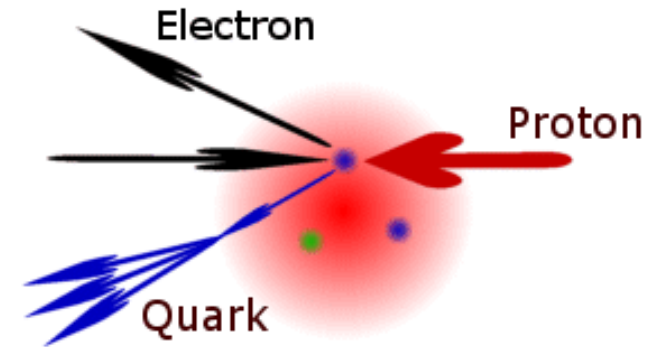




Simultaneous QCD & Electroweak Fits to HERA Inclusive DIS data

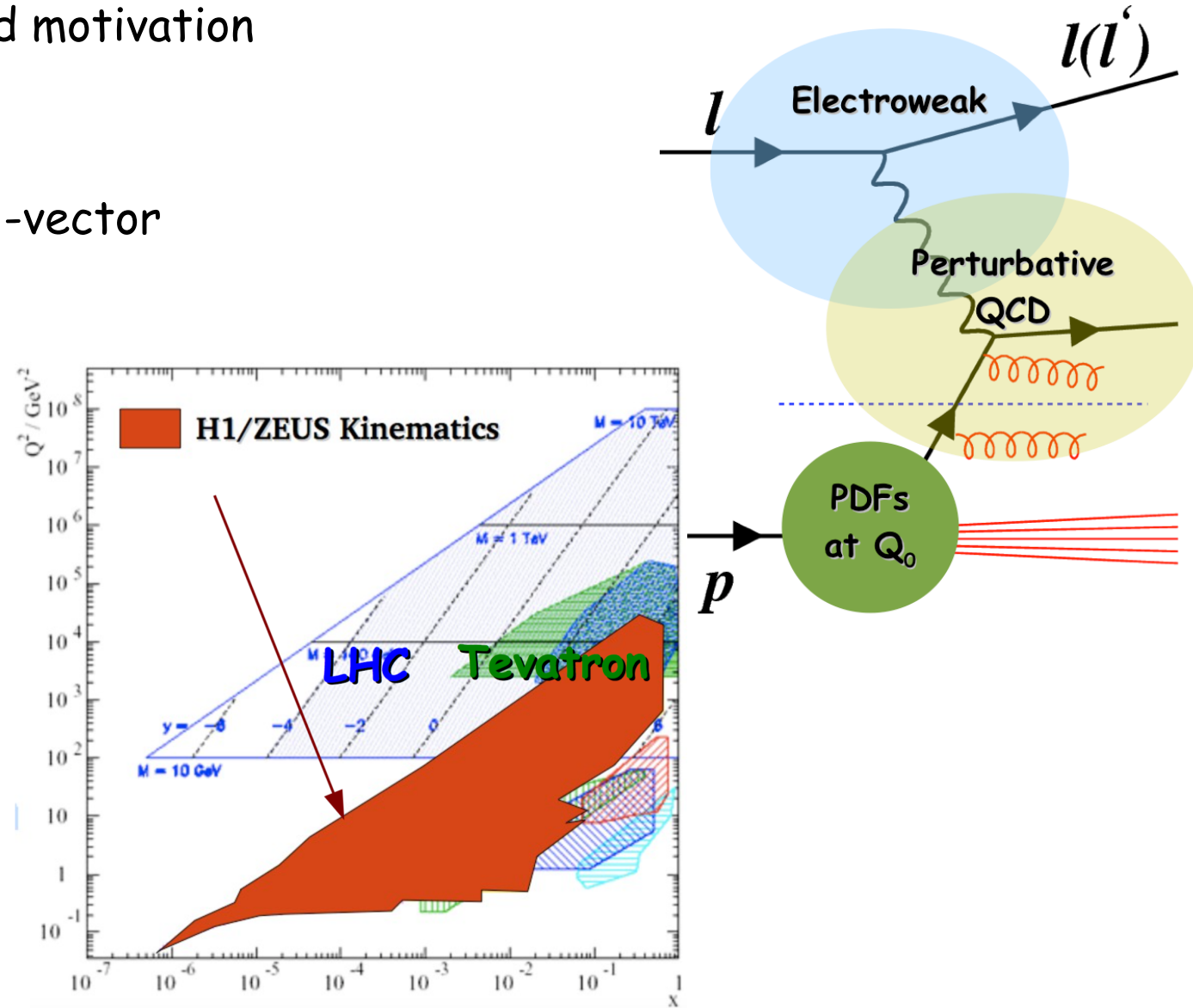
U.Schneekloth on behalf of H1 & ZEUS collaborations

Outline

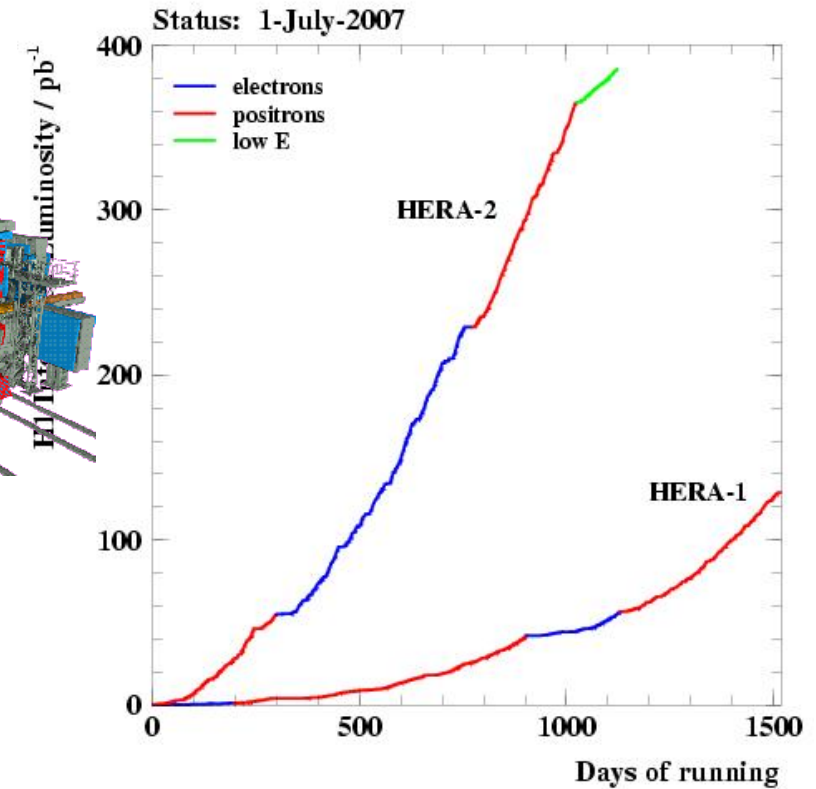
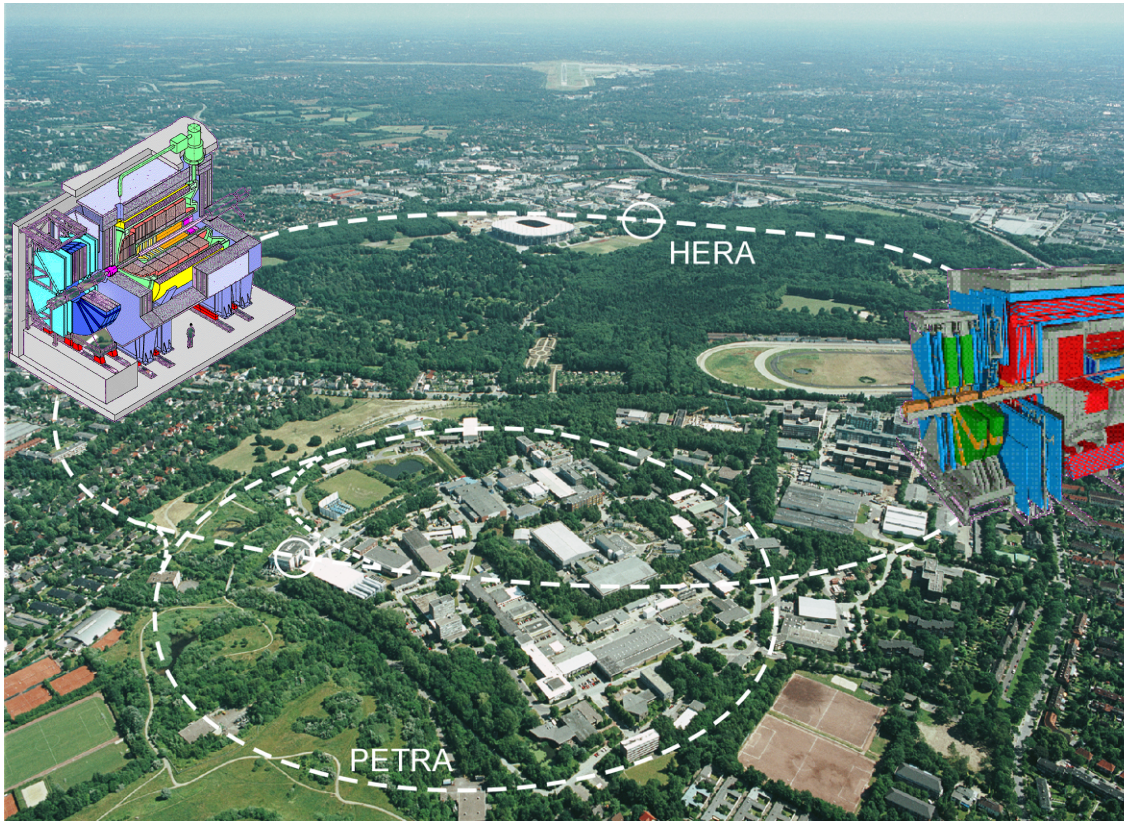
Deep Inelastic Scattering at HERA

- Introduction and motivation
- Polarized DIS
- Global QCD fits
- Vector and axial-vector couplings
- Boson masses
- $\sin^2\theta_W$ and M_W
- Conclusions

HERA a unique facility
DIS best tool to probe proton structures



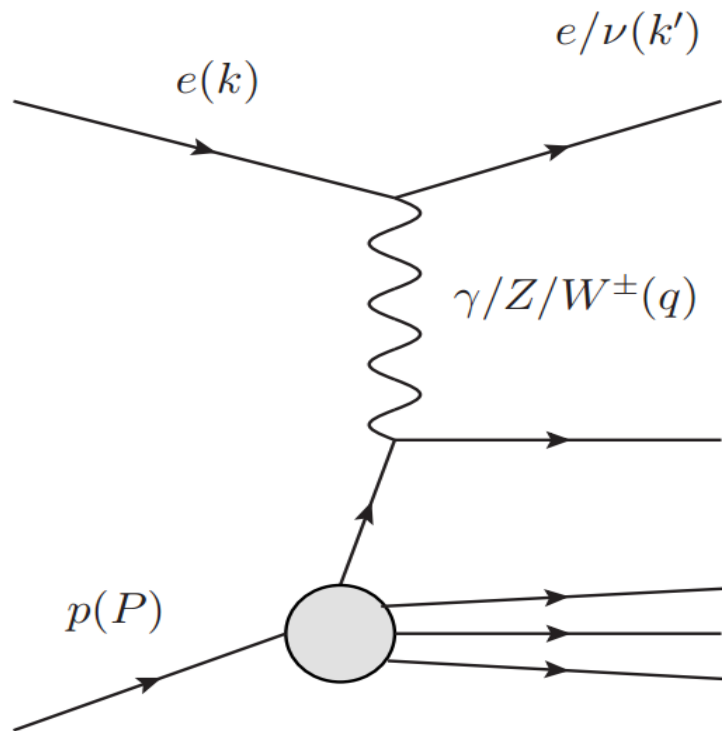
HERA: the only ep Collider



HERA (1992-2007): $\sqrt{s} = 252 - 318 \text{ GeV}$

$E_e = 27.5 \text{ GeV}$, $E_p = 920, 820, 575, 460 \text{ GeV}$

Deep Inelastic Scattering at HERA



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

 $X(P')$

$$E_p = 920(820, 460, 575) \text{ GeV}$$

$$E_e = 27.5 \text{ GeV}$$

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

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

$$x_{Bj} = \frac{Q^2}{2pq}$$

$$y = \frac{pq}{pk}$$

$$s = (p + k)^2$$

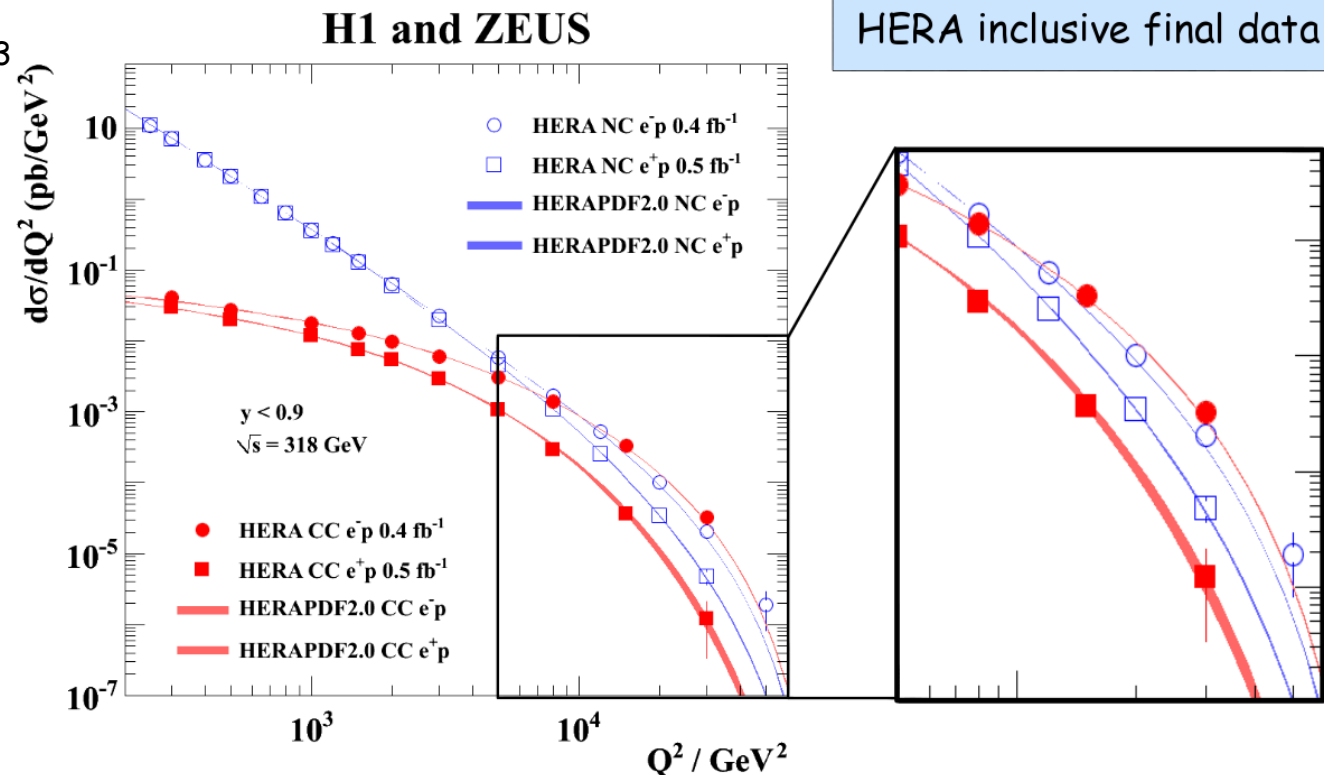
$$Q^2 = xys$$

Experimental luminosity (H1 & ZEUS):

$\sim 0.5 \text{ fb}^{-1}$ data from each experiment

Deep Inelastic Scattering at HERA

- H1 and ZEUS published all HERA inclusive DIS measurements (22 papers 1997-2014)
- Recently, very detailed analysis with combined H1 and ZEUS data sets w/o polarization, EPJ C75(2015), 580 (150+ page paper)
- Including some electroweak results:
 - NC/CC ep cross sections
 - NC e-p and e+p cross sections
 - Struct. funct. $xF_3^{\nu Z}$
- This talk DIS with polarization



Polarised DIS

- Generalised structure functions depend on e-beam polarization

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

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

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

- Structure functions in QP model

NC

NC sensitive to $\sin^2 q_W$ via

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

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

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

- 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

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

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

CC sensitive to $\sin^2 q_W$

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)

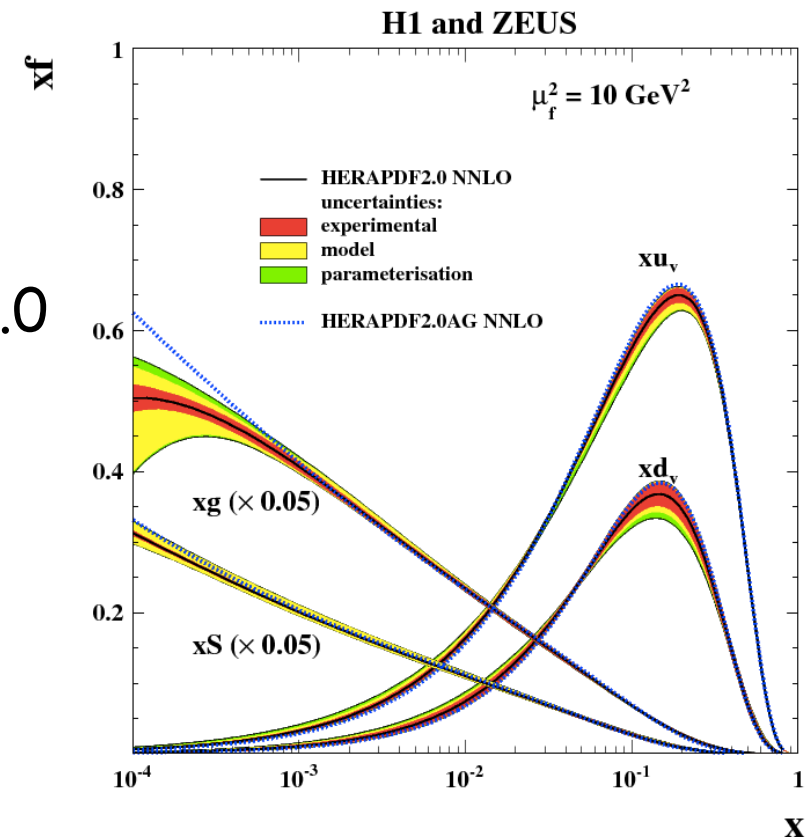
$$xf(x) = Ax^B(1-x)^C(1+Dx+Ex^2)$$

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

- Starting scale $Q_0^2 = 1.9 \text{ GeV}^2$
- Model and parameterisation uncertainties $\rightarrow$ HERAPDF2.0
- Corrections calculated using EPRC code: ΔR

desy.de/~hspiesb/eprc.html

- No ISR/FSR corrections



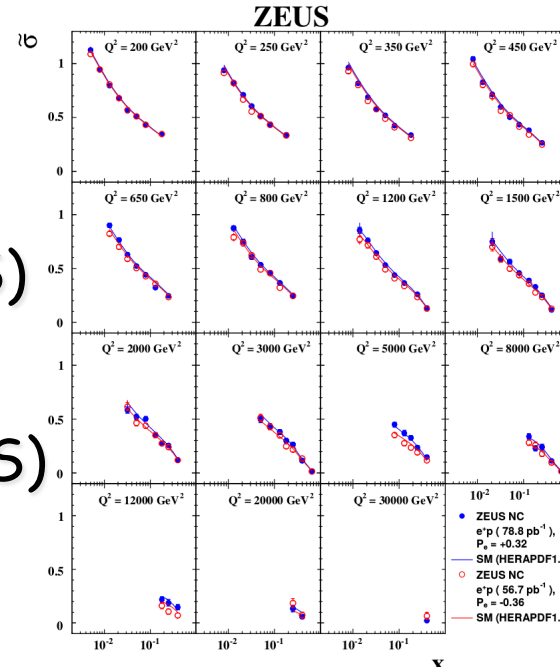
Vector and axial-vector couplings

Uncombined data sets

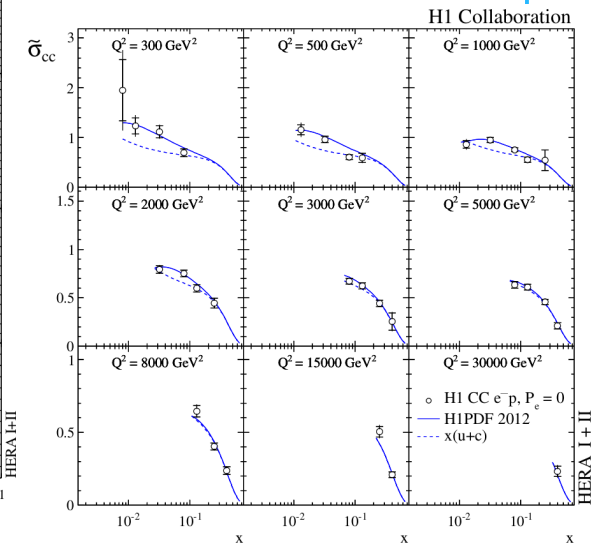
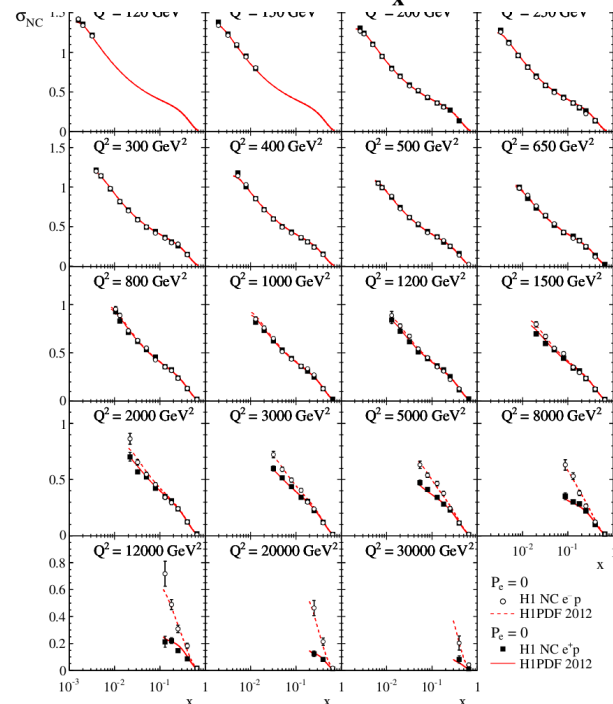
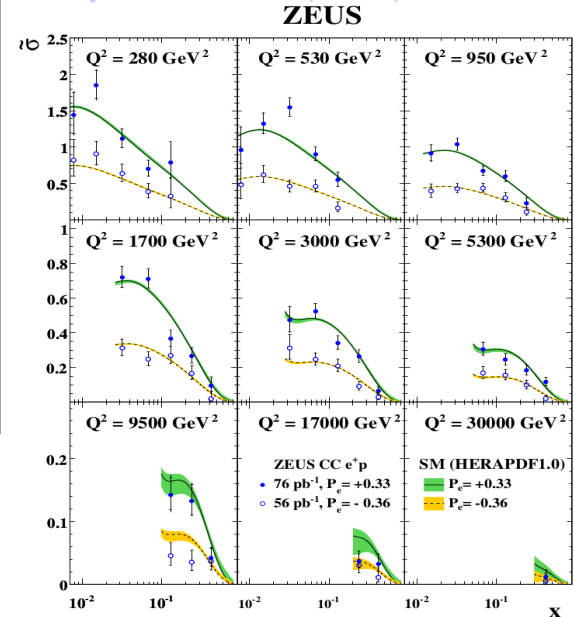
- All HERAI data (H1 & ZEUS)
 - unpolarised
- Reduced E_p data (H1 & ZEUS)
- HERAII
 - H1 unpolarized data
 - ZEUS polarized data

Data from $Q^2 = 3.5 \text{ GeV}^2$

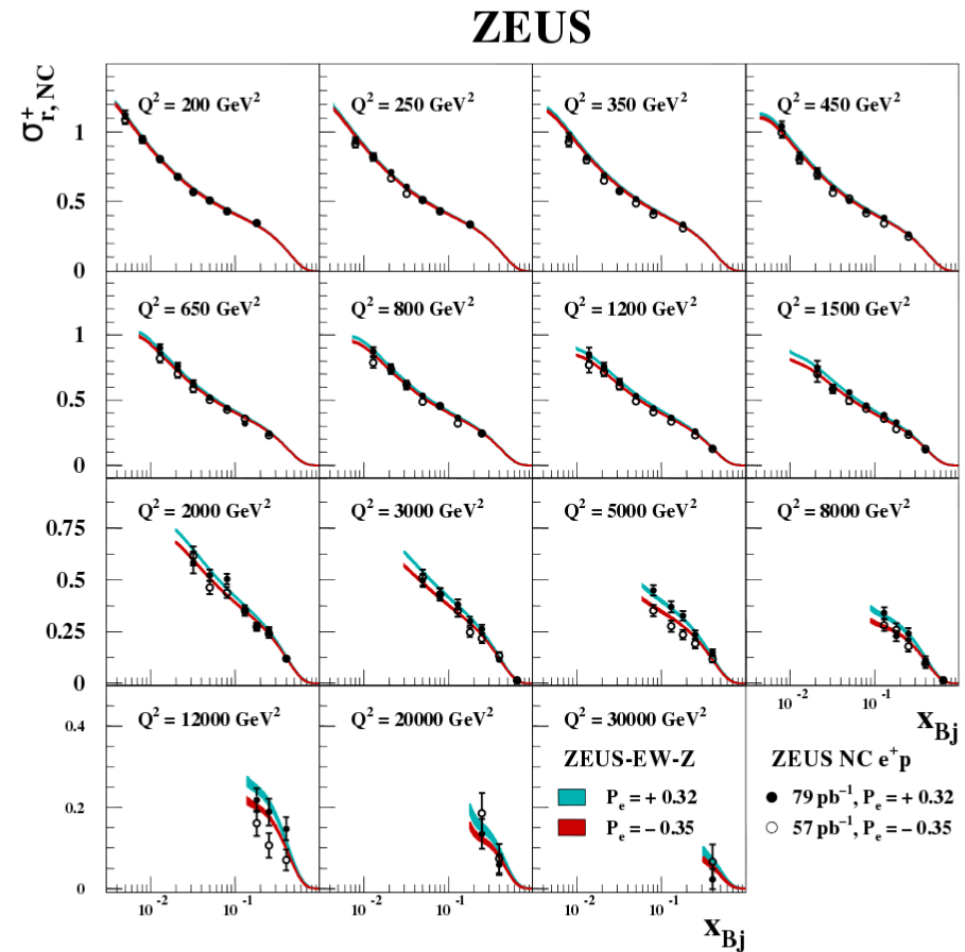
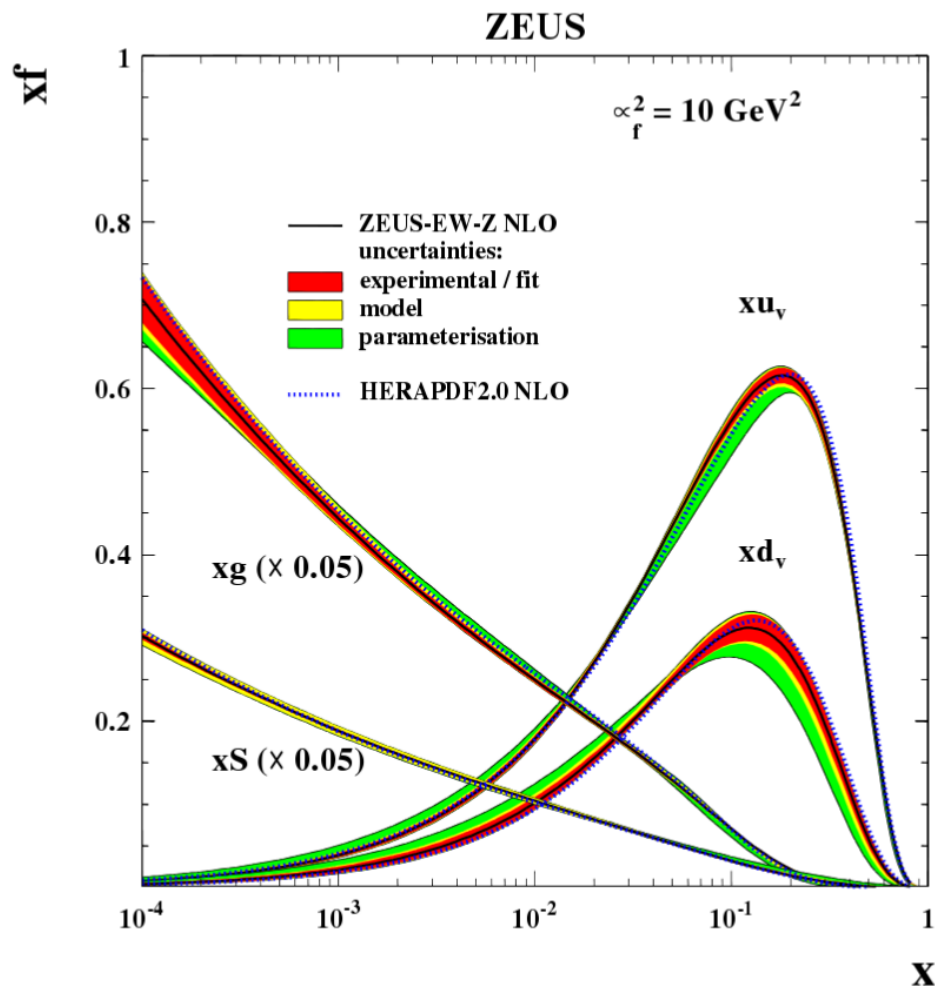
- DGLAP evolution @ NLO
- HF scheme - GN VFNS NLO



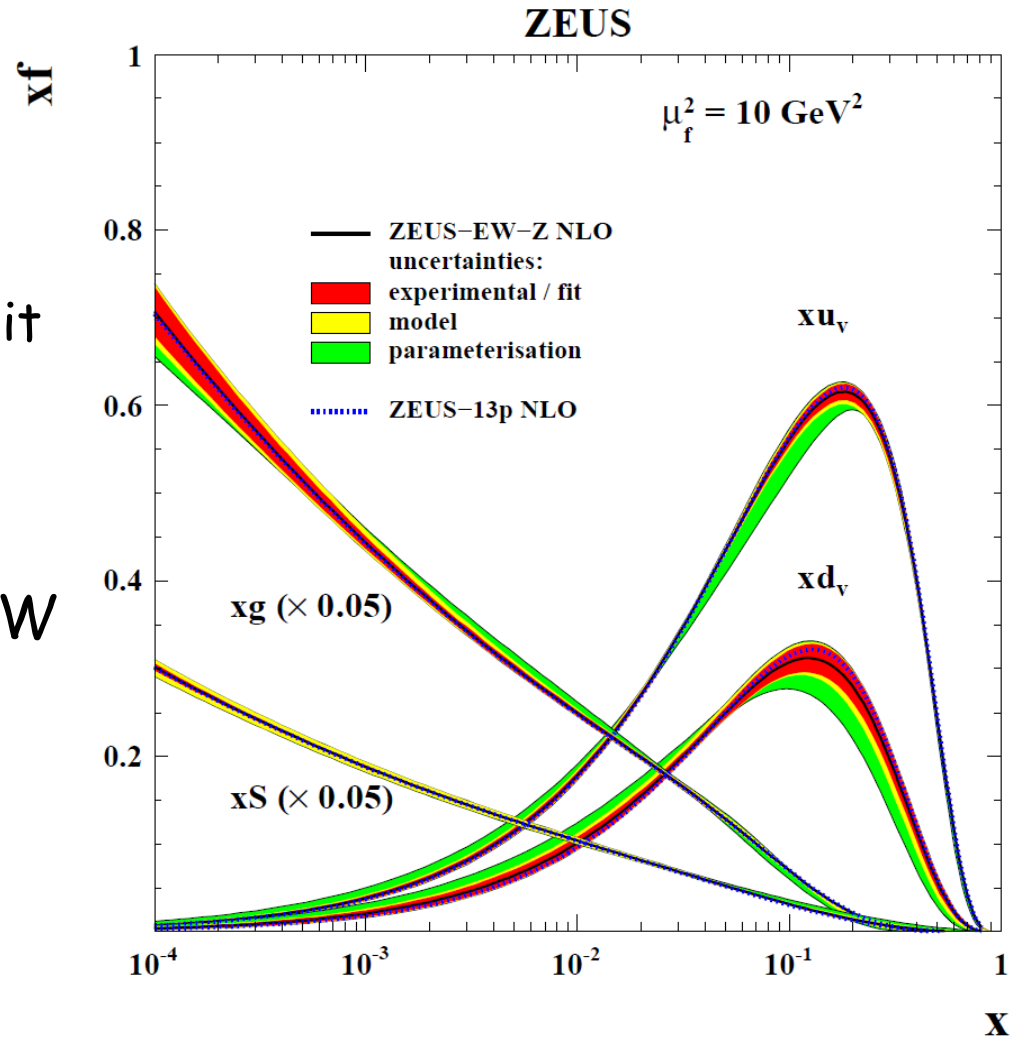
Phys. Rev. D 93 (2016) 092002



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



- 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

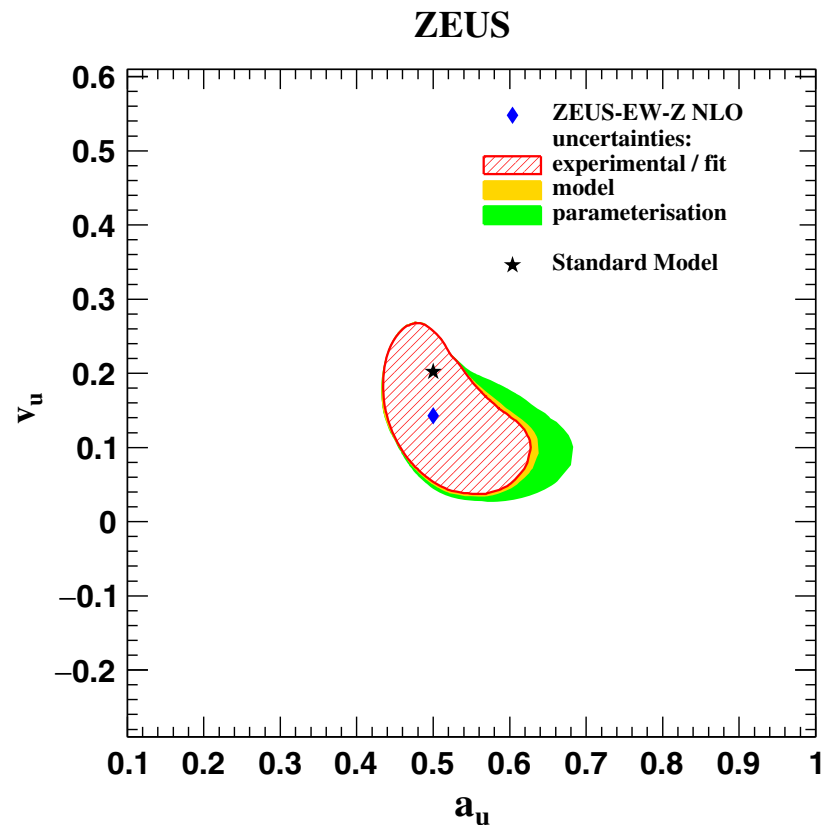
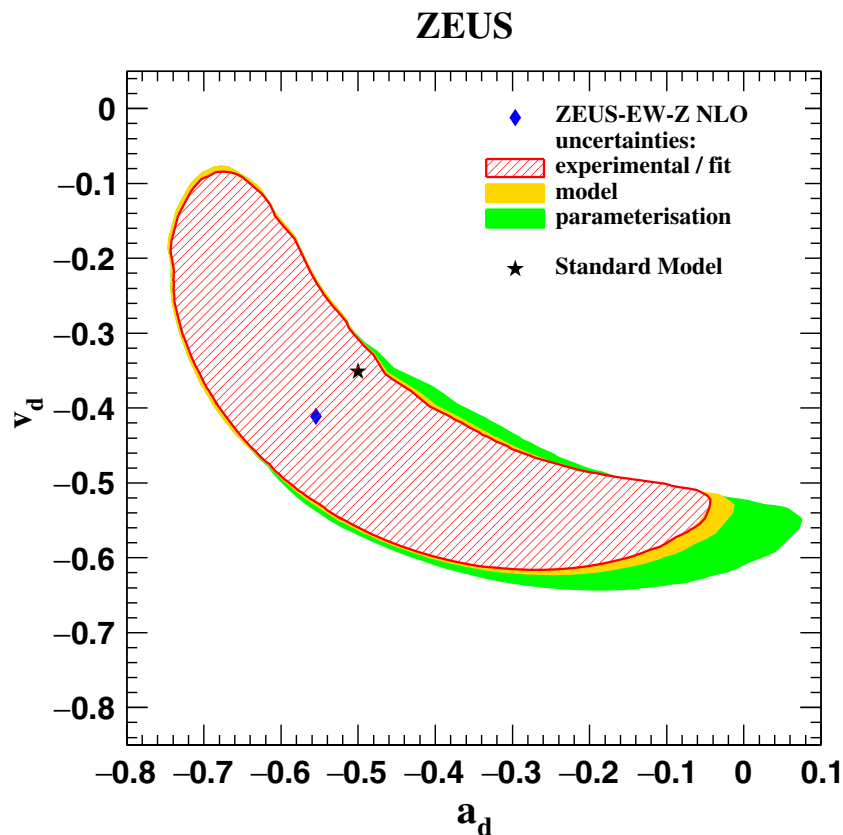


- Detailed studies performed to check stability of EW couplings with respect to various QCD parameters
 - HPDF1: QCD parameters and all constants fixed to HERAPDF2.0
 - HPDF2: QCD parameters fixed to HERAPDF2.0 + on-shell value of $\sin^2 q_w$
 - 13p - reference fit described before

→ 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



$$a_u = 0.50^{+0.09}_{-0.05}(\text{exp/fit})^{+0.04}_{-0.02}(\text{mod})^{+0.08}_{-0.01}(\text{par}) = 0.50^{+0.12}_{-0.05}(\text{tot})$$

0.5

$$a_d = -0.56^{+0.34}_{-0.14}(\text{exp/fit})^{+0.11}_{-0.05}(\text{mod})^{+0.20}_{-0.00}(\text{par}) = -0.56^{+0.41}_{-0.15}(\text{tot})$$

-0.5

$$v_u = 0.14^{+0.08}_{-0.08}(\text{exp/fit})^{+0.01}_{-0.00}(\text{mod})^{+0.03}_{-0.01}(\text{par}) = 0.14^{+0.09}_{-0.09}(\text{tot})$$

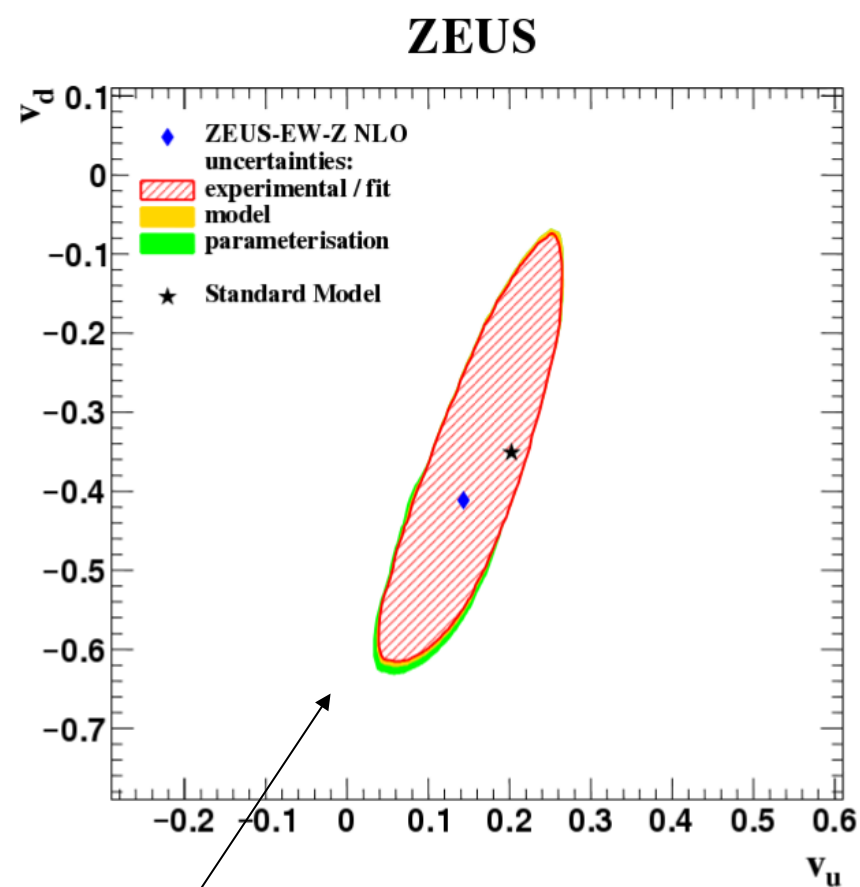
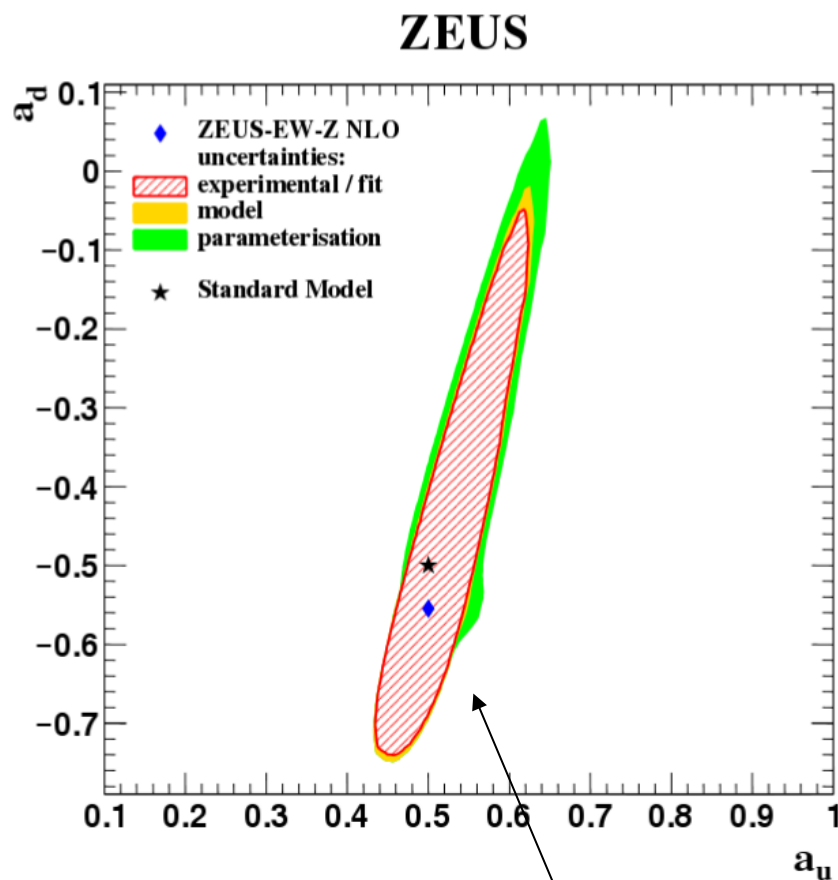
0.202

$$v_d = -0.41^{+0.24}_{-0.16}(\text{exp/fit})^{+0.04}_{-0.07}(\text{mod})^{+0.00}_{-0.08}(\text{par}) = -0.41^{+0.25}_{-0.20}(\text{tot})$$

-0.351

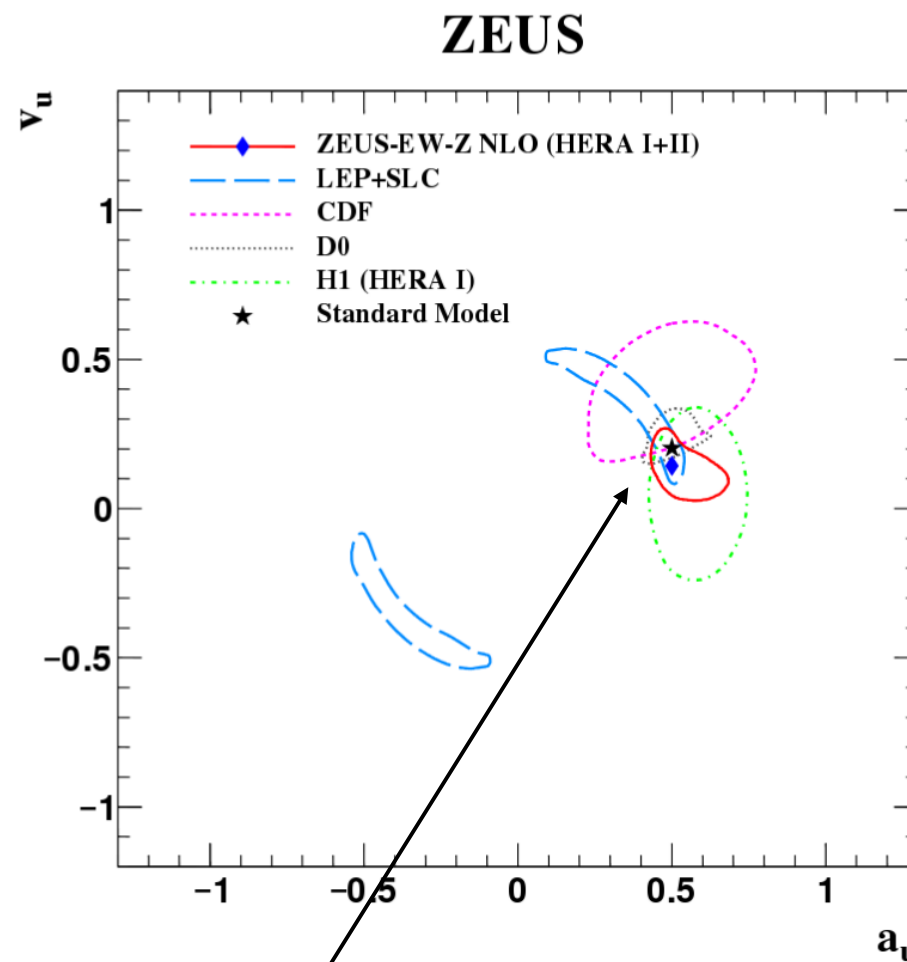
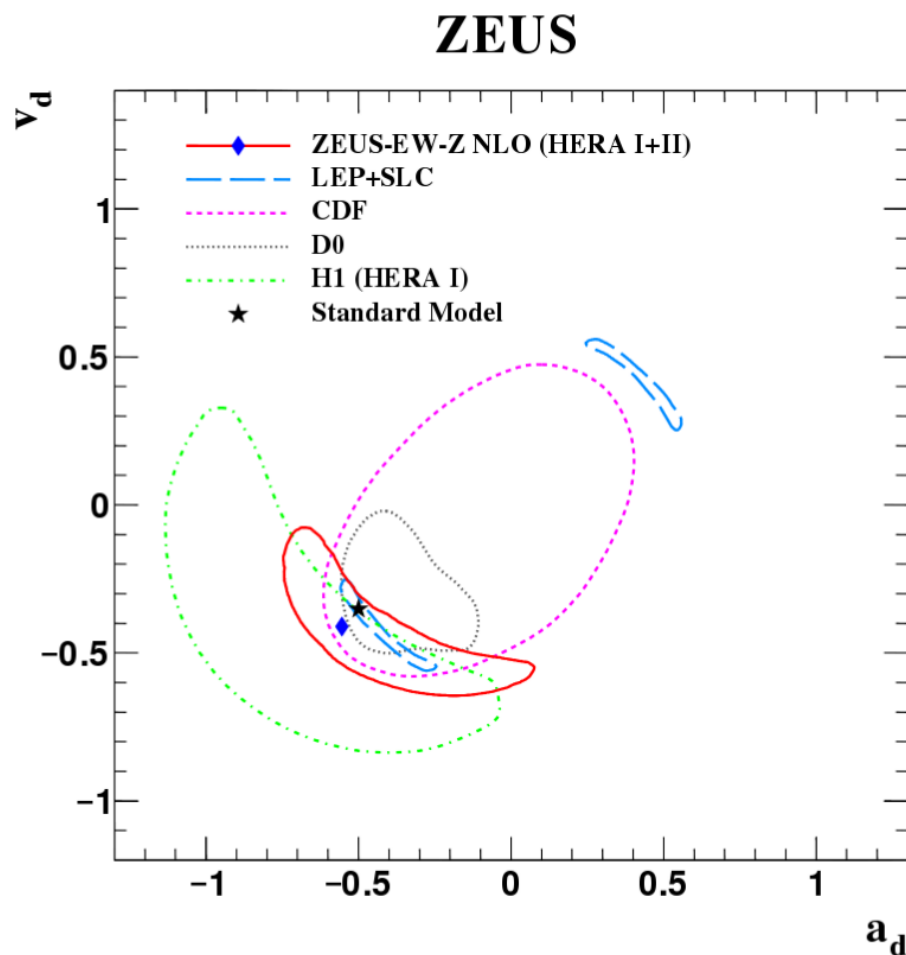
Standard Model

- 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



HERA data remarkably sensitive to **u-type** quark couplings

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

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

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

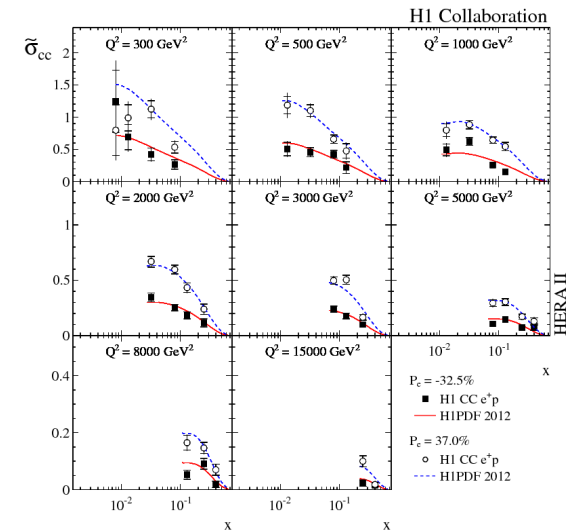
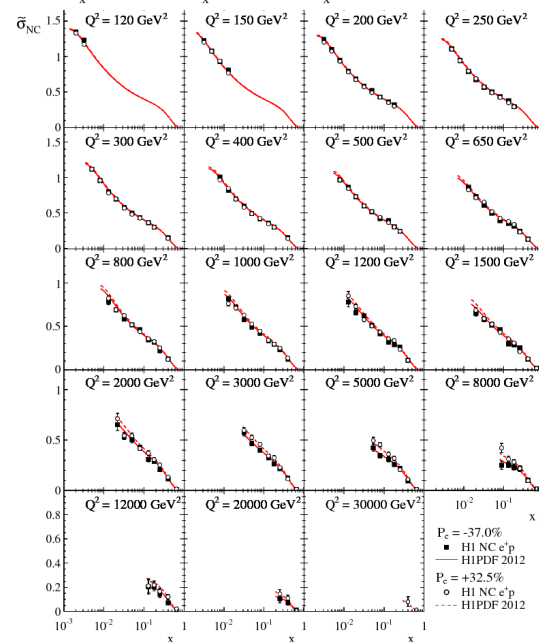
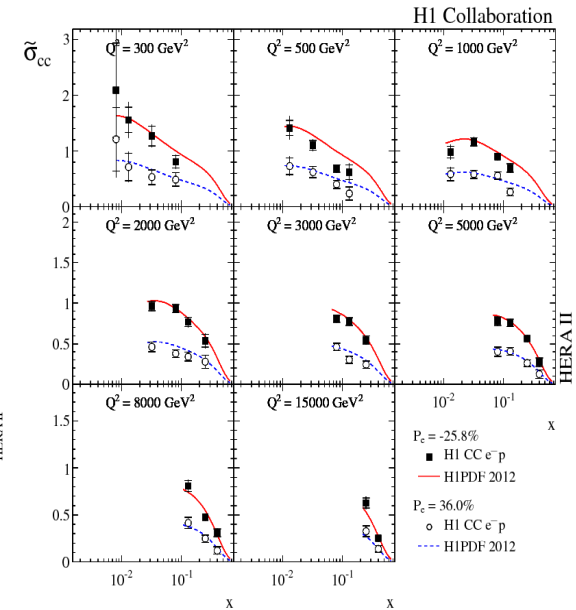
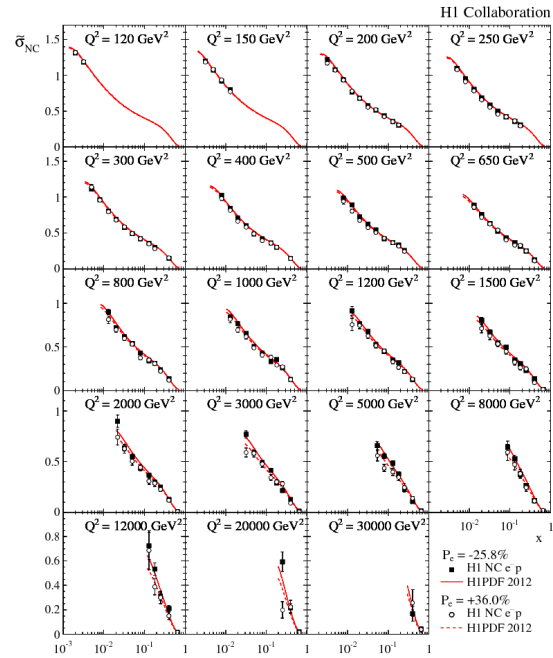
Fit parameters

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

Uncombined data sets

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

Data from $Q^2 = 12 \text{ GeV}^2$

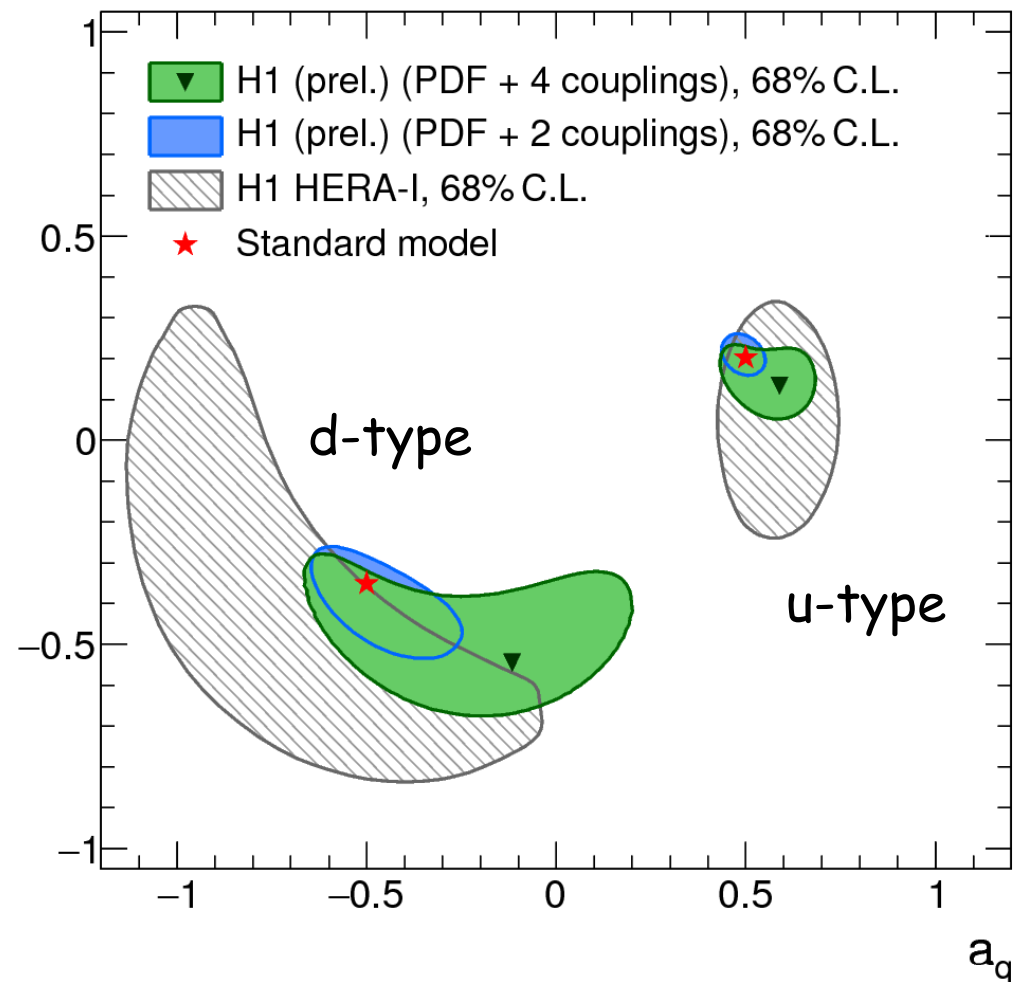


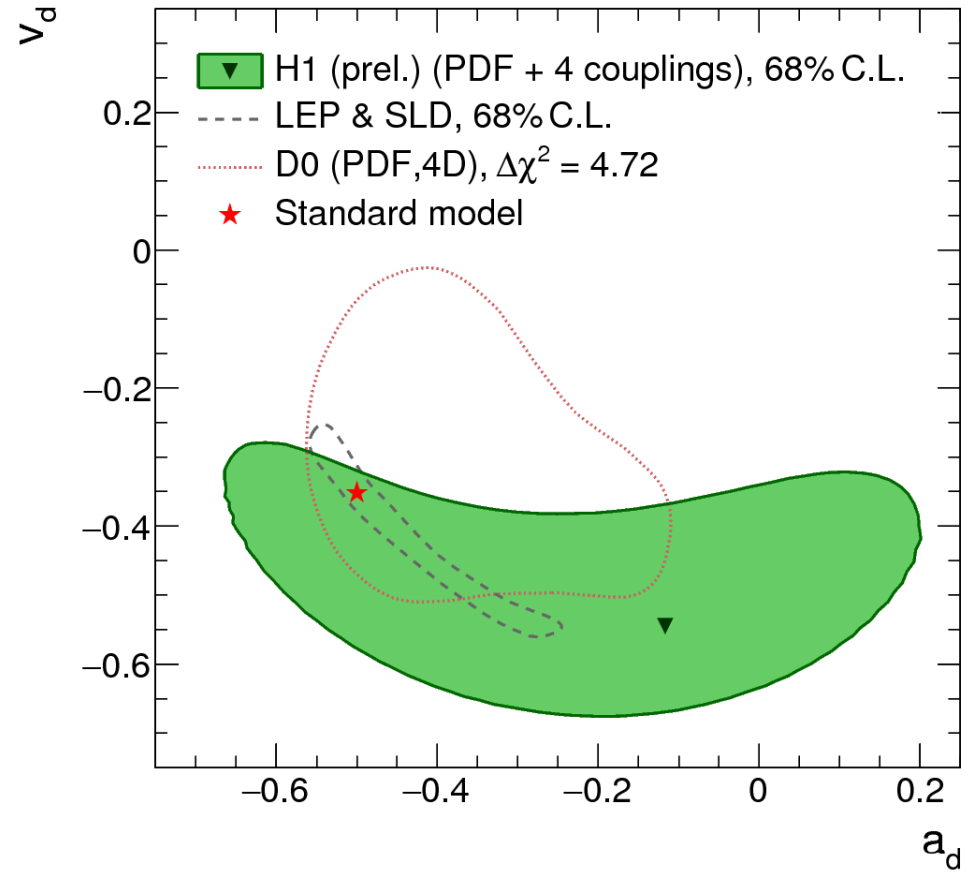
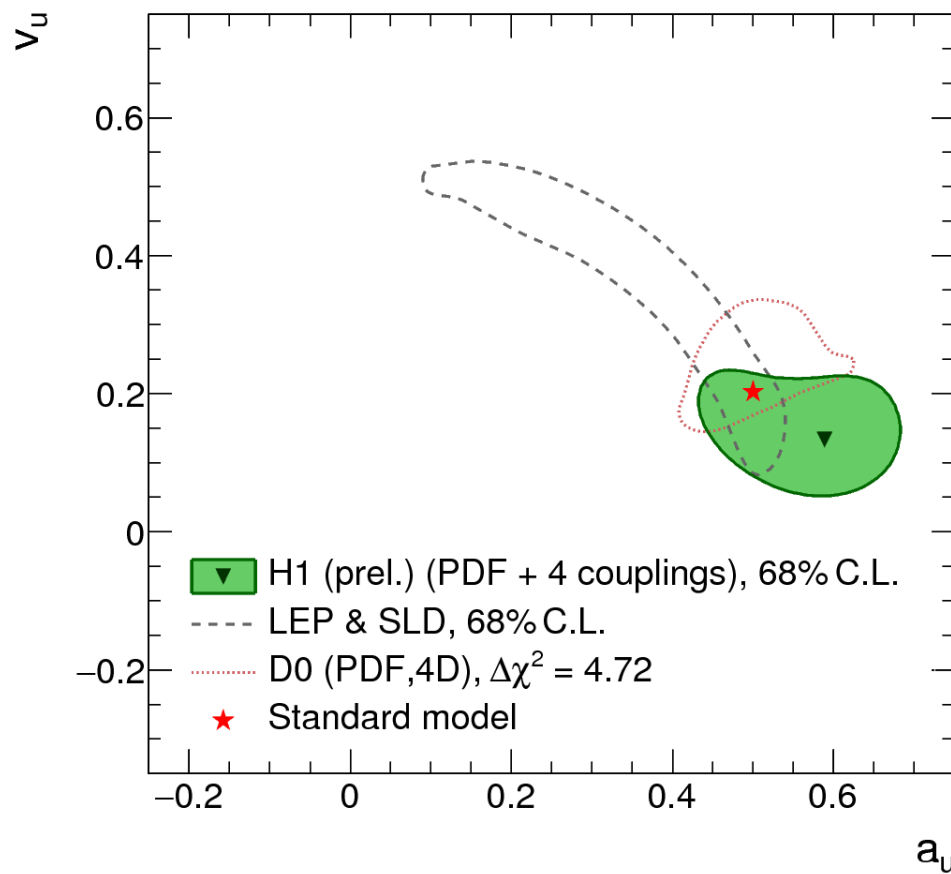
Fit: PDF + 4 couplings

- $\chi^2 / \text{ndf} = 1370.5 / (1388 - 21)$
- u-type couplings constrained better than 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

Fit: PDF + 2 couplings

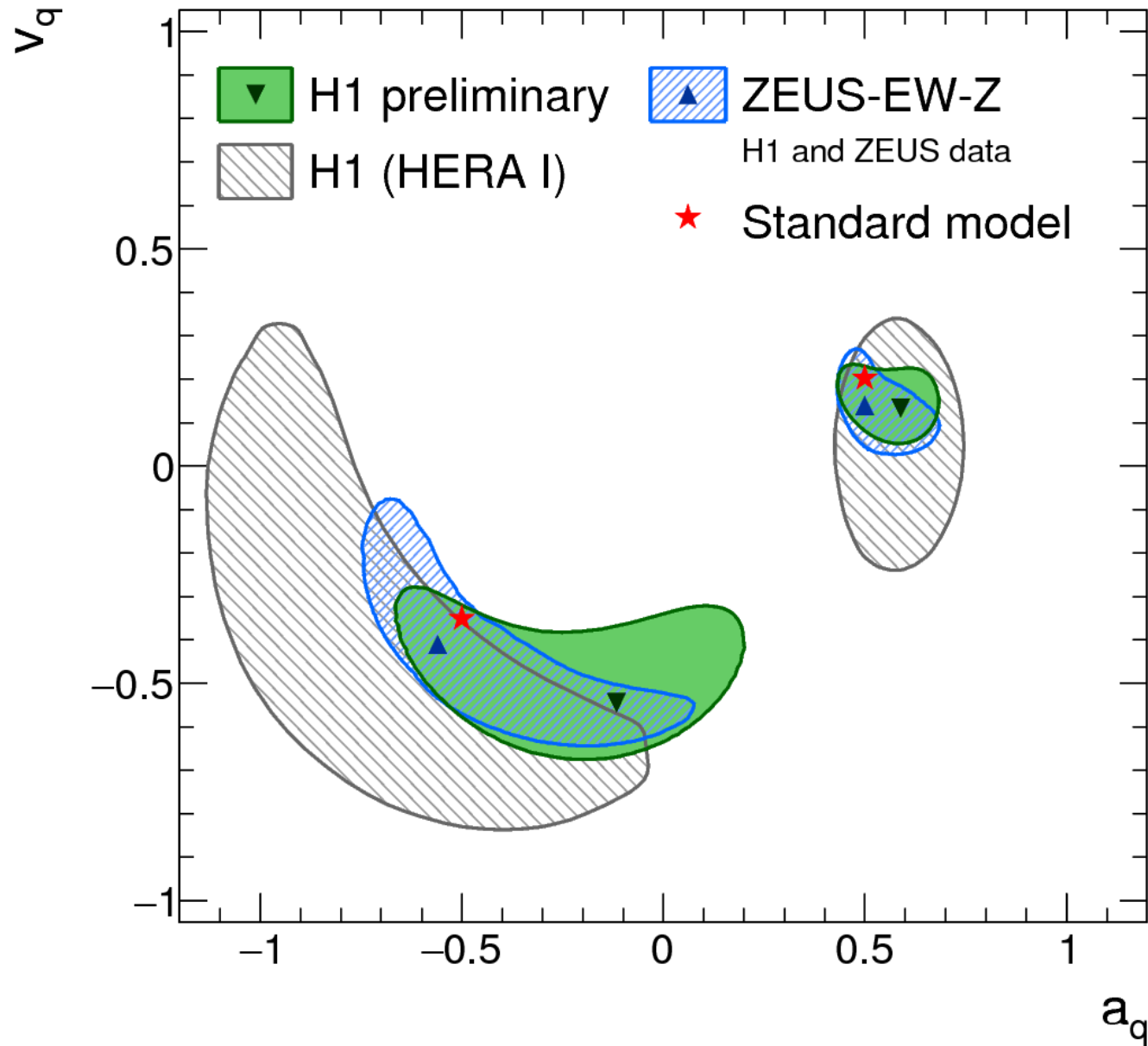
- Reduced correlations and uncertainties
- Correlations between $a_u - a_d$ and $v_u - v_d$ large





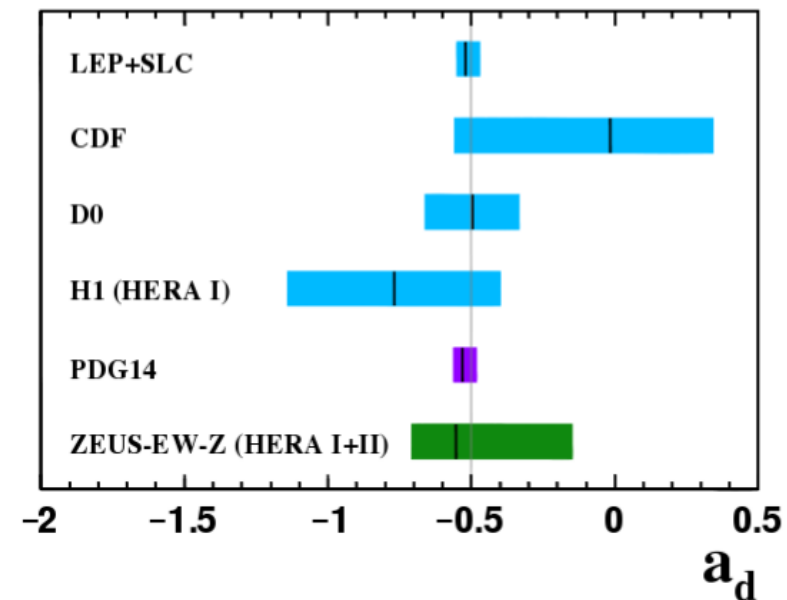
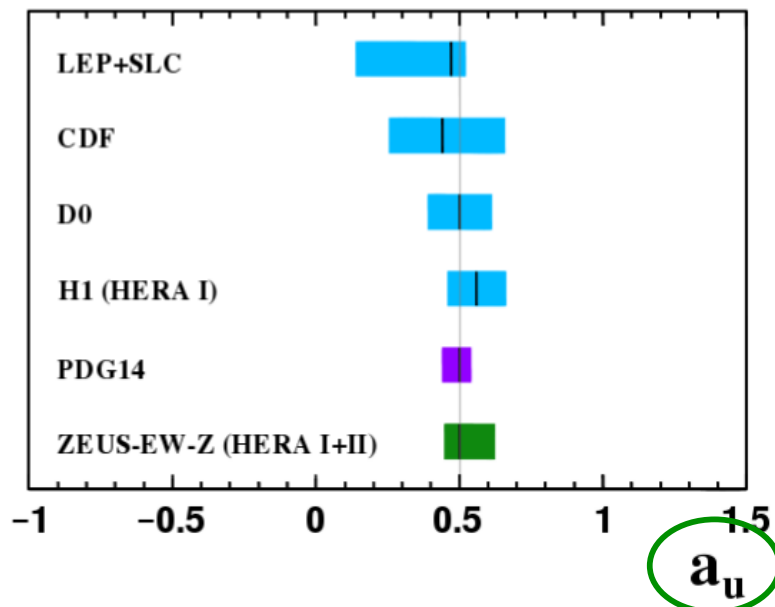
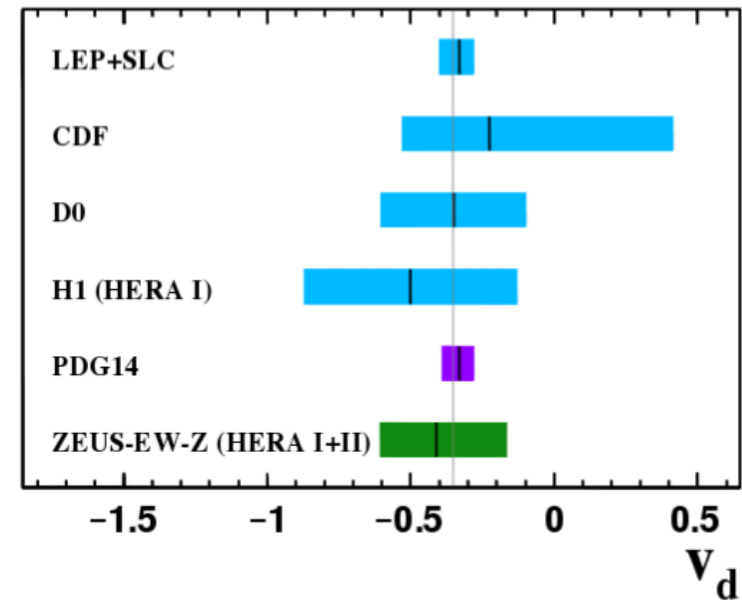
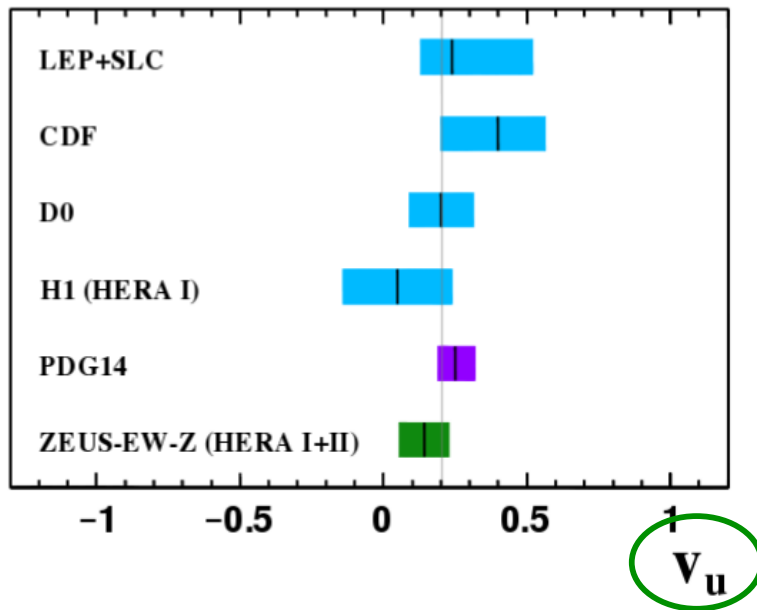
Comparable precision of complementary processes

H1 and ZEUS Results Combined





Comparison with other measurements



High sensitivity of HERA data to u-type quark couplings

Probing Standard Model

Standard Model is now over constrained

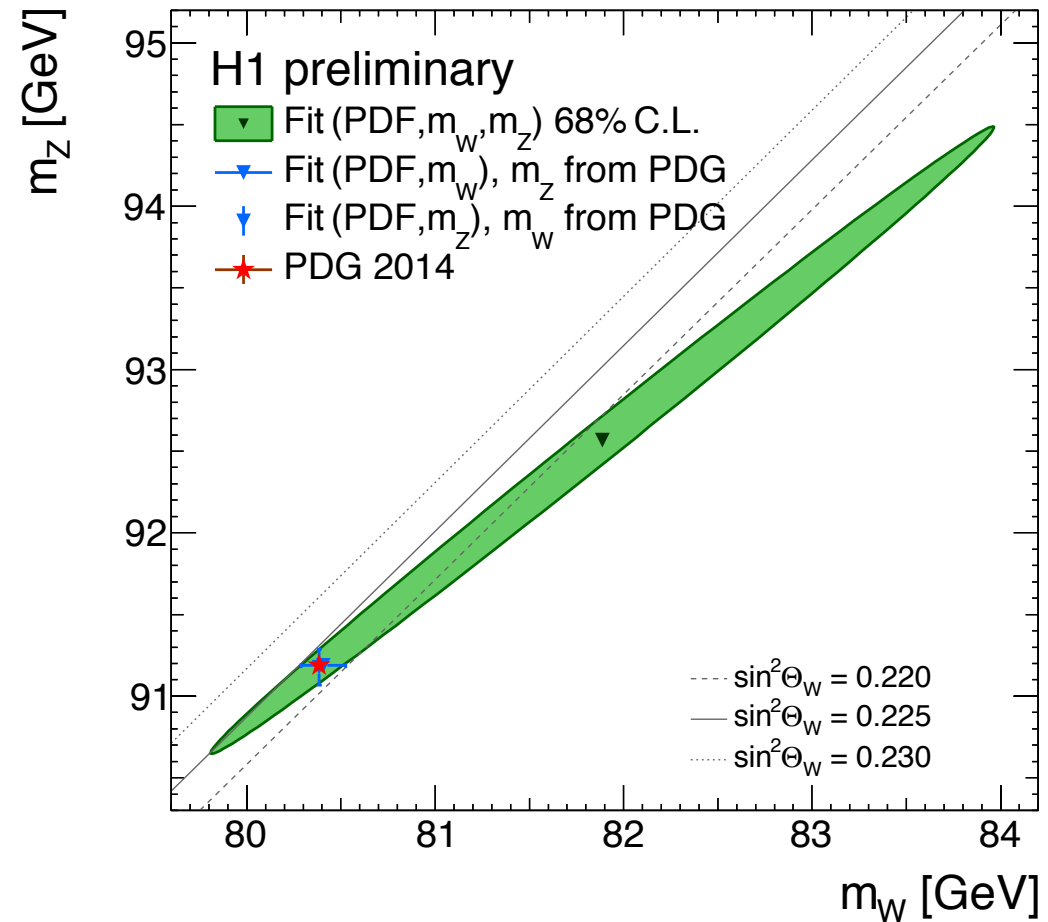
- Important to study consistency in many complementary processes
- HERA: Space-like momentum transfers
- Only purely virtual exchange of bosons

$(m_W - m_Z) + \text{PDF fits}$

- 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



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

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

Different view on SM parameters

- Fermi coupling constant G_F

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

- Weak mixing angle

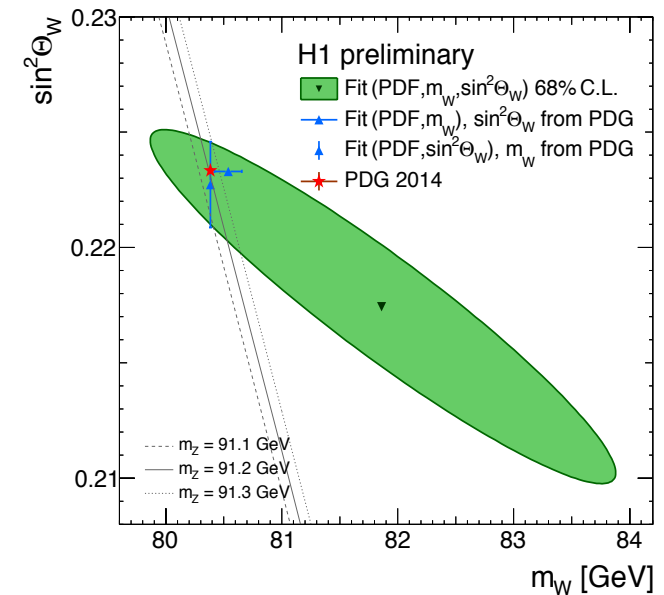
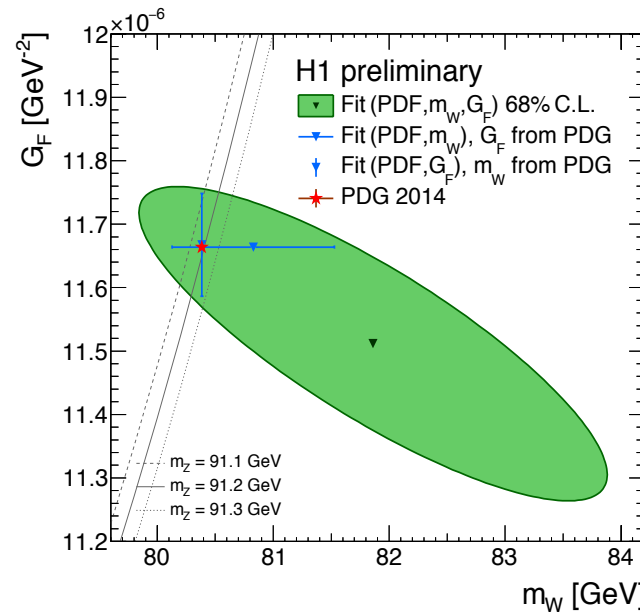
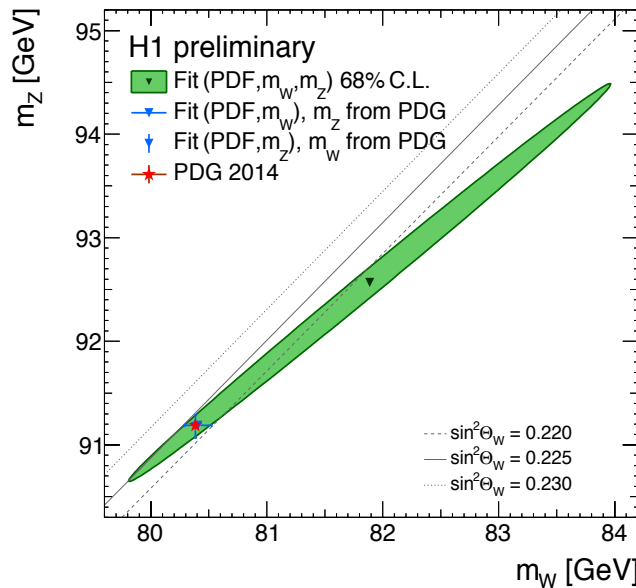
$$\sin^2 \theta_W = 1 - \frac{m_W^2}{m_Z^2}$$

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

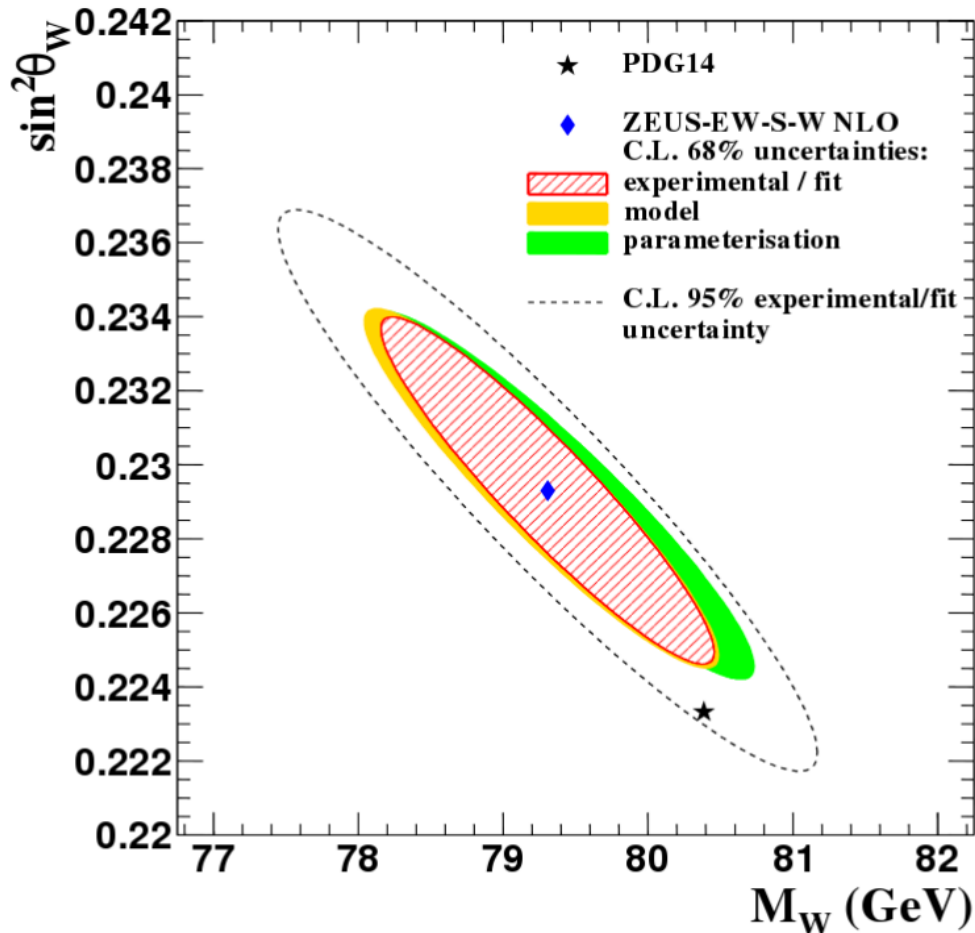
- Similar measurement by ZEUS

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

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

- All extracted quantities agree with world average values

ZEUS



$$M_W^{PDG14} = 80.385 \pm 0.015 \text{ GeV}$$

$$\sin^2\theta_W^{PDG14 \text{ on-shell}} = 0.22333 \pm 0.00011$$

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

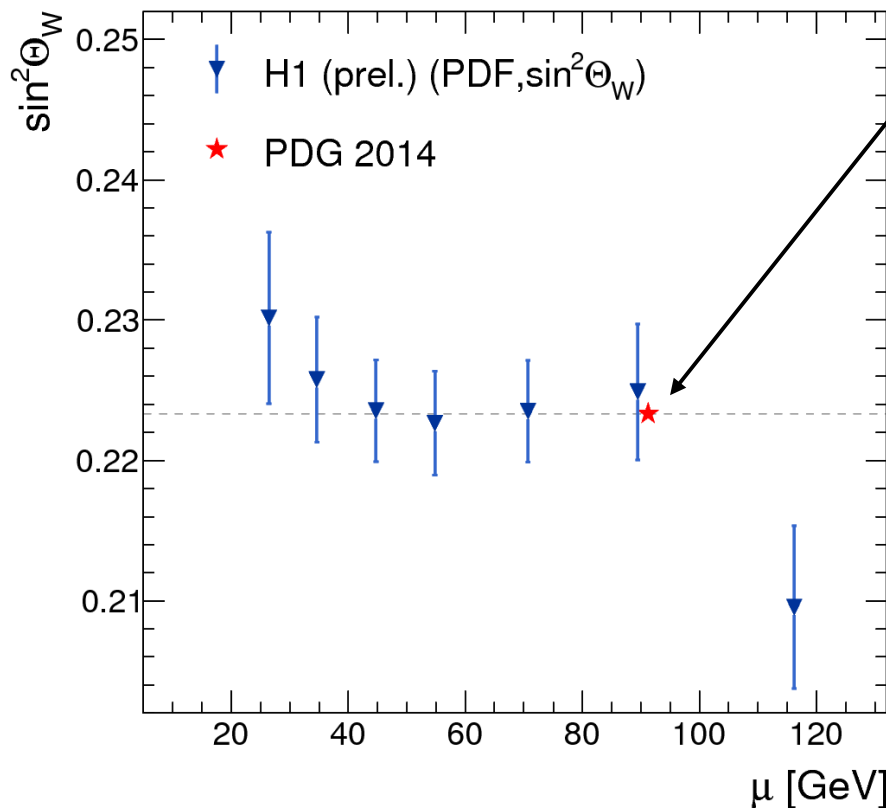
On-shell $\sin^2\theta_W$

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

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

- Consistent with PDG14

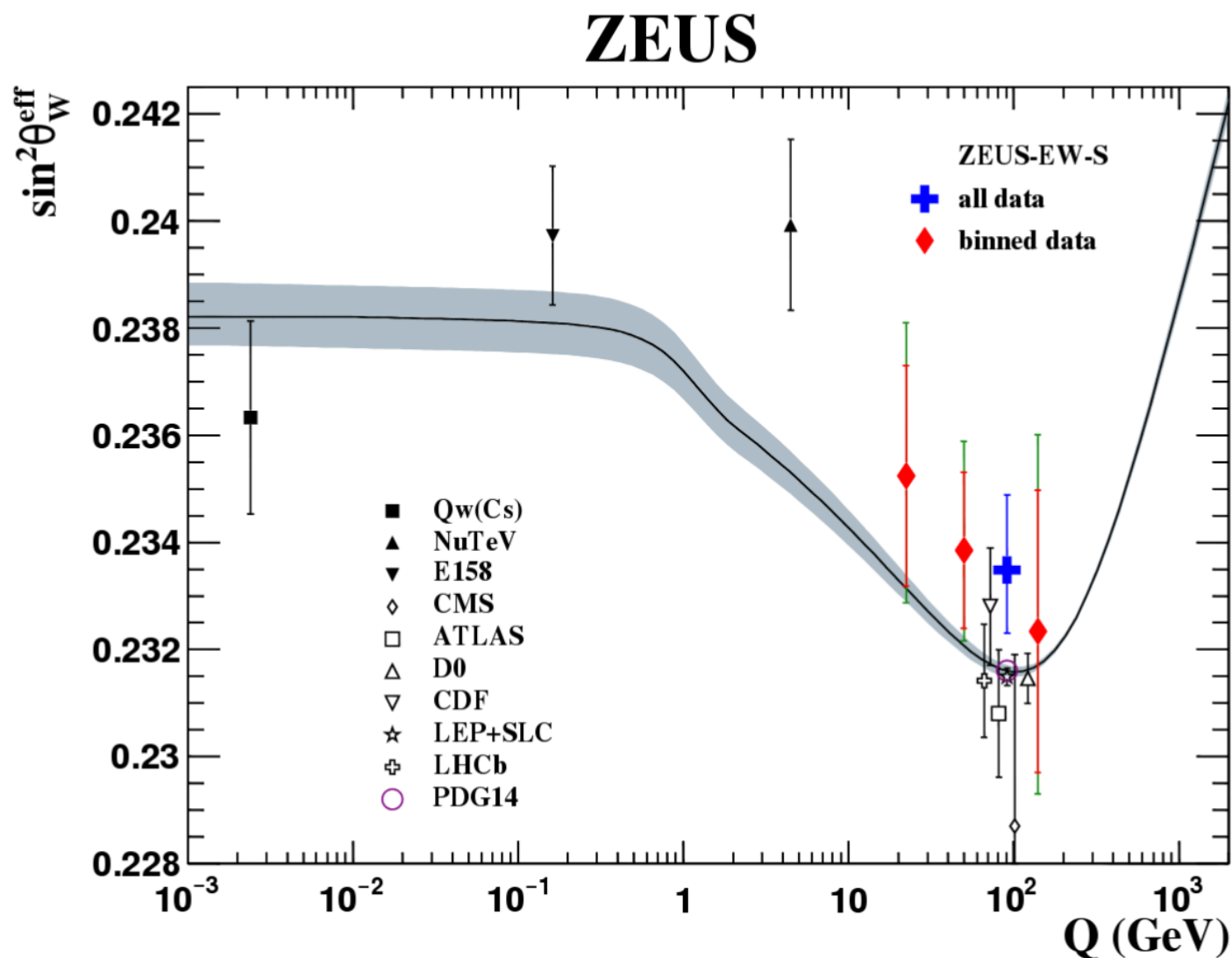
$$\sin^2\theta_W^{PDG\ 14\ On-shell} = 0.22333 \pm 0.00011$$



- $\sin^2\theta_W$ determined in Q^2 bins
- Unique measurement of weak mixing angle at different scales
- Agreement with PDG14

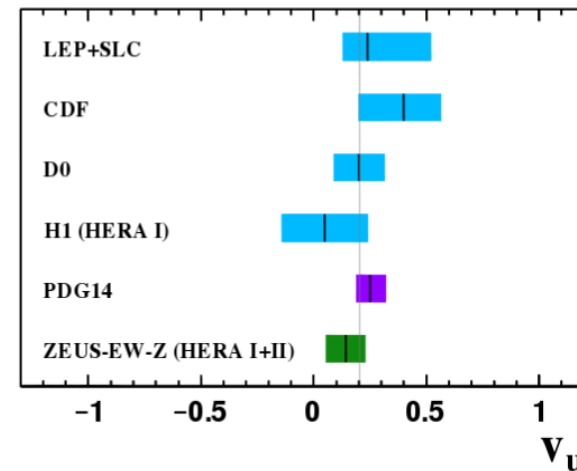
Effective $\sin^2\theta_w$

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



Summary

- HERA polarized 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