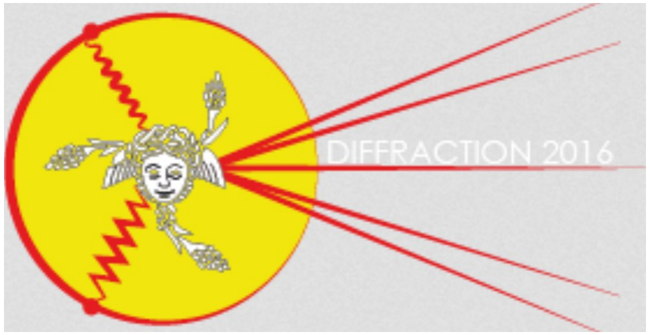
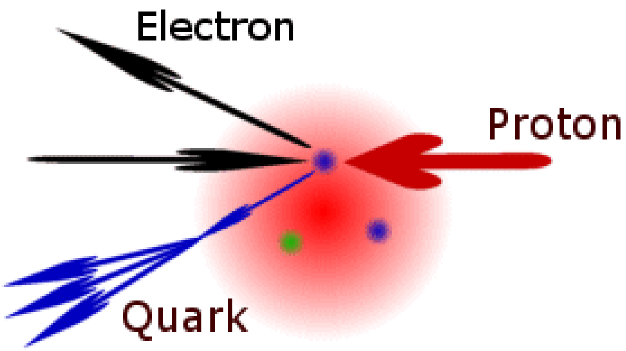
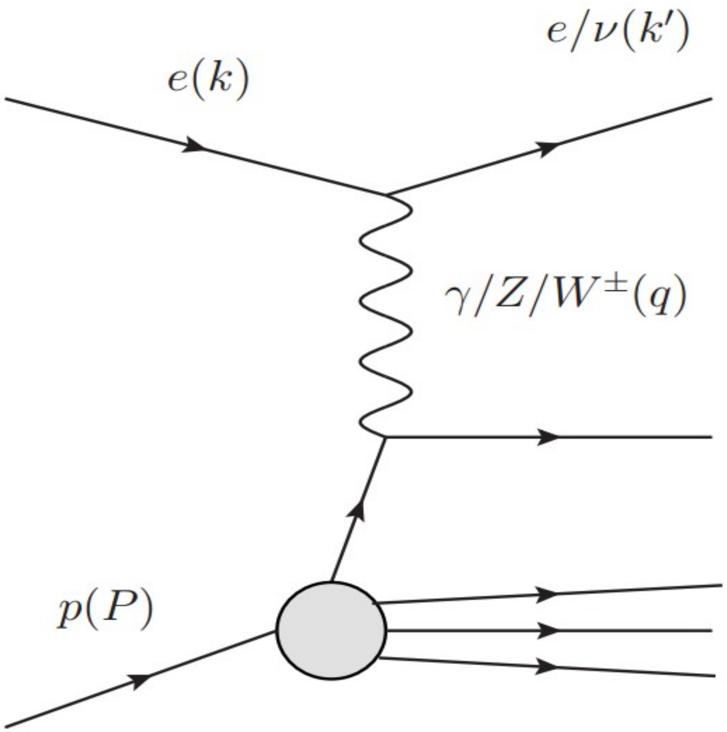




Simultaneous QCD & Electroweak fits to HERA inclusive DIS data

K. Wichmann on behalf of H1 & ZEUS collaborations

Deep Inelastic Scattering at HERA



- Lepton beams polarised for HERAII
  → crucial for the EW measurements

$$E_P = 920(820, 460, 575)\,GeV$$
$$E_e = 27.5\,GeV$$

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

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

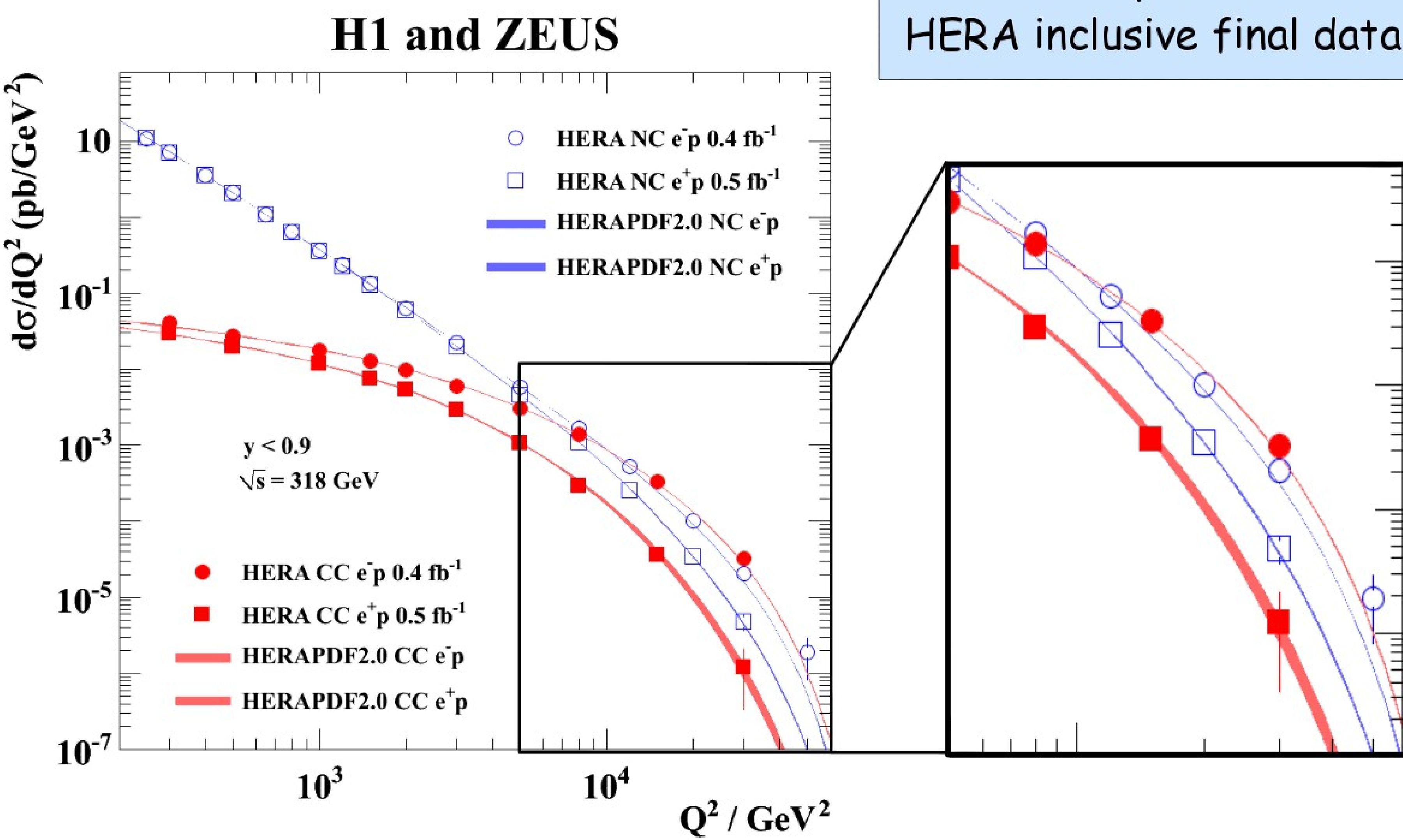
$$x_{Bj} = \frac{Q^2}{2\,pq} \qquad y = \frac{pq}{pk}$$

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

Experimental luminosity (H1 & ZEUS):

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

Fantastic precision of HERA inclusive final data



- NC and CC at tree level

$$Y_\pm = 1 \pm (1-y)^2$$

$$\frac{d\sigma_{NC}^{\pm}}{dQ^2\,dx} = \frac{2\pi\alpha^2}{x}\left[\frac{1}{Q^2}\right]^2 \left(Y_+ \boldsymbol{F}_2 + Y_- x \boldsymbol{F}_3 + y^2 \boldsymbol{F}_L\right)$$

$$\frac{d\sigma_{CC}^{\pm}}{dQ^2\,dx} = \frac{1\pm P}{2}\,\frac{G_F^2}{4\pi x}\left[\frac{m_W^2}{m_W^2+Q^2}\right]^2 \left(Y_+ \boldsymbol{W}_2^{\pm} \pm Y_- x \boldsymbol{W}_3^{\pm} - y^2 \boldsymbol{W}_L^{\pm}\right)$$

Polarised DIS

- Generalised structure functions depend on e-beam polarisation

$$P_e = \frac{N_R - N_L}{N_R + N_L}$$

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

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

- Structure functions in QP model

NC

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

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

NC sensitive to $\sin^2\theta_W$ via

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

- Calculation in on-shell scheme

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

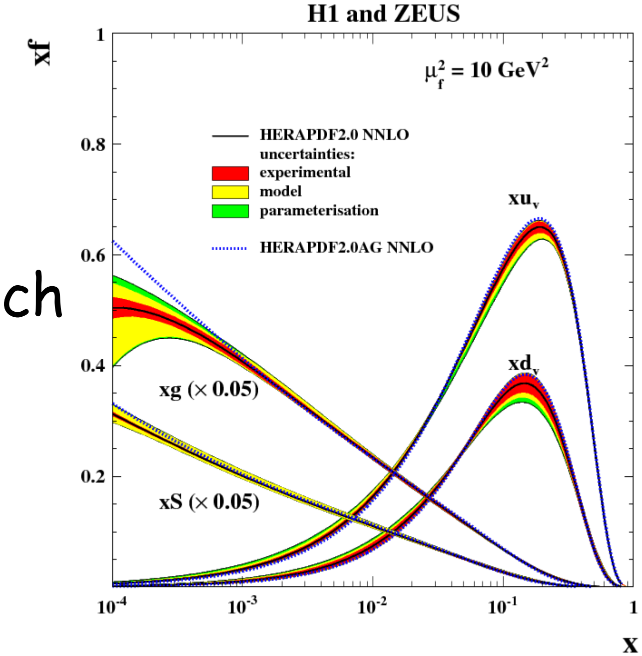
CC

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

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

CC sensitive to $\sin^2\theta_W$

Global QCD fits



- Data: NC & CC, e^+p and e^-p scattering
- Global PDF fits closely follow HERAPDF2.0 approach
- DGLAP evolution using QCDNUM
- 13 parameter fit (HERAPDF2.0 – DUbar)

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

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

- Starting scale Q^2_0 = 1.9 GeV^2
- Model and parameterisation uncertainties → HERAPDF2.0
- Corrections calculated using EPRC code: ΔR

  desy.de/~hspiesb/eprc.html

  - No ISR/FSR corrections

Vector and axial-vector couplings

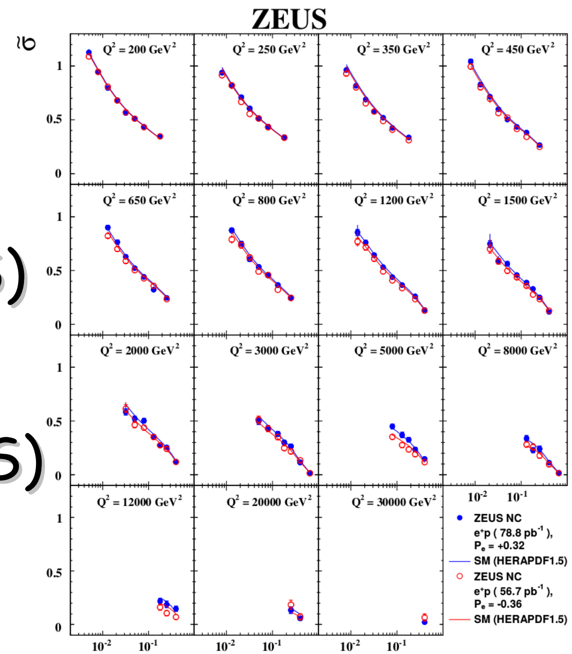
Data used

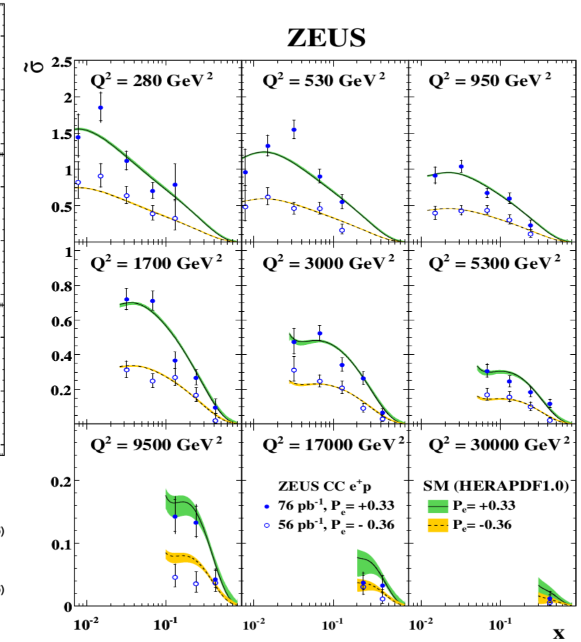
Phys. Rev. D 93 (2016) 092002

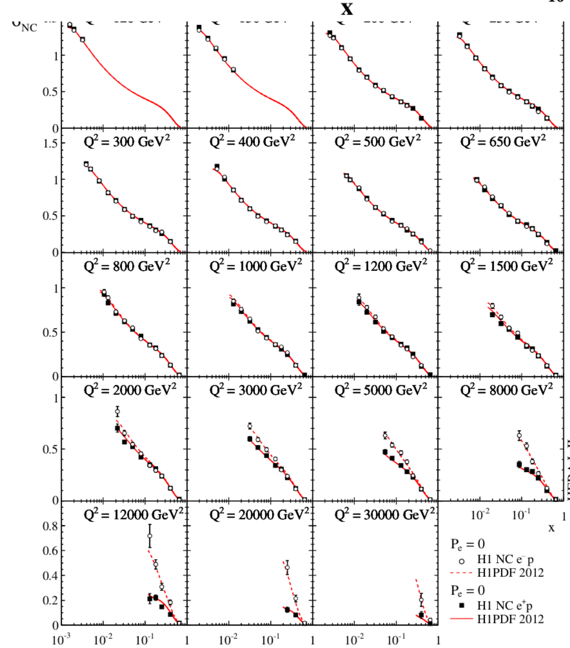
Uncombined data sets

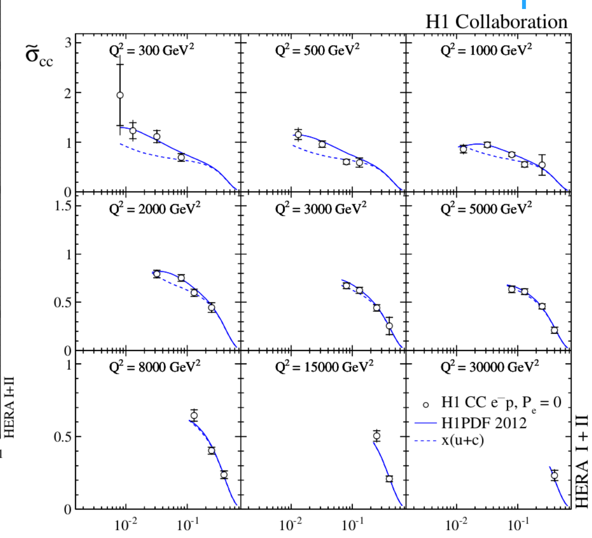
- All HERAI data (H1 & ZEUS)
  - unpolarised
- Reduced E_p data (H1 & ZEUS)
- HERAII
  - H1 unpolarised data
  - ZEUS polarised data

Data from $Q^2 = 3.5$ GeV^2





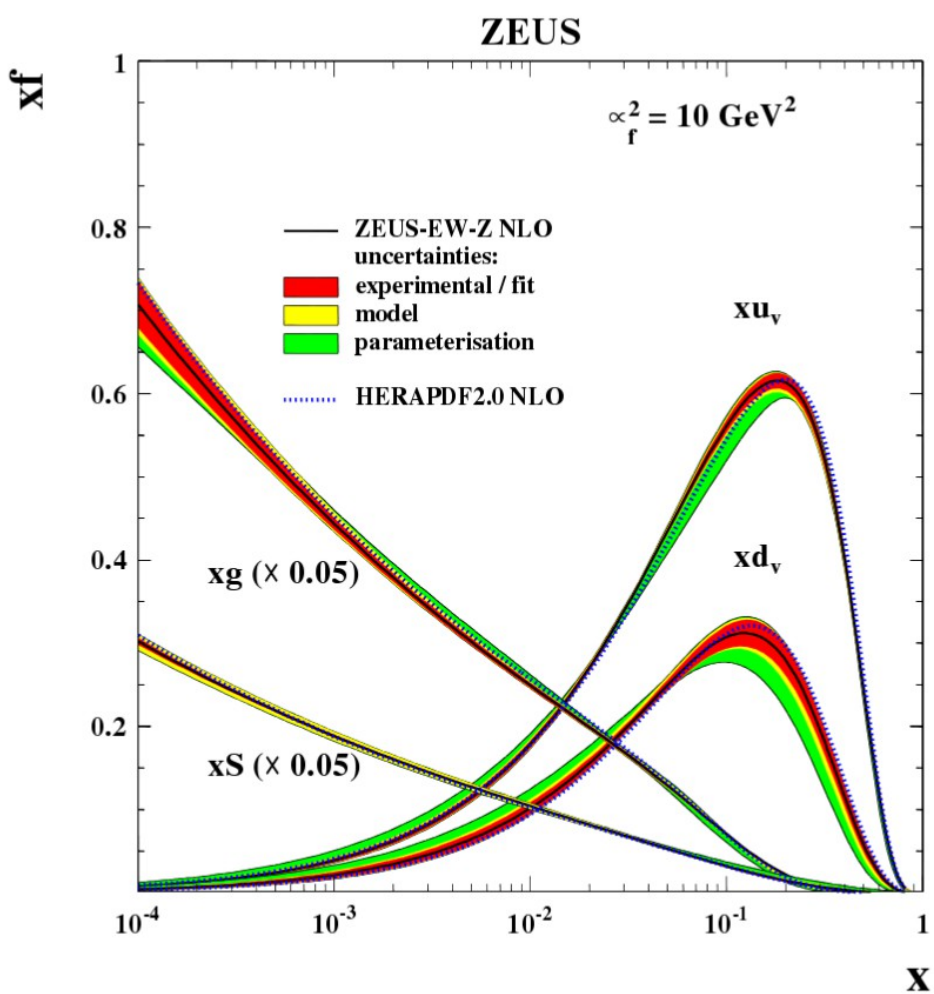


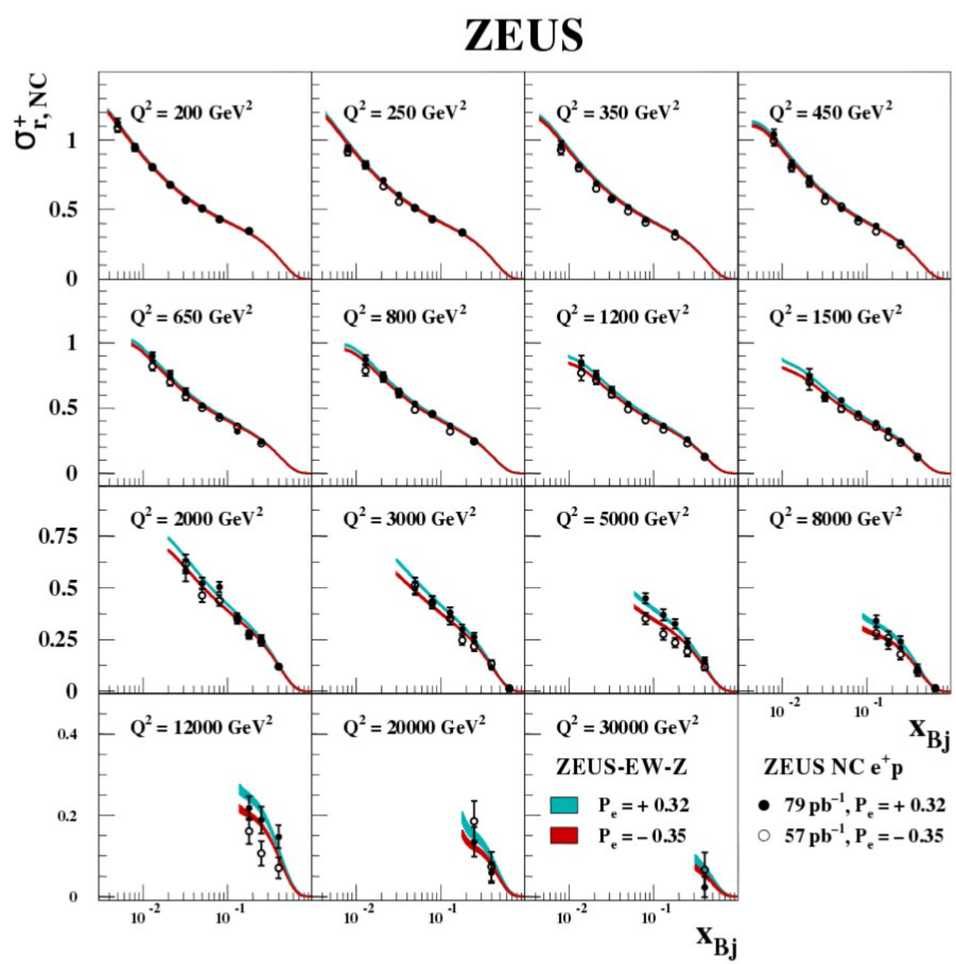


- DGLAP evolution @ NLO
- HF scheme – GN VFNS NLO (RT OPT)

Fit results

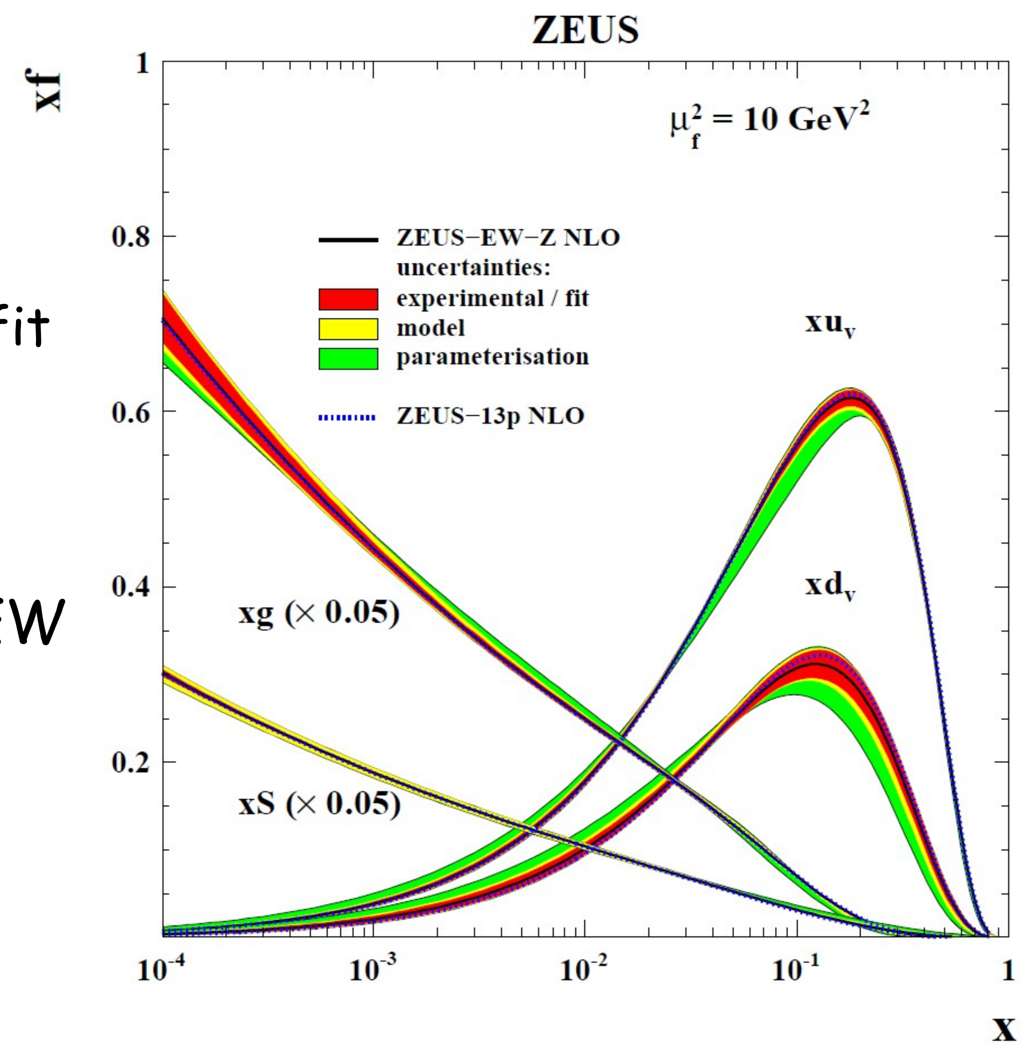
- Simultaneous QCD and EW fit:
  - 13 QCD parameters + 4 EW couplings





QCD & EW parameters uncorrelated

- Reference fit ZEUS-13p:
  - QCD parameters fixed to 13p fit
  - Only 4 EW couplings fitted
- Very similar results
- Correlation between QCD and EW parameters small



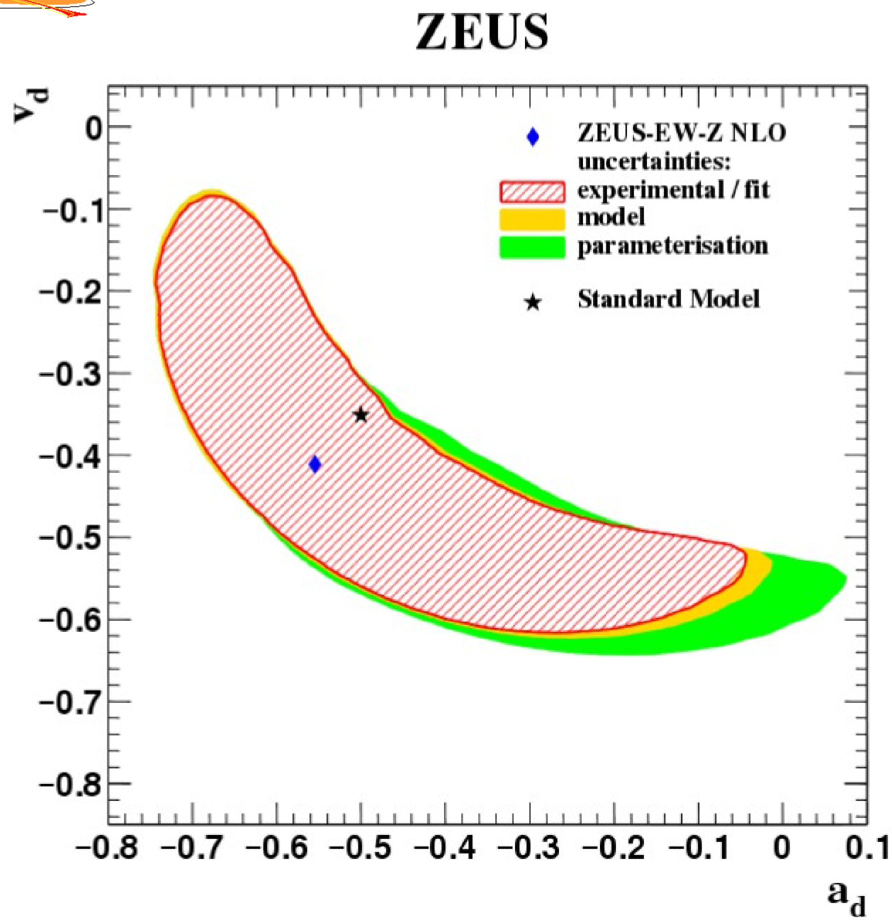
QCD & EW parameters uncorrelated

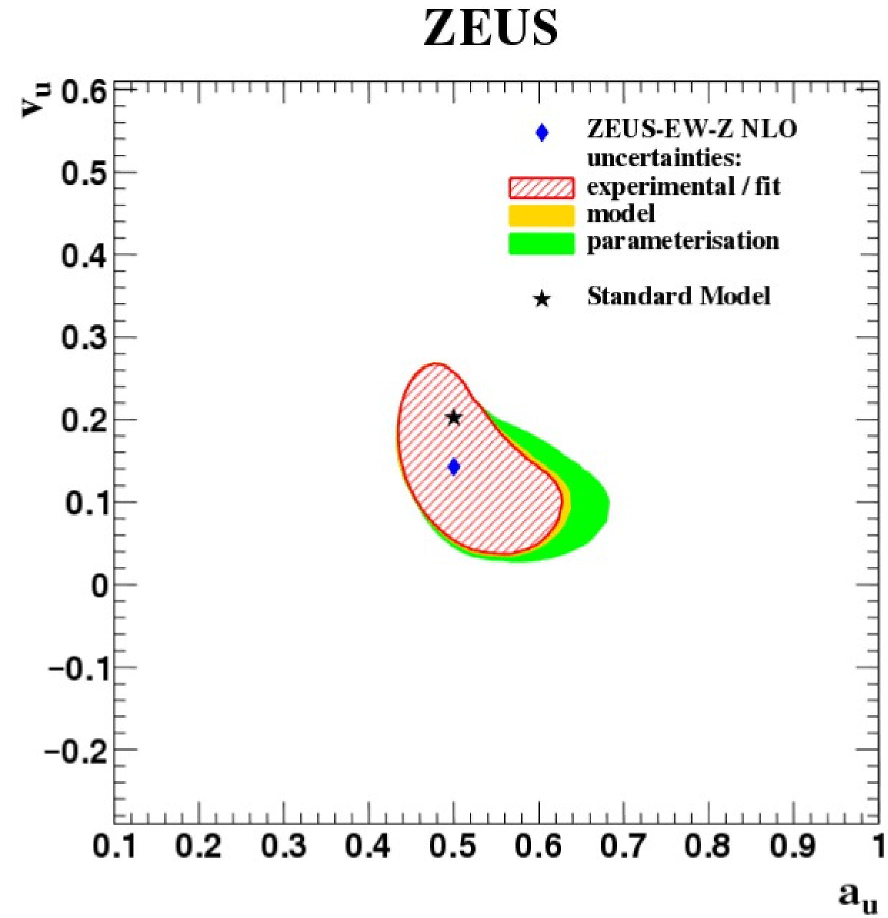
- Detailed studies performed to check stability of EW couplings with respect to various QCD parameters
  - HPDF1: QCD parameters and all constants fixed to HERAPDF2.0
  - HPDF2: QCD parameters fixed to HERAPDF2.0 + on-shell value of $\sin^2\theta_W$
  - 13p – reference fit described before

→ Results for couplings very similar

	a_u	exp	tot	a_d	exp	tot	v_u	exp	tot	v_d	exp	tot
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	$^{+0.24}_{-0.16}$	$^{+0.25}_{-0.20}$
13p	+0.49	$^{+0.07}_{-0.04}$		−0.57	$^{+0.30}_{-0.13}$		+0.15	$^{+0.08}_{-0.08}$		−0.40	$^{+0.22}_{-0.17}$	
HPDF1	+0.47	$^{+0.06}_{-0.03}$		−0.62	$^{+0.23}_{-0.11}$		+0.16	$^{+0.08}_{-0.08}$		−0.35	$^{+0.22}_{-0.19}$	
HPDF2	+0.49	$^{+0.06}_{-0.03}$		−0.63	$^{+0.24}_{-0.11}$		+0.15	$^{+0.08}_{-0.08}$		−0.36	$^{+0.22}_{-0.19}$	
SM	+0.50			−0.50			+0.20			−0.35		

Correlations

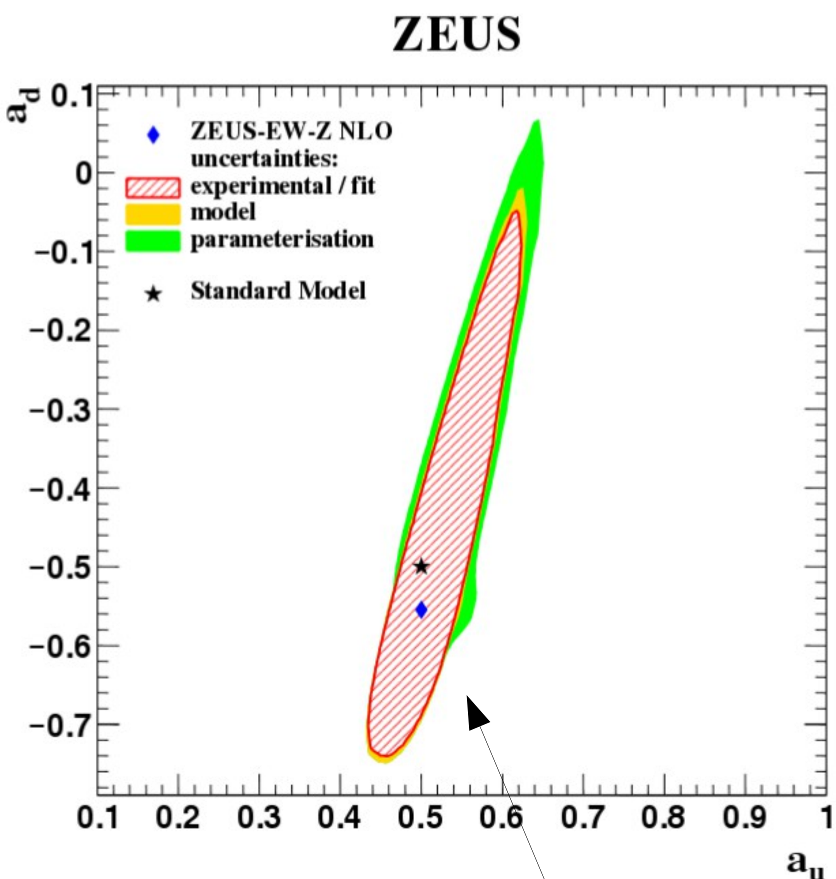


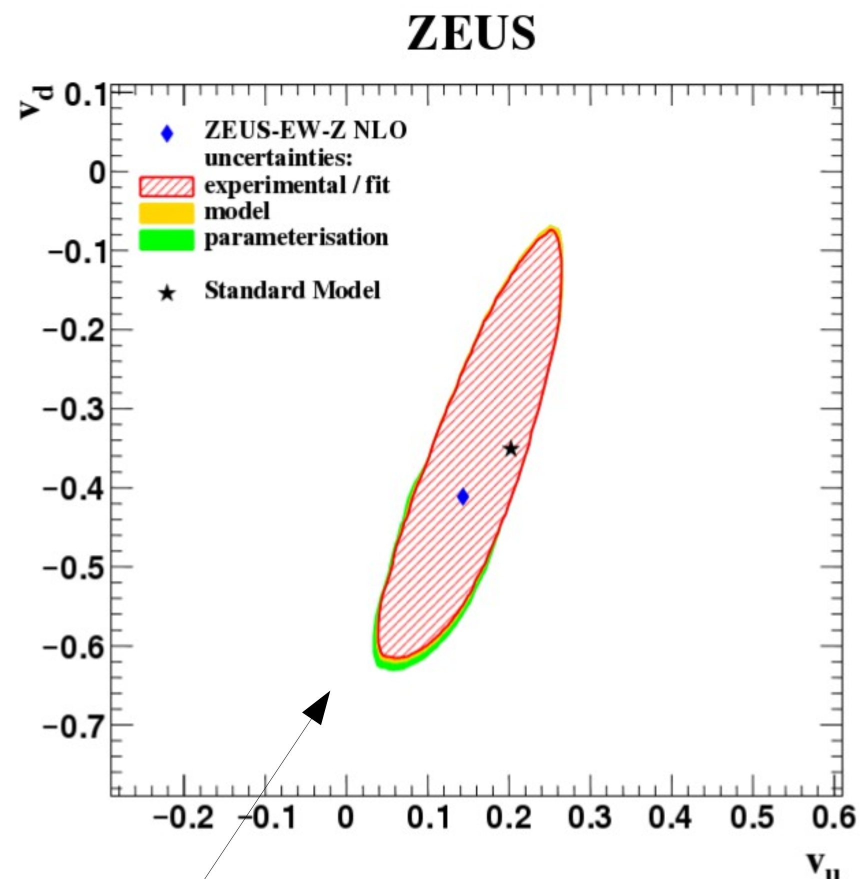


	Standard Model
$a_u = 0.50^{+0.09}_{-0.05}(exp/fit)\,^{+0.04}_{-0.02}(mod)\,^{+0.08}_{-0.01}(par) = \mathbf{0.50^{+0.12}_{-0.05}}(tot)$	**0.5**
$a_d = -0.56^{+0.34}_{-0.14}(exp/fit)\,^{+0.11}_{-0.05}(mod)\,^{+0.20}_{-0.00}(par) = \mathbf{-0.56^{+0.41}_{-0.15}}(tot)$	**-0.5**
$v_u = 0.14^{+0.08}_{-0.08}(exp/fit)\,^{+0.01}_{-0.00}(mod)\,^{+0.03}_{-0.01}(par)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

Correlations

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

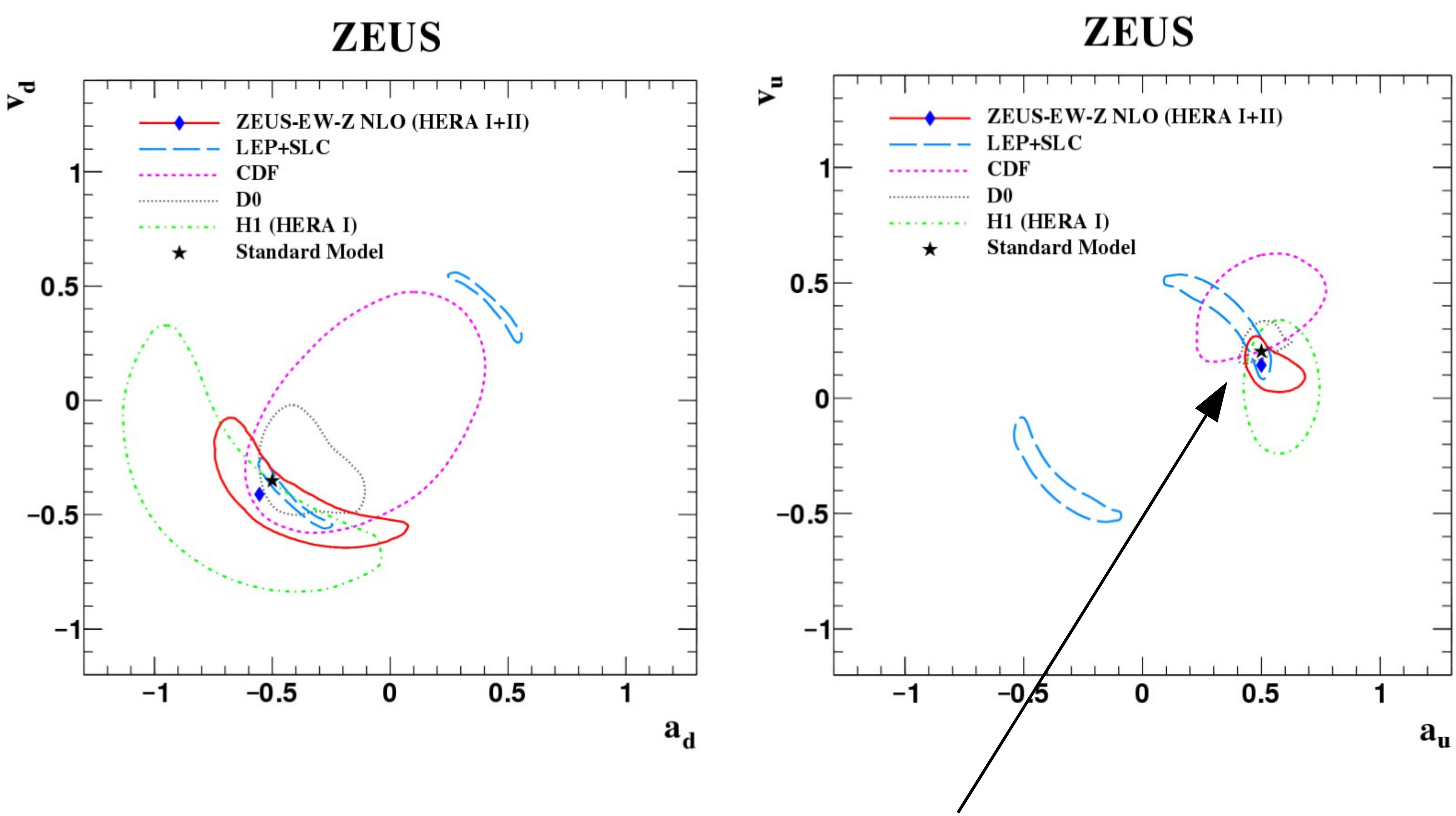




	a_u	a_d	v_u	v_d
a_u	1.000	0.861	−0.555	−0.729
a_d	0.861	1.000	−0.636	−0.880
v_u	−0.555	−0.636	1.000	0.851
v_d	−0.729	−0.880	0.851	1.000

Insignificant correlations of couplings to PDF parameters

Comparison with other measurements



HERA data remarkably sensitive to u-type quark couplings

H1 fit methodology

H1prelim-16-041

- Lots of basics same as in ZEUS measurement
  - Differences/different approaches pointed out
- Calculations performed strictly in on-shell scheme
  - Parameters are: α, m_W, m_Z, (m_t, m_H, ...)
- Polarisation measurements considered as independent measurements in fits
- New C++ code for PDF and more general fits developed: Alpos
- DGLAP evolution @ NNLO

K. Wichmann

Diffraction 2016

χ² Definition

- Uncertainties on cross sections are assumed to be 'log-normal' distributed (relative uncertainties)
- Uncertainties on polarisation measurements are assumed to be 'normal' distributed
- Correlations of syst. uncertainties between different datasets are considered

$$\chi^2 = \left(\log(d) - \log(t)\right)^T V_R^{-1} \left(\log(d) - \log(t)\right) + (d-t)^T V_A^{-1} (d-t)$$

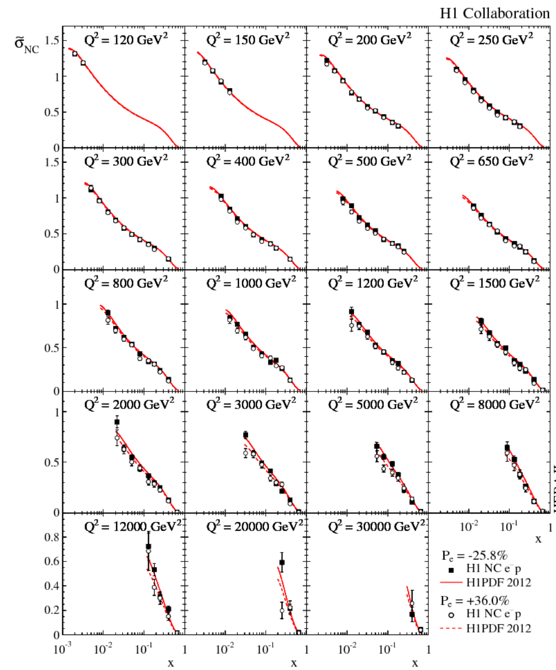
Fit parameters

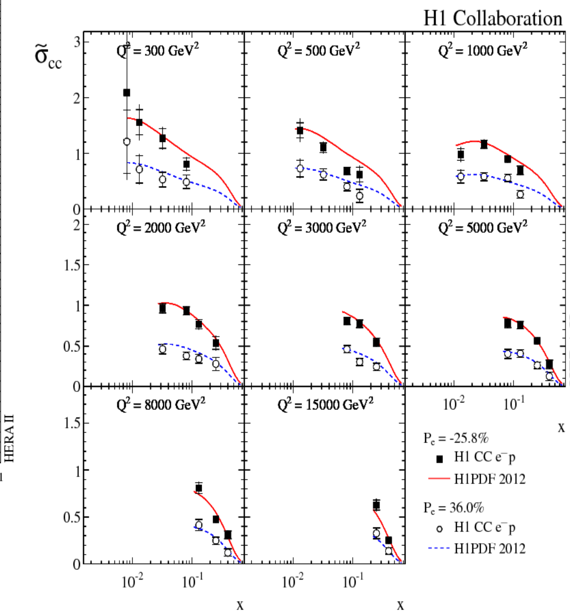
- 13 PDF parameters
- 4 polarisation values
- 4 Light-quark couplings (or other SM parameters)
- More general also 'nuisance parameters' of syst. uncertainties

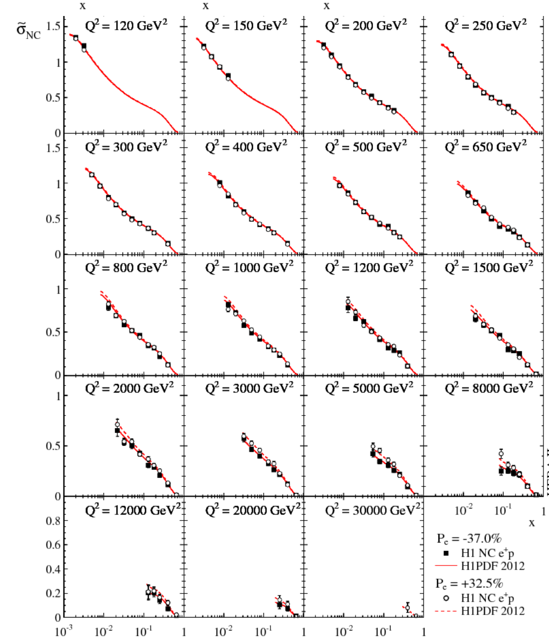
Data used

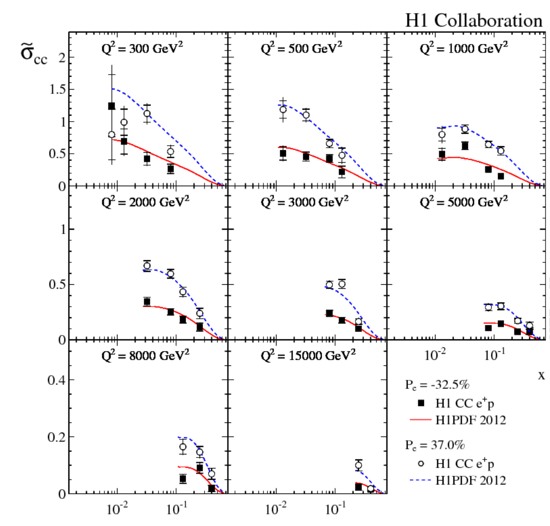
<u>Uncombined data sets</u>

- H1 HERAI data
  - unpolarised
- Reduced E_p H1 data
- HERAII
  - H1 polarised data









Data from $Q^2 = 12\ GeV^2$

- HF scheme: ZM-VFNS as implemented in QCDNUM

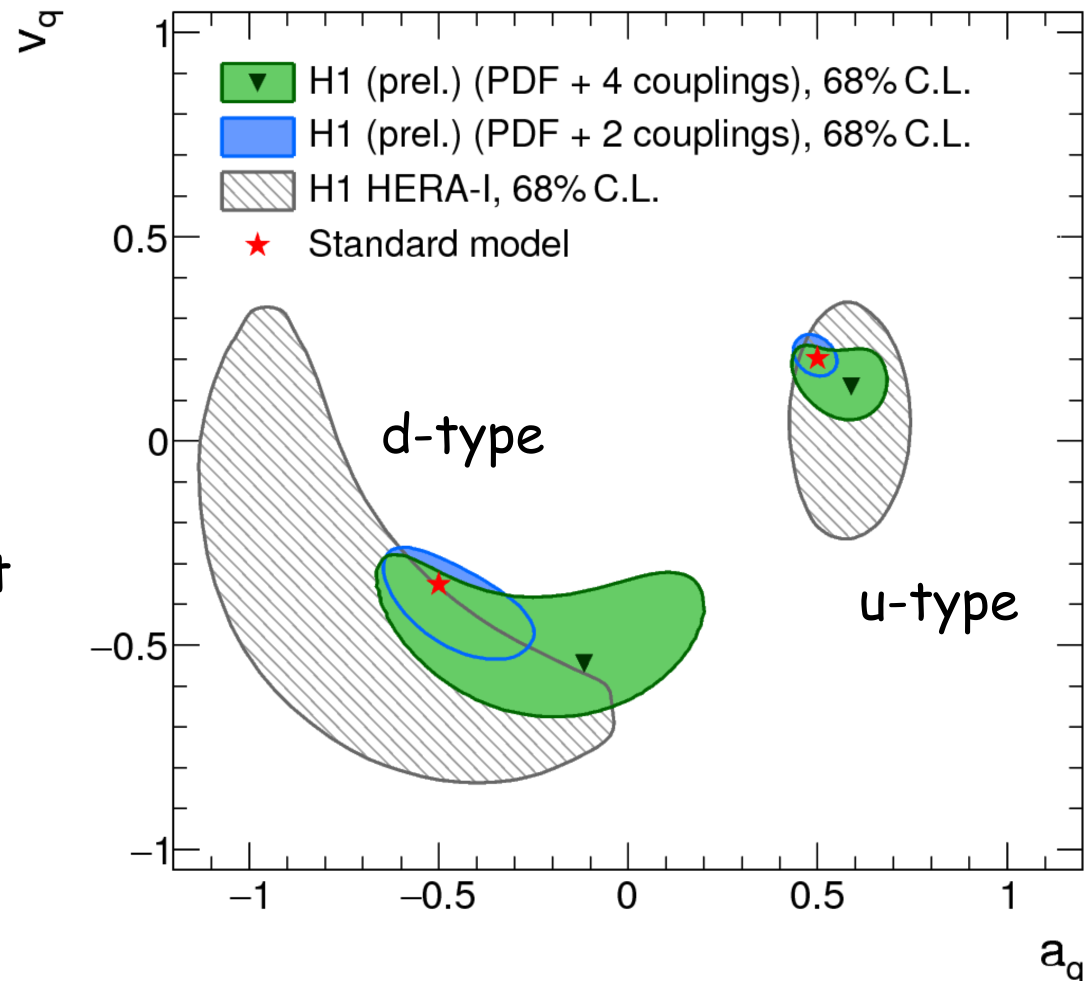
Light quark couplings @ H1

<u>Fit: PDF + 4 couplings</u>

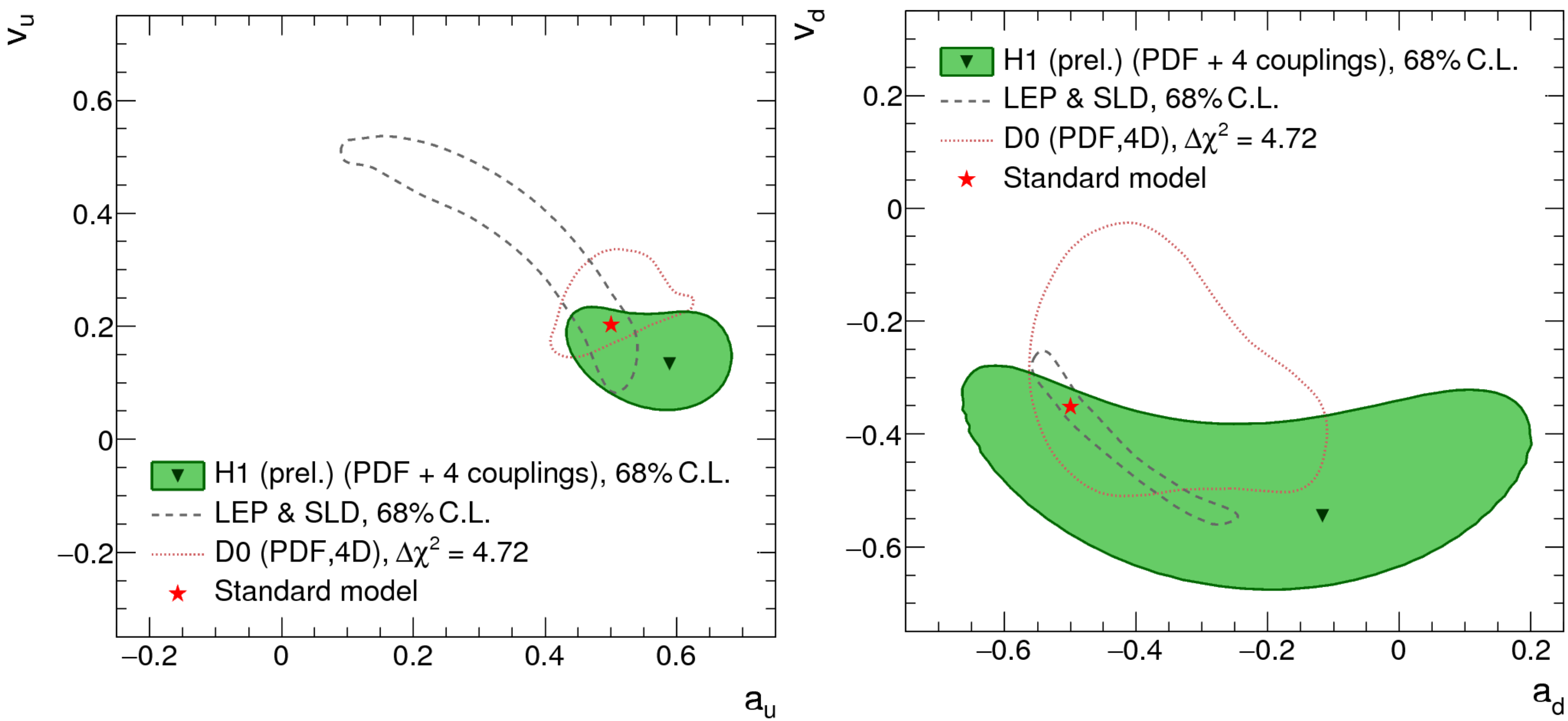
- χ^2 / ndf = 1370.5 / (1388 – 21)
- u-type couplings constrained better then d-type
  → sensitivity from valence quarks
- Results compatible with SM
- PDF uncertainties small
- Considerably improved sensitivity using final H1 HERA-II data
- Polarisation in HERA-II important for vector couplings

<u>Fit: PDF + 2 couplings</u>

- Reduced correlations and uncertainties
- Correlations between a_u-a_d and v_u-v_d large

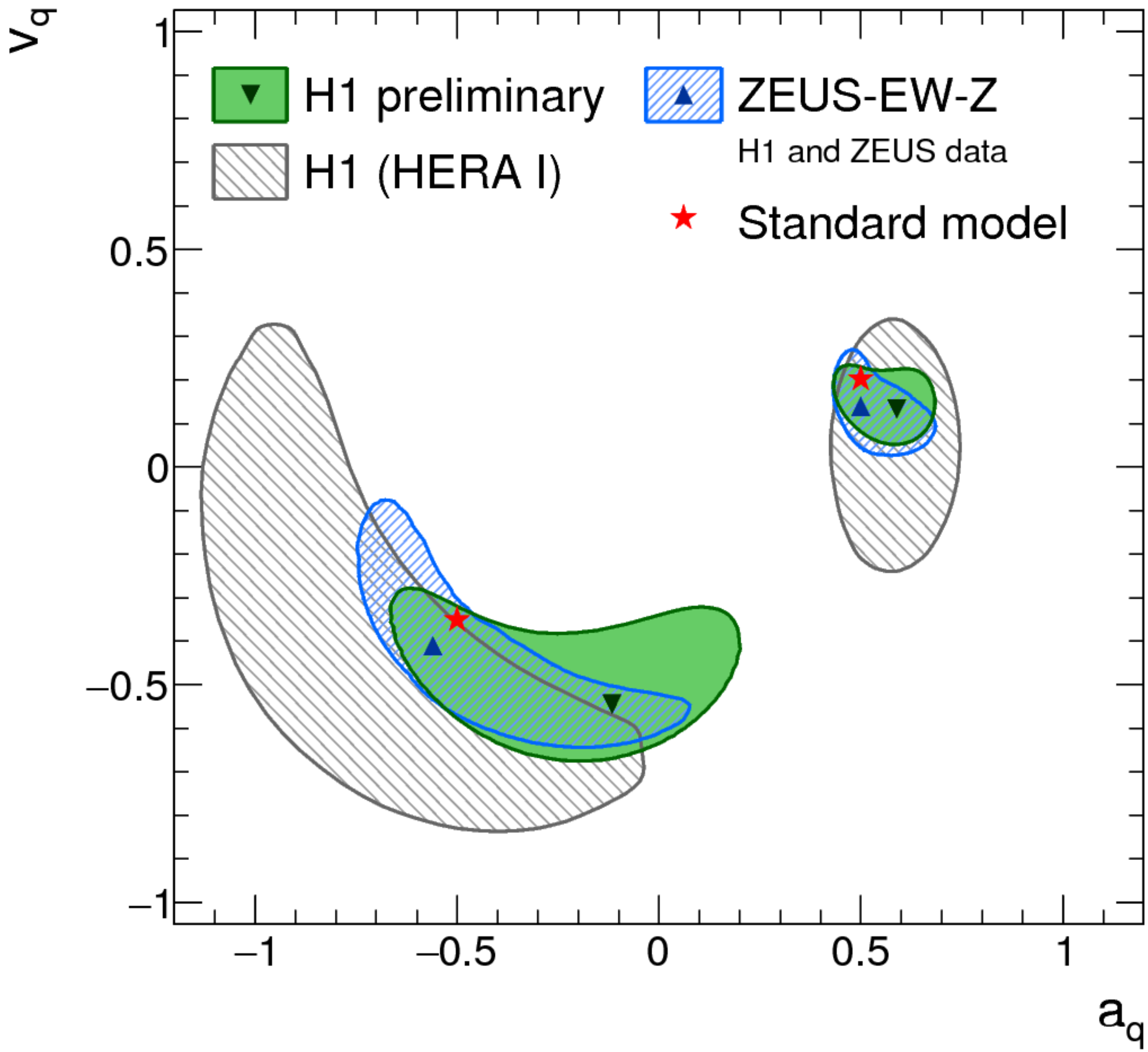


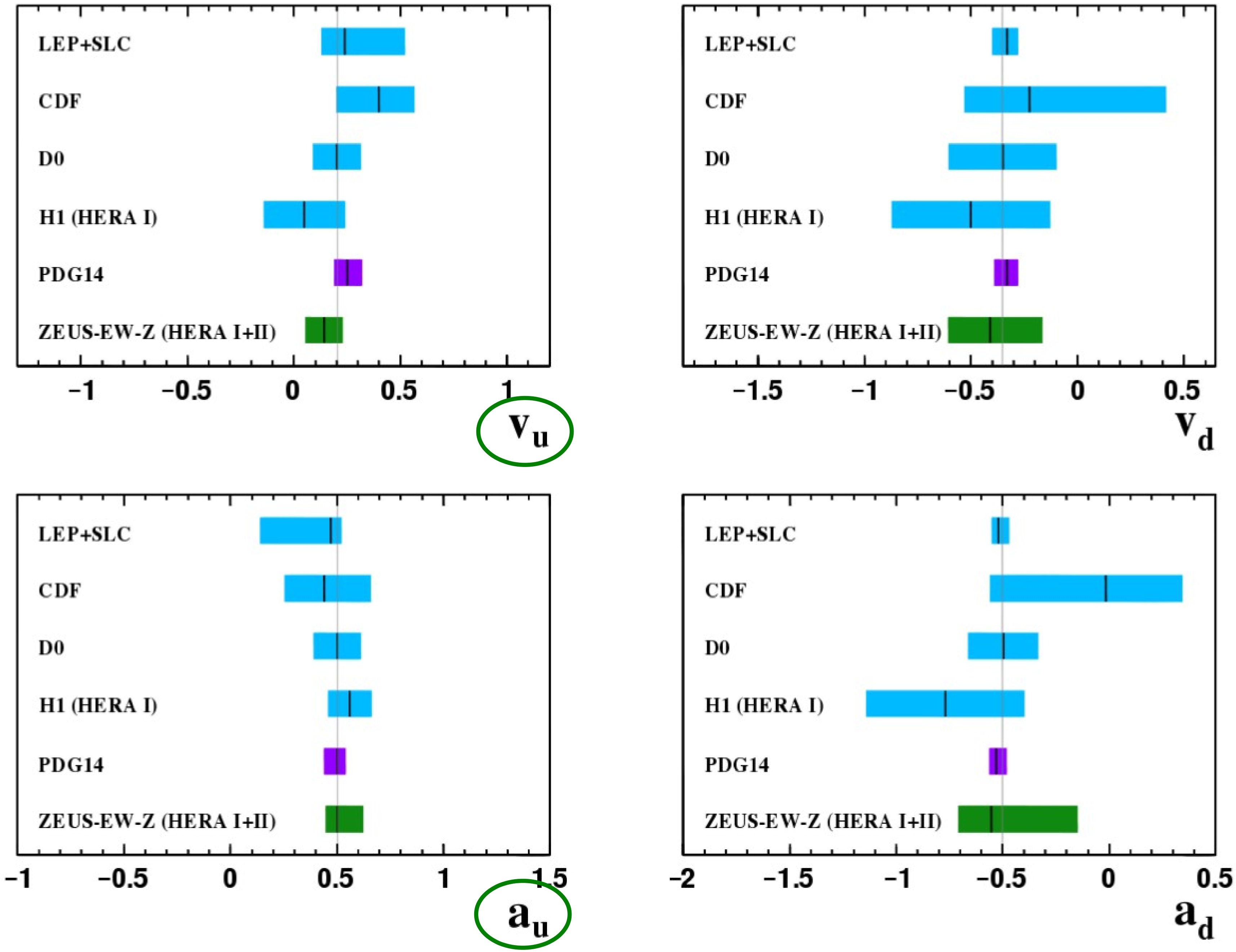
Comparison with other measurements



- Comparable precision of complementary processes

H1 and ZEUS Results Combined





High sensitivity of HERA data to u-type quark couplings

Probing Standard Model

Standard Model is now overconstrained

• Important to study consistency in many complementary processes

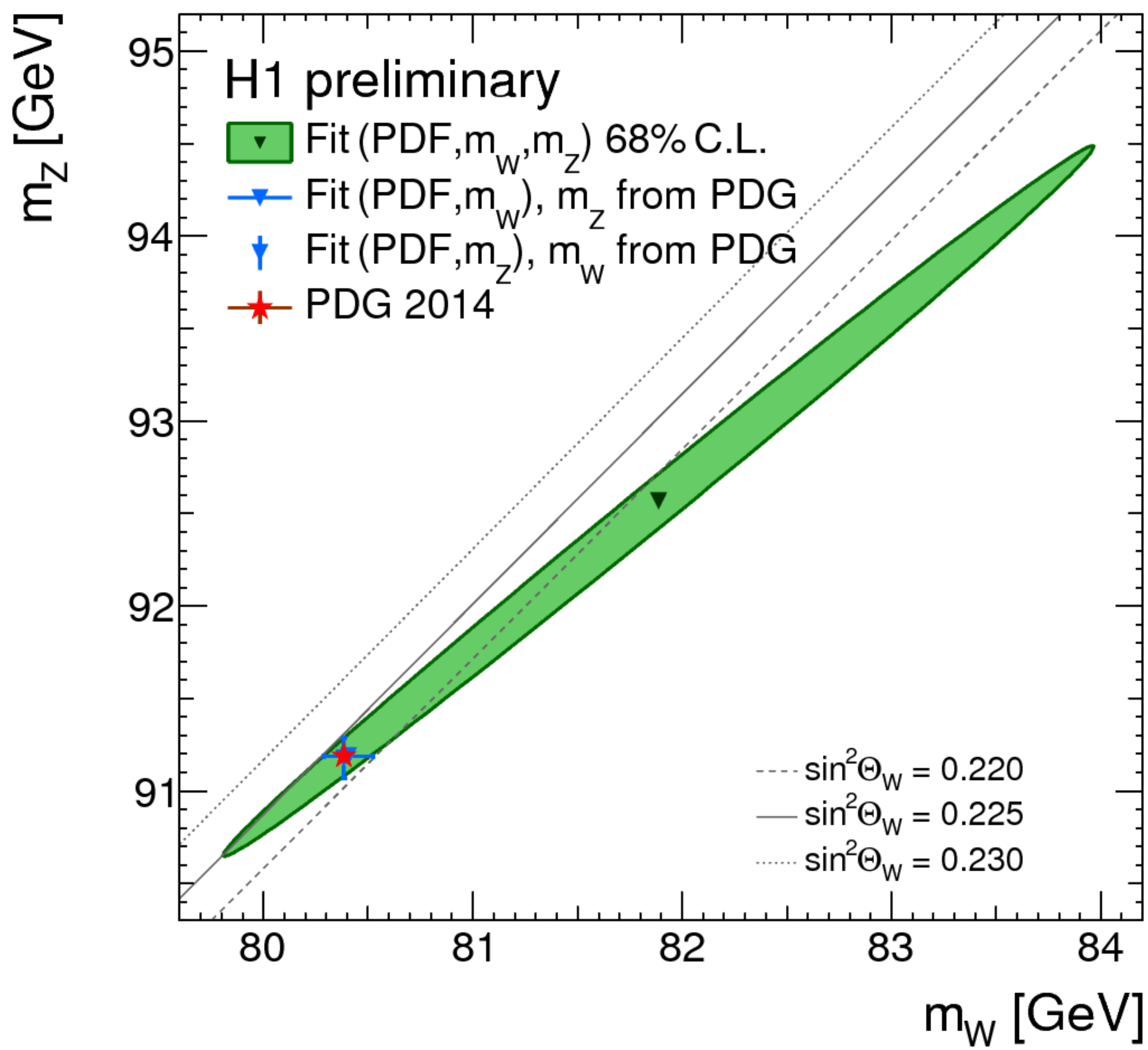
• HERA: Space-like momentum transfers

• Only purely virtual exchange of bosons

Boson masses

(m_W - m_Z) + PDF fits

- Assume α is known
- on-shell masses m_W and m_Z are only free EW parameters
- Agreement with SM
- Large correlation between m_W and m_Z



Mass of W boson

- Take other masses (m_Z) as external input to calculations

$$m_W = 80.407 \pm 0.118 \text{ (exp,pdf-fit)} \pm 0.005 \text{ } (m_Z, m_t, m_H) \text{ GeV}$$

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

Study of Standard Model Parameters

Different view on SM parameters

- Fermi coupling constant G_F

$$G_F = \frac{\pi \alpha}{\sqrt{2} m_W^2 \sin^2\theta_W}\left(1+\Delta r\right)$$

- Weak mixing angle

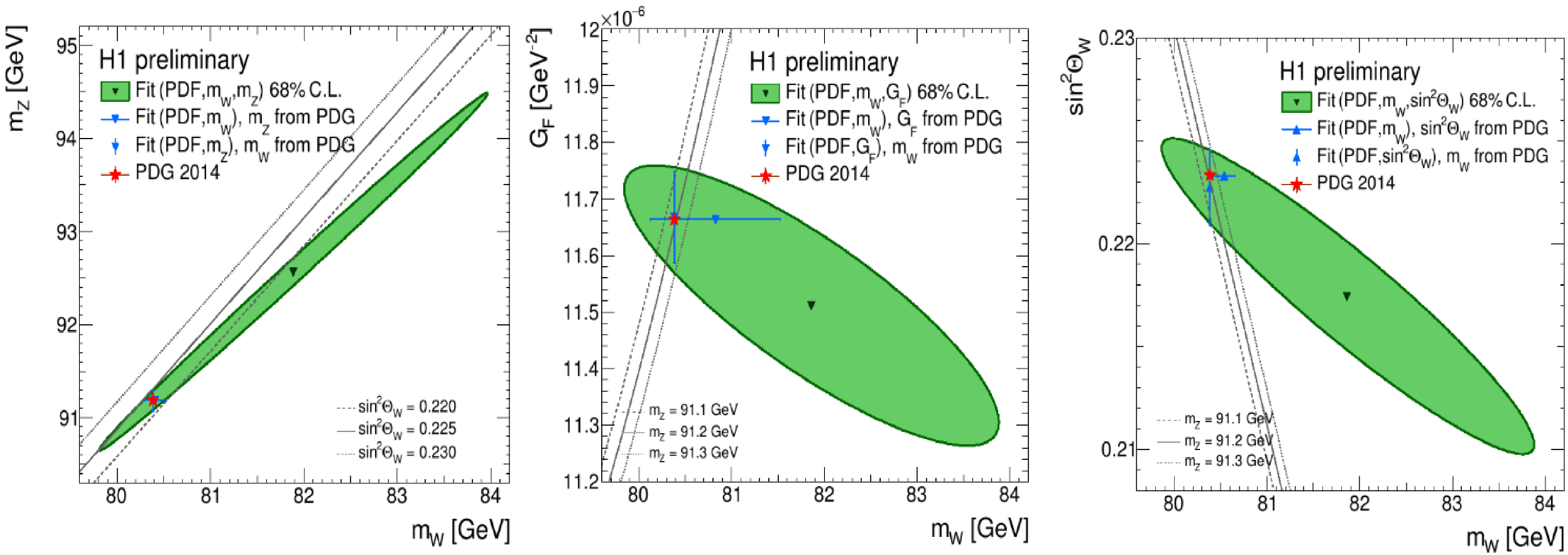
$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$$

Perform calculations consistently in on-shell scheme (α, m_Z, m_W)

- Calculate m_Z (iteratively) from G_F or $\sin^2\theta_W$

Results from fits together with PDF and m_W

- H1 values consistent with precise values from PDG
- Correlation to m_W are different for m_Z, $\sin^2\theta_W$ and G_F



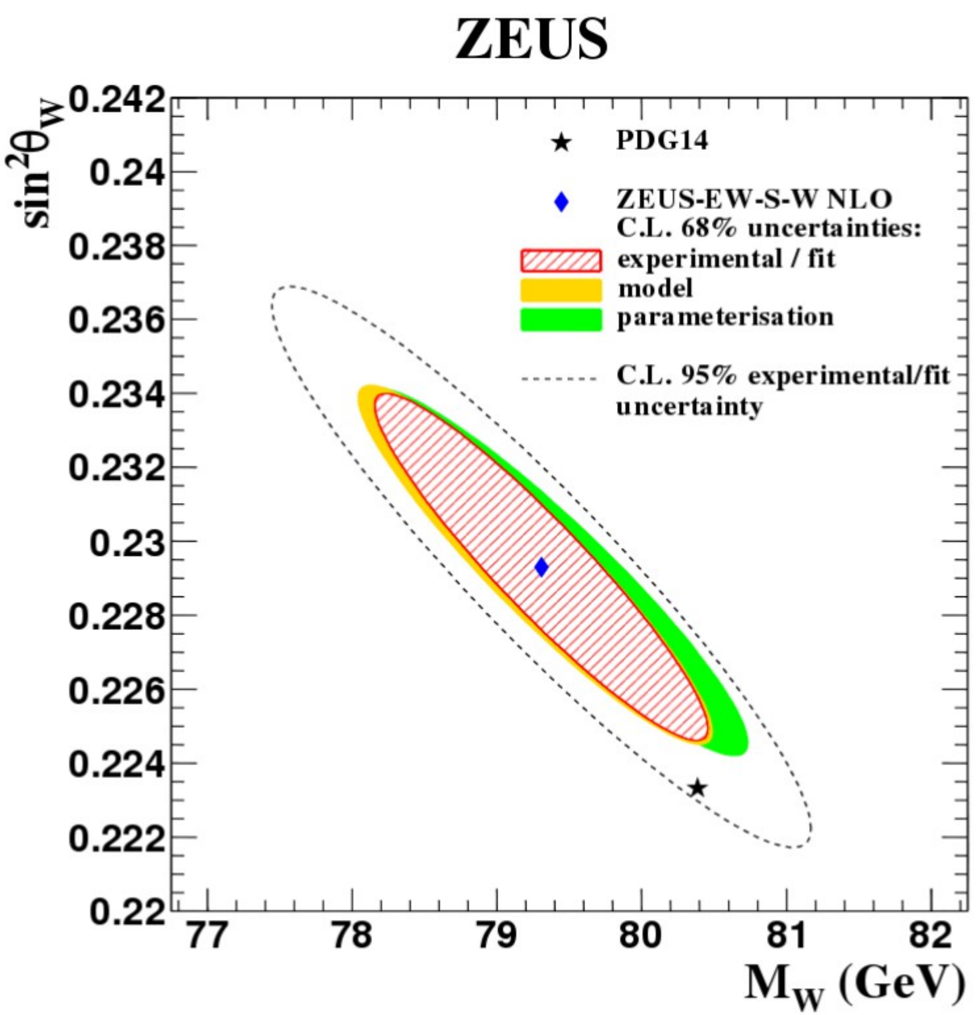
Simultaneous extraction of $\sin^2\theta_W$ and M_W

- Similar measurement by ZEUS

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

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

- All extracted quantities agree with world average values



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

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

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

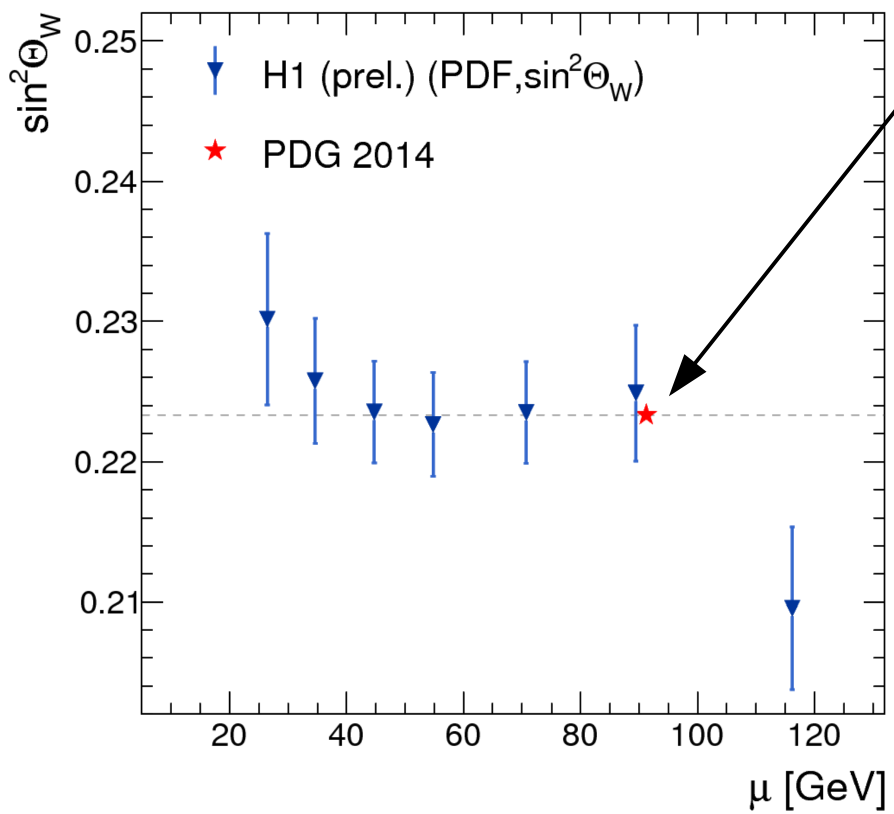
On-shell $\sin^2\theta_W$

- $\sin^2\theta_W$ determined simultaneously with PDF parameters (ZEUS-EW-S)

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

- Consistent with PDG14

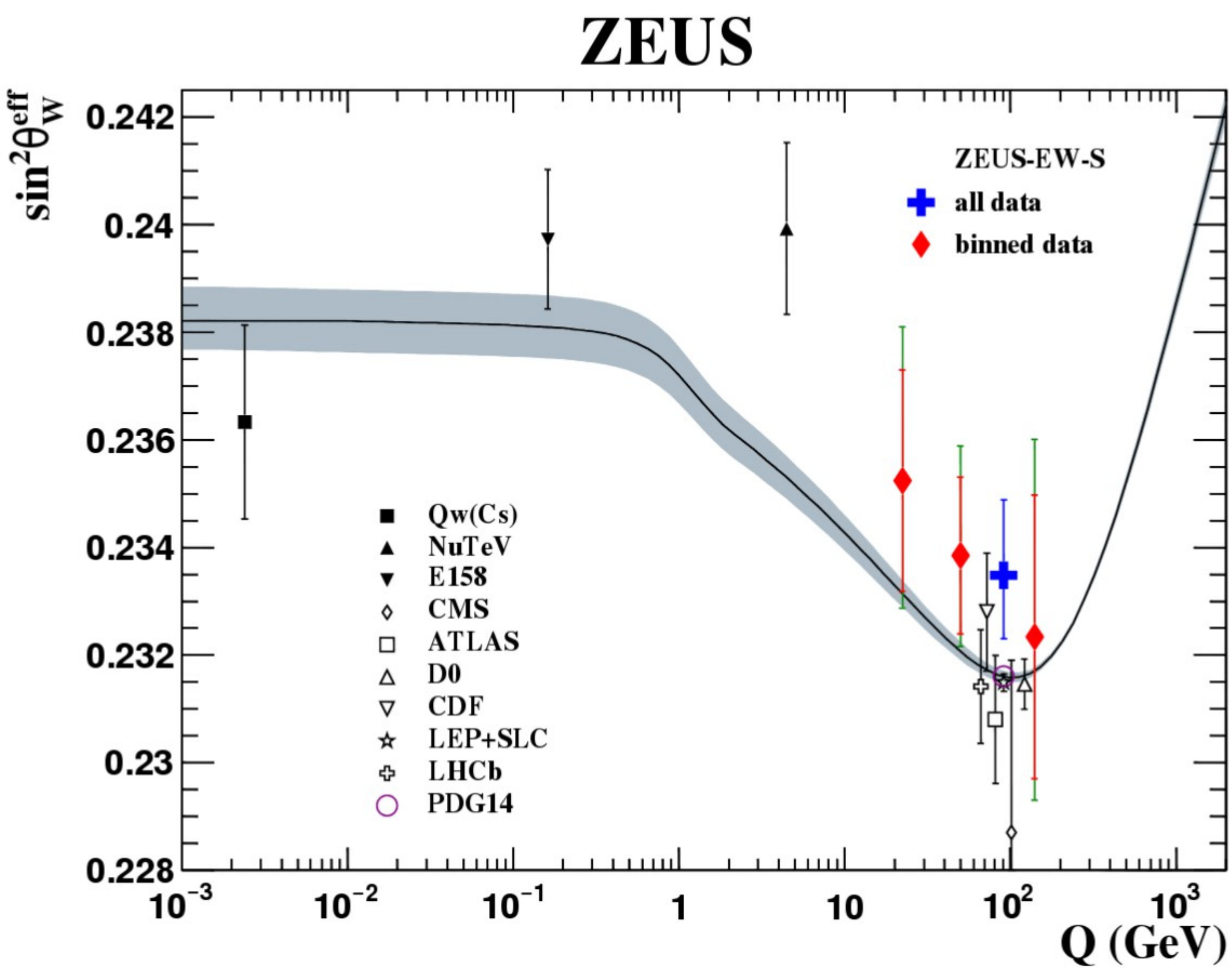
$$\sin^2\theta_W^{PDG14\,On-shell} = 0.22333 \pm 0.00011$$



- $\sin^2\theta_W$ determined in Q^2 bins
- Unique measurement of weak mixing angle at different scales
- Agreement with PDG14
- Can be translated to Msbar scheme

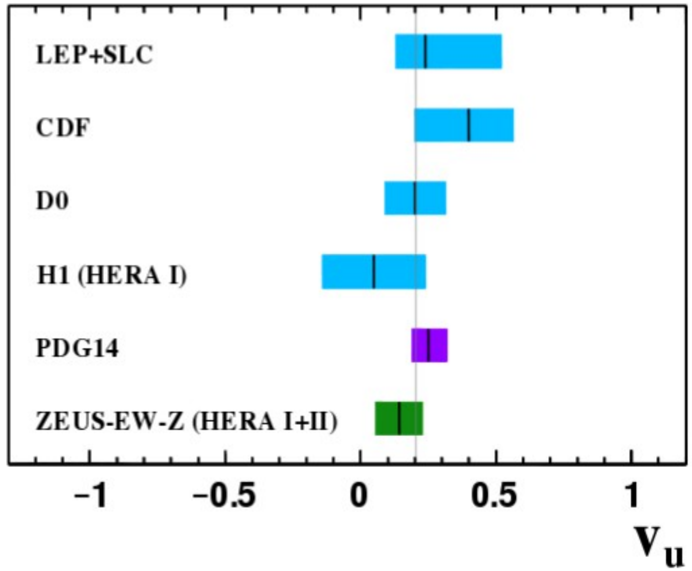
Effective $\sin^2\theta_W$

- On-shell measurements were translated to $\sin^2\theta_W^{eff}$
- First observation of effective $\sin^2\theta_W$ running from single machine



Summary

- HERA polarised inclusive data sensitive to electroweak parameters
  → Simultaneous PDF and EW fits
- Axial and vector-axial couplings to quarks agree with world average
- Measurements of u-type quark couplings among the most accurate

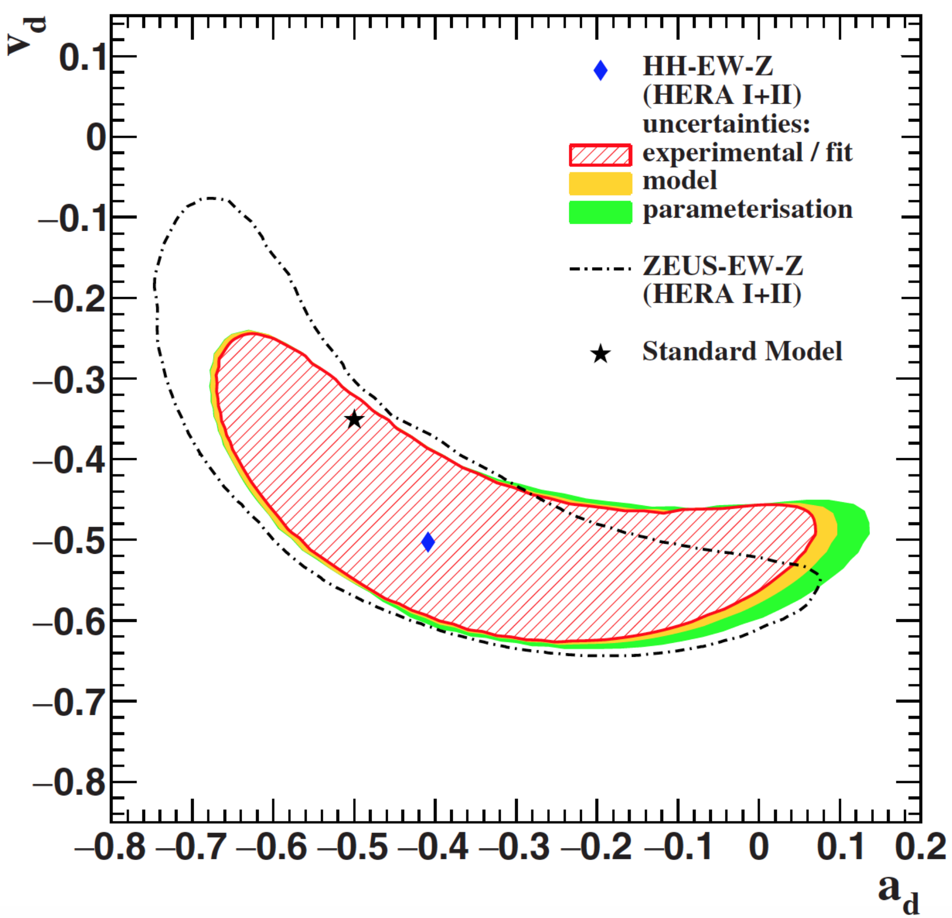


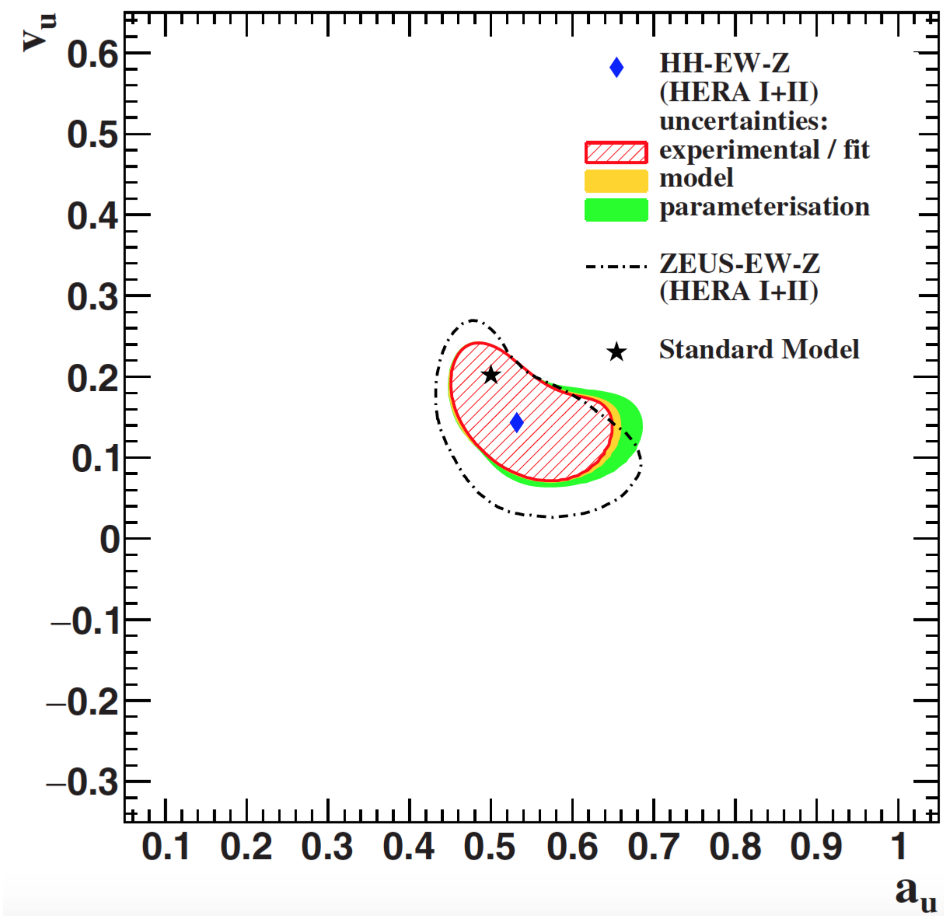
- Standard Model tests performed
  - Good consistency for M_Z, M_W, G_F and weak mixing angle
  - value of $\sin^2\theta_W$ competitive with measurements from neutrino sector
- $\sin^2\theta_W$ on-shell and effective determined for different scales
- Mass of W boson was determined at space-like momentum transfer

Back-up slides

Using all polarised HERA data in QCD+EW fit

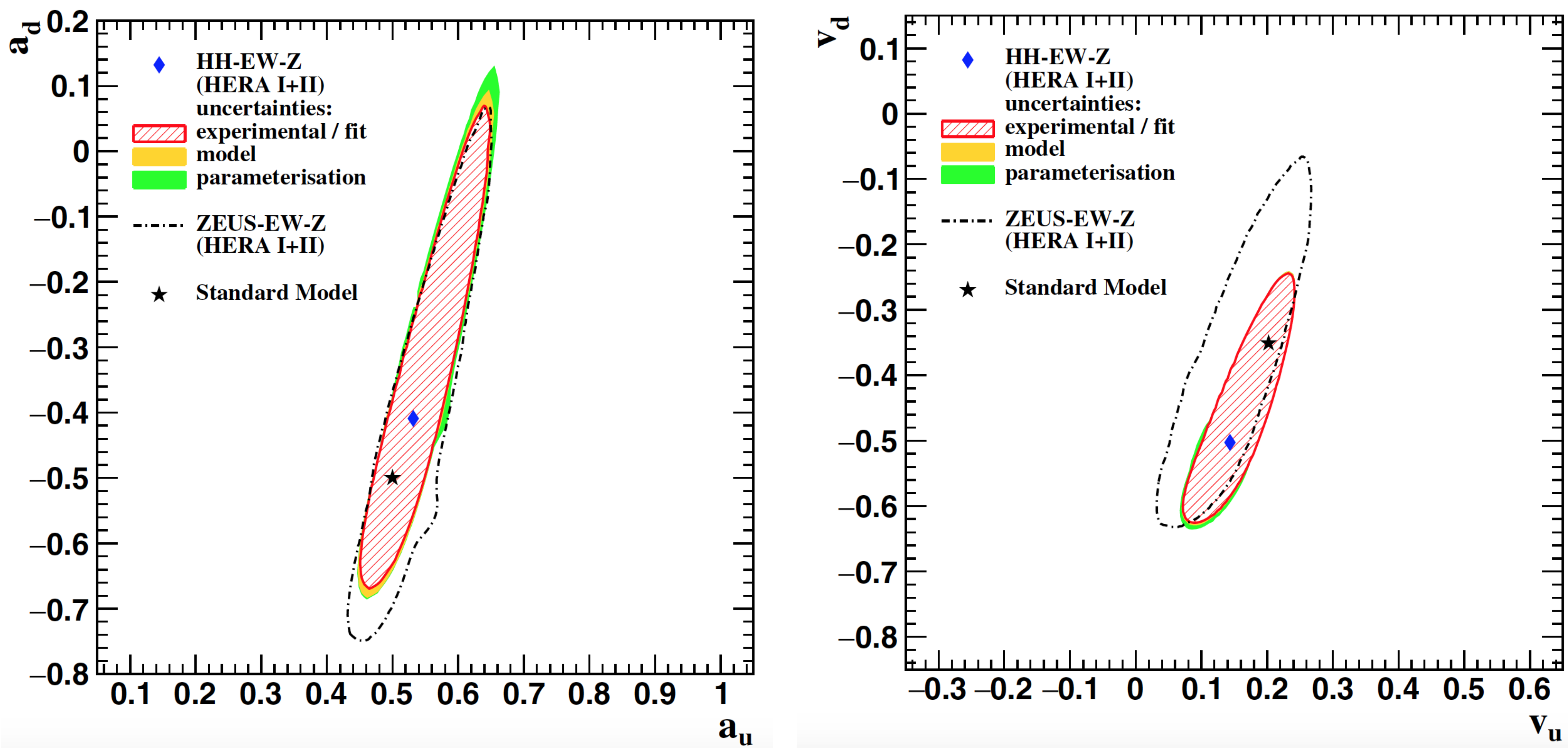
DESY-16-063, accepted by PRD





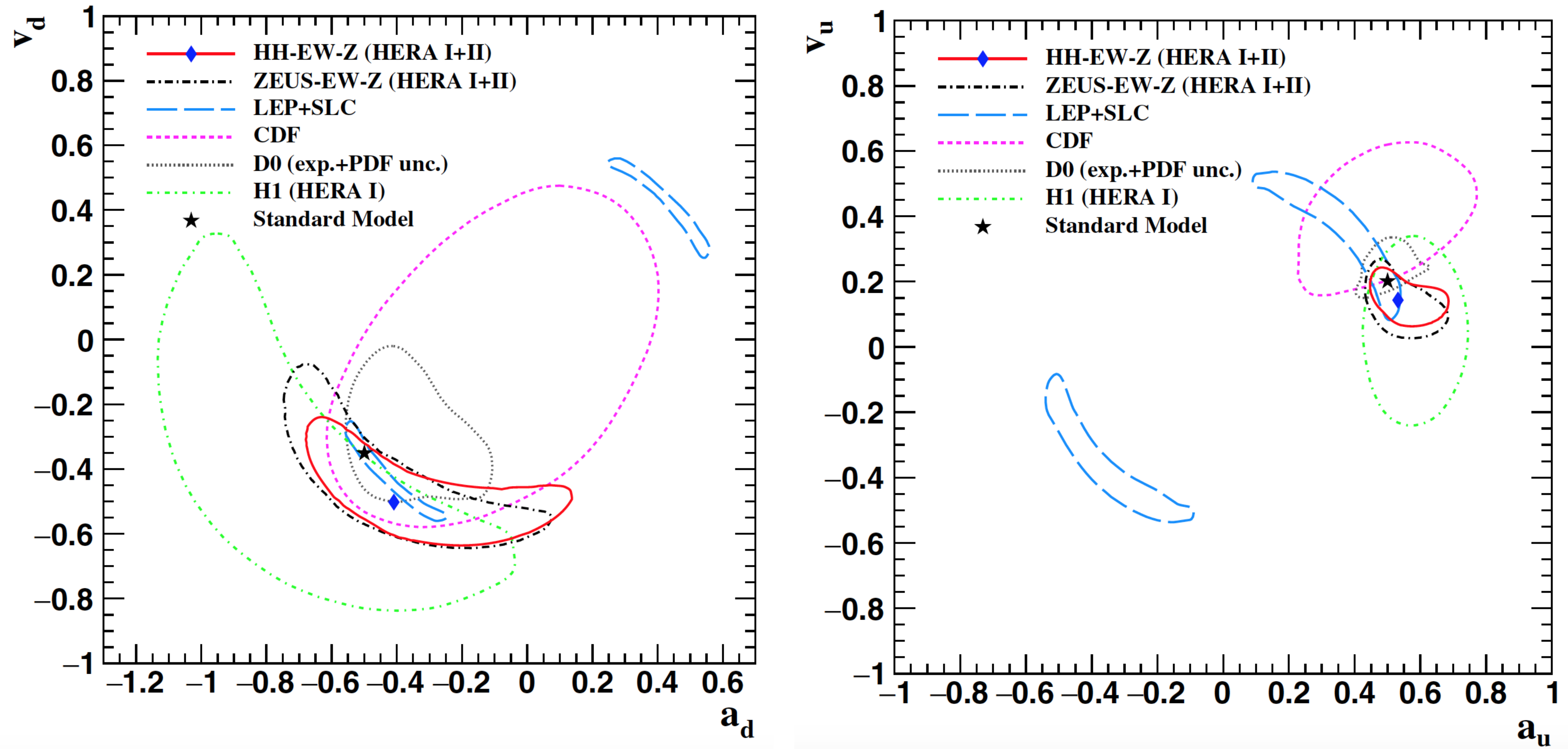
Using all polarised HERA data in QCD+EW fit

DESY-16-063, accepted by PRD



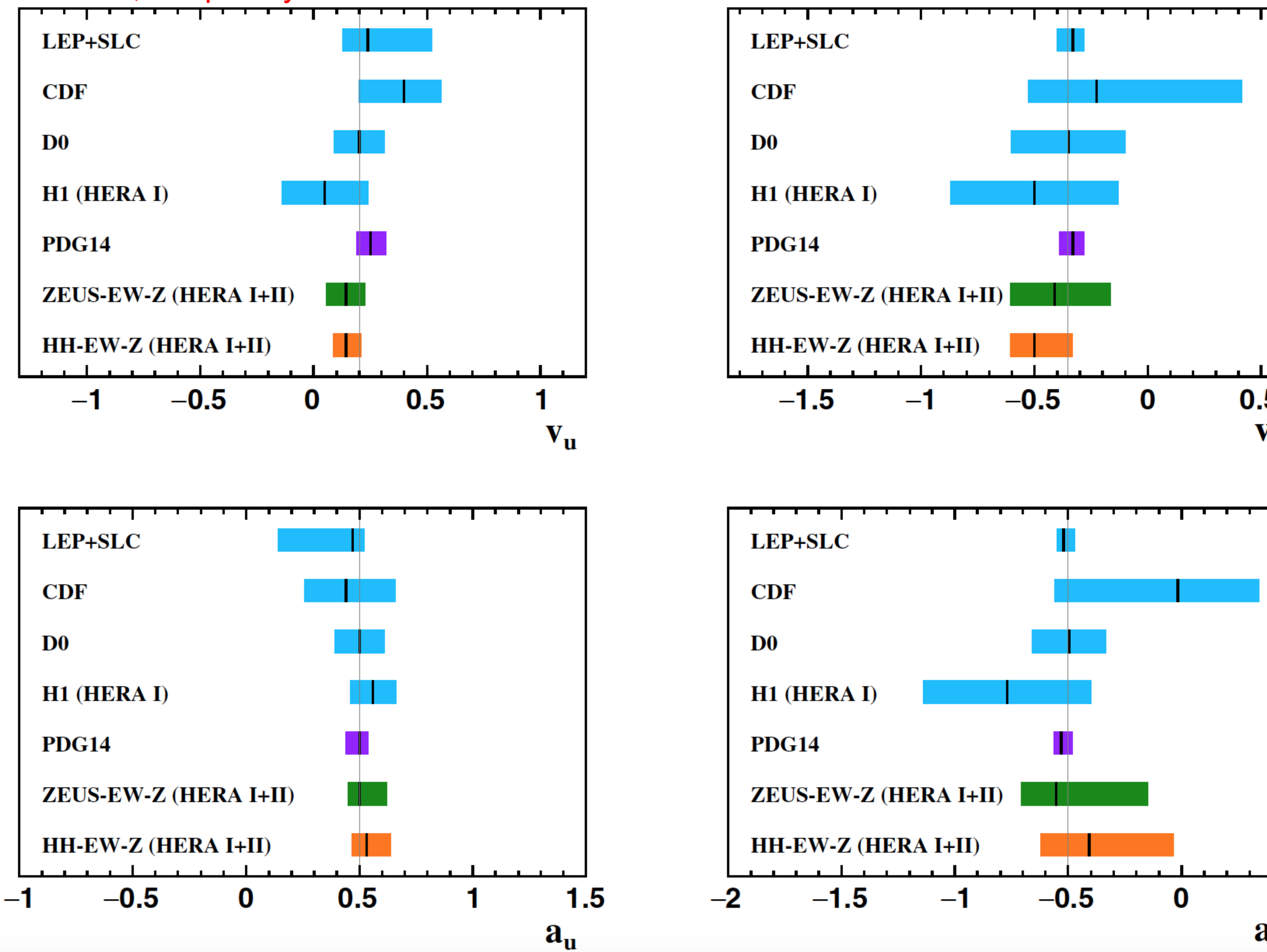
Using all polarised HERA data in QCD+EW fit

DESY-16-063, accepted by PRD



Using all polarised HERA data in QCD+EW fit

DESY-16-063, accepted by PRD



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);

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

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

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

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.

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

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

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

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

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

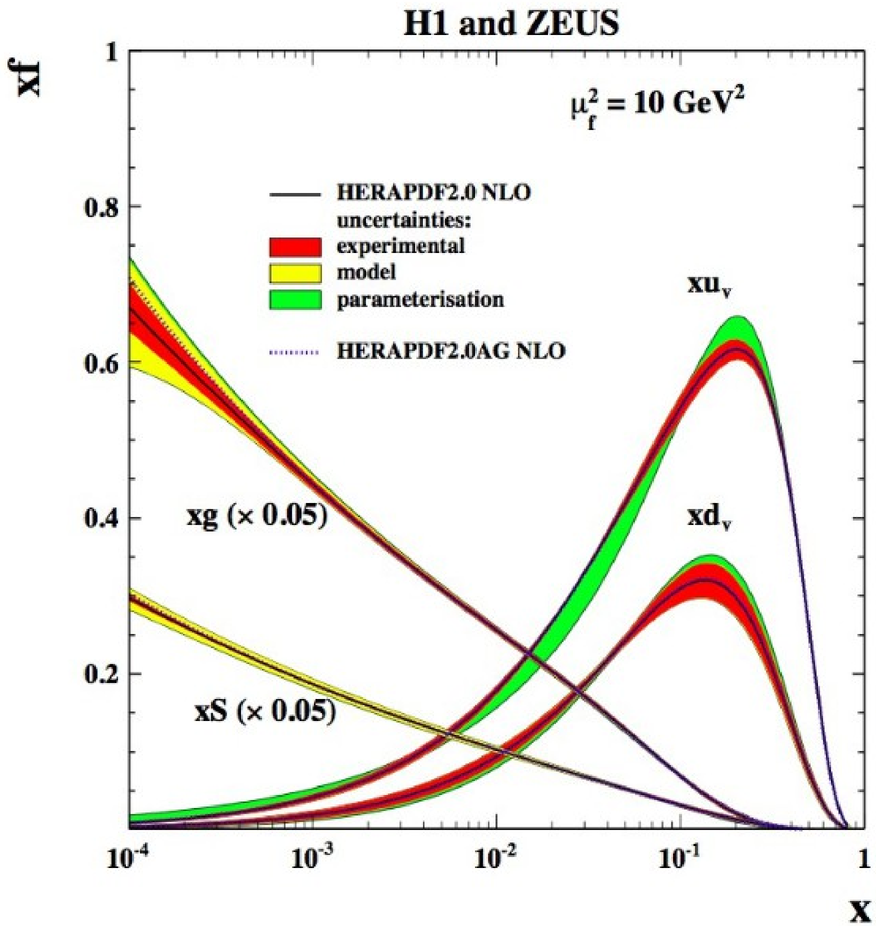
$P_Z >> P_Z^2$ (γZ interference is dominant)
$\mathbf{v_e}$ is very small (~0.04).

→

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

From slides by Amanda Cooper-Sarkar

Color decomposition of uncertainties



- **Experimental uncertainties:**
  - Hessian method
  - Conventional $\Delta\chi^2 = 1$ => 68% CL

Variation	Standard Value	Lower Limit	Upper Limit
Q^2_{min} [GeV^2]	3.5	2.5	5.0
Q^2_{min} [GeV^2] HiQ2	10.0	7.5	12.5
M_c(NLO) [GeV]	1.47	1.41	1.53
M_c (NNLO) [GeV]	1.43	1.37	1.49
M_b [GeV]	4.5	4.25	4.75
f_s	0.4	0.3	0.5
μ_{f_0} [GeV]	1.9	1.6	2.2

Adding D and E parameters to each PDF

- **Parametrisation uncertainties**
  - largest deviation
- **Model uncertainties**
  - all variations added in quadrature

Fit methology I

Determine light-quark couplings

- Use iterative minimisation procedure ('fit') of cross section predictions to data

Unfortunate correlation

- PDFs have considerable uncertainties
- These PDFs are essentially determined from H1 structure function data
  -> Large correlations
- Consider PDF uncertainty by simultaneous fit of PDFs and light quark couplings

Consistency of fit-parameters in SM formalism

- Perform calculations strictly in on-shell scheme
  Parameters are: α, m_Z, m_W, (m_t, m_H, ...)

Polarisation measurement

- Measurements of the beam polarisations are measurements on their own

-> Consider these measurements as independent measurements in fit

1-loop EW corrections

- May be considered in terms of 'EW form factors'
- Are ignored in the present analysis, but will be included in the future

Fit methology II

New C++-based fitting code for PDF and more general fits developed (Alpos)

- DGLAP evolution of PDFs in NNLO QCD (QCDNUM with ZMVFNS)
- PDFs are parameterised at starting scale Q_0^2 = 1.9GeV^2 (similar to HERAPDF2.0)

xg	xg	→	$xg(x) = A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g}$,
xu_v	$xU = xu + xc$		$xu_v(x) = A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1 + E_{u_v}x^2\right)$,
xd_v	$xD = xd + xs$		$xd_v(x) = A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}$,
$x\bar{U}$	$x\bar{U} = x\bar{u} + x\bar{c}$		$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}(1 + D_{\bar{U}}x)$,
$x\bar{D}$	$x\bar{D} = x\bar{d} + x\bar{s}$		$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}$.

fixed or constrained by sum-rules

parameters set equal but free

- Use only data with $Q^2 >= 12$ GeV^2

χ^2 Definition

- Uncertainties on cross sections are assumed to be 'log-normal' distributed (relative uncertainties)
- Uncertainties on polarisation measurements are assumed to be 'normal' distributed
- Correlations of syst. uncertainties between different datasets are considered

$$\chi^2 = \left(\log(d) - \log(t)\right)^T V_R^{-1}\left(\log(d) - \log(t)\right) + (d-t)^T V_A^{-1}(d-t)$$

Fit parameters

- 13 PDF parameters
- 4 polarisation values
- 4 Light-quark couplings (or other SM parameters)
- More general also 'nuisance parameters' of syst. uncertainties

Polarised deep-inelastic ep scattering

Neutral and charged current at tree level

$$\frac{d\sigma^{\pm}_{NC}}{dQ^2dx}=\frac{2\pi\alpha^2}{x}\left[\frac{1}{Q^2}\right]^2(Y_+\boldsymbol{F_2}+Y_-x\boldsymbol{F_3}+y^2\boldsymbol{F_L})$$

$$\frac{d\sigma^{\pm}_{CC}}{dQ^2dx}=\frac{1\pm P}{2}\frac{G_F^2}{4\pi x}\left[\frac{m_W^2}{m_W^2+Q^2}\right]^2(Y_+\boldsymbol{W_2^{\pm}}\pm Y_-x\boldsymbol{W_3^{\pm}}-y^2\boldsymbol{W_L^{\pm}})$$

$$Y_\pm=1\pm(1-y)^2$$

Generalised structure functions

$$\boldsymbol{F_2}=F_2^{\gamma}+\kappa_Z(-v_e\mp Pa_e)F_2^{\gamma Z}+\kappa_Z^2(v_e^2+a_e^2\pm Pv_ea_e)F_2^Z$$

$$x\boldsymbol{F_3}=+\kappa_Z(\pm a_e+Pv_e)F_3^{\gamma Z}+\kappa_Z^2\left(\mp 2v_ea_e-P(v_e^2+a_e^2)\right)xF_3^Z$$

Z⁰-exchange

$$\kappa_Z(Q^2)=\frac{Q^2}{Q^2+m_Z^2}\frac{G_Fm_Z^2}{2\sqrt{2}\pi\alpha}$$

Structure functions in QPM

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

$$\left[xF_3^{\gamma Z},xF_3^Z\right]=x\sum_q\left[2e_qa_q,2v_qa_q\right]\{q-\bar{q}\}$$

Calculations in on-shell scheme

$$G_F=\frac{2\pi\alpha}{2\sqrt{2}m_W^2}\left(1-\frac{m_W^2}{m_Z^2}\right)^{-1}(1+\Delta r)$$

Corrections to G_F

$$\Delta r=\Delta r(\alpha,m_W,m_Z,m_t,m_H,\ldots)$$

Weak couplings to Z-boson

$$v_f=I^{(3)}_{f,L}-2e_f\sin^2\theta_W \qquad (f=e,u,d,\ldots)$$

$$a_f=I^{(3)}_{f,L}$$

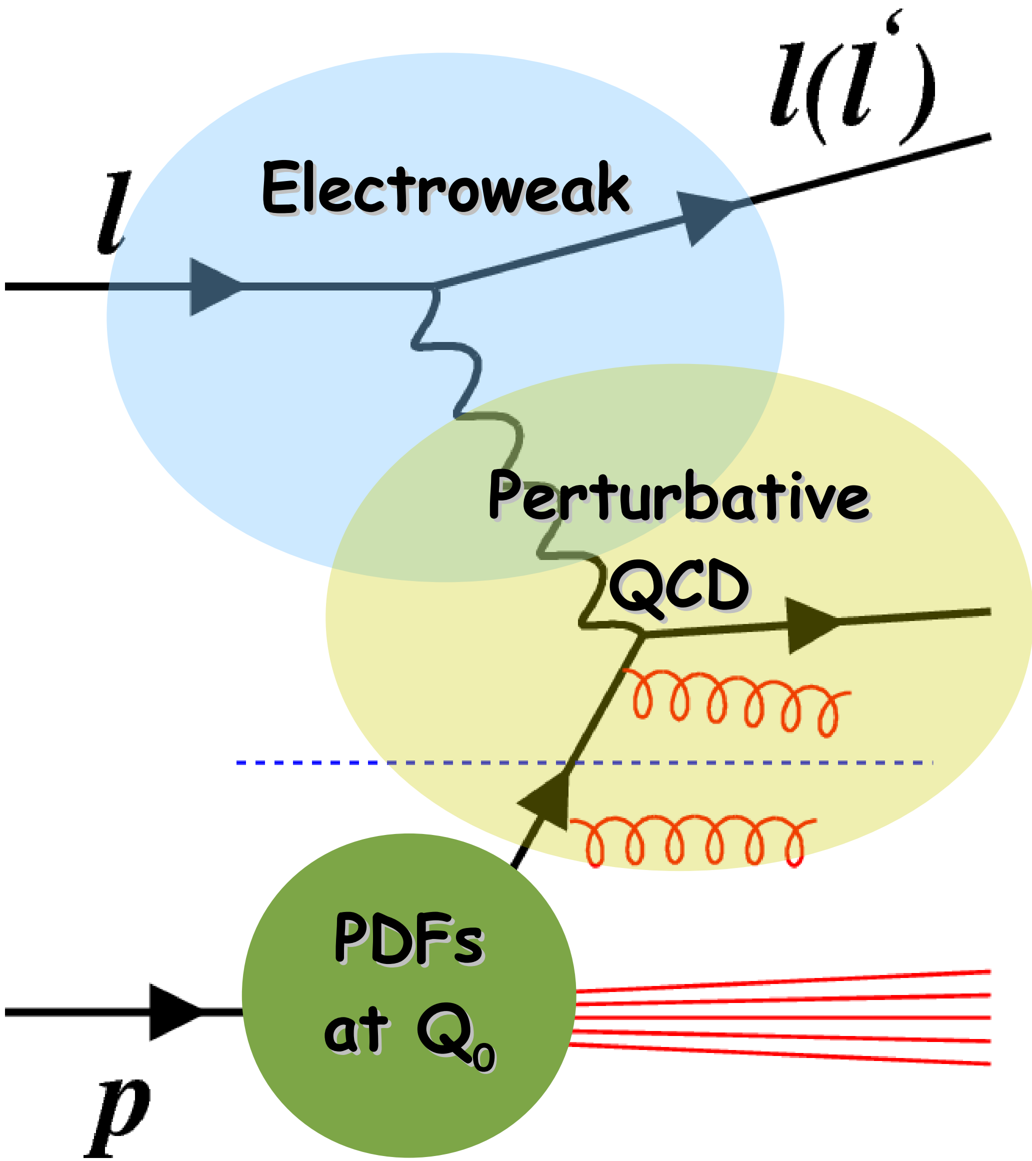
Parameters to calculations

Parameters to cross section calculation: α, m_Z, m_W, (m_t, m_H, ...)

More general, also couplings: v_e,a_e , v_u,a_u and v_d,a_d

K. Wichmann Diffraction 2016 QCD+EW fits

Deep Inelastic Scattering @ HERA



- Fix pQCD & PDFs
  ! Test Electroweak
- Fix Electroweak
  ! Test pQCD & PDFs

- Fix Electroweak & pQCD
  ! Determine PDFs