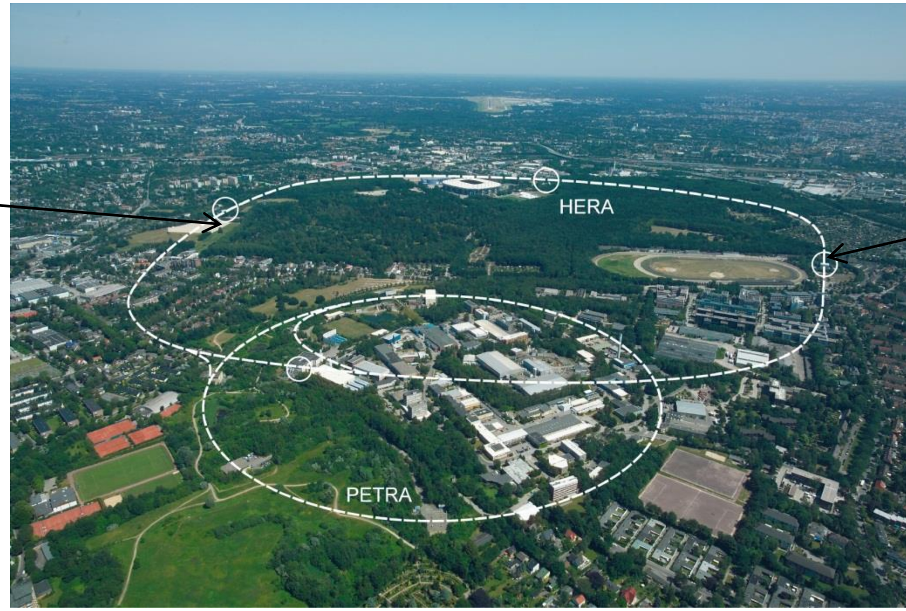


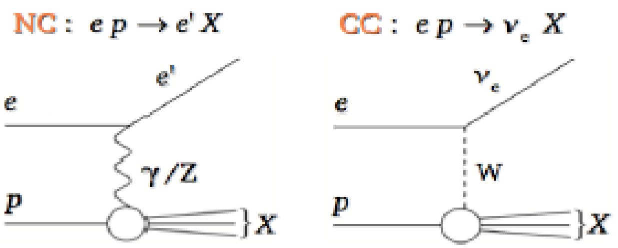
Electroweak effects at HERA using ZEUS polarised data

Phys Rev D93(2016)092002

AM Cooper-Sarkar, Oxford

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

NC: $e\,p \to e'\,X$ CC: $e\,p \to \nu_e\,X$



- 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.o.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

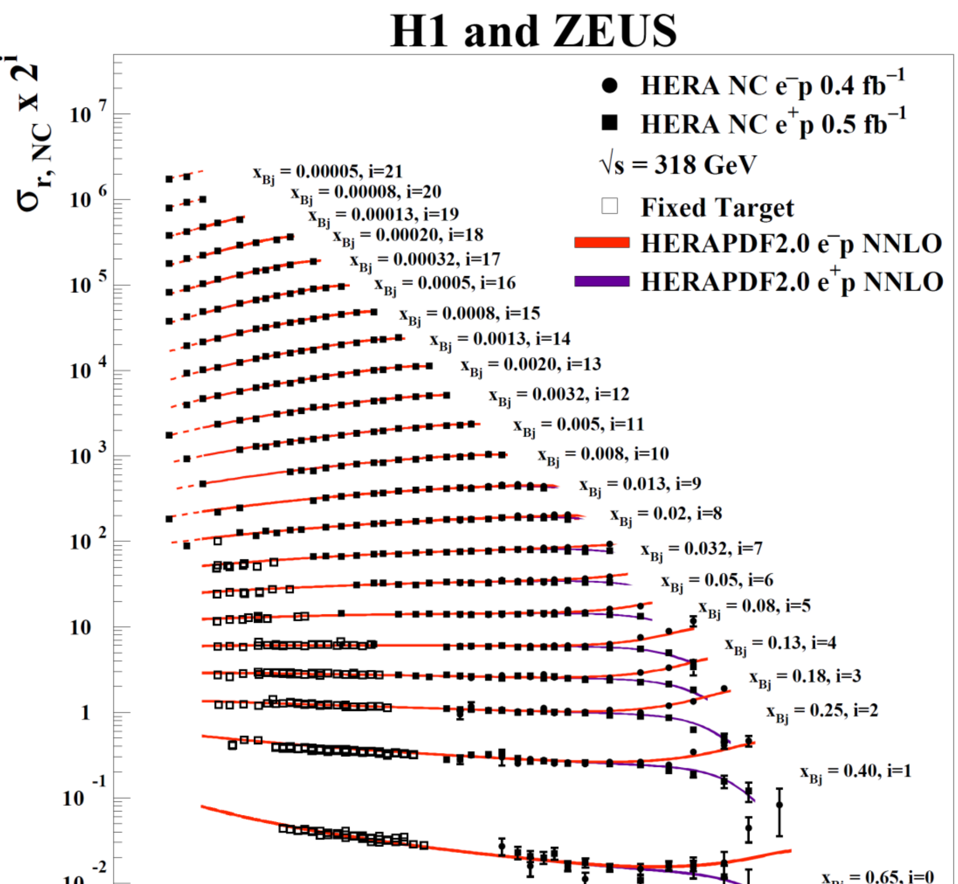
$F_L \propto \alpha_s \times g$ gluon at NLO

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



The HERA data combination
EPJC75(2015)580

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

Final inclusive data from all HERA running

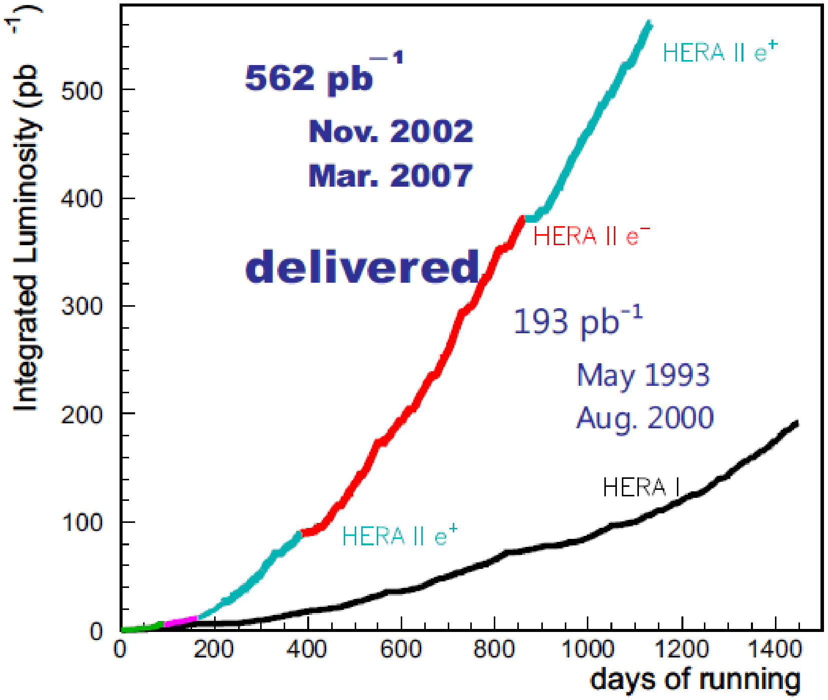
~500pb^{-1} per experiment split ~equally between e^+ and e^- beams: EPJC75(2015)580

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

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

√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
The ZEUS HERA-II data represents 300pb^{-1}
With polarisations of the order of 25-35%
ranging roughly equal between left-handed and right-handed

Data Set process	year	x_{Bj} from	to	Q^2[GeV^2] from	to	e^+/e^-	points	$\mathcal{L}$ pb^{-1}	P_e	Ref.
NC	06-07	0.0063	0.75	185	50000	e^+p	90	78.8±1.4	+0.316 ± 0.013	[5]
							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 ± 0.012	[7]
							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 ± 0.011	[4]
							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 ± 0.011	[6]
							37	104.0±1.9	−0.267 ± 0.011	

For the HERA data combination EPJC75(2015)580 the RH and LH polarised data were combined and corrected to zero polarisation. So uncombined data are used in the present study

The ZEUS analysis uses these polarised data, H1 data are used unpolarised

The neutral current NC cross sections are given by

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

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

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

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

$$x\tilde{F}_3^{\pm} = -(a_e \pm P_e v_e)\chi_Z xF_3^{\gamma Z} + (2v_e a_e \pm P_e(v_e^2+a_e^2))\chi_Z^2 xF_3^Z\ ,$$

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

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

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)

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

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

In the first part of this analysis the SM expressions for the NC coupling parameters are replaced with free parameters a_u, a_d, v_u, v_d

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 a multiplying polynomial $(1+Dx+Ex^2)$

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

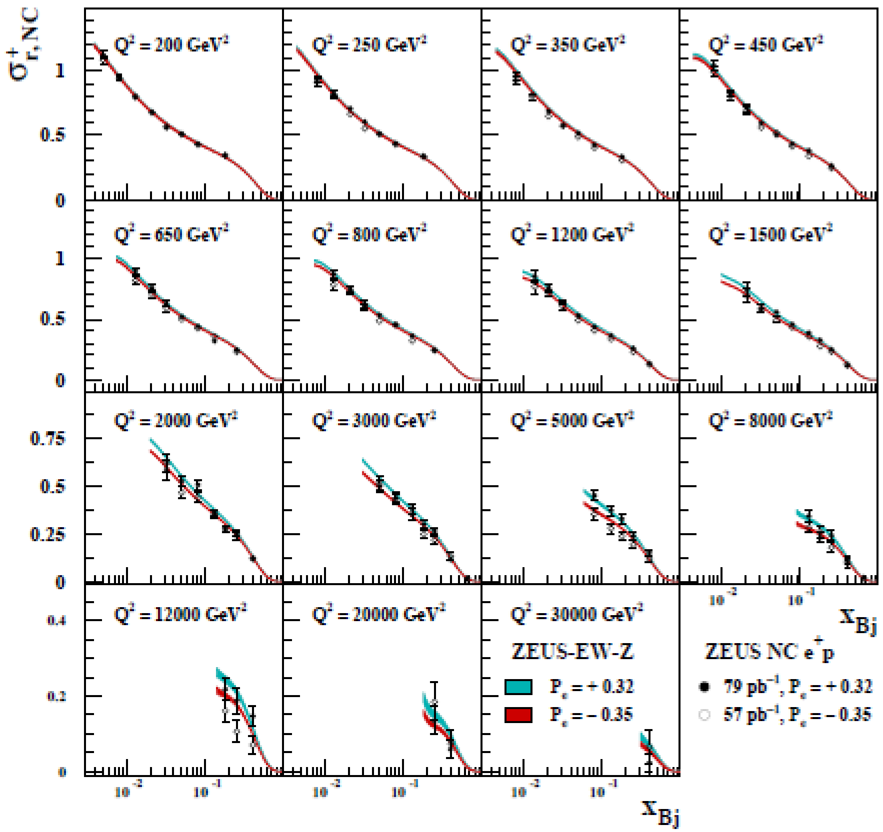
$$\frac{d^2\sigma_{CC}(e^+p)}{dx_{Bj}dQ^2} = (1+P_e)\frac{G_F^2 M_W^4}{2\pi x_{Bj}(Q^2+M_W^2)^2}\, x\left[(\bar{u}+\bar{c})+(1-y)^2(d+s+b)\right],$$

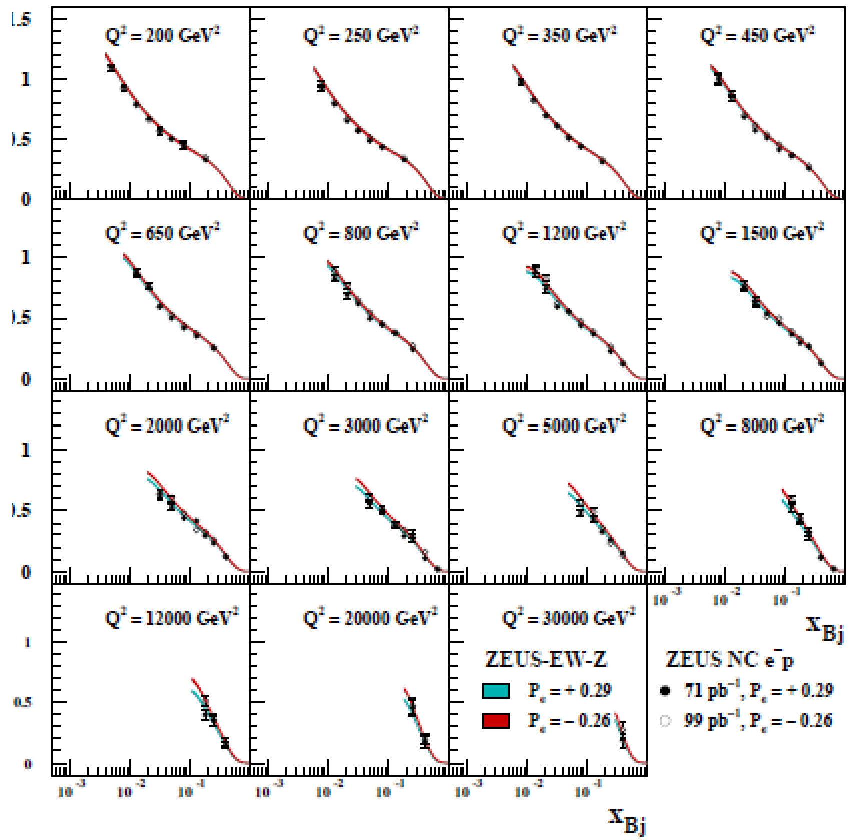
$$\frac{d^2\sigma_{CC}(e^-p)}{dx_{Bj}dQ^2} = (1-P_e)\frac{G_F^2 M_W^4}{2\pi x_{Bj}(Q^2+M_W^2)^2}\, x\left[(u+c)+(1-y)^2(\bar{d}+\bar{s}+\bar{b})\right].$$

LO expressions for illustration

Later on in the analysis they also contribute to the determination of M_w and $\sin^2\theta_W$ through the propagator AND $G_F = \frac{\pi\alpha_0}{\sqrt{2}\,\sin^2\theta_W\, M_W^2}\frac{1}{1-\Delta R}$

The simultaneous NLO QCD and LO EW fit – called ZEUS-EW- Z --was done to the uncombined H1 and ZEUS data.





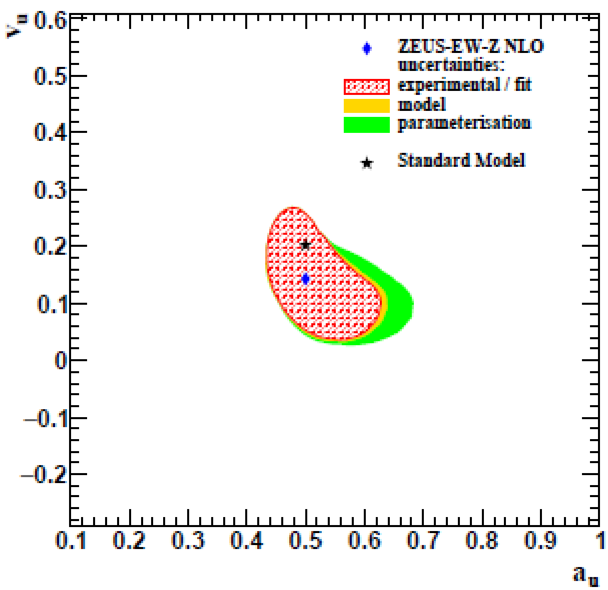
For Q^2_{min}=3.5 GeV^2 the number of data points is 2942 of which 501 are ZEUS cross sections for polarised beams. The χ2/ndf =3270/2925 =1.12 for a fit with NC couplings free .The description of the data is illustrated here for the NC e+ and e- polarised data..

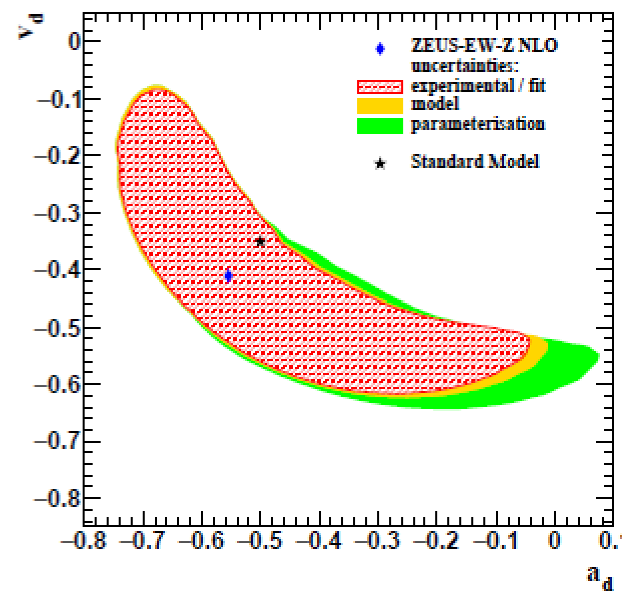
Now take a look at the extracted NC couplings

		Standard Model
$a_u = 0.50^{+0.09}_{-0.05}(exp/fit)\ {}^{+0.04}_{-0.02}(mod)\ {}^{+0.08}_{-0.01}(par) = \mathbf{0.50^{+0.12}_{-0.05}(tot)}$	**0.5**	
$a_d = -0.56^{+0.34}_{-0.14}(exp/fit)\ {}^{+0.11}_{-0.05}(mod)\ {}^{+0.20}_{-0.00}(par) = \mathbf{-0.56^{+0.41}_{-0.15}(tot)}$	**-0.5**	
$v_u = 0.14^{+0.08}_{-0.08}(exp/fit)\ {}^{+0.01}_{-0.00}(mod)\ {}^{+0.03}_{-0.01}(par) = \mathbf{0.14^{+0.09}_{-0.09}(tot)}$	**0.202**	
$v_d = -0.41^{+0.24}_{-0.16}(exp/fit)\ {}^{+0.04}_{-0.07}(mod)\ {}^{+0.00}_{-0.08}(par) = \mathbf{-0.41^{+0.25}_{-0.20}(tot)}$	**-0.351**	

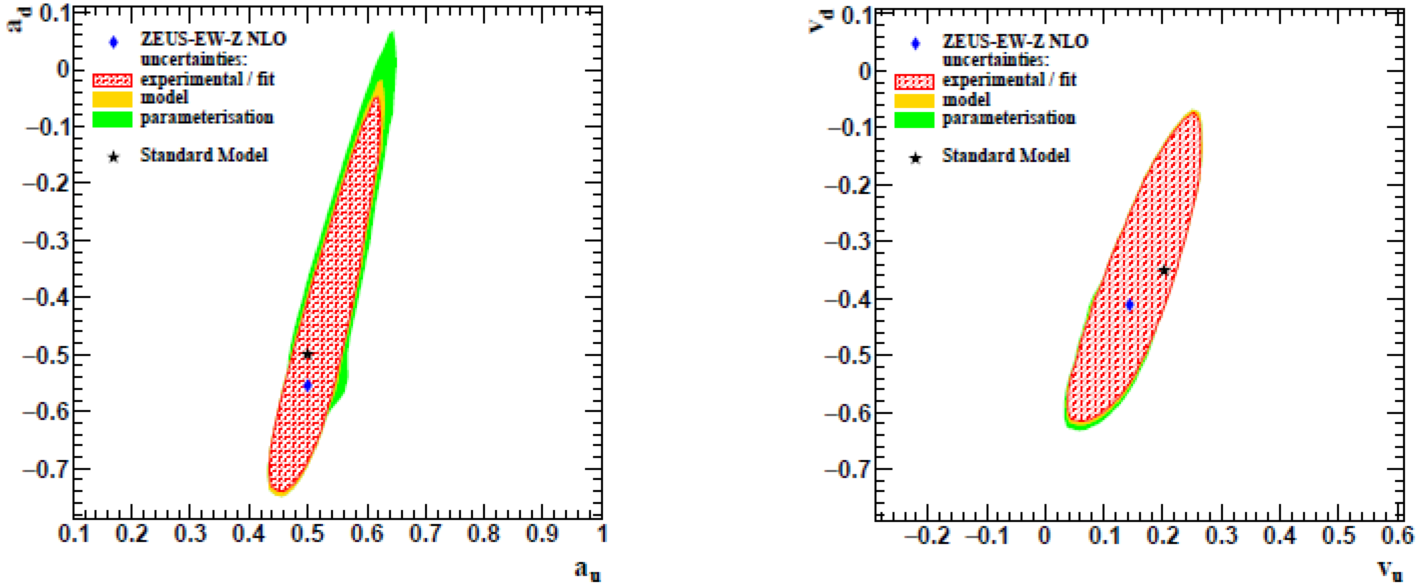
The model and parametrization uncertainties are evaluated as well as the experimental uncertainties from the central fit.

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





There is only weak correlation between the EW and the PDF parameters, The vector and axial-vector couplings in the fit show a strong correlation

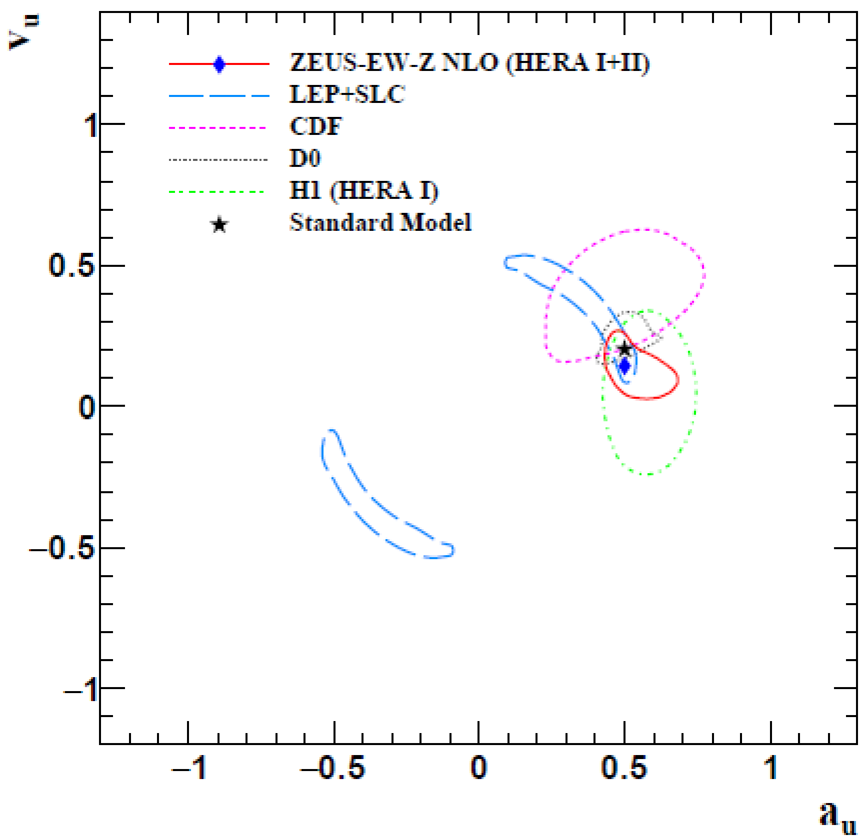


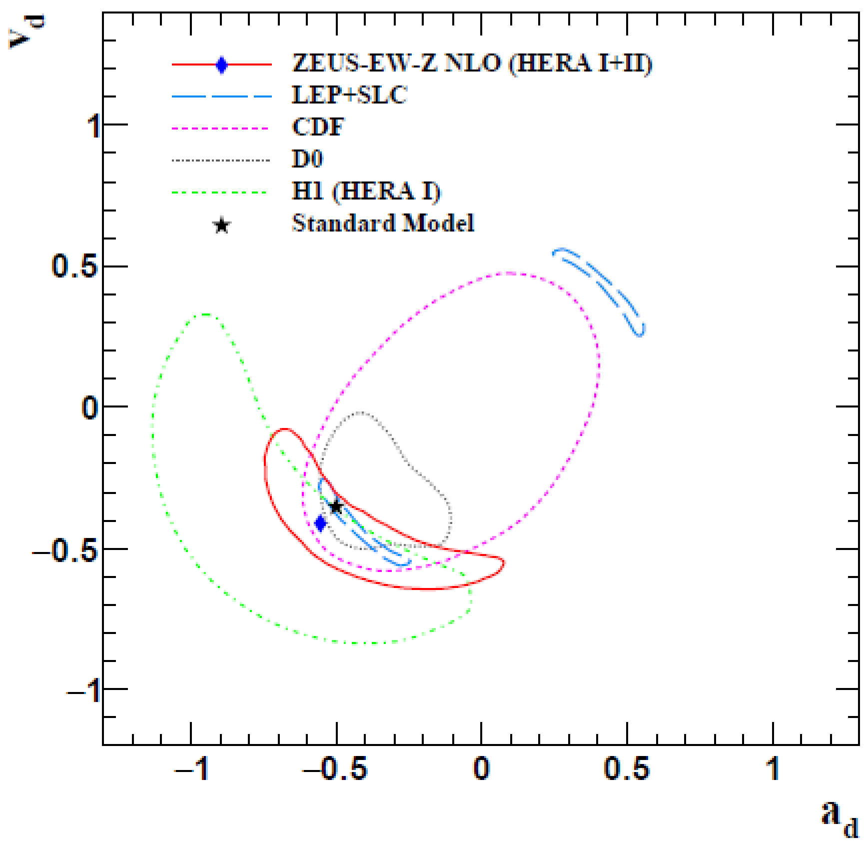
	a_u	exp	tot	a_d	exp	tot	v_u	exp	tot	v_d	exp	tot
EW-Z	+.500	$^{+.086}_{-.047}$	$^{+.122}_{-.050}$	−.555	$^{+.337}_{-.144}$	$^{+.407}_{-.152}$	+.143	$^{+.084}_{-.081}$	$^{+.085}_{-.088}$	−.411	$^{+.243}_{-.164}$	$^{+.246}_{-.195}$
13p	+.485	$^{+.073}_{-.038}$		−.567	$^{+.295}_{-.130}$		+.145	$^{+.079}_{-.076}$		−.402	$^{+.216}_{-.171}$	
HPDF1*	+.474	$^{+.059}_{-.033}$		−.619	$^{+.233}_{-.107}$		+.156	$^{+.076}_{-.076}$		−.353	$^{+.215}_{-.190}$	
HPDF2*	+.486	$^{+.061}_{-.034}$		−.634	$^{+.239}_{-.110}$		+.149	$^{+.078}_{-.078}$		−.357	$^{+.220}_{-.194}$	
SM	+.500			−.500			+.202			−.351		

The results of this simultaneous PDF and EW analysis can be compared with the results of fitting the EW parameters with fixed PDFs, either from a dedicated fit to these data (13p), or using the HERAPDF2.0 fit.

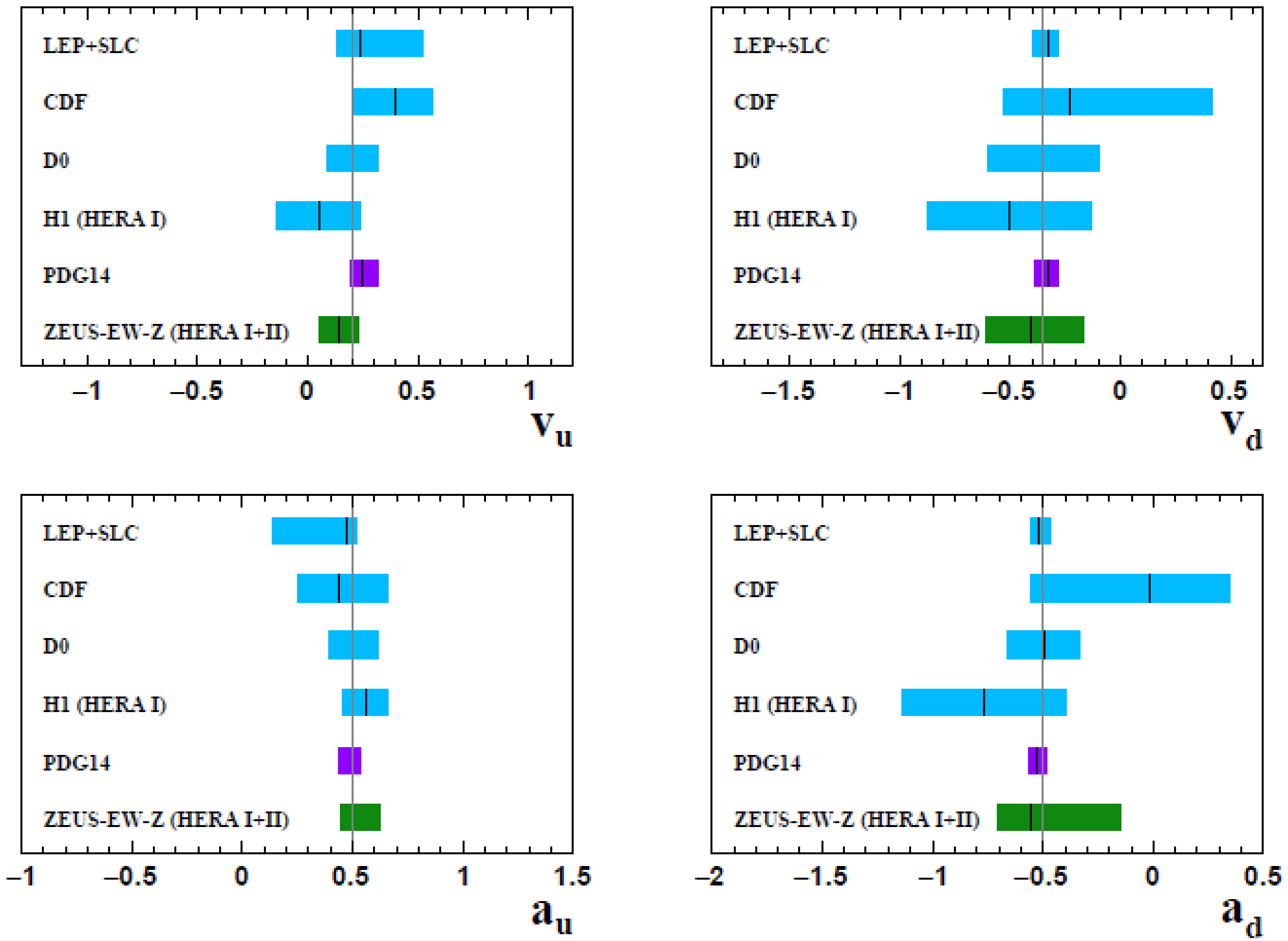
(Note this fit did not use the on-shell $\sin^2\theta_W$, so it has been repeated for consistency)

ZEUS-EW-Z results are compatible with the SM and competitive with previous measurements for the u-type quarks





Another way to see this is shown here.
The ZEUS result is the best for a single measurement for a_u, v_u
It is not yet included in the PDG average and will have impact.



The data can also be used to determine $\sin^2\theta_W$ and M_W

- DIS inclusive cross sections depend on $\sin^2\theta_W$ through:
  - χ_Z term in NC cross sections;
  - Vector couplings of Z to quarks; $v_u = 1/2 - 4/3\sin^2\theta_W$ $v_d = -1/2 + 2/3\sin^2\theta_W$,

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

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

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

  - CC cross sections via G_F

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

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

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

ΔR is an EW correction.

arXiv:hep-ph/9902277

- Re-expressing G_F through $\sin^2\theta_W$ and M_W allows to use both CC and NC for $\sin^2\theta_W$ determination.

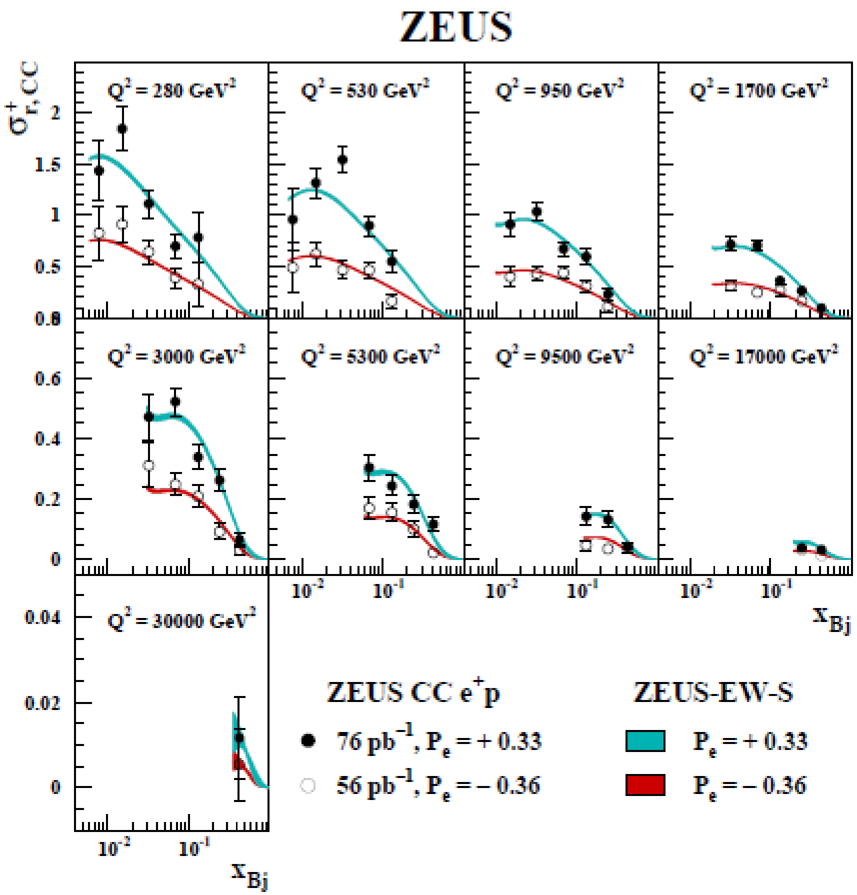
- Current analysis exploits all three dependences for $\sin^2\theta_W$ extraction.

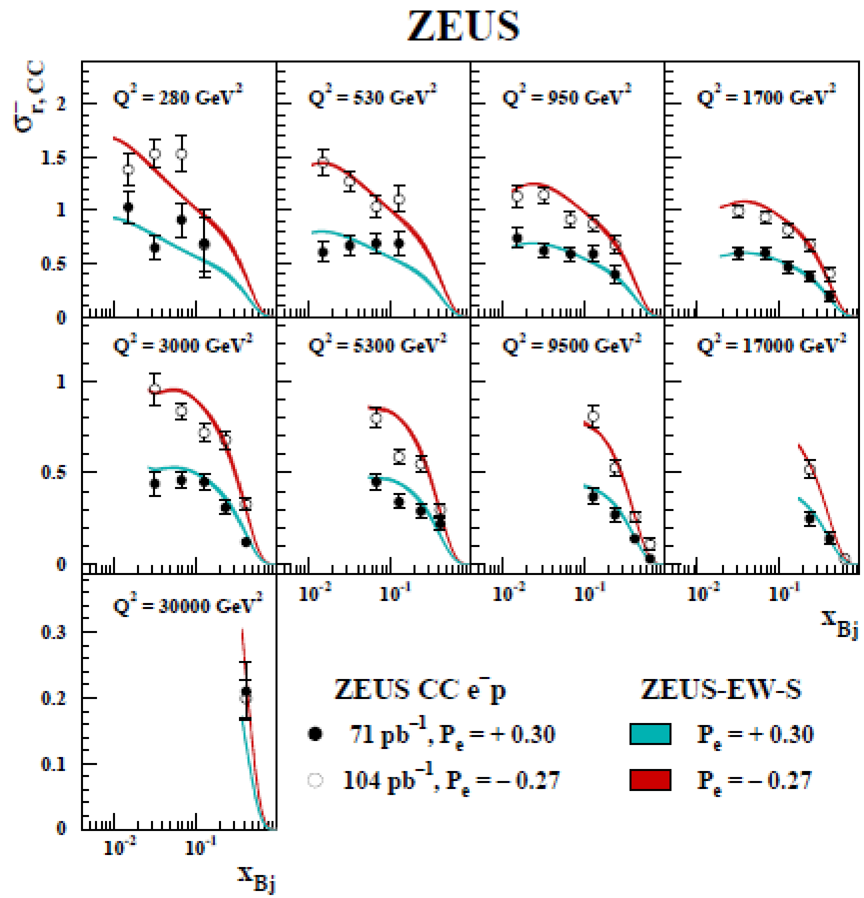
The information from the χ_Z term and from G_F are both important, the vector couplings do not contribute much

$\sin^2\theta_W$ is fitted as a parameter along with the PDF parameters-- this fit is called ZEUS-EW-S

Strictly speaking, since $\sin^2\theta_W$ is no longer $=(1-M_W^2/M_Z^2)$ this is no longer in the on-shell scheme

The description of the data is also good, illustrated here on CC data





- $\chi^2 = 3270 / 2928 = 1.118$

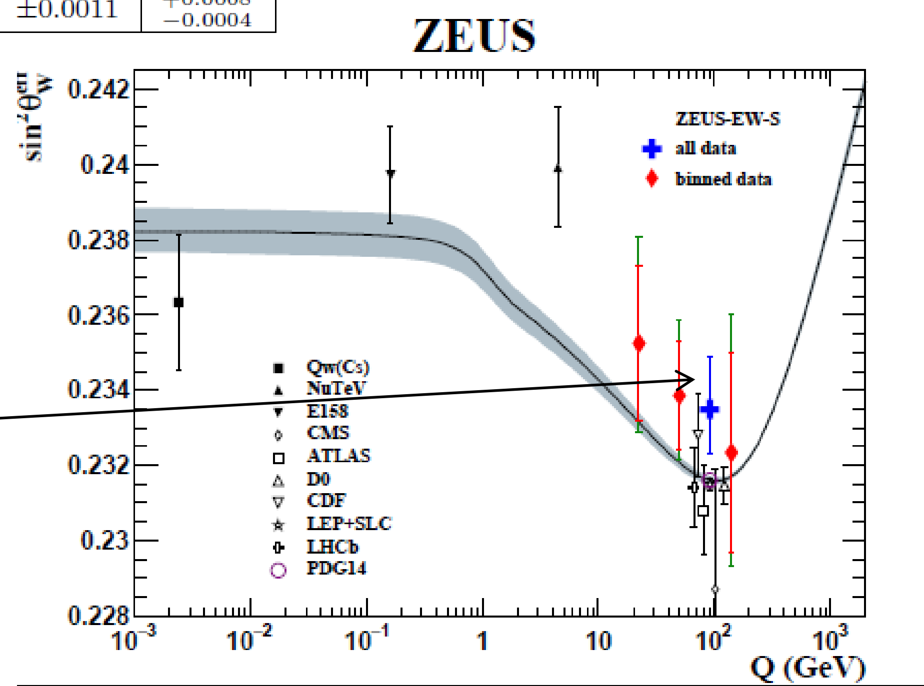
The fitted value of $\sin^2\theta_W$ is:

$$\sin^2\theta_W = 0.2252 \pm 0.0011_{(exp/fit)}\ {}^{+0.0003}_{-0.0001}{}_{(mod)}\ {}^{0.0007}_{-0.0001}{}_{(par)} = \mathbf{0.2252}^{+0.0013}_{-0.0011}{}_{(tot)}$$

The data were also split into three Q^2 regions and fitted with PDF parameters fixed (to the ZEUS-EW-S PDF values) in order to look at the running of $\sin^2\theta_W$.
Uncertainties on these values are then assigned by ratio of the total uncertainties on the fit to the full range (as above) to as similar fit in which PDF parameters are fixed. $\sin^2\theta_W = 0.2241 \pm 0.0009$

bin	$Q^2_{\rm min}$ (GeV^2)	$Q^2_{\rm max}$ (GeV^2)	scale (GeV)	$\sin^2\theta_W$ on-shell	exp unc.	$\sin^2\theta_W^{\rm eff}$ effective	exp unc.	PDF unc.
1	200	1000	22.3	0.2254	±0.0020	0.2352	±0.0020	$^{+0.0020}_{-0.0012}$
2	1000	5000	49.9	0.2251	±0.0014	0.2339	±0.0015	$^{+0.0014}_{-0.0008}$
3	5000	50000	139.8	0.2240	±0.0026	0.2323	±0.0026	$^{+0.0025}_{-0.0015}$
All Data			M_Z	0.2252	±0.0011	0.2335	±0.0011	$^{+0.0008}_{-0.0004}$

The values of $\sin^2\theta_W$ for different Q^2 are given in this table, where the scales of the measurement are taken as the log-average Q^2 of the bins.



They are then translated to values of $\sin^2\theta_W^{\rm eff}$ using the procedure from: Czarnecki and Marciano, IJMPA15(2009)2365

The mass of the W boson can also be fitted using the dependence of the W-propagator of the CC events and the dependence of G_F

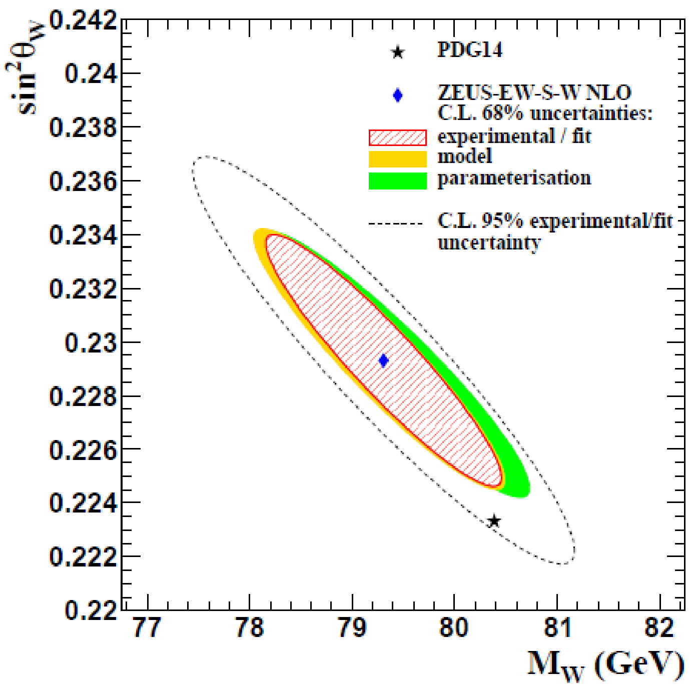
$$G_F = \frac{\pi \alpha_0}{\sqrt{2}\, \sin^2\theta_W\, M_W^2} \frac{1}{1-\Delta R}$$

This ties the fit to the NC data through the common use of $\sin^2\theta_W$
The fitted value from this ZEUS-EW-W fit with $\sin^2\theta_W$ =0.22333 fixed is:

$$M_W = 80.68 \pm 0.28_{(exp/fit)} {}^{+0.12}_{-0.01(mod)} {}^{+0.23}_{-0.01(par)} GeV = \mathbf{80.68^{+0.38}_{-0.28(tot)}\ GeV}$$

This represents one of few determinations in a space-like rather than time-like process

Finally $\sin^2\theta_W$ and M_W can be determined simultaneously (ZEUS-EW-S-W)



$$M_W = 79.30 \pm 0.76_{(exp/fit)} {}^{+0.38}_{-0.08(mod)} {}^{+0.48}_{-0.10(par)} GeV = \mathbf{79.30^{+0.98}_{-0.77(tot)}\ GeV}$$

$$\sin^2\theta_W = 0.2293 \pm 0.0031_{(exp/fit)} {}^{+0.0005}_{-0.0001(mod)} {}^{+0.0003}_{-0.0001(par)} = \mathbf{0.2293^{+0.0032}_{-0.0031(tot)}}$$

Summary

A combined QCD and electroweak fit to all available HERA inclusive DIS cross sections taking into account beam polarisation for ZEUS data gives results on:

1. The couplings of the Z boson to u and d-type quarks that are competitively precise for the u-type couplings.
2. $\sin^2\theta_W$ and its running
3. M_W – from a space-like process

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

extras

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

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

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

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

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

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 $\sigma^P = Y_+ F_2^P + Y_- xF_3^P$

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

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

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

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

$\chi_Z >> \chi_Z^2$ (γZ interference is dominant)

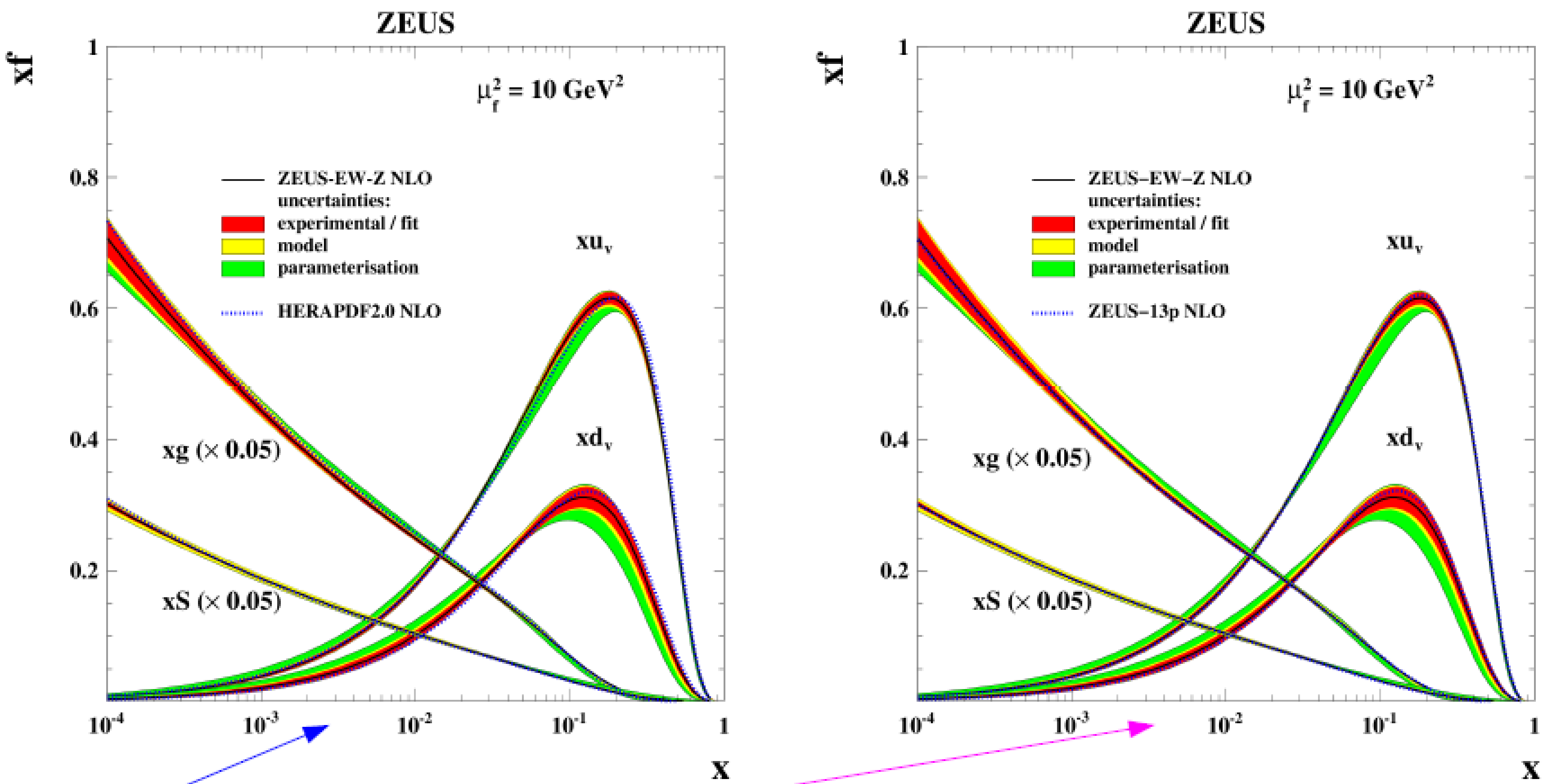
$\mathbf{v_e}$ is very small (~0.04).

→

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

The reduced cross sections used were published after QED corrections were applied using the HERACLES program interfaced to DJANGO. Corrections for LO ISR and FSR of the electron are mostly ~1% but can reach 15% in some bins.The uncertainty on these corrections was assessed using HECTOR and EPRC to be below 2% of the correction.
Updated values of ZEUS polarisations are used presented as compared to the original publications

Effect of coupling determination on PDFs



- HERAPDF2.0 and ZEUS-13p PDFs with couplings set to SM agree with ZEUS-EW-Z PDFs.
  - Releasing couplings has little effect on PDFs.

There is only weak correlation between the EW and the PDF parameters,
The QCD part of the fit can be repeated at NNLO with little pull on the EW parameters

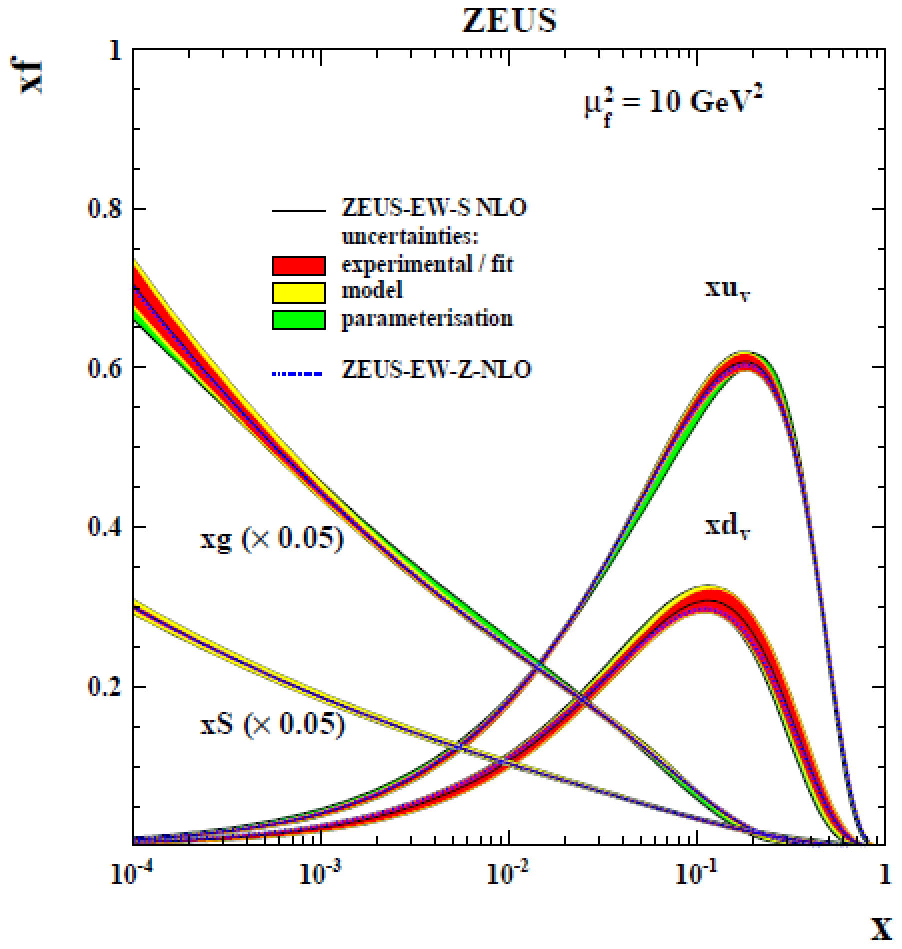
Correlation matrix for the fit parameters

NO.	Bg	Cg	Aprig	Bprig	Buv	Cuv	Euv	Bdv	Cdv	CUbar	ADbar	BDbar	CDbar	auEW	adEW	vuEW	vdEW
Bg	1.000	-0.014	-0.449	0.824	-0.216	0.172	0.250	-0.084	-0.085	-0.098	-0.107	-0.136	0.046	0.025	0.003	0.015	0.018
Cg	-0.014	1.000	0.831	0.457	0.341	-0.373	-0.550	0.010	0.296	-0.018	-0.082	-0.103	-0.434	0.105	0.095	-0.098	-0.111
Aprig	-0.449	0.831	1.000	0.120	0.548	-0.404	-0.629	0.233	0.274	0.159	0.081	0.072	-0.148	-0.052	0.000	-0.043	-0.054
Bprig	0.824	0.457	0.120	1.000	0.106	-0.037	-0.082	0.075	0.047	0.043	0.011	-0.014	0.012	-0.029	-0.011	-0.001	-0.002
Buv	-0.216	0.341	0.548	0.106	1.000	-0.409	-0.774	0.465	-0.086	0.690	0.476	0.395	0.439	-0.360	-0.178	0.079	0.070
Cuv	0.172	-0.373	-0.404	-0.037	-0.409	1.000	0.828	-0.297	-0.235	-0.188	-0.095	-0.069	-0.040	0.110	0.029	0.040	0.028
Euv	0.250	-0.550	-0.629	-0.082	-0.774	0.828	1.000	-0.296	-0.066	-0.363	-0.170	-0.117	-0.092	0.192	0.087	-0.023	-0.017
Bdv	-0.084	0.010	0.233	0.075	0.465	-0.297	-0.296	1.000	0.518	0.405	0.350	0.291	0.673	-0.335	-0.134	0.038	0.021
Cdv	-0.085	0.296	0.274	0.047	-0.086	-0.235	-0.066	0.518	1.000	-0.137	-0.186	-0.193	-0.139	0.110	0.128	-0.101	-0.128
CUbar	-0.098	-0.018	0.159	0.043	0.690	-0.188	-0.363	0.405	-0.137	1.000	0.673	0.635	0.329	-0.320	-0.137	0.055	0.052
ADbar	-0.107	-0.082	0.081	0.011	0.476	-0.095	-0.170	0.350	-0.186	0.673	1.000	0.959	0.477	-0.272	-0.137	0.056	0.059
BDbar	-0.136	-0.103	0.072	-0.014	0.395	-0.069	-0.117	0.291	-0.193	0.635	0.959	1.000	0.415	-0.239	-0.120	0.047	0.053
CDbar	0.046	-0.434	-0.148	0.012	0.439	-0.040	-0.092	0.673	-0.139	0.329	0.477	0.415	1.000	-0.449	-0.271	0.148	0.153
auEW	0.025	0.105	-0.052	-0.029	-0.360	0.110	0.192	-0.335	0.110	-0.320	-0.272	-0.239	-0.449	1.000	0.861	-0.555	-0.729
adEW	0.003	0.095	0.000	-0.011	-0.178	0.029	0.087	-0.134	0.128	-0.137	-0.137	-0.120	-0.271	0.861	1.000	-0.636	-0.880
vuEW	0.015	-0.098	-0.043	-0.001	0.079	0.040	-0.023	0.038	-0.101	0.055	0.056	0.047	0.148	-0.555	-0.636	1.000	0.851
vdEW	0.018	-0.111	-0.054	-0.002	0.070	0.028	-0.017	0.021	-0.128	0.052	0.059	0.053	0.153	-0.729	-0.880	0.851	1.000

World results (full uncertainties)

	a_u	a_b	v_u	v_d
LEP	$0.47^{+0.05}_{-0.33}$	$-0.52^{+0.05}_{-0.03}$	$0.24^{+0.28}_{-0.11}$	$-0.33^{+0.05}_{-0.07}$
D0	0.50±0.11	-0.50±0.17	0.20±0.11	0.35±0.25
CDF	$0.44^{+0.22}_{-0.19}$	$-0.02^{+0.36}_{-0.54}$	$0.40^{+0.17}_{-0.20}$	$-0.23^{+0.64}_{-0.30}$
H1: HERA1 (publ.)	0.56±0.10	-0.77±-0.37	0.05±0.19	-0.50±0.37
ZEUS: HERA1+2 (prel.)	0.51±0.20	-0.54±0.37	0.05±0.10	-0.64±0.24
ZEUS-EW-Z	$0.500^{+0.122}_{-0.050}$	$-0.555^{+0.407}_{-0.152}$	$0.143^{+0.085}_{-0.088}$	$-0.411^{+0.246}_{-0.195}$
PDG14	$0.50^{+0.04}_{-0.06}$	$-0.523^{+0.050}_{-0.029}$	$0.25^{+0.07}_{-0.06}$	$-0.33^{+0.05}_{-0.06}$
SM	0.5	-0.5	0.202	-0.351

The PDF fit is consistent with the one where NC couplings are fitted



Fits to M_W and $\sin^2\theta_W$

We first fit M_W purely from the $G_F^2\, M_W^4/(M_W^2+Q^2)^2$ term in the CC propagator

M_W =79.39 ± 0.56 GeV $^{+0.06}_{-0.18}$(mod) $^{+0.02}_{-0.60}$(param) GeV

We can ALSo fit M_W from the NC data using by replacing GF above with

$$GF= \pi\alpha/ (\sqrt{2}\, \sin^2\theta_W\, M_W^2\,)\ {}^*1/(1-\Delta R)$$

Where ΔR is an EW correction coming from EPRC

Working at this level also adds such $1/(1-\Delta R)$ terms to the Z propagators

This is of course in addition to using the CC propagator

This ties the fit to the NC data through the common use of $\sin^2\theta_{W,}$ which is fixed at 0.22333

More accurate than using the propagator alone

M_W =80.68 ± 0.28 GeV $^{+0.12}_{-0.01}$(mod) $^{+0.23}_{-0.00}$(param) GeV

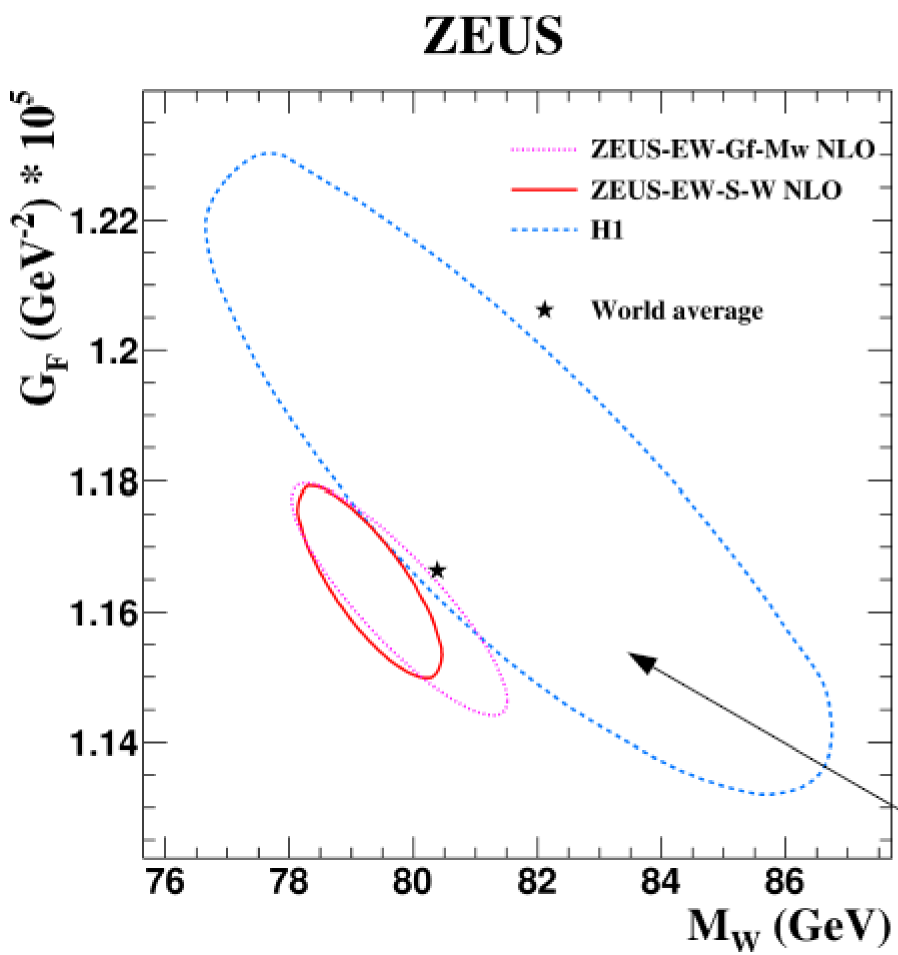
Then we can do $\sin^2\theta_W$ and M_W fits simultaneously using all the information from points I to iii above PLUS the W-propagator and we get

$\sin^2\theta_W = 0.2293 \pm 0.0031\ ^{+0.0005}_{-0.001(mod)}\ ^{+0.0003}_{-0.001(param)}$

and M_W = 79.3 ± 0.76 GeV $^{+0.38}_{-0.08(model)}$ $^{+0.48}_{-0.1(param)}$

G_F and mass of W boson

- G_F and M_W were also determined simultaneously with PDFs as a consistency check.



$$M_W = 79.77 \pm 1.15(\exp)\, GeV$$

$$G_F = (1.1618 \pm 0.0117) * 10^{-5} (\exp)\, GeV^{-2}$$

$$corr(M_W, G_F) = -0.87$$

$$M_W^{World\ average} = 80.385 \pm 0.015\, GeV$$

$$G_F^{World\ average} = 1.1663787 * 10^{-5} \pm 6 * 10^{-12}\, GeV^{-2}$$

Experimental/fit uncertainties only!!

- Fitter G_F and M_W are consistent with current world average values.

The improvement from using ALL HERA polarised data compared to using just ZEUS polarised data is shown here. arXiv:1604.05083

It is the uncertainties on v_u and v_d which have reduced, as expected

Central values have also shifted somewhat