Combined QCD and EW analysis of HERA data

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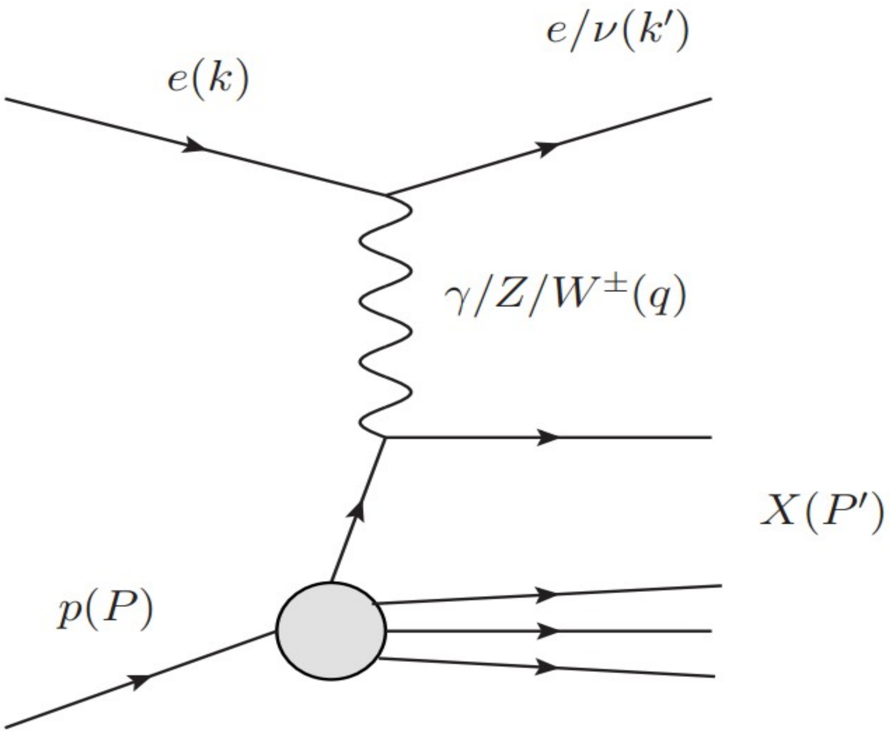
Volodymyr Myronenko
DESY

on behalf of
the ZEUS collaboration

Deep-Inelastic Scattering
Hamburg, Germany 2016

Deep Inelastic Scattering at HERA



$$E_P = 920(820, 460, 575)\, GeV$$

$$E_e = 27.5\, GeV$$

$$\sqrt{s} = 318(300, 225, 252)\, GeV$$

- Lepton beams were polarised at HERAII
  - Crucial for the EW measuremets

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

$$x_{Bj} = \frac{Q^2}{2\, pq} \qquad y = \frac{pq}{pk}$$

$$s = (p + k)^2 \qquad Q^2 = xys$$

Experimental achievements (H1 & ZEUS):

~ 0.5fb^{-1} DIS data from each experiment

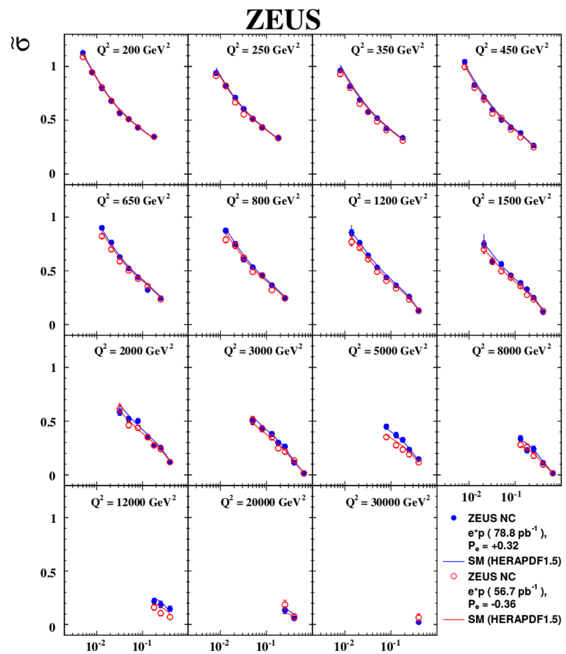
Data considered

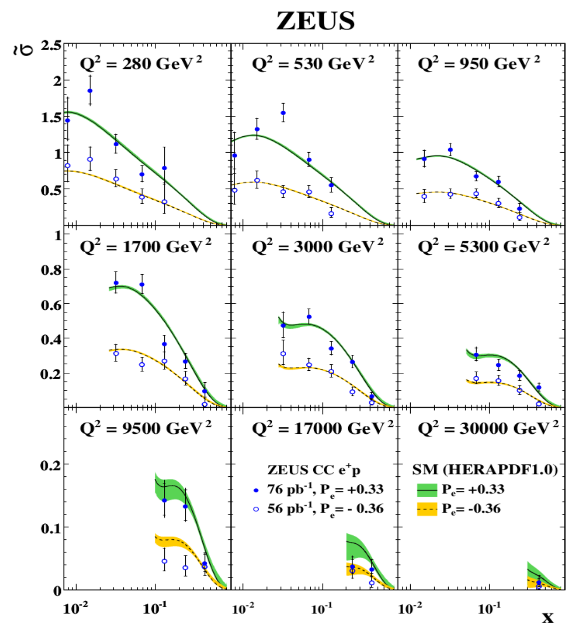
- Data used in the analysis (uncombined data sets, correlations as in HERAPDF2.0):

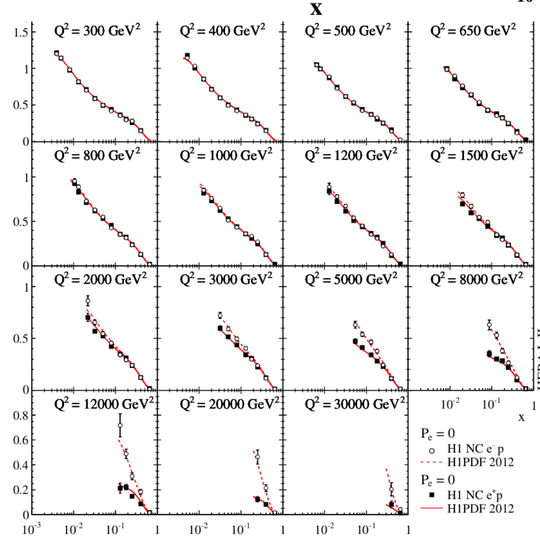
  - HERAI: H1 + ZEUS
    $P_e = 0$;

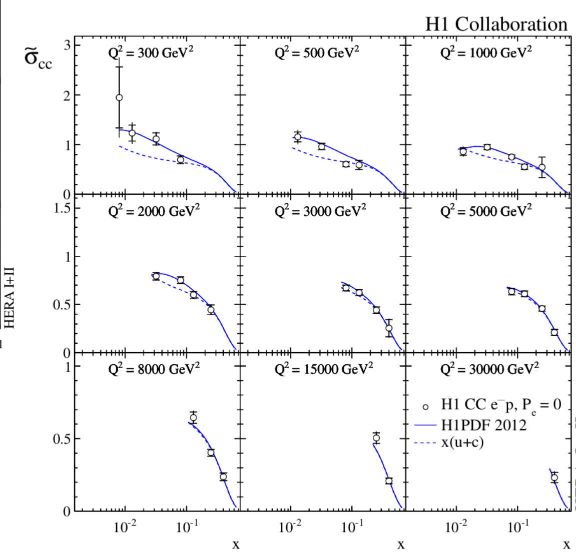
  - Reduced E_P runs:
    H1 + ZEUS, $P_e = 0$;

  - HERAII:
    - H1 data with $P_e = 0$;
    - ZEUS data with $P_e \neq 0$;









Global QCD analysis

- $Q_{min}^2 = 3.5$ GeV^2.
- HF scheme: GM VFNS NLO (RT OPT).
- PDFs parametrised with 13p (HERAPDF2.0 - $D\bar{U}$) at $Q_0^2 = 1.9$ GeV^2

$$xf(x) = Ax^B(1-x)^C(1+Dx+Ex^2)$$

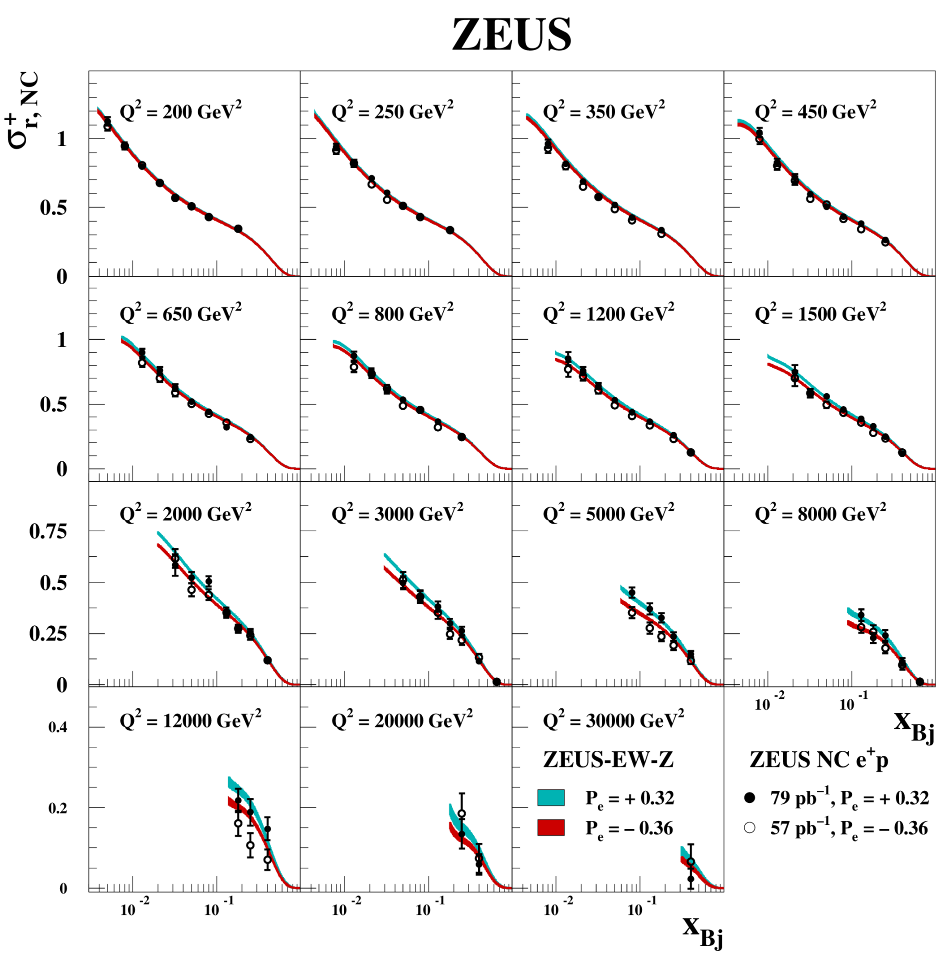
$$xg(x), xu_v(x), xd_v(x), x\bar{U}(x), x\bar{D}(x)$$

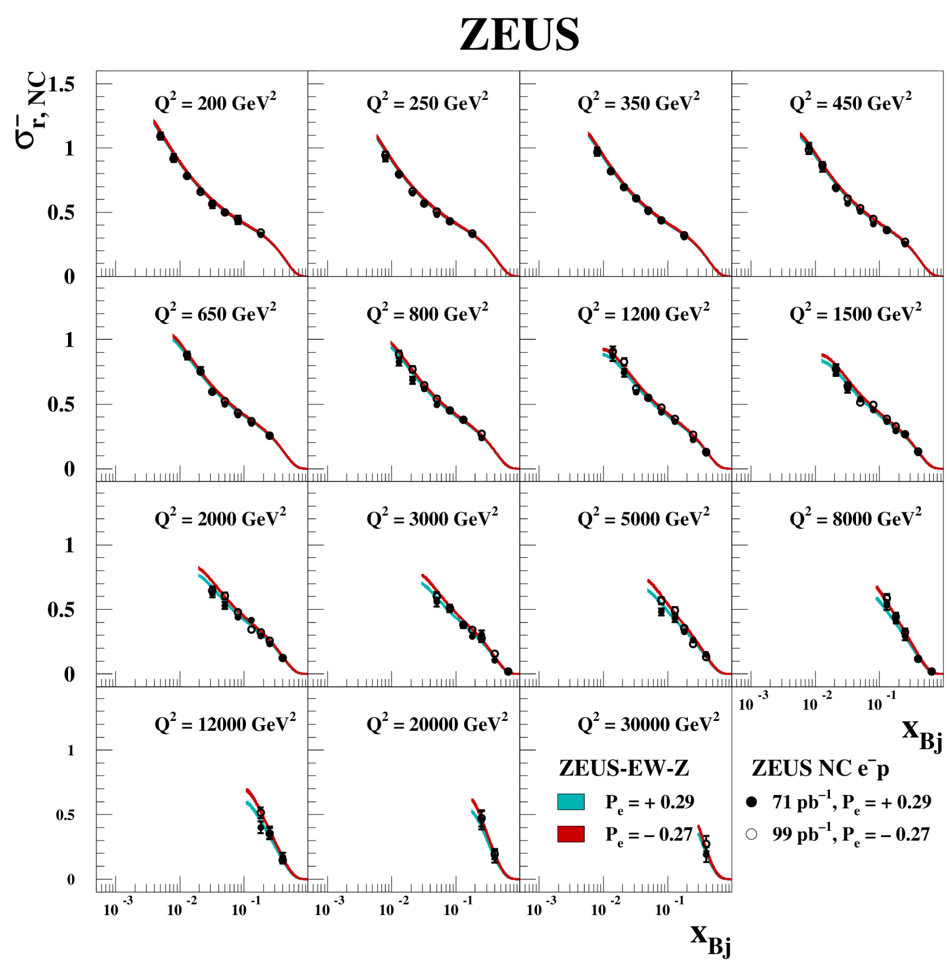
- Free parameters: PDF parameters + couplings of Z^0 to quarks (a_u, a_d, v_u, v_d), or M_W, or $\sin^2\theta_W$ (On-shell scheme).
- Model and parameterisation uncertainty estimation → HERAPDF2.0 strategy.
- Correction calculated using EPRC code: Δr. No ISR/FSR corrections.

desy.de/~hspiesb/eprc.html

Data description (ZEUS-EW-Z)

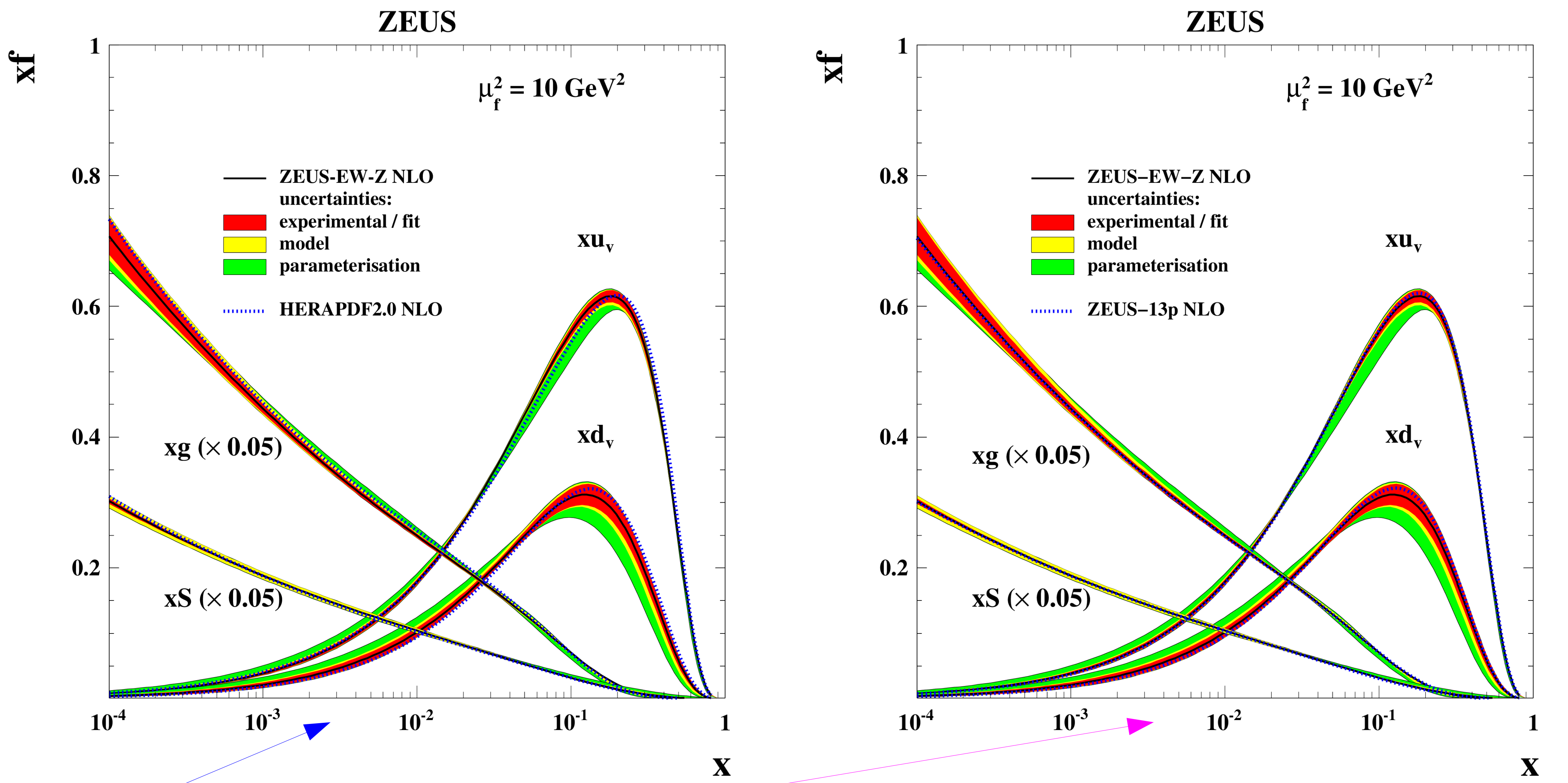
- Fitted predictions describe data well.





- $\chi^2 = 3270 / 2925 = 1.12$

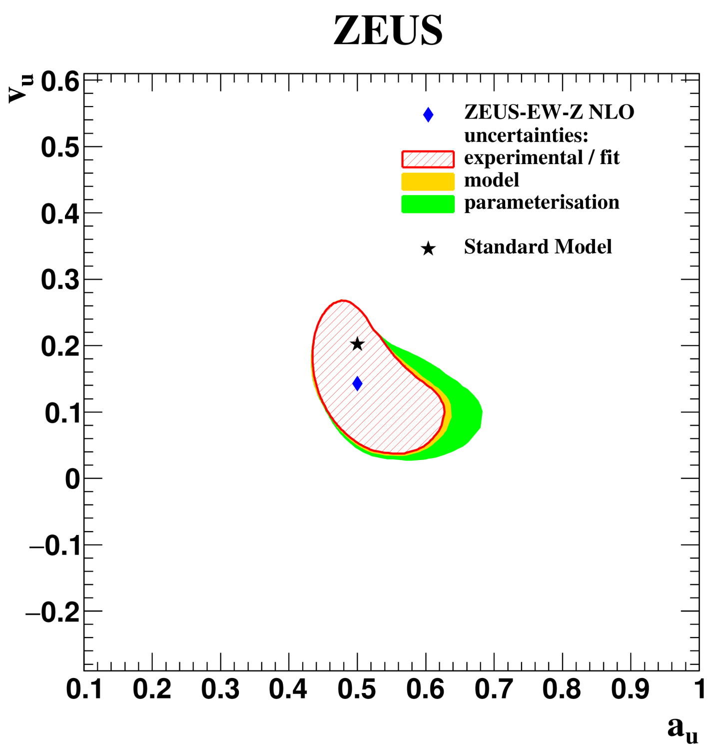
Effect of coupling determination on PDFs

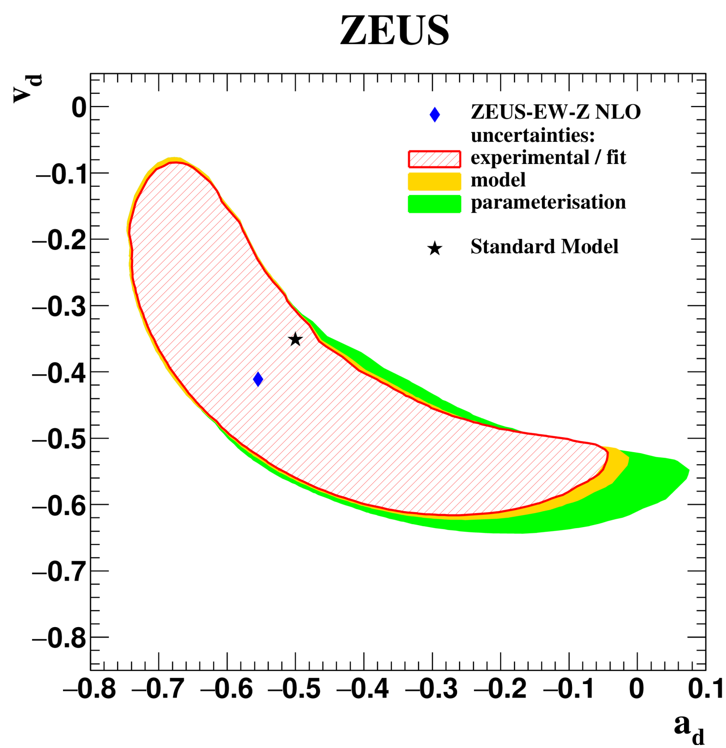


- HERAPDF2.0 and ZEUS-13p PDFs with couplings set to SM agree with ZEUS-EW-Z PDFs.
    - Releasing couplings has little effect on PDFs.

Couplings of quarks to Z boson

- Couplings were determined simultaneously with PDFs (ZEUS-EW-Z)

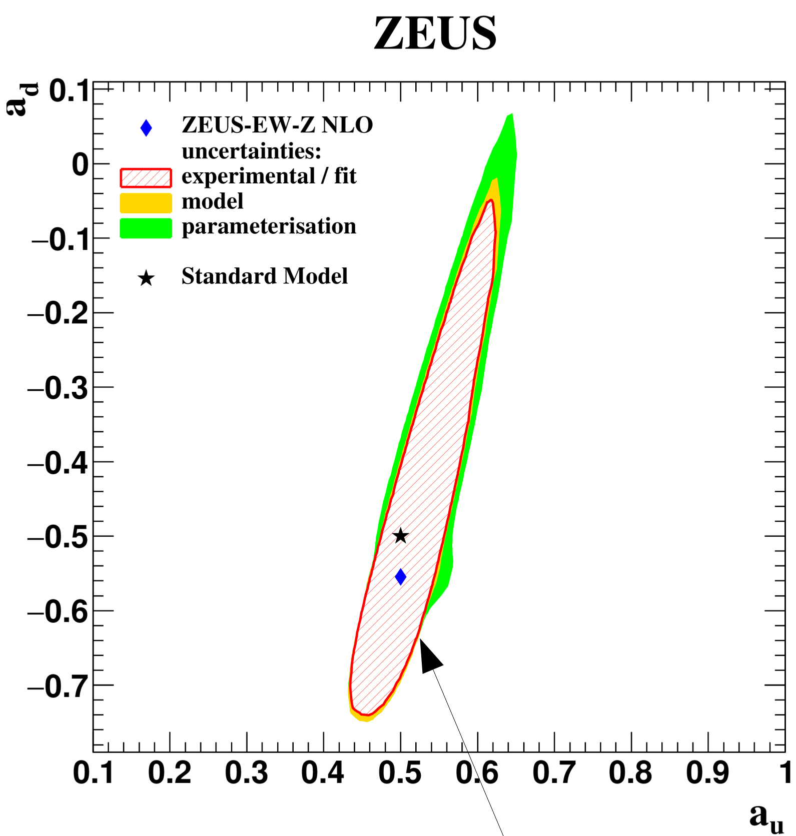


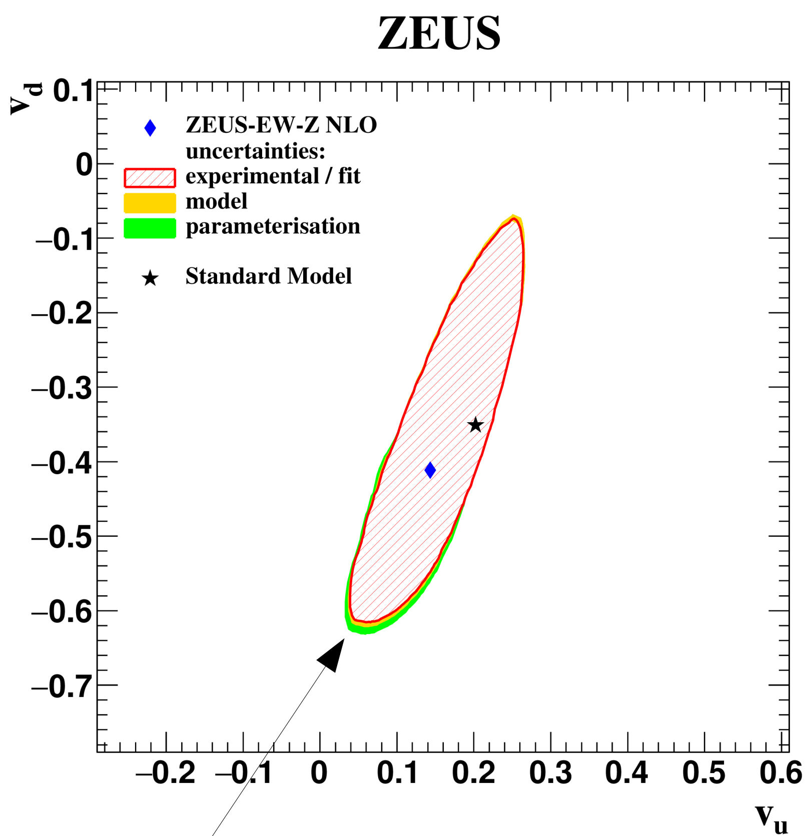


	Standard Model
$a_u = 0.50^{+0.09}_{-0.05}(exp/fit)\,^{+0.04}_{-0.02}(mod)\,^{+0.08}_{-0.01}(par) = \mathbf{0.50^{+0.12}_{-0.05}}(tot)$	**0.5**
$a_d = -0.56^{+0.34}_{-0.14}(exp/fit)\,^{+0.11}_{-0.05}(mod)\,^{+0.20}_{-0.00}(par) = \mathbf{-0.56^{+0.41}_{-0.15}}(tot)$	**-0.5**
$v_u = 0.14^{+0.08}_{-0.08}(exp/fit)\,^{+0.01}_{-0.00}(mod)\,^{+0.03}_{-0.01}(par)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

Couplings of quarks to Z boson

- Vector and axial-vector couplings in the fit show high correlation



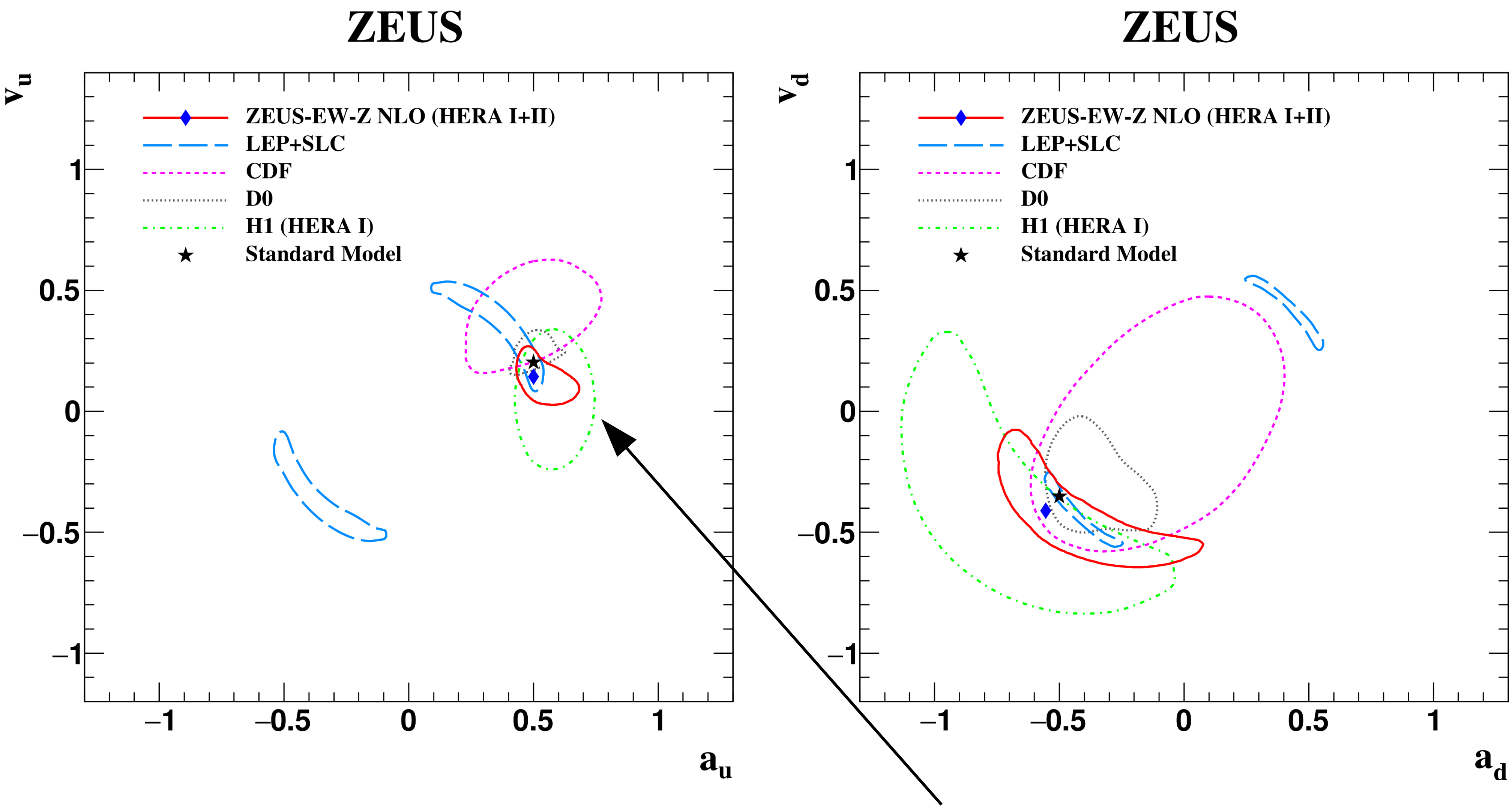


	a_u	a_d	v_u	v_d
a_u	1.000	0.861	−0.555	−0.729
a_d	0.861	1.000	−0.636	−0.880
v_u	−0.555	−0.636	1.000	0.851
v_d	−0.729	−0.880	0.851	1.000

Insignificant correlations of couplings to PDF parameters

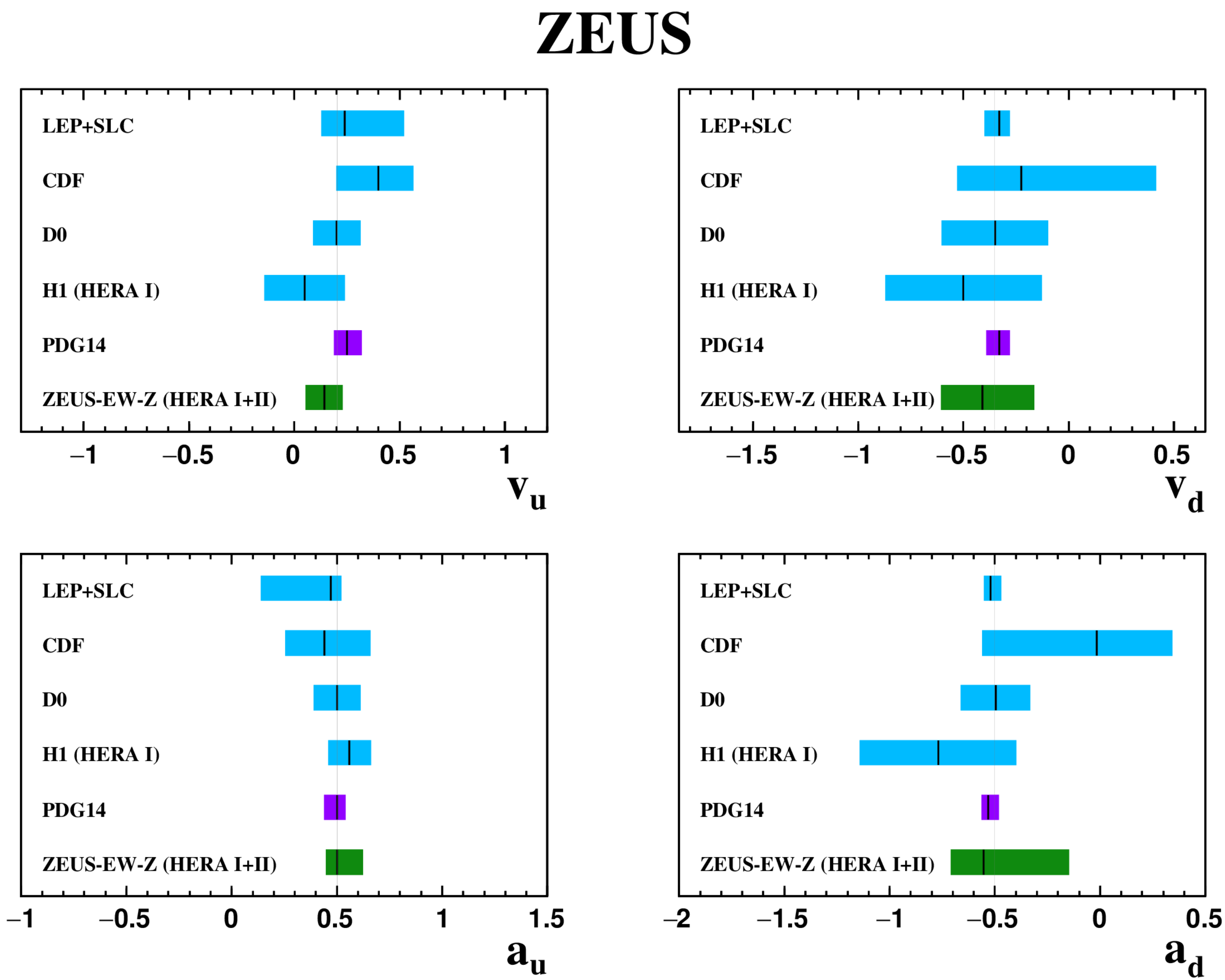
Couplings of quarks to Z boson

- ZEUS-EW-Z results are compatible with previous measurements



- HERA data show remarkable sensitivity to the u-type quark couplings.

Couplings of quarks to Z boson

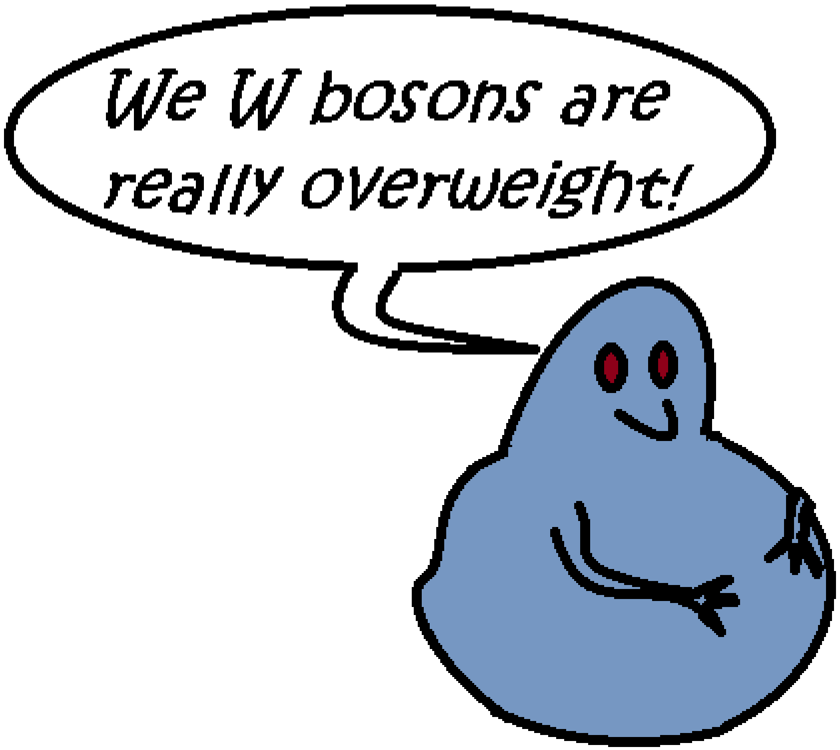


- PDG average values do not yet include current ZEUS-EW-Z results.
- Results presented here have a potential to decrease uncertainties of average values (u-quark in particular)

Mass of W boson

- Mass of W boson was determined simultaneously with PDFs (ZEUS-EW-W)

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



$$M_W^{PDG\ 14} = 80.385 \pm 0.015\, GeV$$

G_F in CC was re-expressed with:

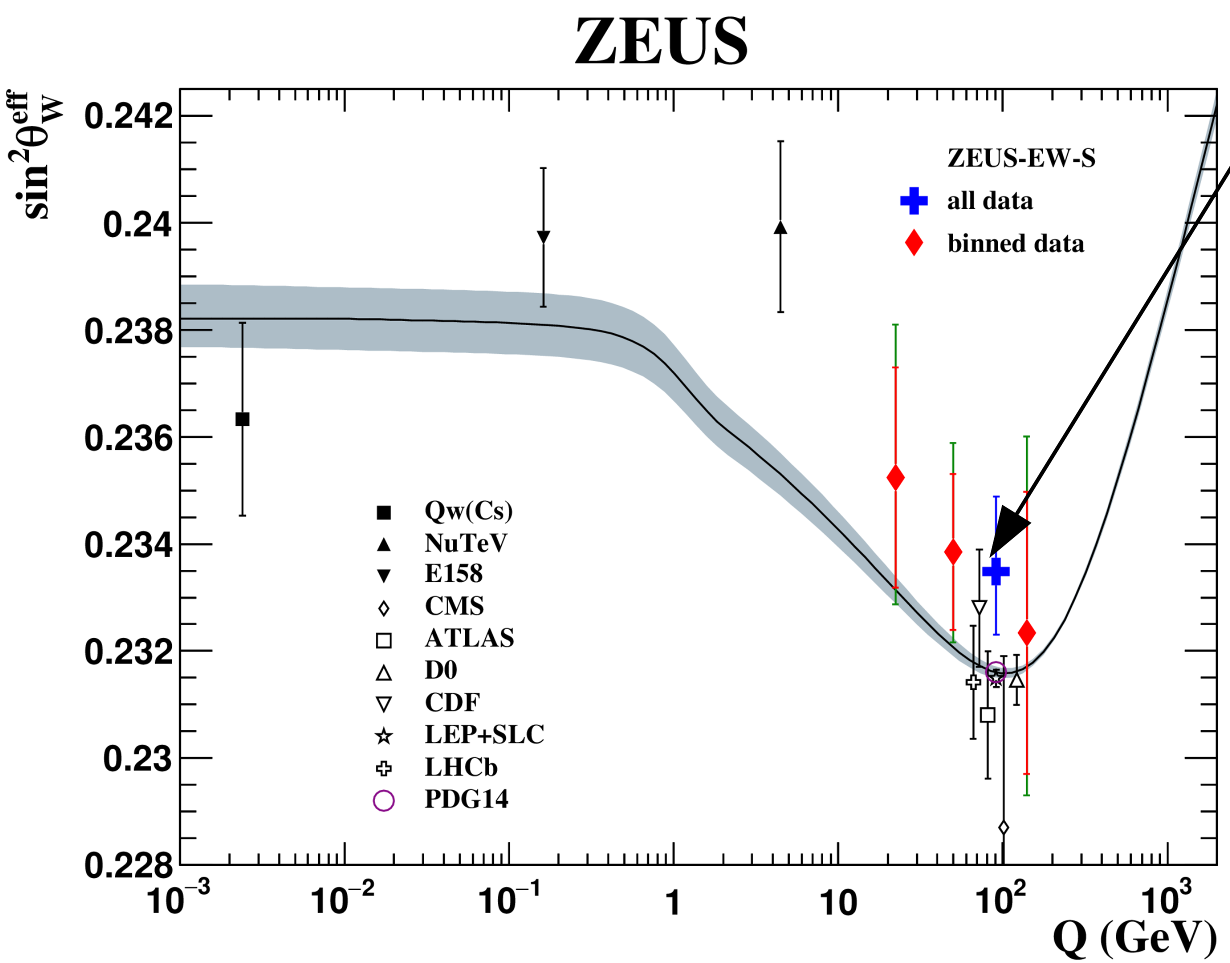
$$G_F = \frac{\pi\alpha}{\sqrt{2}\,\sin^2\theta_W M_W^2}\frac{1}{1-\Delta R}$$

- M_W form ZEUS-EW-W is consistent with current world average.

$\sin^2\theta_W$ from HERA data

- $\sin^2\theta_W$ was determined simultaneously with PDFs (ZEUS-EW-S)

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



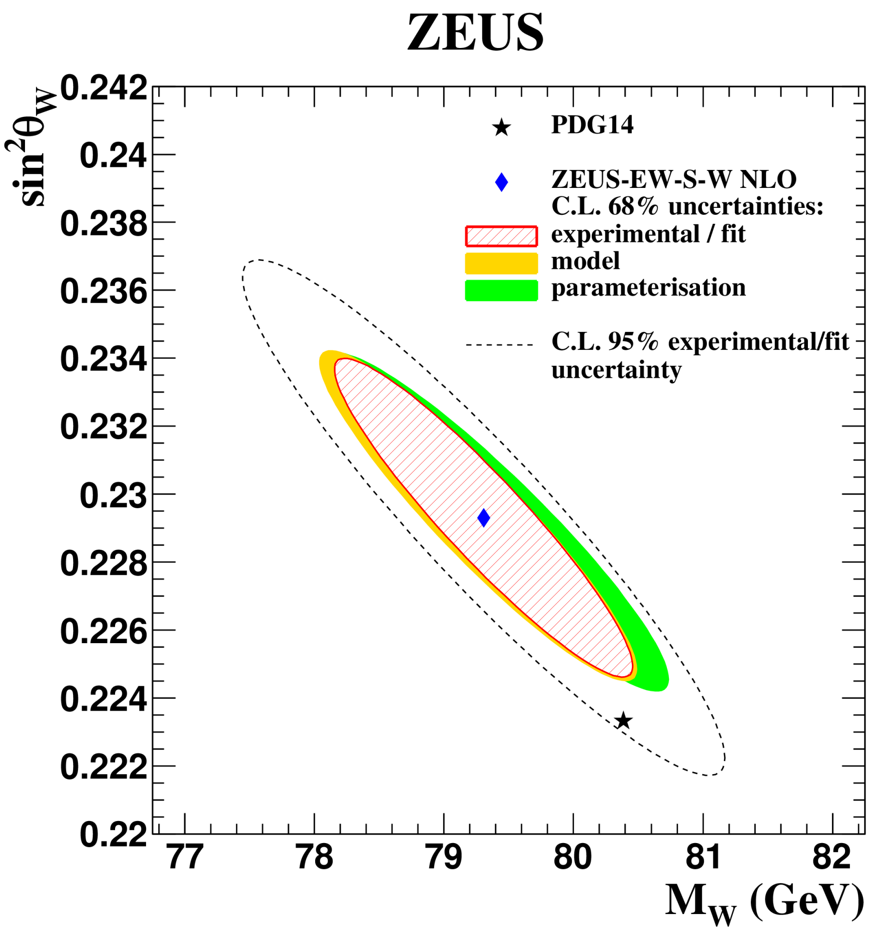
$$\sin^2\theta_W^{PDG\,14\,On-shell} = 0.22333 \pm 0.00011$$

- First confirmation of $\sin^2\theta_W$ running from a single machine.

- On-shell measurements were translated to $\sin^2\theta_W^{eff}$.

$\sin^2\theta_W$ and mass of W boson

- $\sin^2\theta_W$ and M_W were determined simultaneously with PDFs (ZEUS-EW-S-W)



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

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

$$corr(M_W, \sin^2\theta_W) = -0.930$$

$$M_W^{PDG\,14} = 80.385 \pm 0.015\, GeV$$

$$\sin^2\theta_W^{PDG\,14\,On-shell} = 0.22333 \pm 0.00011$$

- All extracted quantities agree with World average values.

Summary

- The simultaneous QCD and EW analysis of HERA data was performed.

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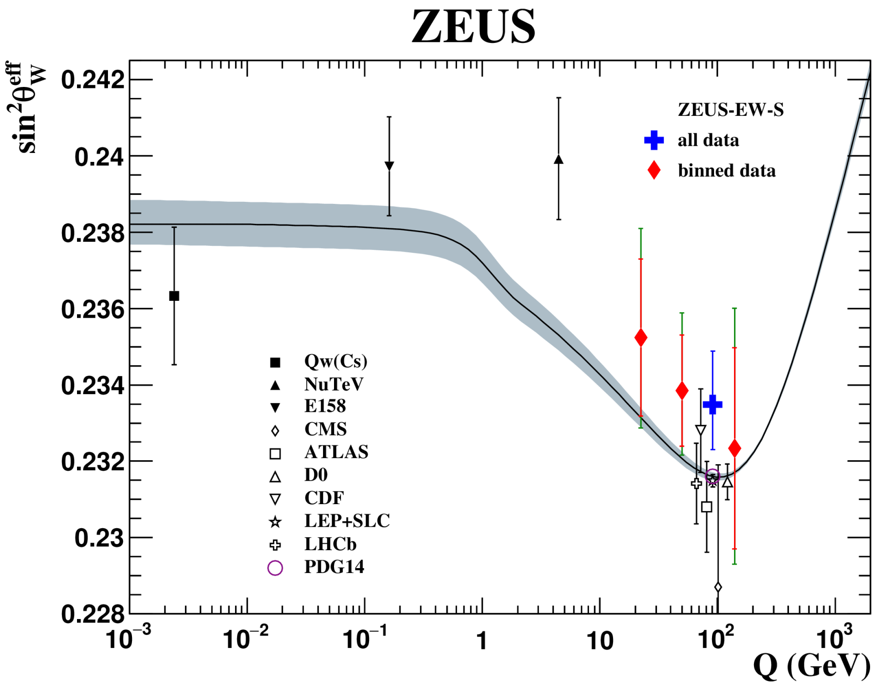
- Couplings of u- and d-type quarks to Z boson were determined:
  - Fitted couplings are consistent with SM predictions;
  - Results are compatible with those from other measurements;
  - Couplings of u-quarks are constrained significantly better than those of d-quarks.

- $\sin^2\theta_W$ at on-shell scheme was determined:
  - Fitted value is competitive with measurements from other experiments;
  - Result is consistent with current world average.

- Mass of W boson was determined:
  - Fitted value of M_W is consistent with current world average.



Backup

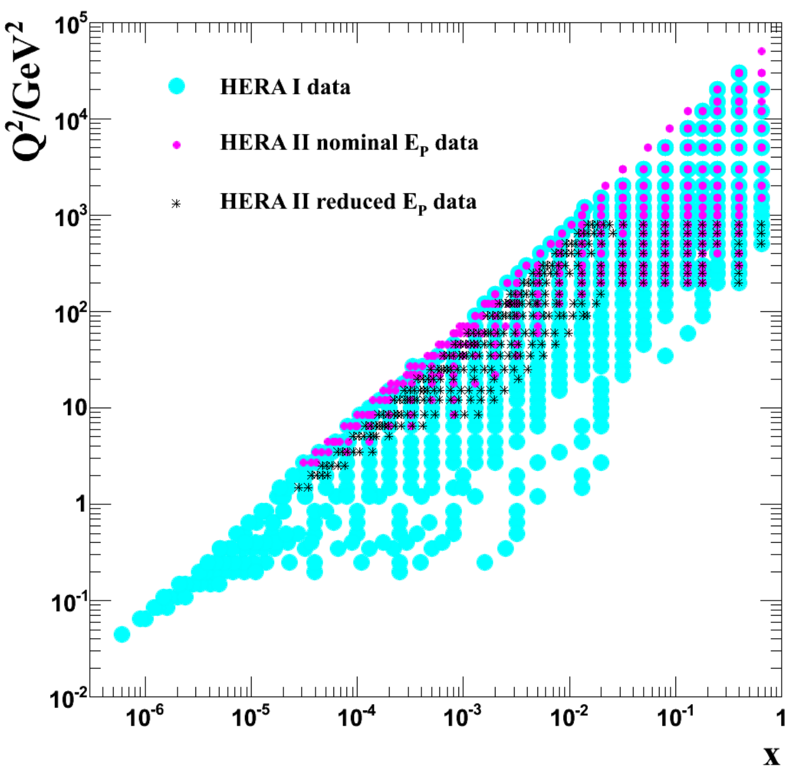
not necessarily useful...

Full HERA data collection

HERAPDF1.0

HERAPDF1.5

HERAPDF2.0



Data Set		x_{Bj} Grid from	to	Q^2[GeV^2] Grid from	to	$\mathcal{L}$ pb^{-1}	e^+/e^-	$\sqrt{s}$ GeV
HERA I E_p = 820 GeV and E_p = 920 GeV data sets								
H1 svx-mb	95-00	0.000005	0.02	0.2	12	2.1	e^+p	301, 319
H1 low Q^2	96-00	0.0002	0.1	12	150	22	e^+p	301, 319
H1 NC	94-97	0.0032	0.65	150	30000	35.6	e^+p	301
H1 CC	94-97	0.013	0.40	300	15000	35.6	e^+p	301
H1 NC	98-99	0.0032	0.65	150	30000	16.4	e^-p	319
H1 CC	98-99	0.013	0.40	300	15000	16.4	e^-p	319
H1 NC HY	98-99	0.0013	0.01	100	800	16.4	e^-p	319
H1 NC	99-00	0.0013	0.65	100	30000	65.2	e^+p	319
H1 CC	99-00	0.013	0.40	300	15000	65.2	e^+p	319
ZEUS BPC	95	0.000002	0.00006	0.11	0.65	1.65	e^+p	300
ZEUS BPT	97	0.0000006	0.001	0.045	0.65	3.9	e^+p	300
ZEUS SVX	95	0.000012	0.0019	0.6	17	0.2	e^+p	300
ZEUS NC	96-97	0.00006	0.65	2.7	30000	30.0	e^+p	300
ZEUS CC	94-97	0.015	0.42	280	17000	47.7	e^+p	300
ZEUS NC	98-99	0.005	0.65	200	30000	15.9	e^-p	318
ZEUS CC	98-99	0.015	0.42	280	30000	16.4	e^-p	318
ZEUS NC	99-00	0.005	0.65	200	30000	63.2	e^+p	318
ZEUS CC	99-00	0.008	0.42	280	17000	60.9	e^+p	318
HERA II E_p = 920 GeV data sets								
H1 NC $^{1.5p}$	03-07	0.0008	0.65	60	30000	182	e^+p	319
H1 CC $^{1.5p}$	03-07	0.008	0.40	300	15000	182	e^+p	319
H1 NC $^{1.5p}$	03-07	0.0008	0.65	60	50000	151.7	e^-p	319
H1 CC $^{1.5p}$	03-07	0.008	0.40	300	30000	151.7	e^-p	319
H1 NC med Q^2 $^{*y.5}$	03-07	0.0000986	0.005	8.5	90	97.6	e^+p	319
H1 NC low Q^2 $^{*y.5}$	03-07	0.000029	0.00032	2.5	12	5.9	e^+p	319
ZEUS NC	06-07	0.005	0.65	200	30000	135.5	e^+p	318
ZEUS CC $^{1.5p}$	06-07	0.0078	0.42	280	30000	132	e^+p	318
ZEUS NC $^{1.5}$	05-06	0.005	0.65	200	30000	169.9	e^-p	318
ZEUS CC $^{1.5}$	04-06	0.015	0.65	280	30000	175	e^-p	318
ZEUS NC nominal ^{*y}	06-07	0.000092	0.008343	7	110	44.5	e^+p	318
ZEUS NC satellite ^{*y}	06-07	0.000071	0.008343	5	110	44.5	e^+p	318
HERA II E_p = 575 GeV data sets								
H1 NC high Q^2	07	0.00065	0.65	35	800	5.4	e^+p	252
H1 NC low Q^2	07	0.0000279	0.0148	1.5	90	5.9	e^+p	252
ZEUS NC nominal	07	0.000147	0.013349	7	110	7.1	e^+p	251
ZEUS NC satellite	07	0.000125	0.013349	5	110	7.1	e^+p	251
HERA II E_p = 460 GeV data sets								
H1 NC high Q^2	07	0.00081	0.65	35	800	11.8	e^+p	225
H1 NC low Q^2	07	0.0000348	0.0148	1.5	90	12.2	e^+p	225
ZEUS NC nominal	07	0.000184	0.016686	7	110	13.9	e^+p	225
ZEUS NC satellite	07	0.000143	0.016686	5	110	13.9	e^+p	225

Full HERA I data

HERA II data HER

HERA II data LER

- All inclusive DIS results are final and published!

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

Effect of PDFs determination on couplings

- Couplings, fitted at fixed PDFs are well compatible with those from ZEUS-EW-Z fit.

	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	$+.500$			$-.500$			$+.202$			$-.351$		

- Differences in the experimental uncertainties can give a rough estimate of PDF uncertainties in the measurement.

* HERAPDF2.0 used $\sin^2\theta_W$ @ $\overline{MS}$ - HPDF2, this analysis uses $\sin^2\theta_W$ @ On-schell - HPDF1.
The influence of $\sin^2\theta_W$ for PDF extraction only is minimal (checked).

On $\sin^2\theta_W$(+X) fits to DIS data

- DIS inclusive cross sections depend on $\sin^2\theta_W$ through:
  - Z propagator in NC cross sections;
  - Vector couplings of Z to quarks;

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

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

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

  - W propagator (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.

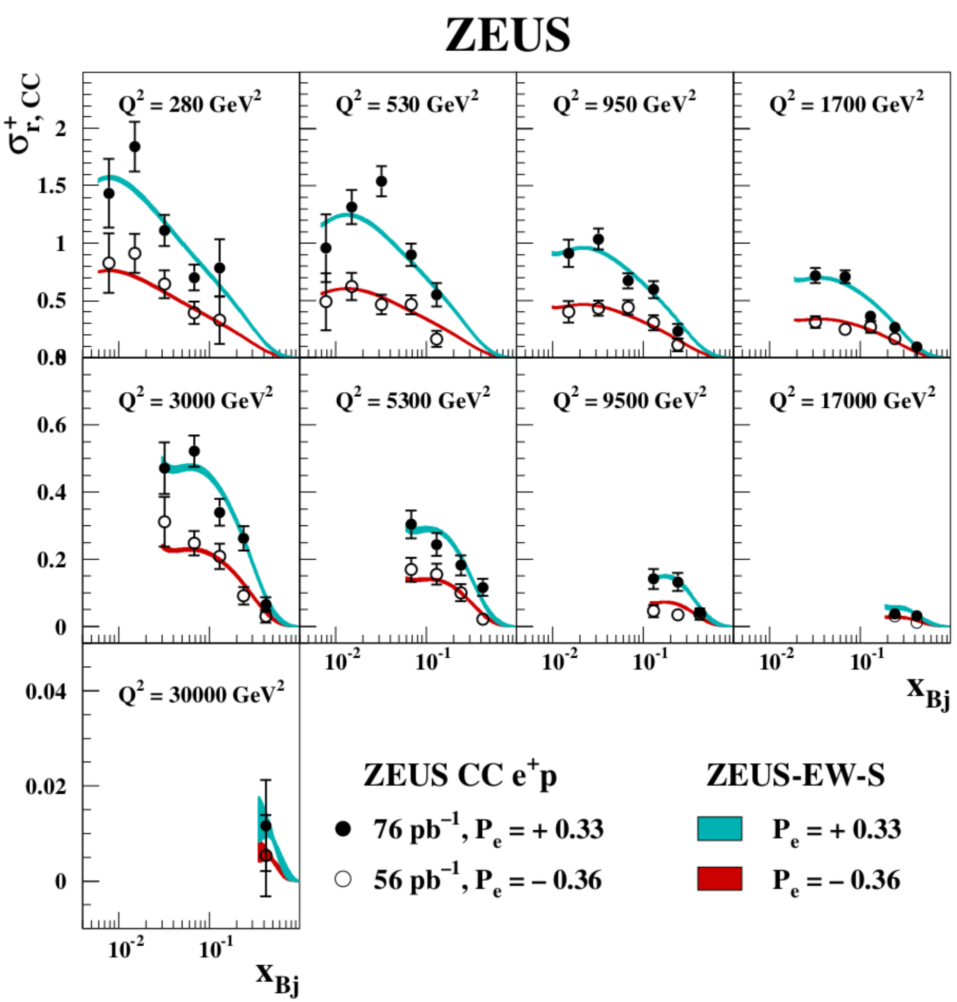
arXiv:hep-ph/9902277

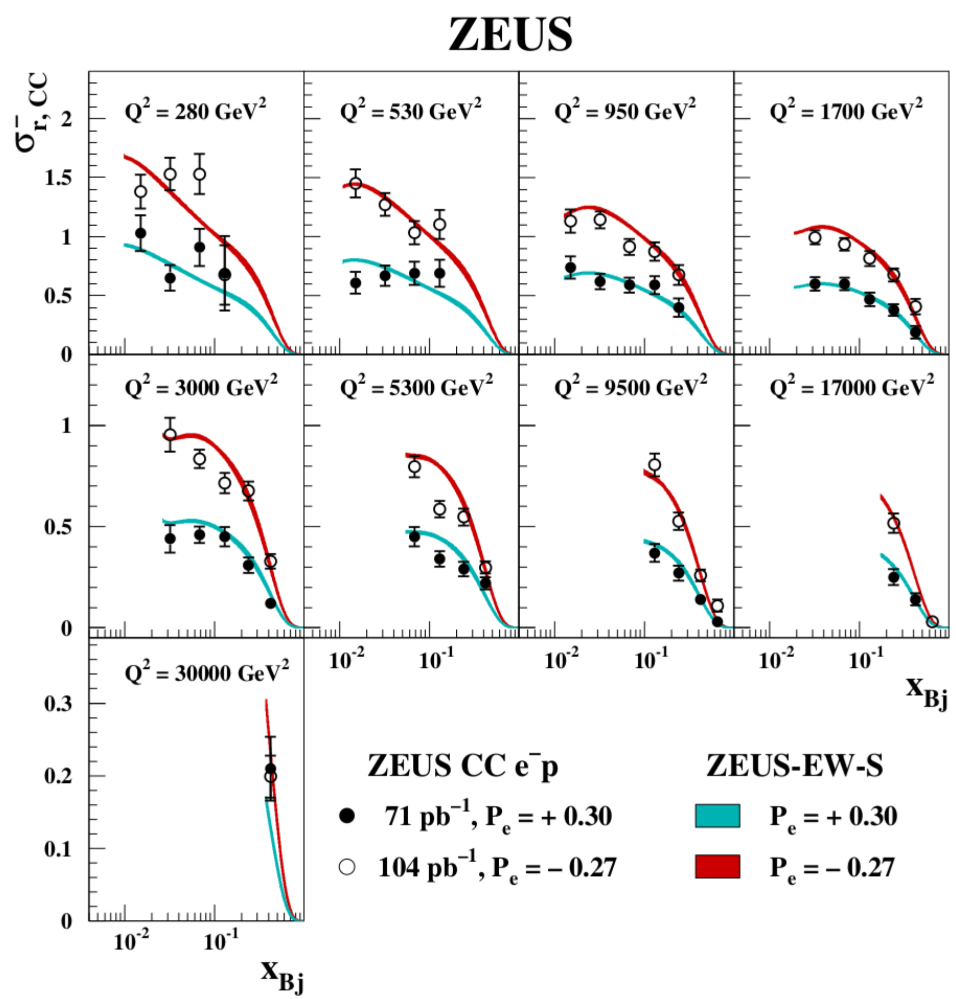
- Re-expressing G_F through $\sin^2\theta_W$ and M_W allows to use both CC and NC for $\sin^2\theta_W$ determination.

- Current analysis exploits all three dependences for $\sin^2\theta_W$ extraction.
- $\sin^2\theta_W$ values extracted in current analysis correspond to On-shell scheme.

Data description (ZEUS-EW-S)

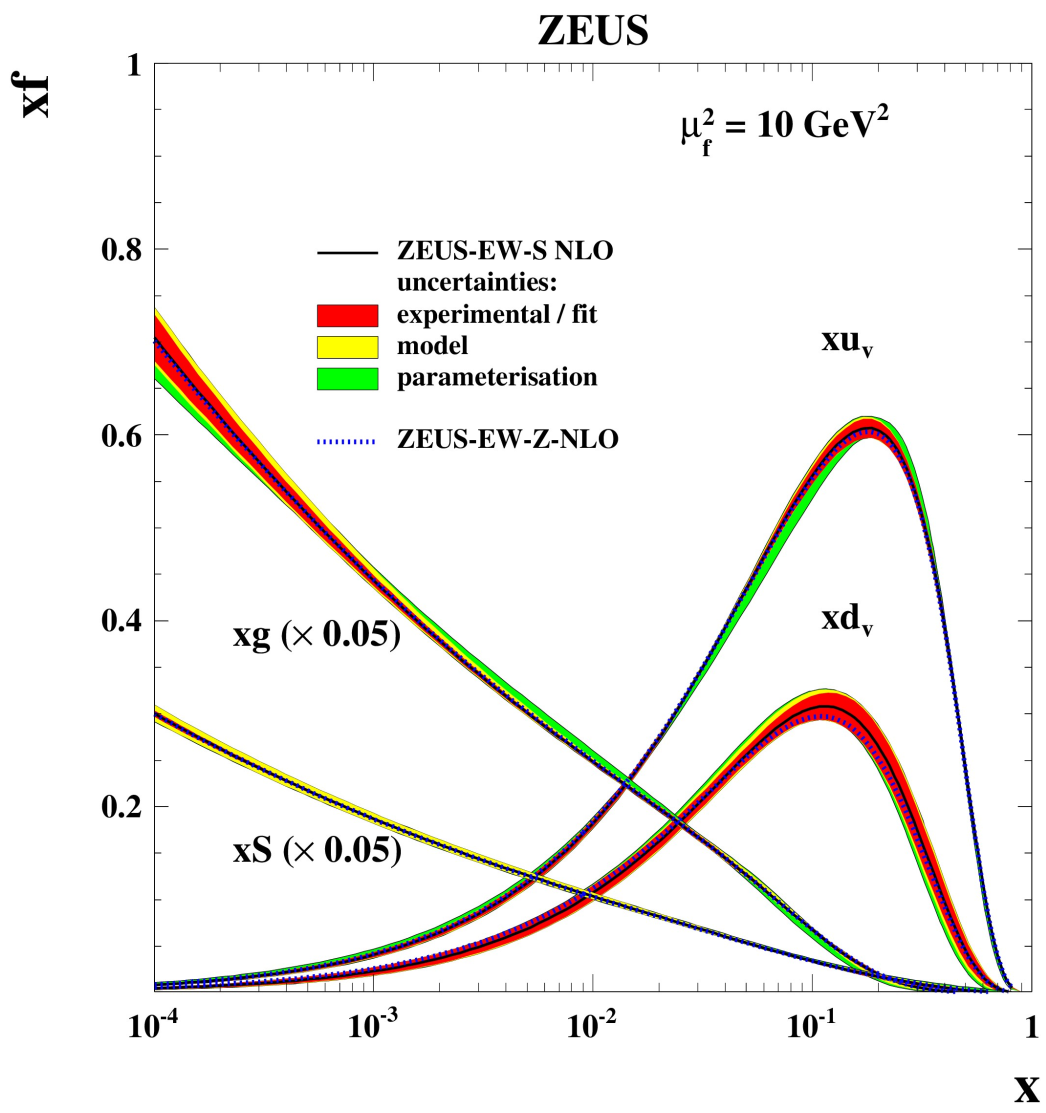
- Fitted predictions describe data reasonably well.





- χ^2 = 3270 / 2928 = 1.118

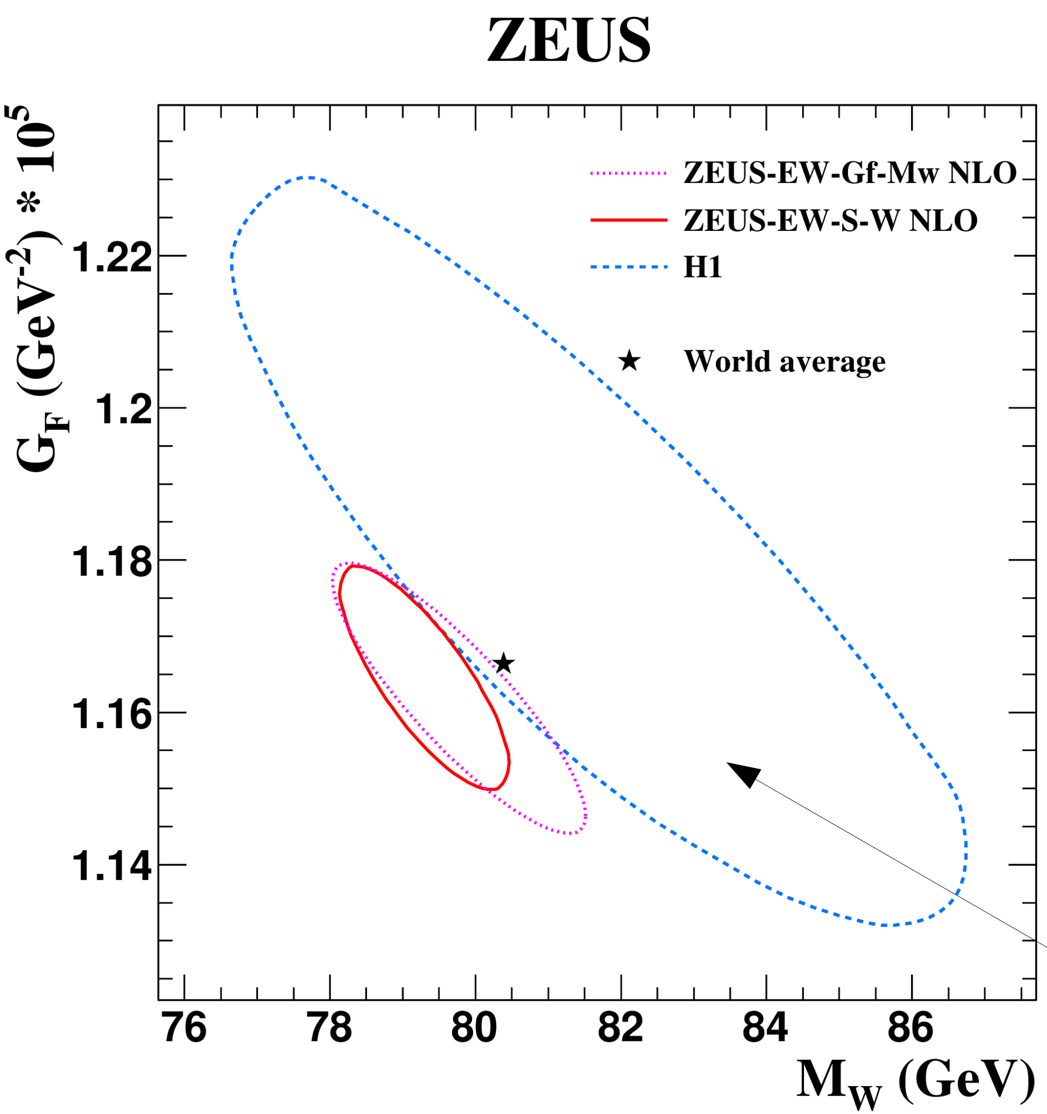
ZEUS-EW-Z vs ZEUS-EW-S



- PDFs from ZEUS-EW-Z and ZEUS-EW-S agree very well.

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.

Quark couplings to Z

Now consider fits to electroweak NC couplings as well as PDF parameters

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

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

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

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

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

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

$$P_Z = \frac{1}{\sin^2 2\theta} \frac{Q^2}{(M_Z^2+Q^2)}$$

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

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

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

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

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

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

→

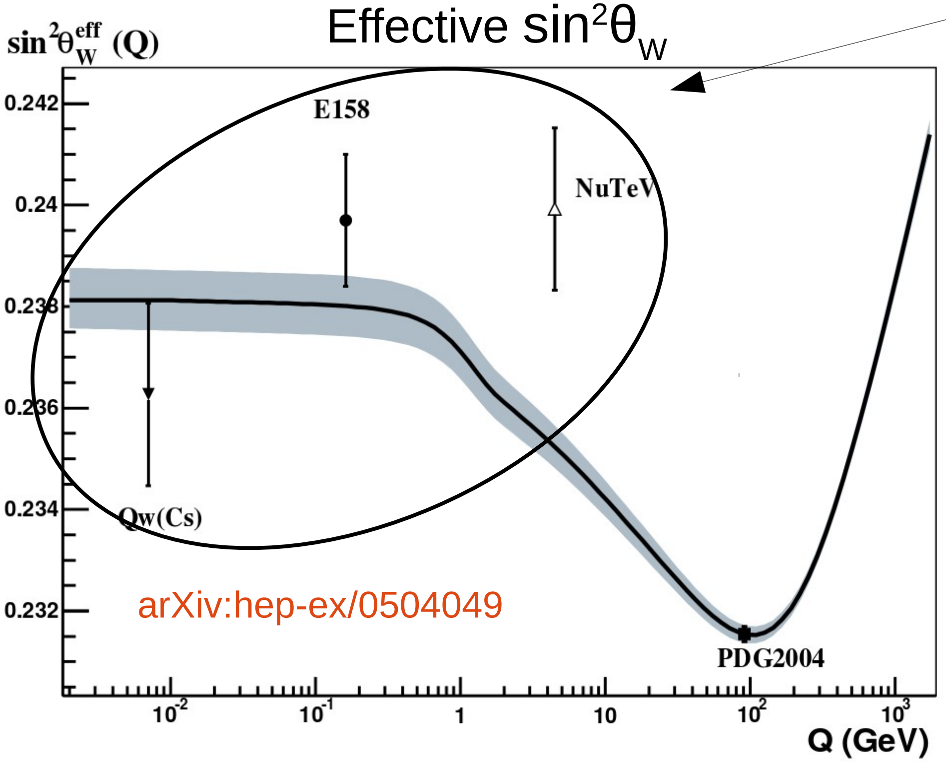
unpolarized $xF_3 \rightarrow a_i$,
polarized $F_2 \rightarrow v_i$

From slides by Amanda Cooper-Sarkar

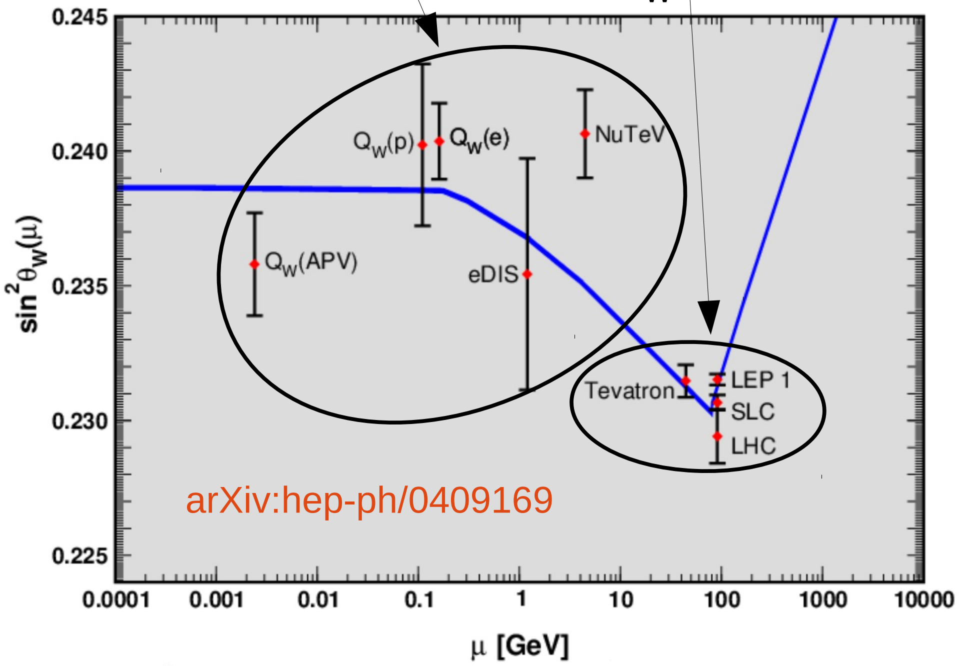
On $\sin^2\theta_W$ running with a scale

- All the measurements were so far done either at the scale μ <≈ 1 GeV or μ = M_Z.

Effective $\sin^2\theta_W$



$\overline{MS}$ $\sin^2\theta_W$



Both of the variants more-or-less follow the same approach:

$$1-4\kappa(Q^2)\sin^2\theta_W(M_Z)=1-4(Q^2)\sin^2\theta_W(Q^2)$$

$$\kappa=\kappa_f(Q^2,\alpha,T_{3f},Q_f,m_f,M_Z)+\kappa_b(Q^2,\alpha,M_W)$$ ← Fermion and boson loop.