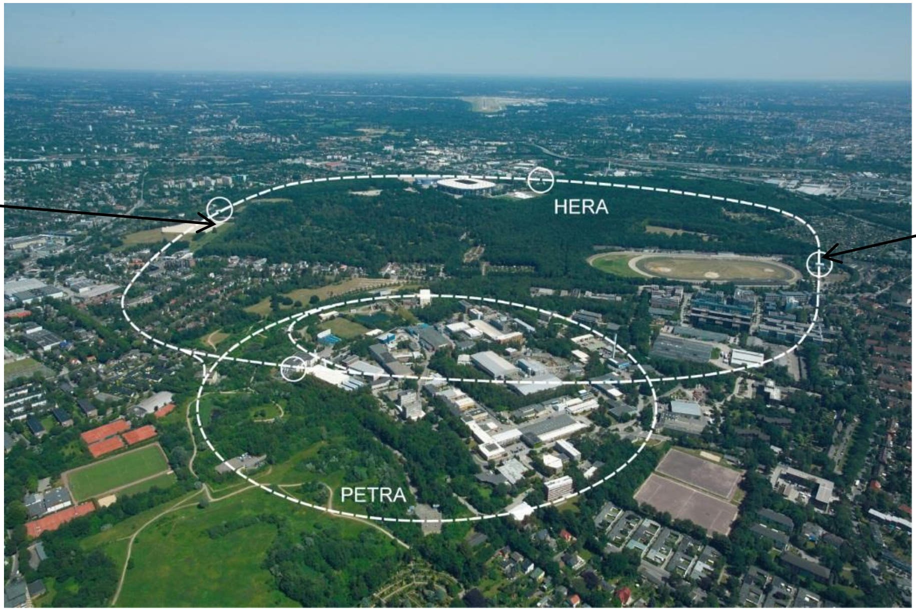


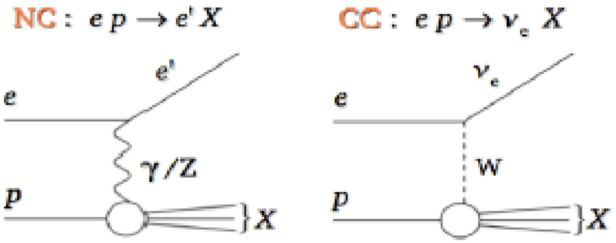
Electroweak effects at HERA using polarised data
arXIV:1604.05083

AM Cooper-Sarkar, Oxford

Low-x 2016

(I Abt, AMCS, B Foster, C Gwenlan, V myronenko, O Turkot, K Wichmann)

Deep Inelastic Scattering (DIS) is the best tool to probe proton structure



- Kinematic variables:

$$Q^2 = -q^2 = -(k - k')^2$$

Virtuality of the exchanged boson

$$x = \frac{Q^2}{2p \cdot q}$$ Bjorken scaling parameter

$$y = \frac{p \cdot q}{p \cdot k}$$ Inelasticity parameter

$$s = (k + p)^2 = \frac{Q^2}{xy}$$ Invariant c.m.

Neutral current: NC

$$\frac{d^2\sigma^{\pm}_{NC}}{dx dQ^2} = \frac{2\alpha\pi^2}{xQ^4}\left(Y_+ F_2 \mp Y_- xF_3 - y^2 F_L\right)$$

$$F_2 \propto \sum_i e_i^2 (xq_i + x\bar{q}_i)$$ quark distributions

$$xF_3 \propto \sum_i (xq_i - x\bar{q}_i)$$ valence quarks

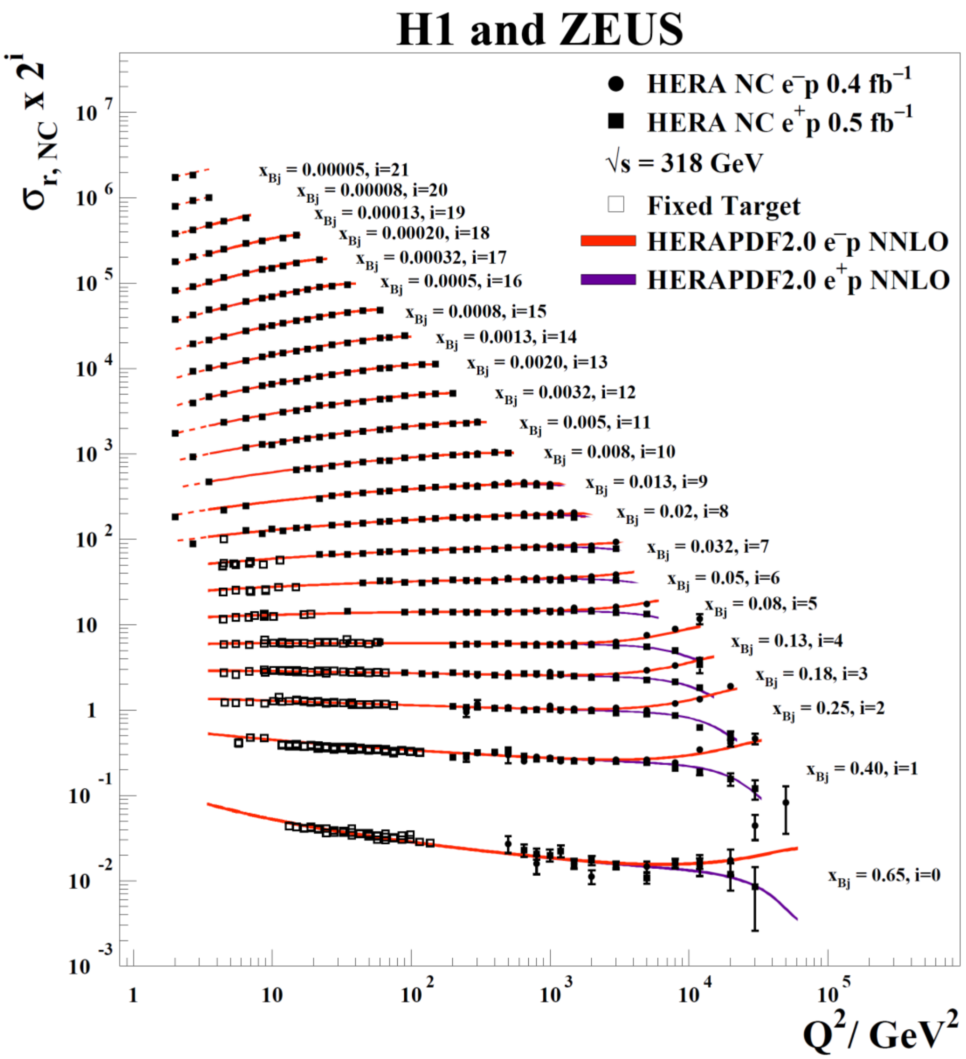
$$F_L \propto \alpha_s \times g$$ gluon at NLO

Charged current: CC

$$\frac{d^2\sigma^{-}_{CC}}{dx dQ^2} = \frac{G_F^2}{2\pi}\frac{M_W^2}{M_W^2 + Q^2}\left(u + c + (1 - y^2)(\bar{d} + \bar{s})\right)$$

$$\frac{d^2\sigma^{-}_{CC}}{dx dQ^2} = \frac{G_F^2}{2\pi}\frac{M_W^2}{M_W^2 + Q^2}\left(\bar{u} + \bar{c} + (1 - y^2)(d + s)\right)$$

flavour decomposition



LO expressions for illustration of the main dependencies on parton distribution functions (PDFs)

Final inclusive data from all HERA running

~500pb^{-1} per experiment split ~equally between e^{+} and e^{-} beams: DESY-15-039

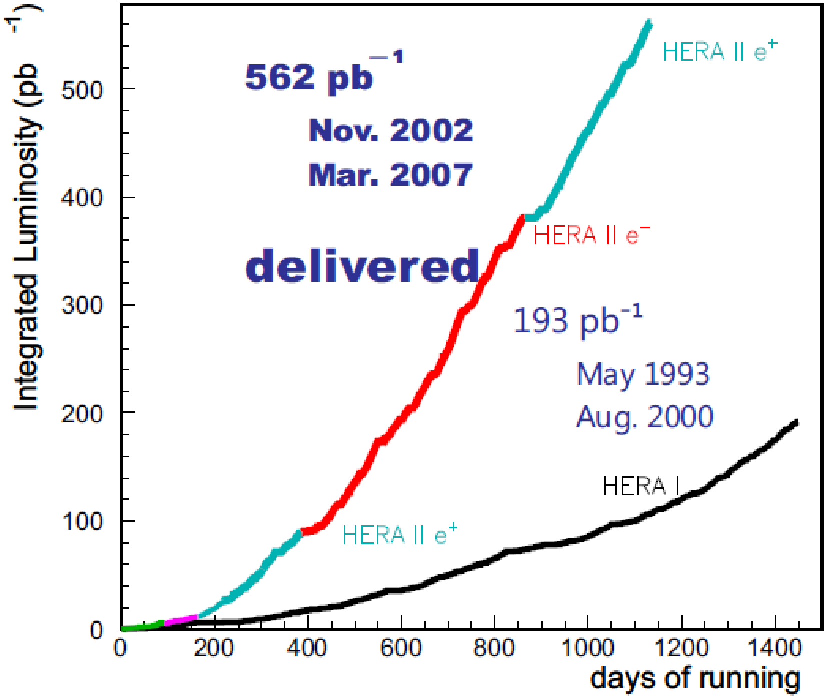
10 fold increase in e^{-} compared to HERA-I

Running at Ep = 920, 820, 575, 460 GeV

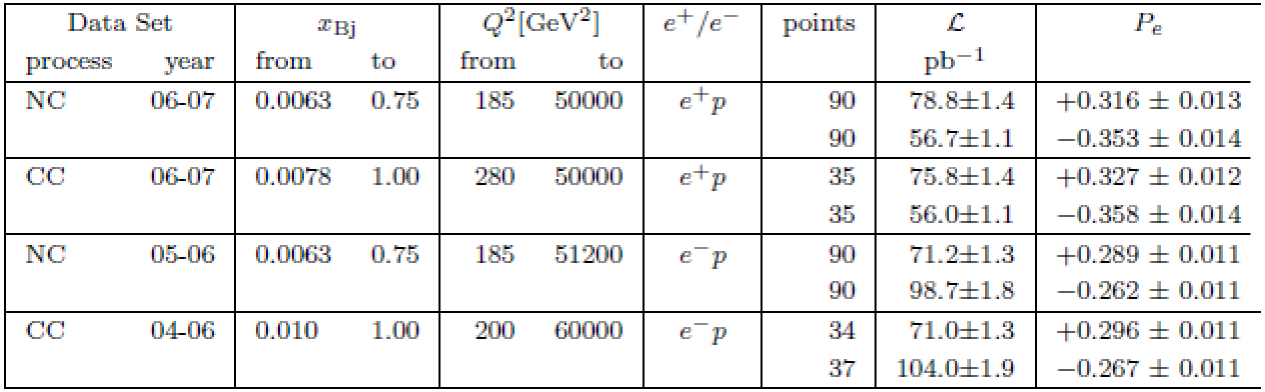
$\sqrt{s}$ = 320, 300, 251, 225 GeV

$0.045 < Q^2 < 50000$ GeV^2 $6.\ 10^{-7} < x_{Bj} < 0.65$

The HERA-II data had polarised electron beams about 300pb^{-1} per experiment
With polarisations of the order of 25-35% ranging roughly equal between left-handed and right-handed

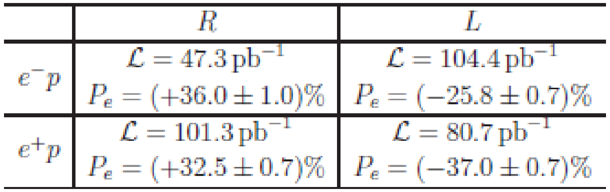


ZEUS



Data Set process	year	x_{Bj} from	to	Q^2[GeV^2] from	to	e^+/e^-	points	$\mathcal{L}$ pb^{-1}	P_e
NC	06-07	0.0063	0.75	185	50000	e^+p	90	78.8±1.4	$+0.316 \pm 0.013$
							90	56.7±1.1	-0.353 ± 0.014
CC	06-07	0.0078	1.00	280	50000	e^+p	35	75.8±1.4	$+0.327 \pm 0.012$
							35	56.0±1.1	-0.358 ± 0.014
NC	05-06	0.0063	0.75	185	51200	e^-p	90	71.2±1.3	$+0.289 \pm 0.011$
							90	98.7±1.8	-0.262 ± 0.011
CC	04-06	0.010	1.00	200	60000	e^-p	34	71.0±1.3	$+0.296 \pm 0.011$
							37	104.0±1.9	-0.267 ± 0.011

H1



	R	L
e^-p	$\mathcal{L} = 47.3\,\mathrm{pb}^{-1}$ $P_e = (+36.0 \pm 1.0)\%$	$\mathcal{L} = 104.4\,\mathrm{pb}^{-1}$ $P_e = (-25.8 \pm 0.7)\%$
e^+p	$\mathcal{L} = 101.3\,\mathrm{pb}^{-1}$ $P_e = (+32.5 \pm 0.7)\%$	$\mathcal{L} = 80.7\,\mathrm{pb}^{-1}$ $P_e = (-37.0 \pm 0.7)\%$

The neutral current NC cross sections are given by

$$\sigma_{r,\mathrm{NC}}^{e^\pm p} = \frac{x_{\mathrm{Bj}} Q^4}{2\pi\alpha_0^2} \frac{1}{Y_+} \frac{d^2\sigma(e^\pm p)}{dx_{\mathrm{Bj}} dQ^2} = \tilde{F}_2(x_{\mathrm{Bj}}, Q^2) \mp \frac{Y_-}{Y_+} x\tilde{F}_3(x_{\mathrm{Bj}}, Q^2) - \frac{y^2}{Y_+} F_L(x_{\mathrm{Bj}}, Q^2). \qquad (2)$$

In this expression the structure functions can be separated into contributions from γ exchange, Z exchange and γ/Z interference

$$\tilde{F}_2^{\pm} = F_2^{\gamma} - (v_e \pm P_e a_e)\chi_Z F_2^{\gamma Z} + (v_e^2 + a_e^2 \pm 2P_e v_e a_e)\chi_Z^2 F_2^Z,$$

$$x\tilde{F}_3^{\pm} = -(a_e \pm P_e v_e)\chi_Z x F_3^{\gamma Z} + (2v_e a_e \pm P_e(v_e^2 + a_e^2))\chi_Z^2 x F_3^Z \ ,$$

$$v_e = -1/2 + 2\sin^2\theta_W \qquad a_e = -1/2.$$

$$\chi_Z = \frac{1}{\sin^2 2\theta_W} \frac{Q^2}{M_Z^2 + Q^2} \frac{1}{1 - \Delta R}$$

Where ΔR accounts for radiative corrections using the EPRC program of Spiesberger

The on-shell definition of $\sin^2\theta_W = 1 - M_W^2/M_Z^2$ was chosen for the analysis =0.22333

$$[F_2^{\gamma}, F_2^{\gamma Z}, F_2^Z] = \sum_q [e_q^2, 2e_q v_q, v_q^2 + a_q^2] x(q + \bar{q}),$$

$$[xF_3^{\gamma Z}, xF_3^Z] = \sum [e_q a_q, v_q a_q] 2x(q - \bar{q}),$$

The structure functions are given in terms of EW couplings to the parton densities v_u,a_d,v_u,v_d (LO expression)

$$v_u = 1/2 - 4/3\sin^2\theta_W,\ a_u = 1/2$$

$$v_d = -1/2 + 2/3\sin^2\theta_W,\ a_d = -1/2.$$

Quark couplings to Z

Decompose the NC cross sections into polarised and unpolarised pieces. Cross sections are related to parton distribution functions PDFs and electroweak parameters

The total cross-section : $\sigma = \sigma^0 + P\,\sigma^P$

The unpolarised cross-section is given by $\sigma^0 = Y_+ F_2^0 + Y_- xF_3^0$

LO expressions for illustration

$$F_2^0 = \Sigma_i\, A_i^0(Q^2)\,[xq_i(x,Q^2) + x\overline{q_i}(x,Q^2)]$$

$$xF_3^0 = \Sigma_i\, B_i^0(Q^2)\,[xq_i(x,Q^2) - x\overline{q_i}(x,Q^2)]$$

$$A_i^0(Q^2) = e_i^2 - 2\, e_i\, \mathbf{v_i}\, \mathbf{v_e}\, \chi_Z + (v_e^2+a_e^2)(\mathbf{v_i}^2+\mathbf{a_i}^2)\, \chi_Z^2$$

$$B_i^0(Q^2) = \quad - 2\, e_i\, \mathbf{a_i}\, a_e\, \chi_Z + 4\mathbf{a_i}\, a_e\, \mathbf{v_i}\, v_e\, \chi_Z^2$$

SM values

$$v_u = 1/2 - 4/3\sin^2\theta_W\,,\ a_u = 1/2$$

$$v_d = -1/2 + 2/3\sin^2\theta_W\,,\ a_d = -1/2.$$

The polarised cross-section is given by $\sigma^P = Y_+ F_2^P + Y_- xF_3^P$

$$F_2^P = \Sigma_i\, A_i^P(Q^2)\,[xq_i(x,Q^2) + x\overline{q_i}(x,Q^2)]$$

$$xF_3^P = \Sigma_i\, B_i^P(Q^2)\,[xq_i(x,Q^2) - x\overline{q_i}(x,Q^2)]$$

$$A_i^P(Q2) = \quad 2\, e_i\, \mathbf{v_i}\, a_e\, \chi_Z - 2\, v_e\, a_e\, (\mathbf{v_i}^2+\mathbf{a_i}^2)\, \chi_Z^2$$

$$B_i^P(Q2) = \quad 2\, e_i\, \mathbf{a_i}\, \mathbf{v_e}\, \chi_Z - 2\, \mathbf{a_i}\, \mathbf{v_i}\, (v_e^2+a_e^2)\, \chi_Z^2$$

$\chi_Z \gg \chi_Z^2$ (γZ interference is dominant)
$\mathbf{v_e}$ is very small (~0.04).

→

unpolarized $xF_3 \rightarrow a_i$,
polarized $F_2 \rightarrow v_i$

A simultaneous NLO QCD and LO EW fit of PDF parameters and electroweak parameters is performed in order to assess the uncertainty on the EW determinations due to uncertainty on PDFs.

The QCD part of the analysis follows the framework of the HERAPDF2.0, including the form of the χ2 and the accounting for correlated experimental uncertainties

$$\begin{aligned} xg(x) &= A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g}, \\ xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1+E_{u_v}x^2\right), \\ xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}, \\ x\bar{U}(x) &= A_{\bar{U}} x^{B}(1-x)^{C_{\bar{U}}}, \\ x\bar{D}(x) &= A_{\bar{D}} x^{B}(1-x)^{C_{\bar{D}}}, \end{aligned}$$

The central parametrisation is given here but Model uncertainties due to variation of:
Q^2_{min}, m_c,m_b,f_s
Parametrisation uncertainties due to variation of Q^2_0 and addition of extra parameters in the multiplying polynomial $(1 + Dx + Ex^2)$

The EW part of the analysis replaces the SM expressions for the NC coupling parameters with free parameters a_u, a_d, v_u, v_d

The charged current cross sections are also used to determine the PDFs

$$\frac{d^2\sigma_{CC}(e^+p)}{dx_{Bj}dQ^2} = (1+P_e)\frac{G_F^2 M_W^4}{2\pi x_{Bj}(Q^2+M_W^2)^2}\, x\left[(\bar{u}+\bar{c}) + (1-y)^2(d+s+b)\right],$$

$$\frac{d^2\sigma_{CC}(e^-p)}{dx_{Bj}dQ^2} = (1-P_e)\frac{G_F^2 M_W^4}{2\pi x_{Bj}(Q^2+M_W^2)^2}\, x\left[(u+c) + (1-y)^2(\bar{d}+\bar{s}+\bar{b})\right].$$

LO expressions for illustration

These cross sections also contribute to the determination of M_w and $\sin^2\theta_W$ through the propagator AND

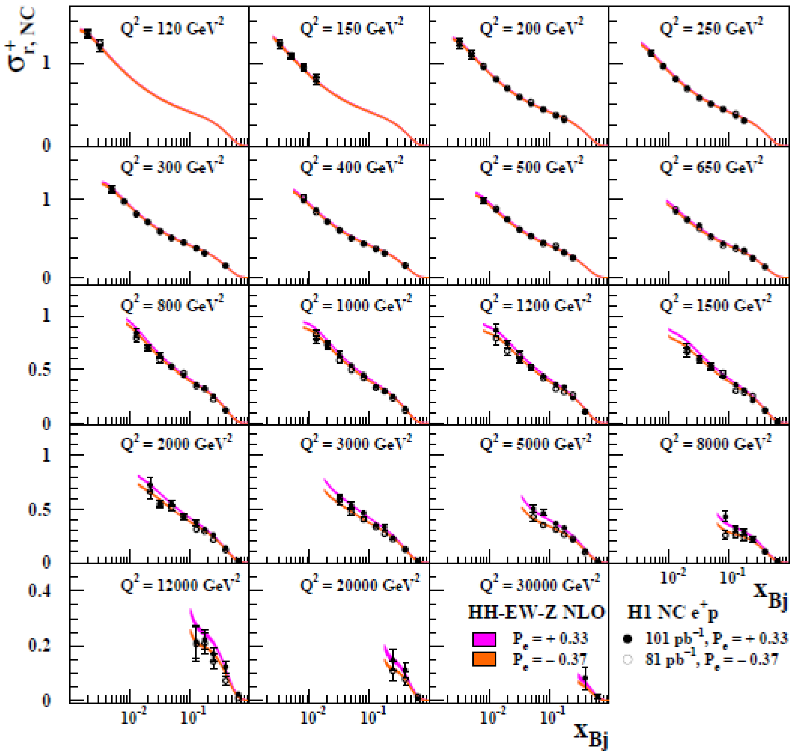
$$G_F = \frac{\pi\alpha_0}{\sqrt{2}\sin^2\theta_W M_W^2}\frac{1}{1-\Delta R}$$

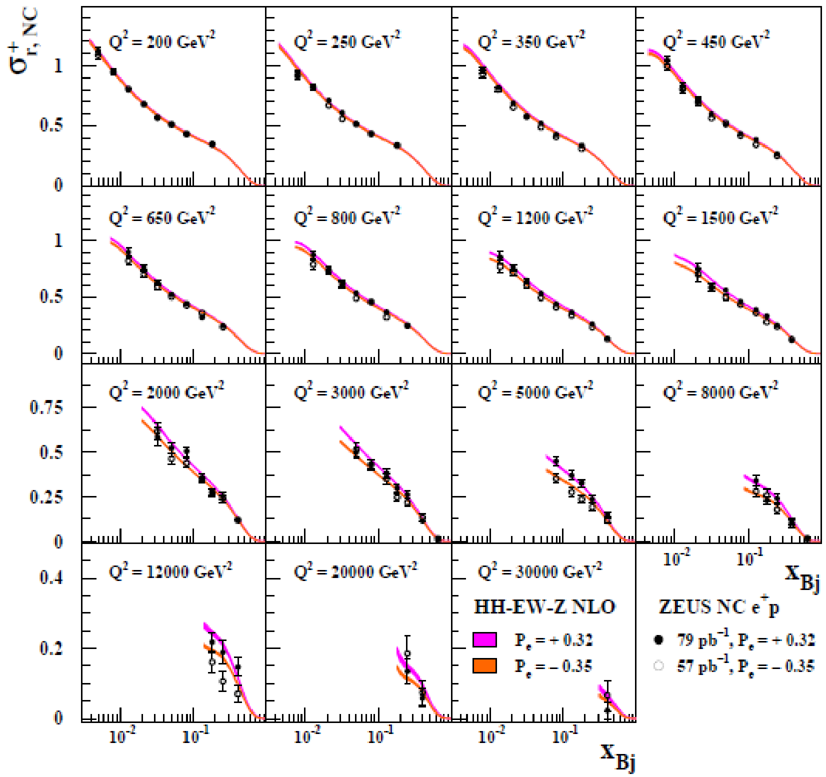
See talk of K Wichmann

A simultaneous QCD and EW fit- called HHEW- was done to the HERA inclusive $e^+ p$ and $e^- p$ NC and CC cross sections for the PDF parameters and the NC electroweak couplings. H1 and ZEUS data are used uncombined.

The polarised data for H1 are used as published. The polarised data of ZEUS have updated polarisations as published in the ZEUS-EW analysis.

Extra uncertainties were added to the ZEUS uncorrelated systematics to account for uncertainties on EW corrections, equivalent to uncertainties already considered by H1

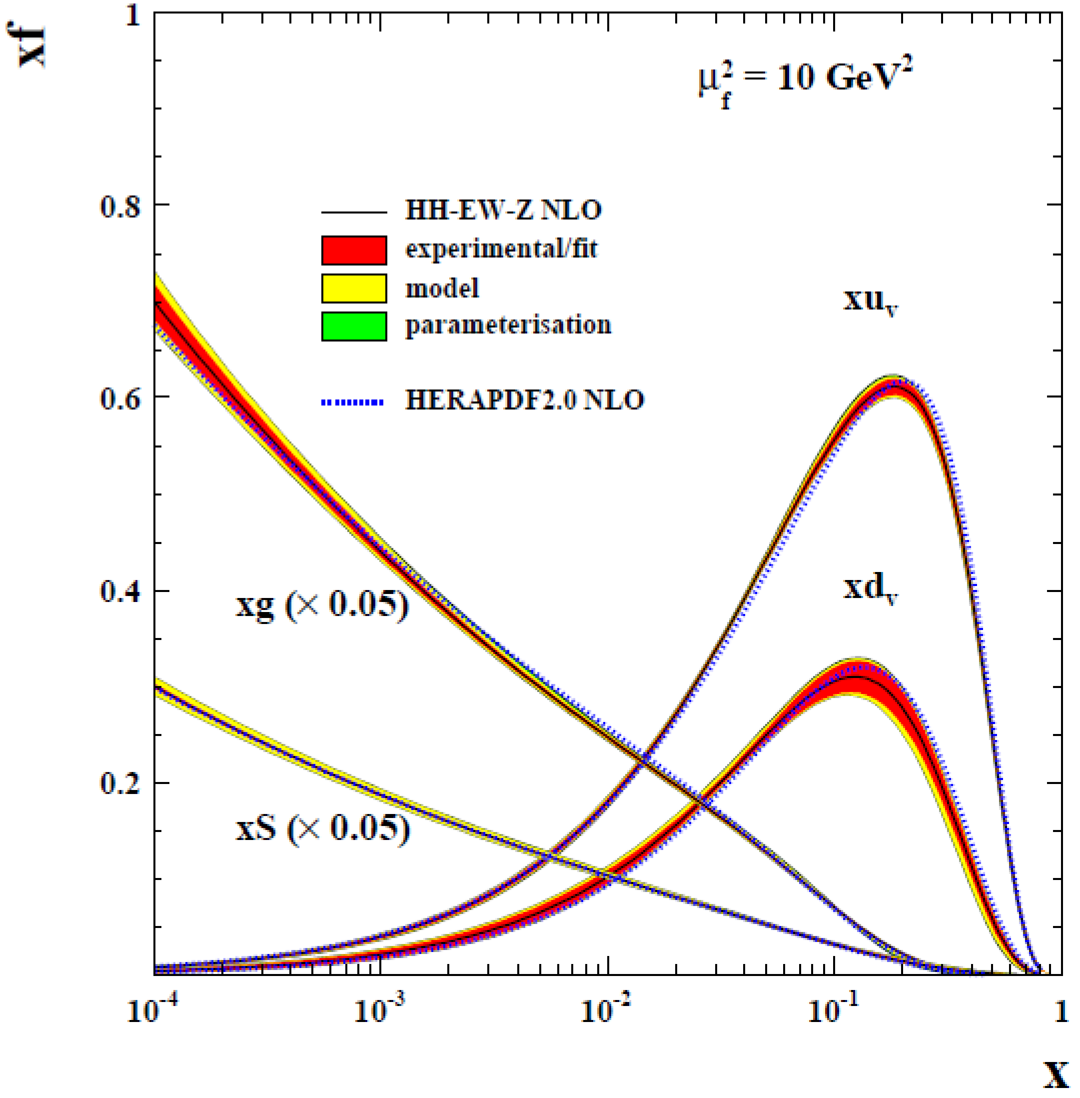




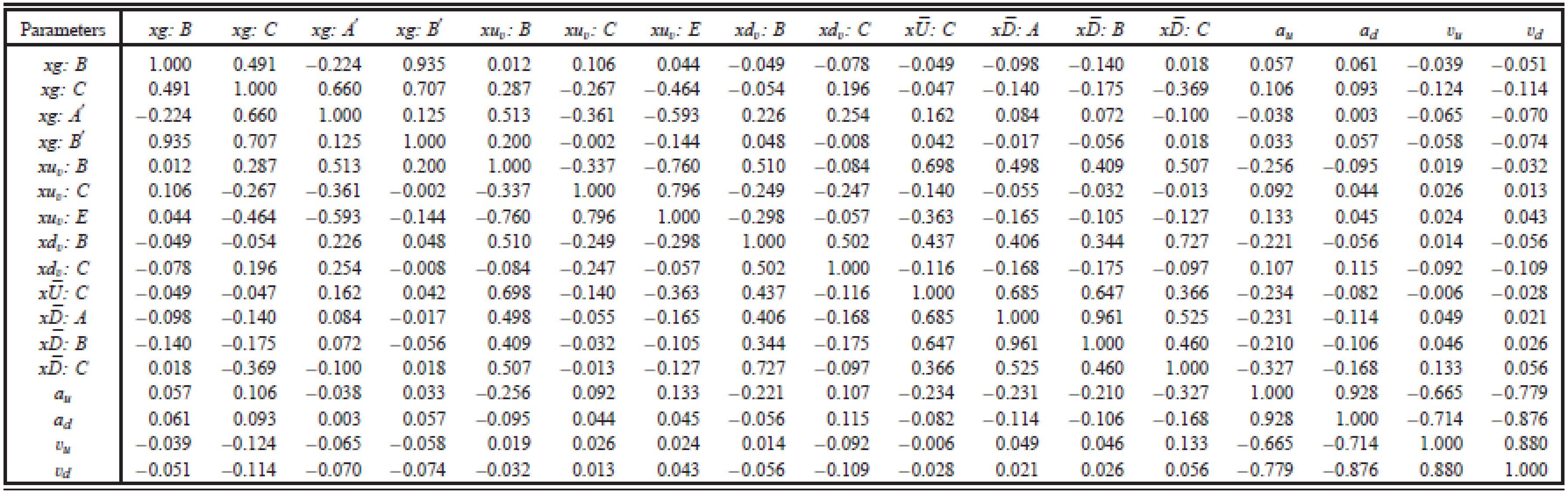
The description of the data is illustrated here for the NC e^+ data for ZEUS and H1

The χ2/ndf = 3556/3231 =1.10

The PDFs are similar to those of HERAPDF2.0



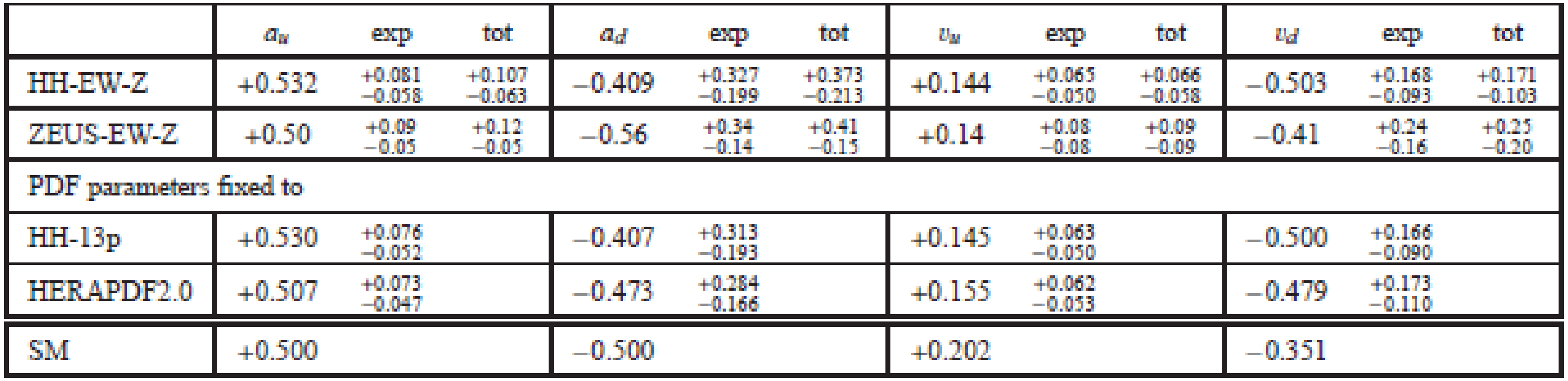
The correlations of the PDF parameters and the electroweak parameters are weak



Parameters	xg: B	xg: C	xg: A'	xg: B'	xu_v: B	xu_v: C	xu_v: E	xd_v: B	xd_v: C	$x\bar{U}$: C	$x\bar{D}$: A	$x\bar{D}$: B	$x\bar{D}$: C	a_u	a_d	v_u	v_d
xg: B	1.000	0.491	−0.224	0.935	0.012	0.106	0.044	−0.049	−0.078	−0.049	−0.098	−0.140	0.018	0.057	0.061	−0.039	−0.051
xg: C	0.491	1.000	0.660	0.707	0.287	−0.267	−0.464	−0.054	0.196	−0.047	−0.140	−0.175	−0.369	0.106	0.093	−0.124	−0.114
xg: A'	−0.224	0.660	1.000	0.125	0.513	−0.361	−0.593	0.226	0.254	0.162	0.084	0.072	−0.100	−0.038	0.003	−0.065	−0.070
xg: B'	0.935	0.707	0.125	1.000	0.200	−0.002	−0.144	0.048	−0.008	0.042	−0.017	−0.056	0.018	0.033	0.057	−0.058	−0.074
xu_v: B	0.012	0.287	0.513	0.200	1.000	−0.337	−0.760	0.510	−0.084	0.698	0.498	0.409	0.507	−0.256	−0.095	0.019	−0.032
xu_v: C	0.106	−0.267	−0.361	−0.002	−0.337	1.000	0.796	−0.249	−0.247	−0.140	−0.055	−0.032	−0.013	0.092	0.044	0.026	0.013
xu_v: E	0.044	−0.464	−0.593	−0.144	−0.760	0.796	1.000	−0.298	−0.057	−0.363	−0.165	−0.105	−0.127	0.133	0.045	0.024	0.043
xd_v: B	−0.049	−0.054	0.226	0.048	0.510	−0.249	−0.298	1.000	0.502	0.437	0.406	0.344	0.727	−0.221	−0.056	0.014	−0.056
xd_v: C	−0.078	0.196	0.254	−0.008	−0.084	−0.247	−0.057	0.502	1.000	−0.116	−0.168	−0.175	−0.097	0.107	0.115	−0.092	−0.109
$x\bar{U}$: C	−0.049	−0.047	0.162	0.042	0.698	−0.140	−0.363	0.437	−0.116	1.000	0.685	0.647	0.366	−0.234	−0.082	−0.006	−0.028
$x\bar{D}$: A	−0.098	−0.140	0.084	−0.017	0.498	−0.055	−0.165	0.406	−0.168	0.685	1.000	0.961	0.525	−0.231	−0.114	0.049	0.021
$x\bar{D}$: B	−0.140	−0.175	0.072	−0.056	0.409	−0.032	−0.105	0.344	−0.175	0.647	0.961	1.000	0.460	−0.210	−0.106	0.046	0.026
$x\bar{D}$: C	0.018	−0.369	−0.100	0.018	0.507	−0.013	−0.127	0.727	−0.097	0.366	0.525	0.460	1.000	−0.327	−0.168	0.133	0.056
a_u	0.057	0.106	−0.038	0.033	−0.256	0.092	0.133	−0.221	0.107	−0.234	−0.231	−0.210	−0.327	1.000	0.928	−0.665	−0.779
a_d	0.061	0.093	0.003	0.057	−0.095	0.044	0.045	−0.056	0.115	−0.082	−0.114	−0.106	−0.168	0.928	1.000	−0.714	−0.876
v_u	−0.039	−0.124	−0.065	−0.058	0.019	0.026	0.024	0.014	−0.092	−0.006	0.049	0.046	0.133	−0.665	−0.714	1.000	0.880
v_d	−0.051	−0.114	−0.070	−0.074	−0.032	0.013	0.043	−0.056	−0.109	−0.028	0.021	0.026	0.056	−0.779	−0.876	0.880	1.000

Table 1: The correlation matrix of all parameters of the HH-EW-Z fit.

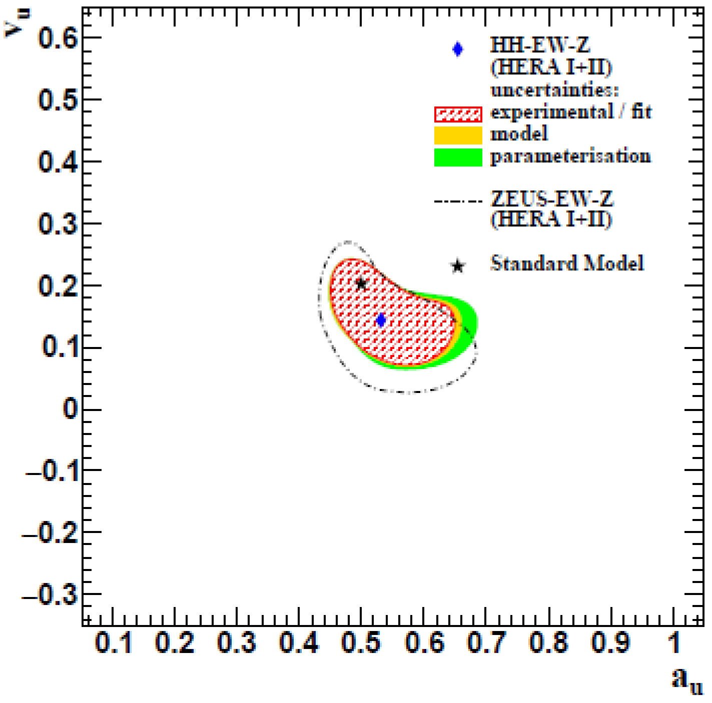
The electroweak parameters are given here and compared to ZEUS-EW-Z (see talk of K Wichmann) and to fits with fixed PDFs, both HERAPDF2.0 and a dedicated PDF fit to the HH-EW data HH-13p

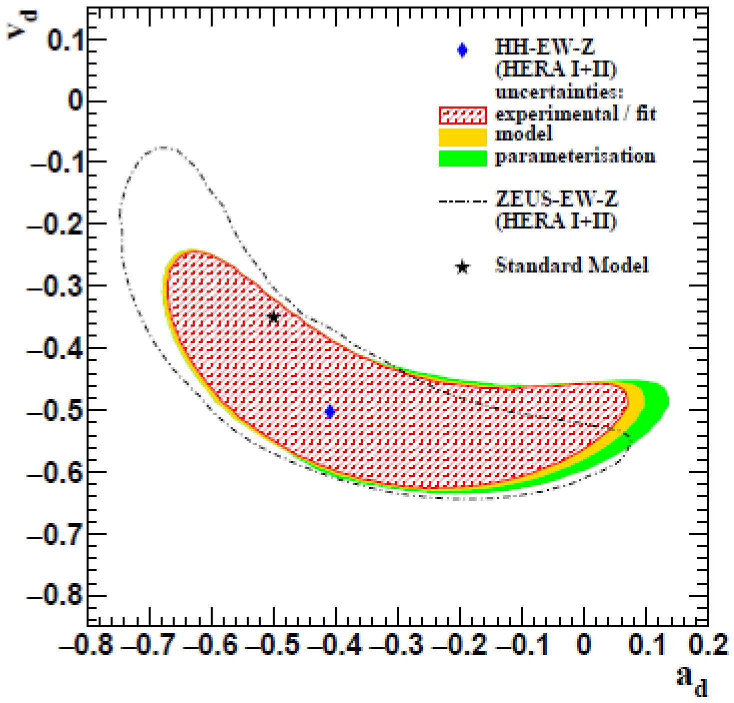


	a_u	exp	tot	a_d	exp	tot	v_u	exp	tot	v_d	exp	tot
HH-EW-Z	$+0.532$	$^{+0.081}_{-0.058}$	$^{+0.107}_{-0.063}$	-0.409	$^{+0.327}_{-0.199}$	$^{+0.373}_{-0.213}$	$+0.144$	$^{+0.065}_{-0.050}$	$^{+0.066}_{-0.058}$	-0.503	$^{+0.168}_{-0.093}$	$^{+0.171}_{-0.103}$
ZEUS-EW-Z	$+0.50$	$^{+0.09}_{-0.05}$	$^{+0.12}_{-0.05}$	-0.56	$^{+0.34}_{-0.14}$	$^{+0.41}_{-0.15}$	$+0.14$	$^{+0.08}_{-0.08}$	$^{+0.09}_{-0.09}$	-0.41	$^{+0.24}_{-0.16}$	$^{+0.25}_{-0.20}$
PDF parameters fixed to												
HH-13p	$+0.530$	$^{+0.076}_{-0.052}$		-0.407	$^{+0.313}_{-0.193}$		$+0.145$	$^{+0.063}_{-0.050}$		-0.500	$^{+0.166}_{-0.090}$	
HERAPDF2.0	$+0.507$	$^{+0.073}_{-0.047}$		-0.473	$^{+0.284}_{-0.166}$		$+0.155$	$^{+0.062}_{-0.053}$		-0.479	$^{+0.173}_{-0.110}$	
SM	$+0.500$			-0.500			$+0.202$			-0.351		

The model and parametrization uncertainties are evaluated as well as the experimental uncertainties from the central fit and these are included in the total uncertainties.

The uncertainties are asymmetric. Two dimensional scans were performed to obtain profile likelihood contours at 68%CL. At each point of the scan the χ2 is minimised wrt the other parameters.





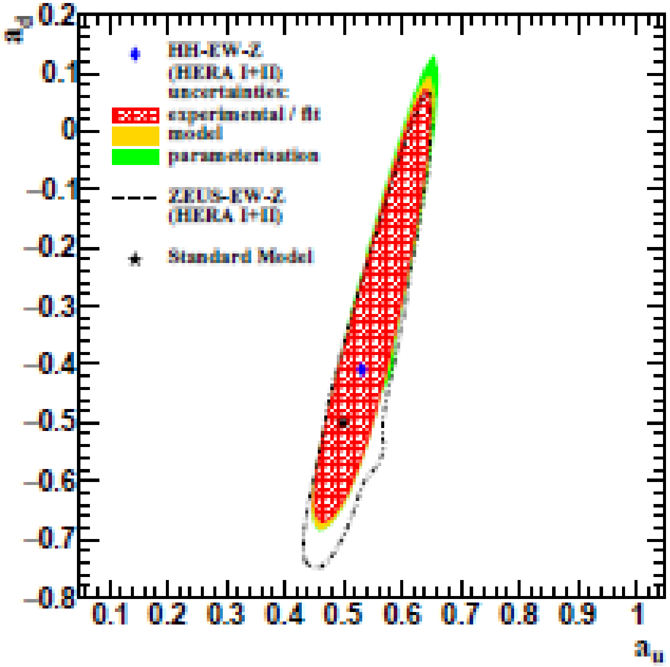
The results of the two dimensional scans are shown here, together with slightly extended contours for variation of model and parametrisation assumptions

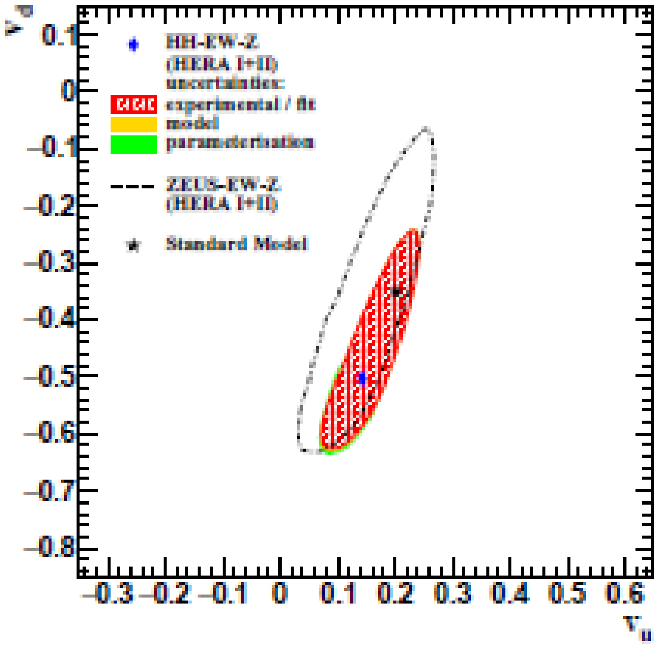
The improvement from using ALL HERA polarised data compared to using just ZEUS polarised data is also illustrated.

It is the uncertainties on v_u and v_d which have reduced, as expected since there is more information from polarisation in a fit to both ZEUS and H1 polarised data

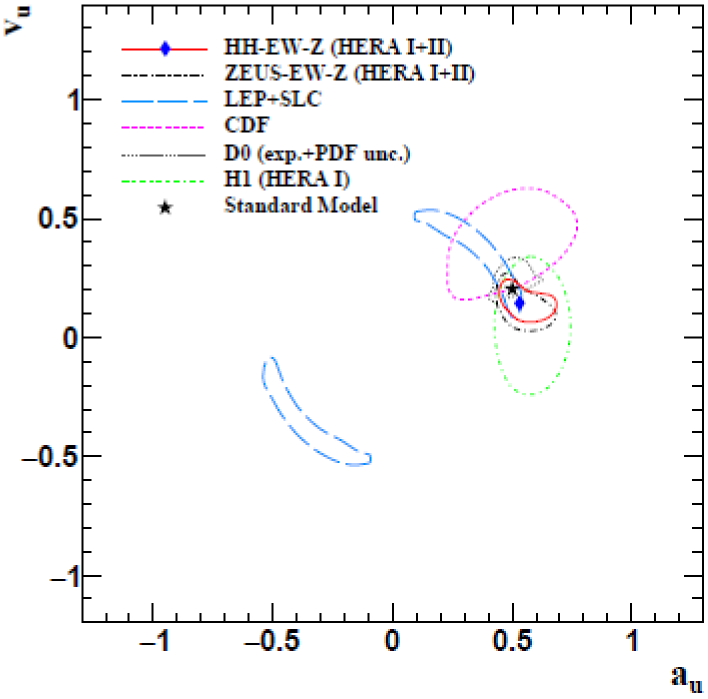
Central values have also shifted somewhat- see talk of K Wichmann on separate ZEUS and H1 analyses

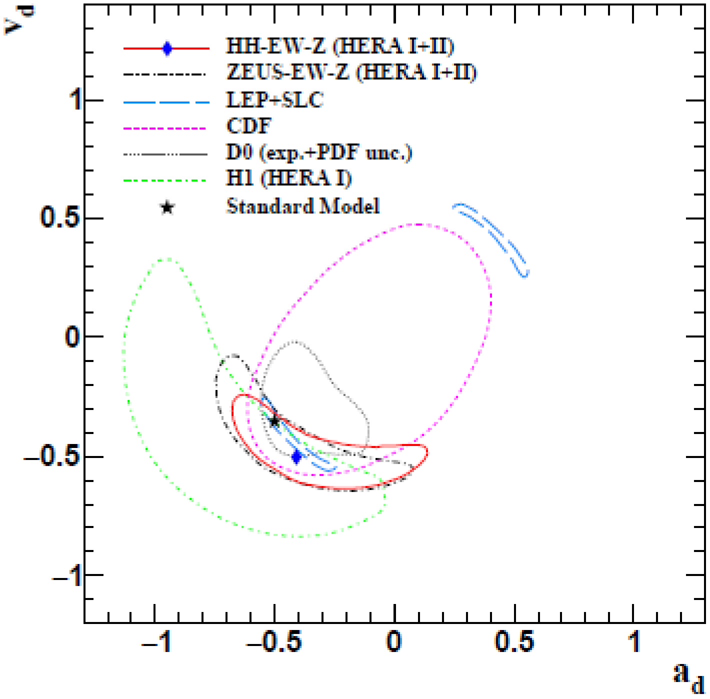
It is the uncertainties on v_u and v_d which have reduced, as expected since there is more information from polarisation in a fit to both ZEUS and H1 polarised data





And let us compare the results with other world data





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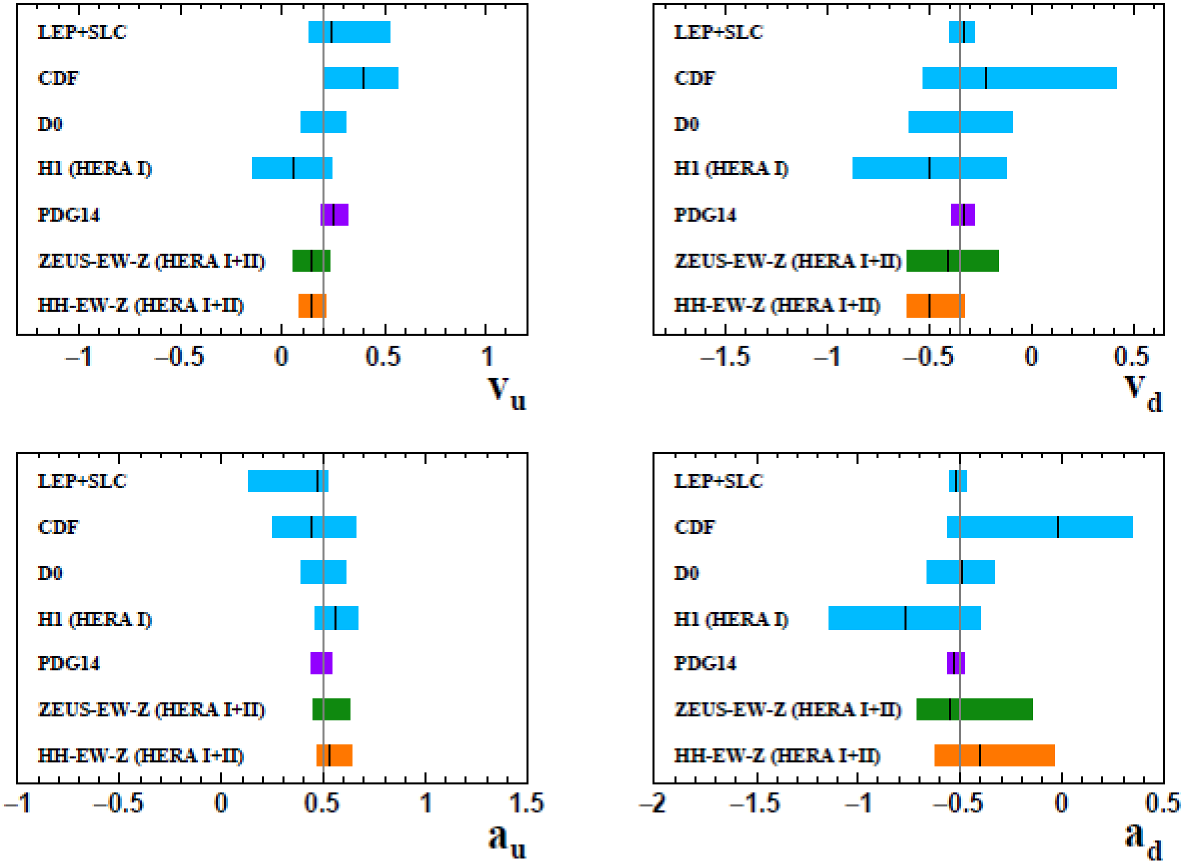


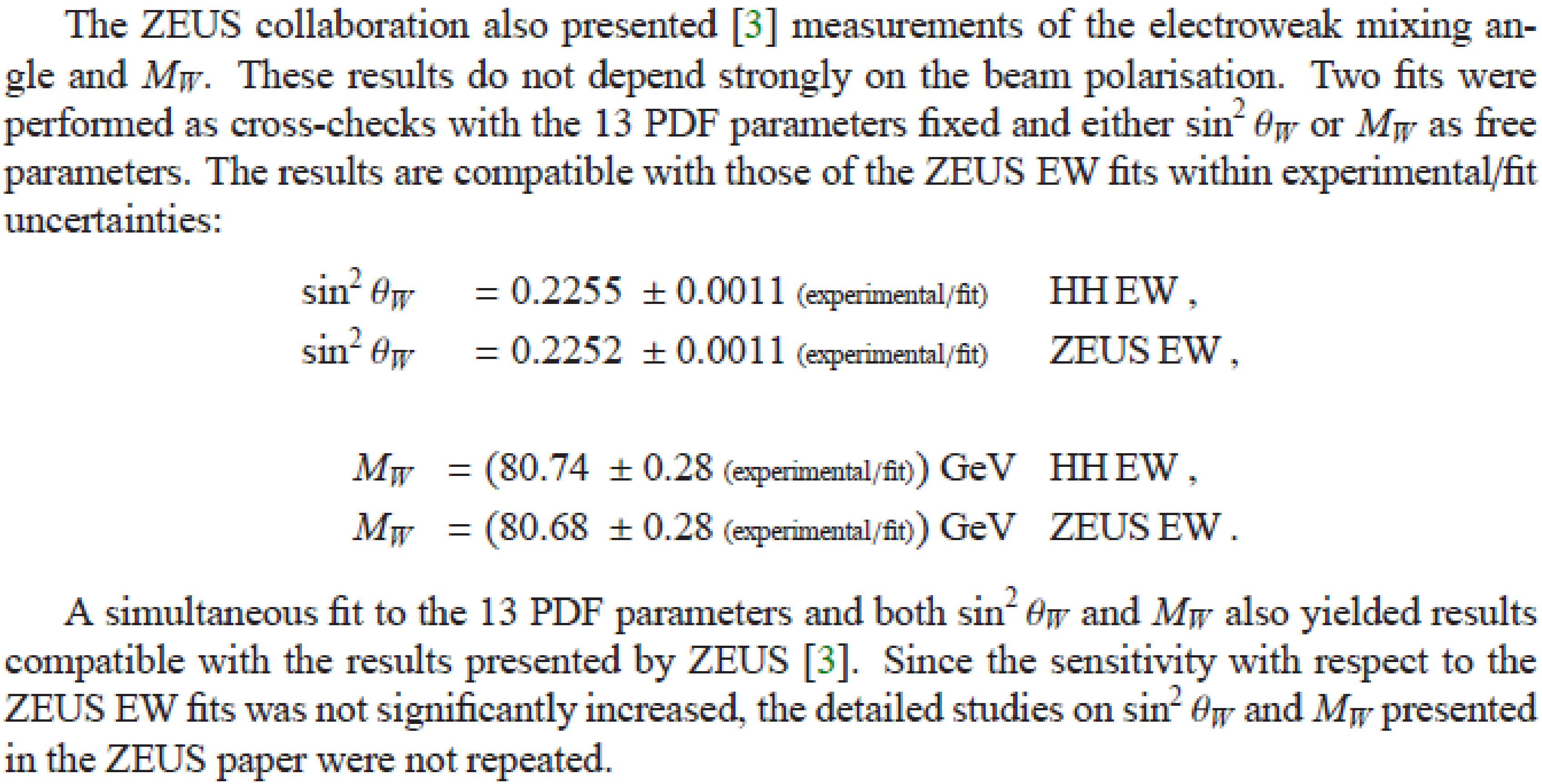
Summary

A combined QCD and electroweak fit to all available HERA inclusive DIS cross sections taking into account beam polarisation for both ZEUS and H1 data gives results on the couplings of the Z boson to u and d-type quarks, which are the most precise values coming from a single process for the u-type couplings.

The correlations between the PDF parameters and electroweak couplings are weak and the resulting PDFs are compatible with the HERAPDF2.0

extras

As described in Section 2, the reduced cross sections used as input to the analysis were published by the individual collaborations after QED corrections were applied. These corrections are mostly on the percent level, but reach 15 % for a few cross sections. The correction factors were calculated by producing Monte Carlo data sets for which radiative corrections were either turned on or off for comparison. This was done with the program Heracles [39] interfaced to the hadronisation programs within the program Djangoh [40]. However, the two collaborations did not use the Heracles program with exactly the same options. The ZEUS collaboration only corrected for LO initial- and final-state radiation of the electron. The H1 collaboration included the effects of quark radiation and Z self-energy [8] [4]. The difference introduced by these extra contributions is, however, always less than 1 % [42]. The H1 collaboration published [8] a cross-check with the programs Hector [43] and EPRC [41] and concluded that the uncertainties are below 2 % in all of the phase space. In addition, the effect of the exchange of two or more photons between the electron and the quarks, which was not implemented in Heracles, was found to be negligible. The H1 collaboration included phase-space-dependent uncertainties in the uncorrelated uncertainties of their published cross sections. The ZEUS collaboration did not assign any uncertainties to their QED corrections. As a cross-check, an extra uncertainty of the size assigned by H1 was also added to the uncorrelated uncertainties on the ZEUS cross sections for polarised beams. In all cases, the effect on the extracted EW parameters was negligible.



The ZEUS collaboration also presented [3] measurements of the electroweak mixing angle and M_W. These results do not depend strongly on the beam polarisation. Two fits were performed as cross-checks with the 13 PDF parameters fixed and either $\sin^2\theta_W$ or M_W as free parameters. The results are compatible with those of the ZEUS EW fits within experimental/fit uncertainties:

$$\begin{aligned} \sin^2\theta_W &= 0.2255 \pm 0.0011 \,\text{(experimental/fit)} \quad &&\text{HH EW}\,, \\ \sin^2\theta_W &= 0.2252 \pm 0.0011 \,\text{(experimental/fit)} \quad &&\text{ZEUS EW}\,, \end{aligned}$$

$$\begin{aligned} M_W &= (80.74 \pm 0.28 \,\text{(experimental/fit)})\ \text{GeV} \quad &&\text{HH EW}\,, \\ M_W &= (80.68 \pm 0.28 \,\text{(experimental/fit)})\ \text{GeV} \quad &&\text{ZEUS EW}\,. \end{aligned}$$

A simultaneous fit to the 13 PDF parameters and both $\sin^2\theta_W$ and M_W also yielded results compatible with the results presented by ZEUS [3]. Since the sensitivity with respect to the ZEUS EW fits was not significantly increased, the detailed studies on $\sin^2\theta_W$ and M_W presented in the ZEUS paper were not repeated.