA measurements of $\sigma_{reduced}$ compared to the predictions of HERAPDF2.0 NNLO(left) and the corresponding predictions of HHT NNLO(right).
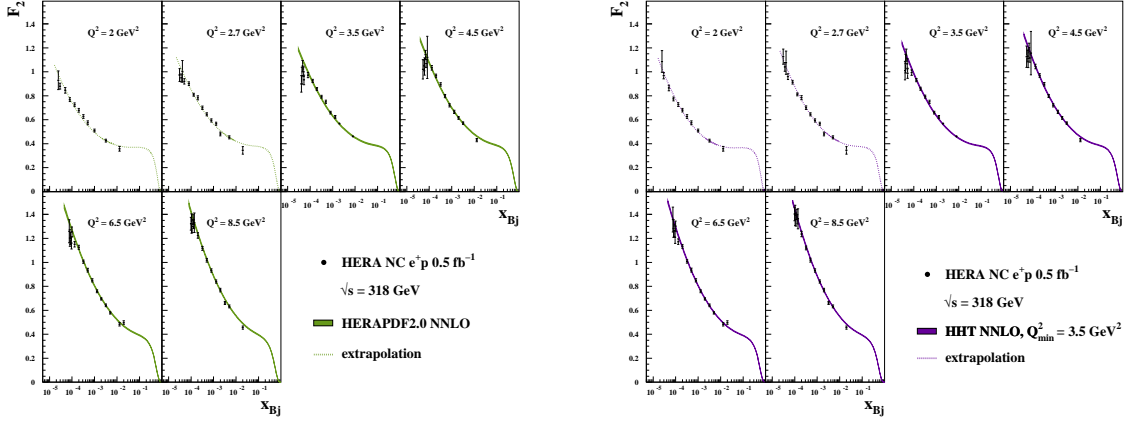
Figure 4: The combined HERA measurements of F_2 compared to the predictions of HERAPDF2.0 NNLO(left) and the corresponding predictions of HHT NNLO(right).

$F_2 - y^2/Y_+ F_L$, $Y_+ = 1 + (1 - y^2)$, for HERAPDF2.0 and HHT at NNLO are shown in Fig. 3 (NLO results are similar). A clear improvement in the description of the data is seen for the fits including higher twist. This is mostly due to the improved description of the turn-over at low x which comes from an increased F_L.

It is also interesting to look at the predictions and extracted data for F_2, see Fig. 4. Measurements of F_2 are extracted as $F_2^{extracted} = F_2^{predicted} * \sigma_{red}^{measured}/\sigma_{red}^{predicted}$. Since F_2 is a dominant part of the cross section this is a reasonable procedure, but clearly if $\sigma_{red}^{measured}$ is lower than $\sigma_{red}^{predicted}$ then $F_2^{extracted}$ will also be low and the consequence for the HERAPDF2.0 F_2 extraction is that $F_2^{extracted}$ itself starts to take a turn-over at low-x, lowQ^2 which is not in agreement with QCD predictions for F_2. However, for the HHT fit this problem is mitigated, the $F_2^{extracted}$ does not take a significant turn-over and is in much better agreement with the predictions. Note that the predictions for F_2 are very similar for the two fits since these depend only on the PDFs and not on the higher
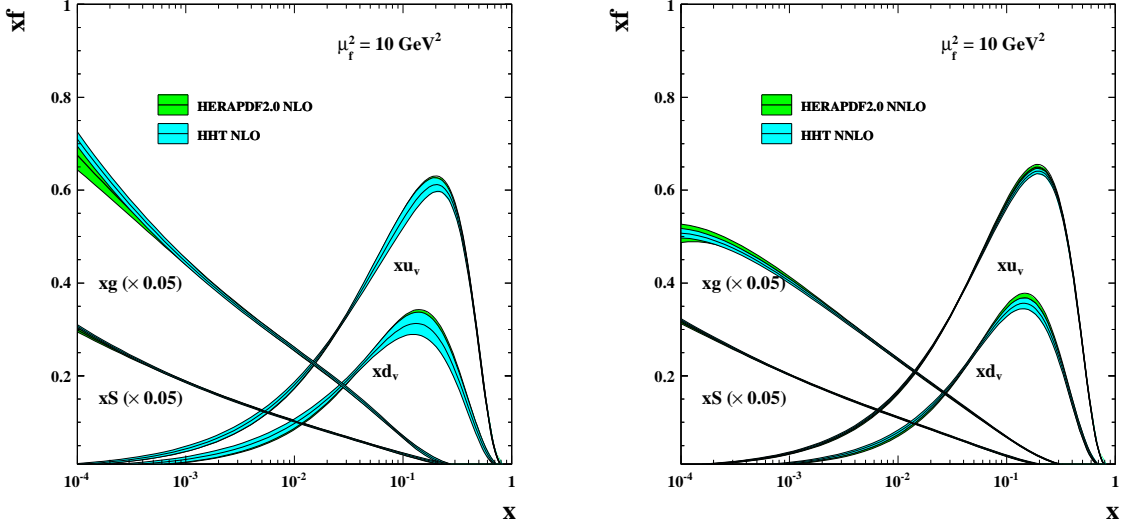
Figure 5: The PDFs resulting from the HHT fits compared to those of HERAPDF2.0 at NLO(left) and at NNLO(right). The gluon and sea distributions are scaled down by a factor of 20. Experimental uncertainties on both fits are shown

twist term. The PDFs extracted from the HHT fits are very similar to the HERAPDF2.0 PDFS as shown in Fig. 5. In particular, despite the fact that a good fit requires a larger F_L contribution at low-x and low-Q^2, the NNLO fit still requires a gluon parametrisation with a substantial negative term such that it the gluon starts to turn over at low-x and Q^2. Using an alternative parametrisation without this term (such that the gluon is always positive definite above the starting scale of evolution) results in much higher χ^2 for both the HERAPDF2.0 fit and the HHT fit.

We have also investigated the inclusion of a higher twist term in F_2 such that $F_2(HT) = F_2 * (1 + A/Q^2)$. In this case there is only a small improvement in χ^2 and the value of A is also small, consistent with zero: $A = 0.12 \pm 0.07 \text{GeV}^2$. If higher twist terms are inlcuded in both F_2 and F_L the result is similar to including the term only for F_L.

The fits shown in Figs. 3,4 were done for $Q^2 > 3.5 \text{ GeV}^2$ as for HERAPDF2.0. However it can be seen that the predictions of the HHT fit describe the data well down to $Q^2 = 2.0 \text{ GeV}^2$. Thus new HHT fits were performed with Q^2_{min}=2.0 GeV^2. The details of the χ^2 are given in Table. 2

The fit quality for the data points in the range $2.0 < Q^2 < 3.5 \text{ GeV}^2$ improves somewhat particularly at NLO. However the fitted parameters are much the same as for the fit with $Q^2_{min} = 3.5 \text{ GeV}^2$. In particular the extracted values of the higher twist parameter A are almost the same. Looking at the predictions for σ_{red} for even lower Q^2 values, see Fig. 6, shows that the description is apparently good even down to $Q^2 = 1.2 \text{ GeV}^2$. However if we look at the corresponding predictions for F_L, see Fig. 2, it is evident that this simple description is not tenable for $Q^2 <\sim 2.0 \text{ GeV}^2$.

In summary, the introduction of a higher twist term in the description of the longitudinal structure function F_L, in the context of pQCD fits within the DGLAP formalism, significantly improves the description of HERA data on deep inelastic scattering at low x and low Q^2 down to $Q^2 <\sim 2.0 \text{ GeV}^2$. The introduction of a similar term in the structure function F_2 is unnecessary

Type of fit $Q^2_{min} = 2.0 \text{GeV}^2$	HERAPDF2.0	HHT	A_{HT}
NNLO χ^2/ndof	1437/1171	1381/1170	5.2 ± 0.7
χ^2/ndp for NCe^+p:$Q^2 > Q^2_{min}$	486/402	457/402	
χ^2/ndp for NCe^+p: $2.0 \text{GeV}^2 < Q^2 < Q^2_{min}$	31/25	26/25	
NLO χ^2/ndof	1433/1171	1398/1170	4.0 ± 0.6
χ^2/ndp for NCe^+p:$Q^2 > Q^2_{min}$	487/402	466/402	
χ^2/ndp for NCe^+p: $Q^2 > Q^2_{min} < Q^2 < 2.0 \text{GeV}^2$	40/25	31/25	

Table 2: Table of χ^2 per degree of freedom (ndof) for HERAPDF2.0 and HHT fits both with $Q^2_{min} = 2.0$ GeV^2. Also given are the χ^2 per number of data points (ndp) for the high precision NC e^+p data at $\sqrt{s} = 318$ GeV for $Q^2 > Q^2_{min}$. The final row in each category represents the χ^2 per number of data points for predictions of the fits from $Q^2 = 3.5$ to $Q^2 = 2.0$. In addition the values of the higher twist parameter A are given for the HHT fits.
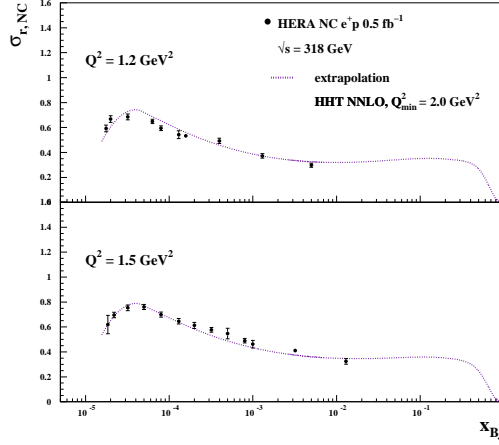
Figure 6: The predictions of the HHT fit done for $Q^2_{min} = 2.0 \text{GeV}^2$, for lower Q^2 data.

confirming the expectation that higher twist terms cancel between the longitudinally and transversely polarised photons in F_2. However further mechanisms are necessary to describe data for $Q^2 < \sim 2.0$ GeV^2.

References

[1] H. Abramowicz et al, Eur. Phys. J75(2015)580 , arXiV:1506.06042

[2] J. Bartels, K. Golec-Biernat and H. Kowalski, Phys Rev D66(2002)14001,

[3] I. Abt et al, arXiV:1603.02299.

[4] R .S .Thorne and R. G. Roberts, Phys.ReV.D57(1998)6871; R.S.Thorne, Phys.Rev.D73(2006)054019; R.S. Thorne, Phys.Rev.D86(2012)074017

[5] S. Forte et al, Nucl.Phys.B834(2010)116