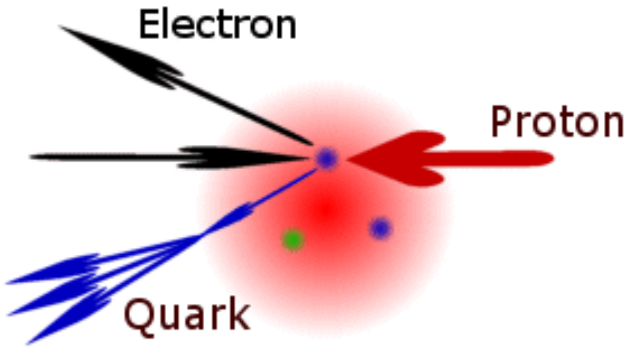


Simultaneous QCD & Electroweak Fits to HERA Inclusive DIS data

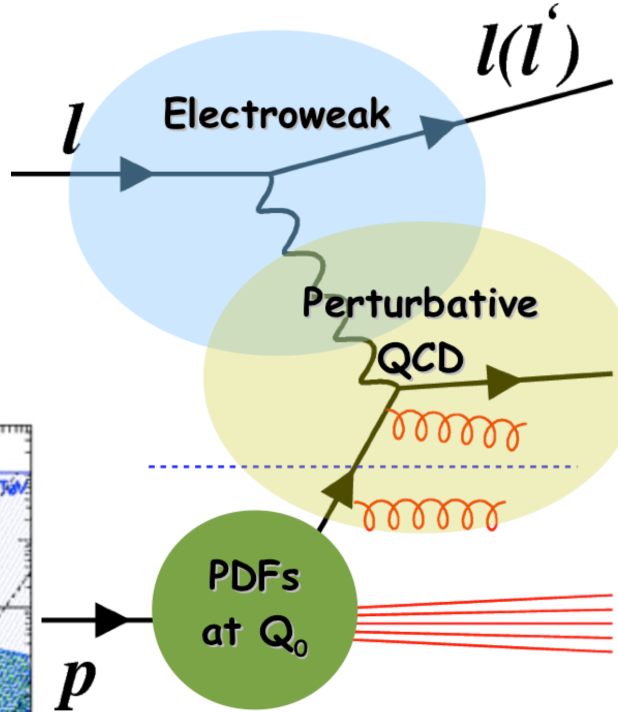
U.Schneekloth on behalf of H1 & ZEUS collaborations

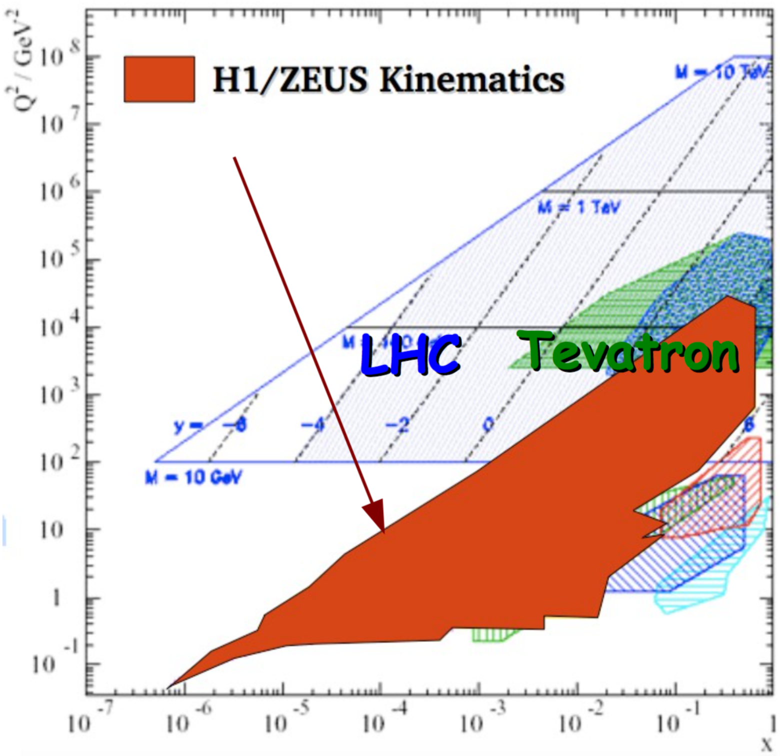
Outline

Deep Inelastic Scattering at HERA

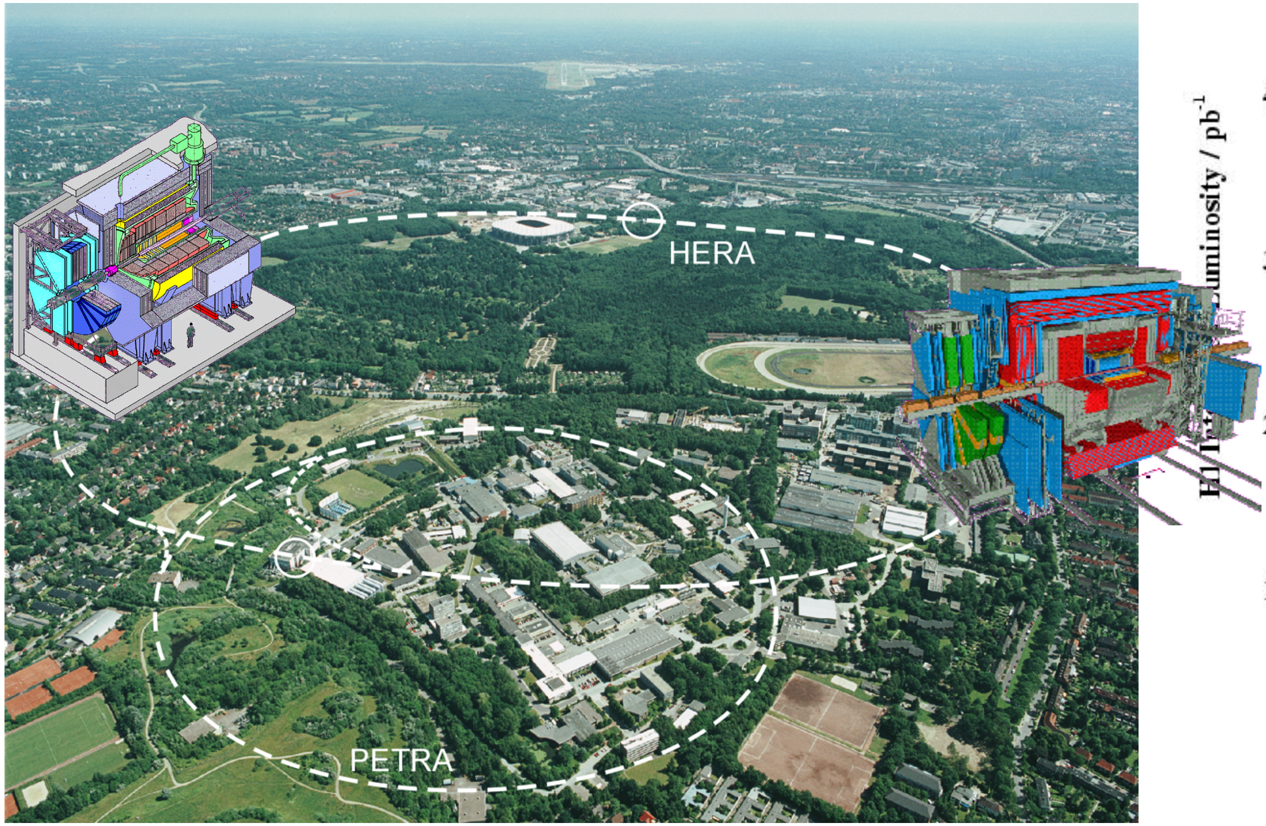
- Introduction and motivation
- Polarized DIS
- Global QCD fits
- Vector and axial-vector couplings
- Boson masses
- $\sin^2\theta_W$ and M_W
- Conclusions

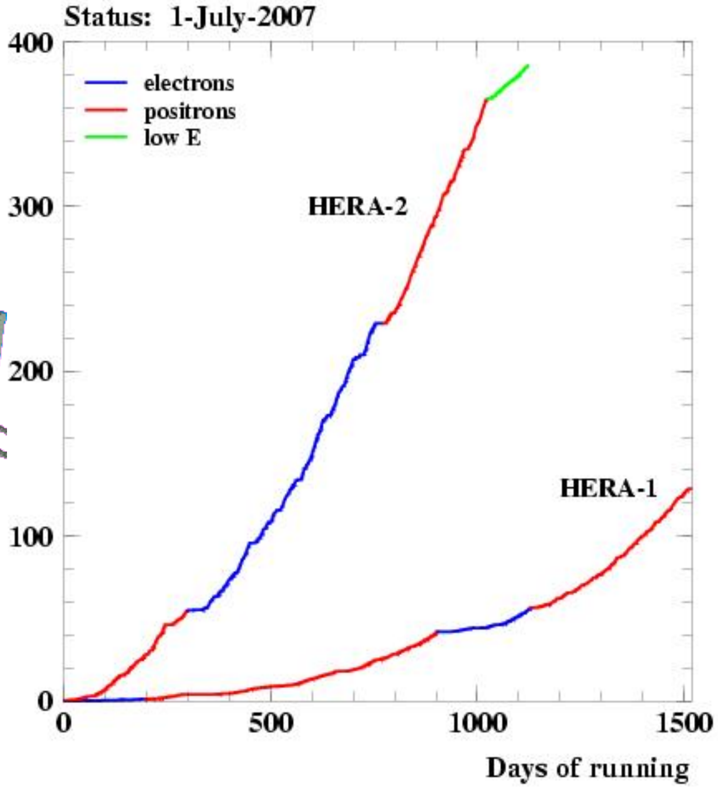
HERA a unique facility
DIS best tool to probe proton structures





HERA: the only ep Collider

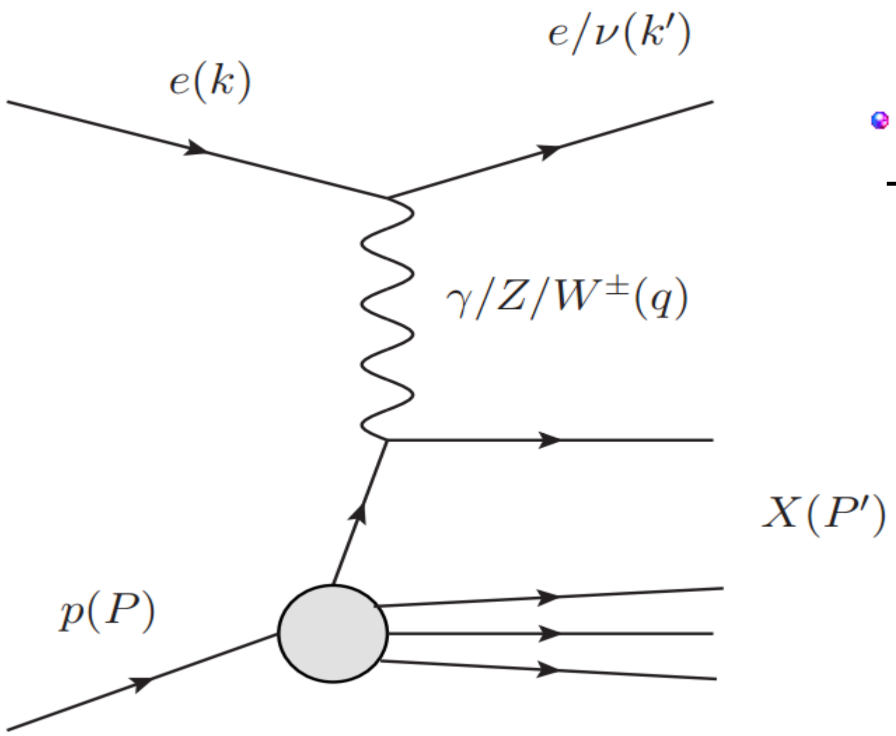




HERA (1992-2007): $\sqrt{s}$ = 252 – 318 GeV

E_e = 27.5GeV, E_p = 920, 820, 575, 460 GeV

Deep Inelastic Scattering at HERA



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

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

$$E_e = 27.5\,GeV$$

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

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

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

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

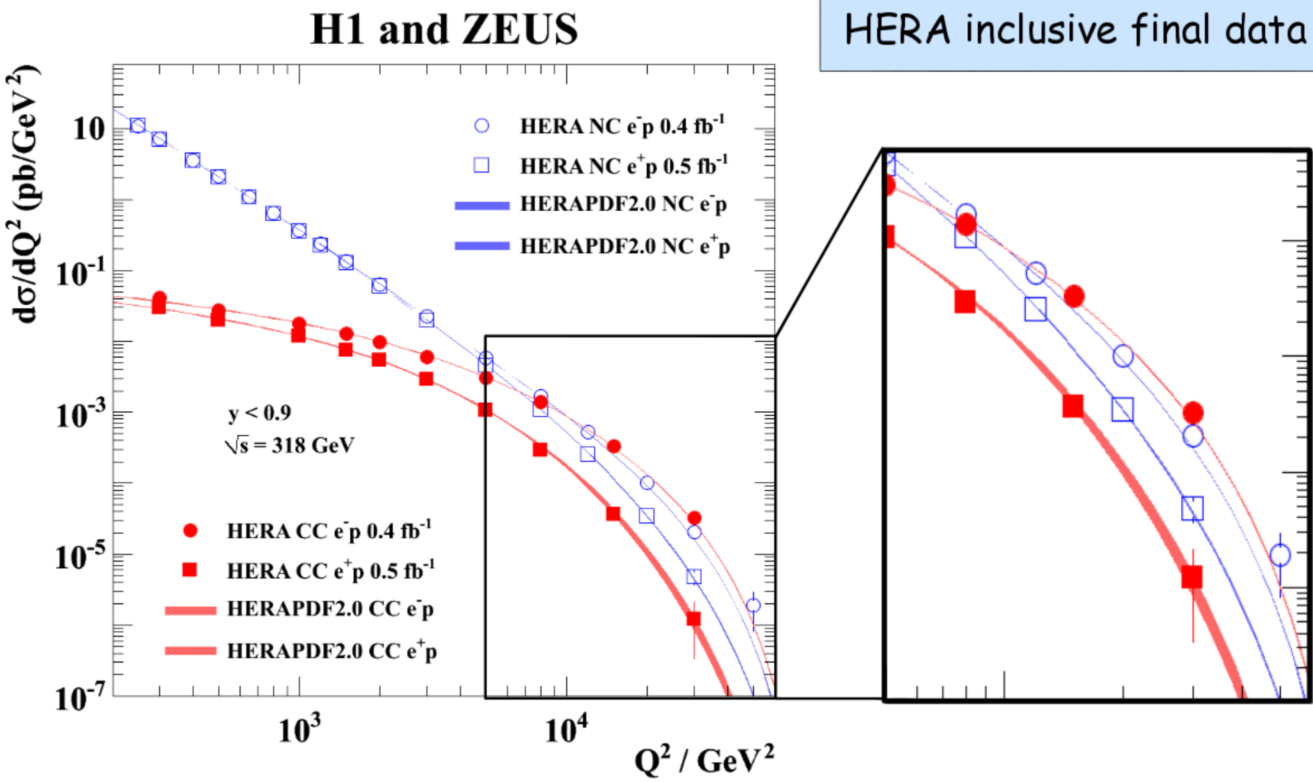
Experimental luminosity (H1 & ZEUS):

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

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. $xF^{\gamma Z}_3$
- This talk DIS with polarization

Fantastic precision of HERA inclusive final data



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

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

$$[x F_3^{\gamma Z}, x F_3^Z] = \sum_q [e_q a_q, v_q a_q] 2x(q - \bar{q}),$$

NC sensitive to sin^{2}q$_W$ via

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

- 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

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

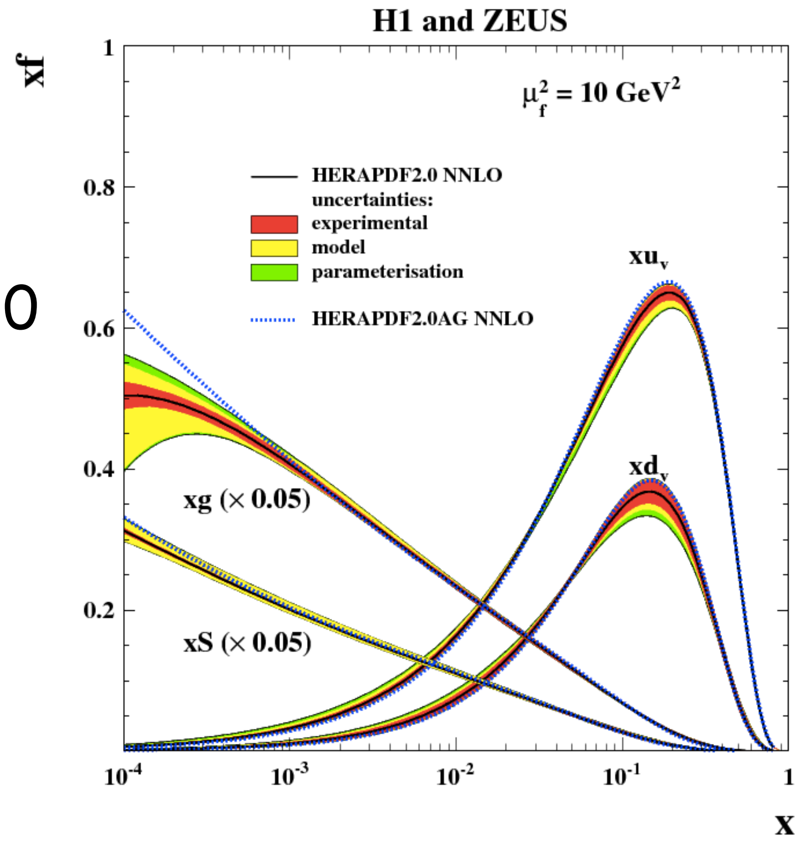
$$\frac{d^2\sigma_{CC}(e^-p)}{dx_{Bj} dQ^2} = (1 - P_e)\frac{G_F^2 M_W^4}{2\pi x_{Bj}(Q^2 + M_W^2)^2} x\,[(u + c) + (1 - y)^2 (\bar{d} + \bar{s} + \bar{b})]$$

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^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

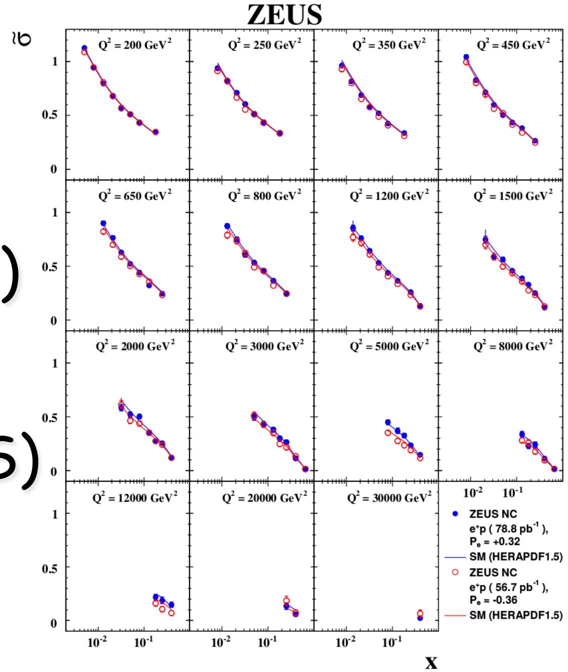
Vector and axial-vector couplings

Uncombined data sets

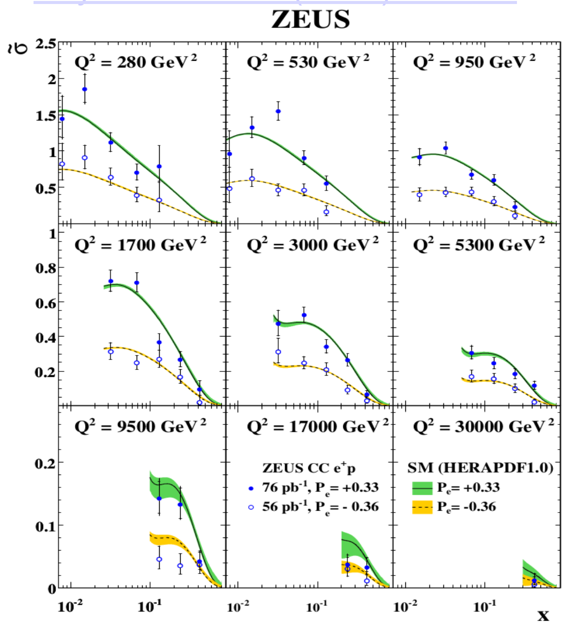
- All HERAI data (H1 & ZEUS)
  - unpolarised
- Reduced E_p data (H1 & ZEUS)
- HERAII
  - H1 unpolarized data
  - ZEUS polarized data

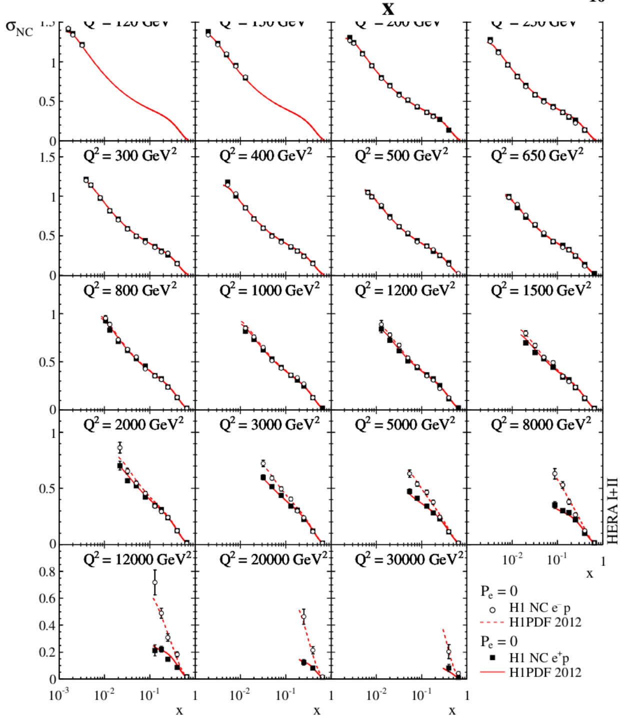
Data from $Q^2 = 3.5\ GeV^2$

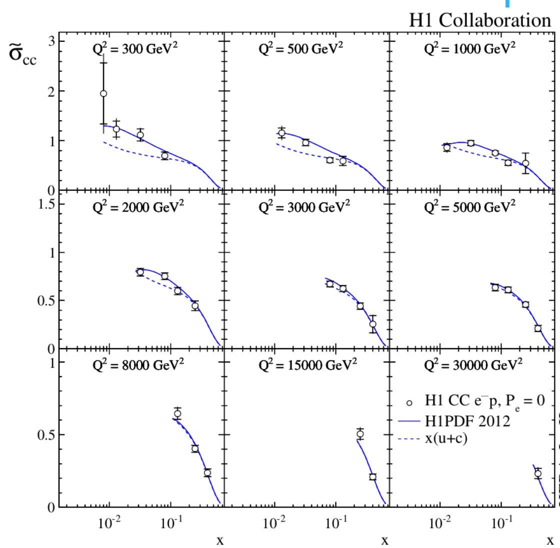
- DGLAP evolution @ NLO
- HF scheme – GN VFNS NLO



Phys. Rev. D 93 (2016) 092002





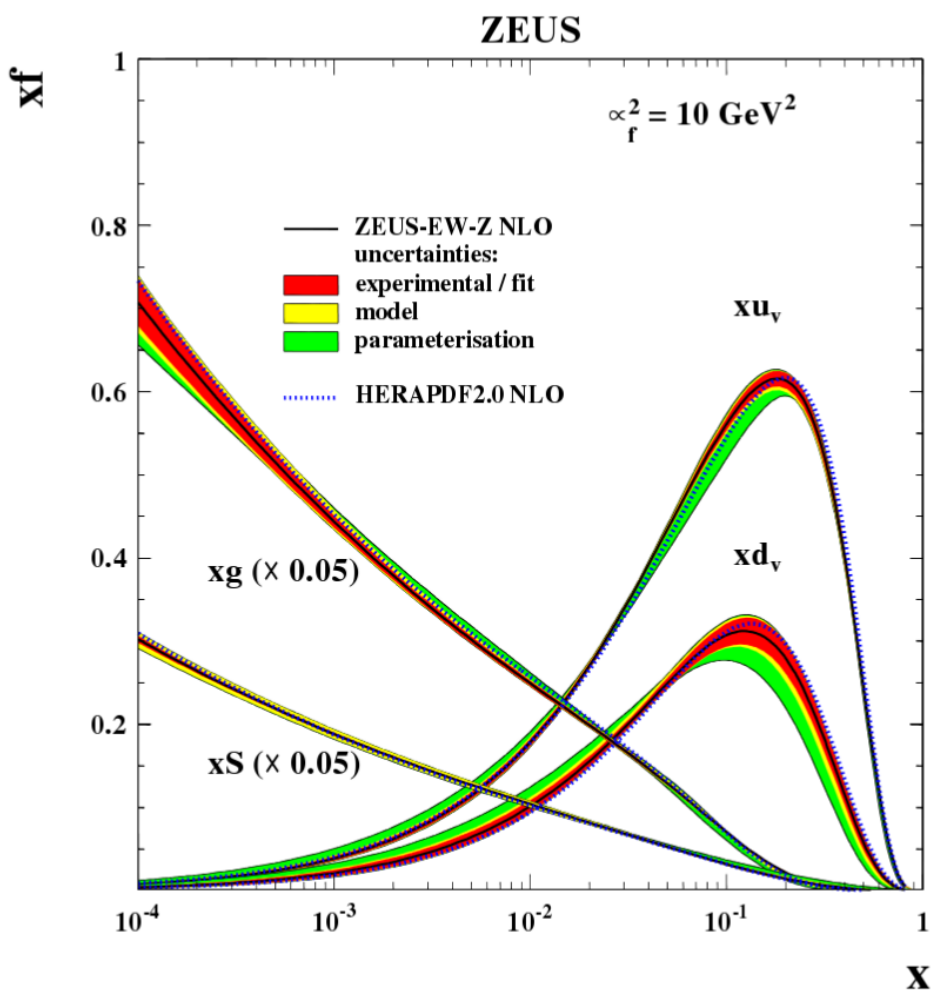


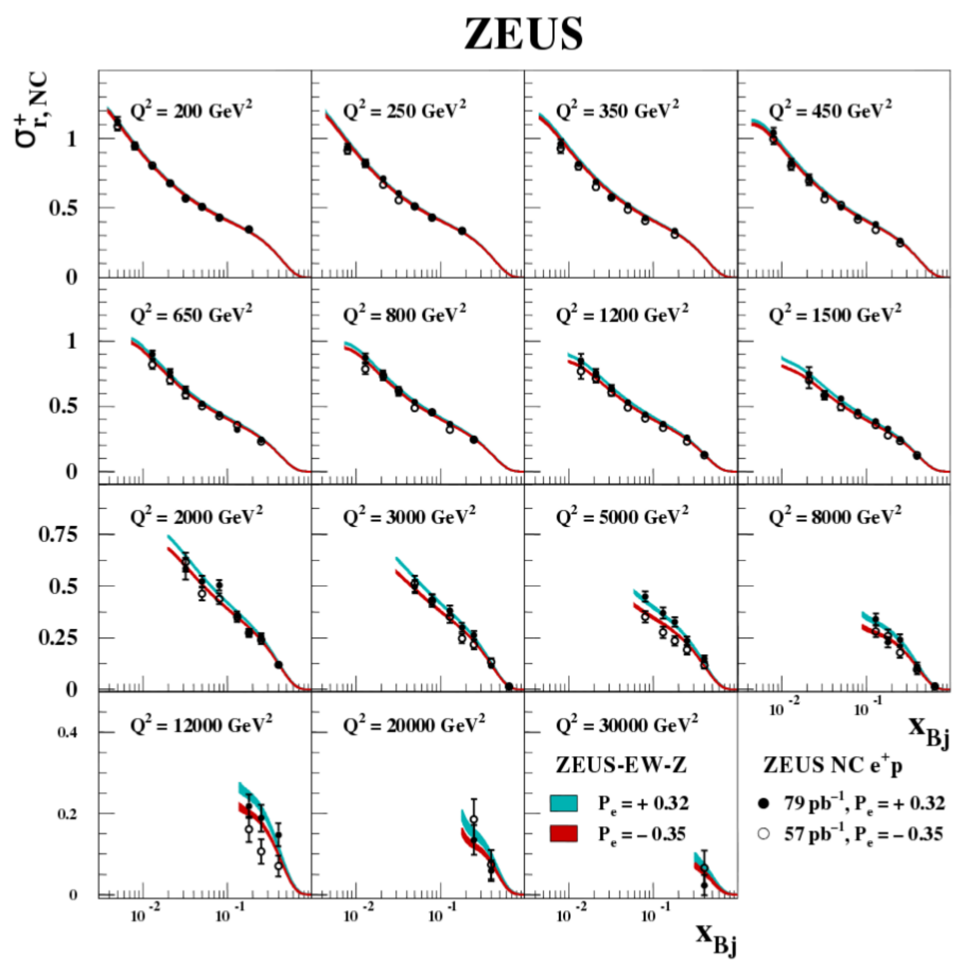
U.Schneekloth

QCD+EW fits

Fit results

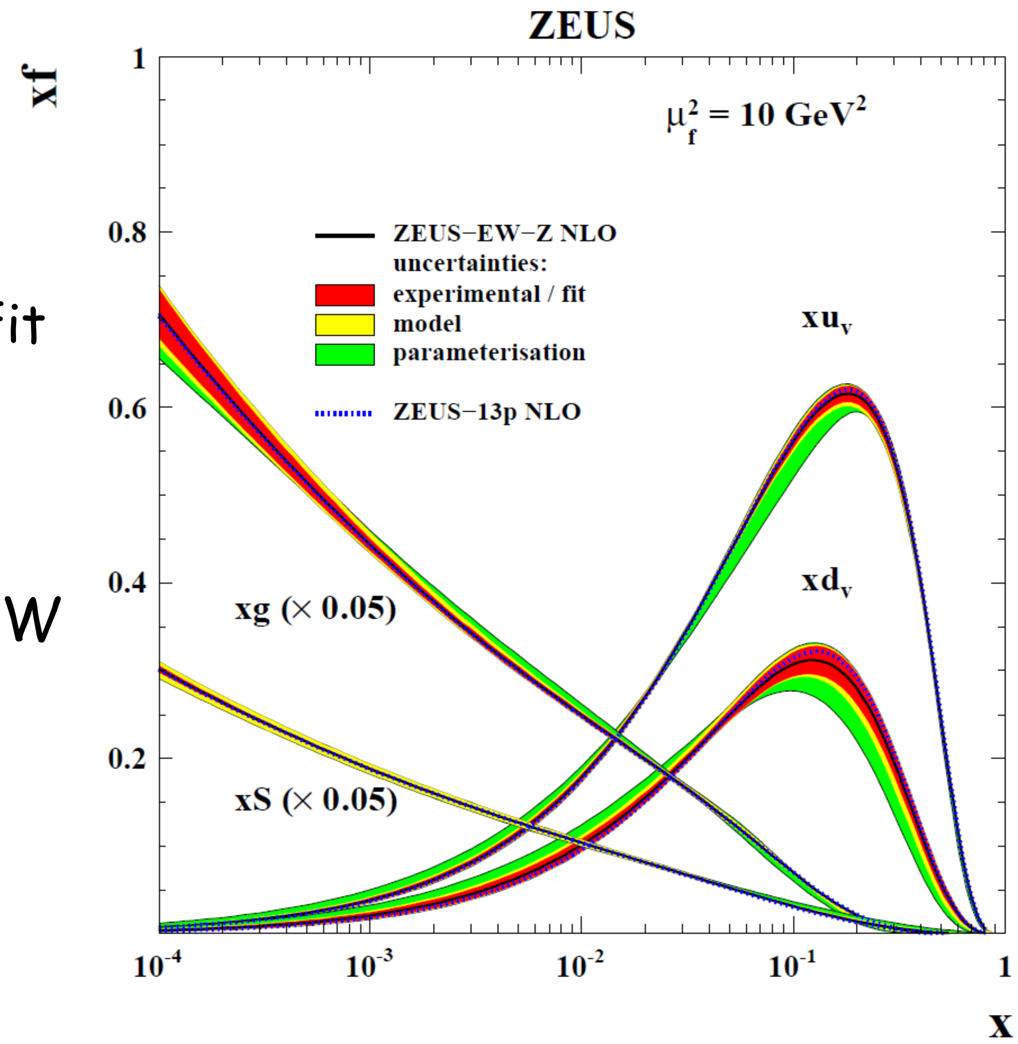
- Simultaneous QCD and EW fit:
  - 13 QCD parameters + 4 EW couplings





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



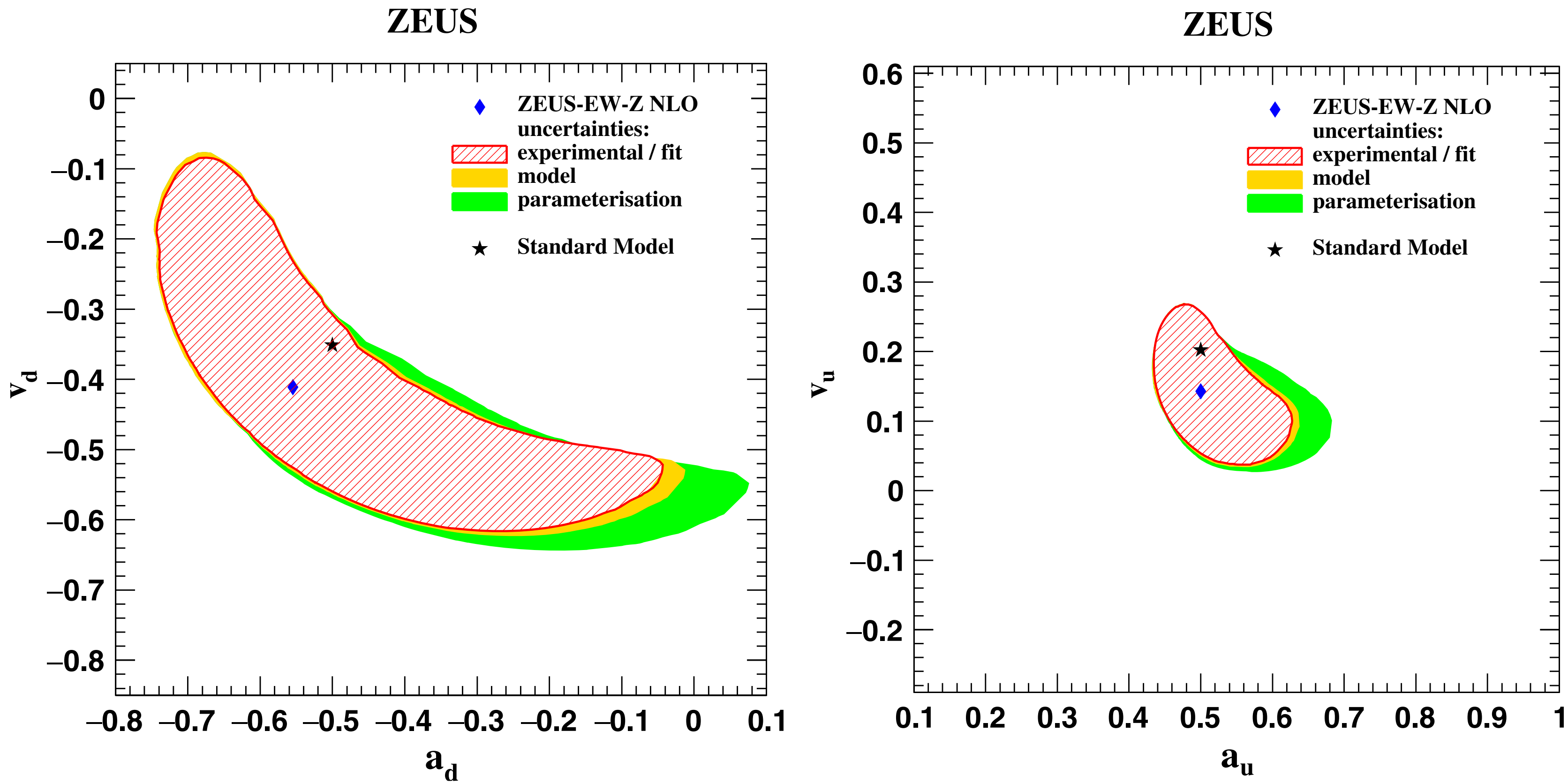
QCD & EW parameters uncorrelated

- 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}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		

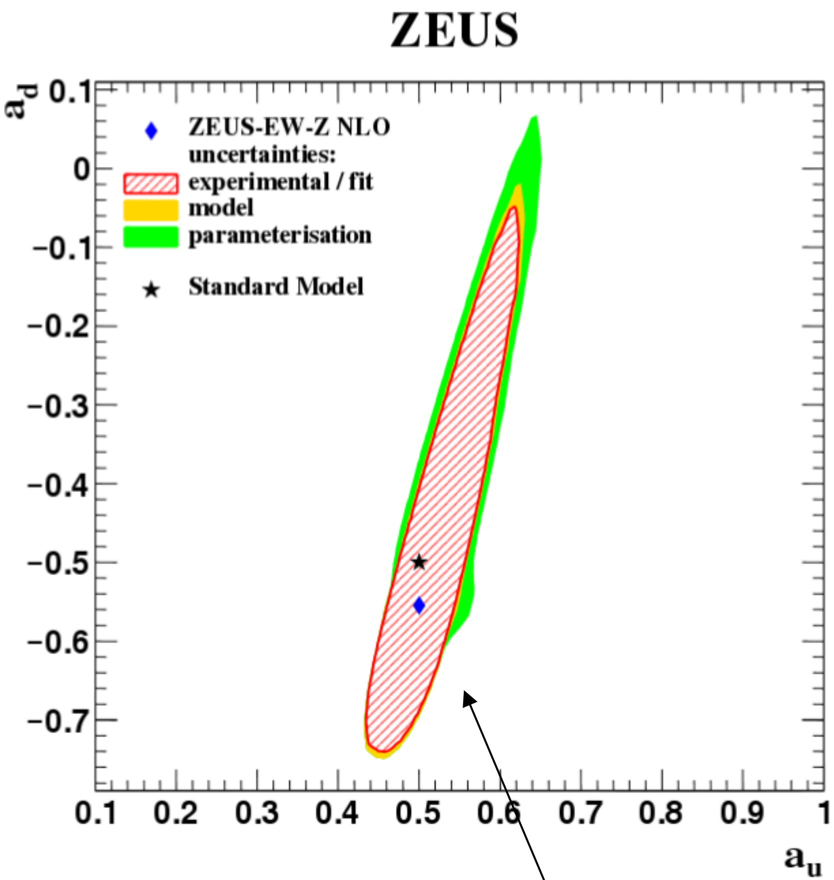
Correlations

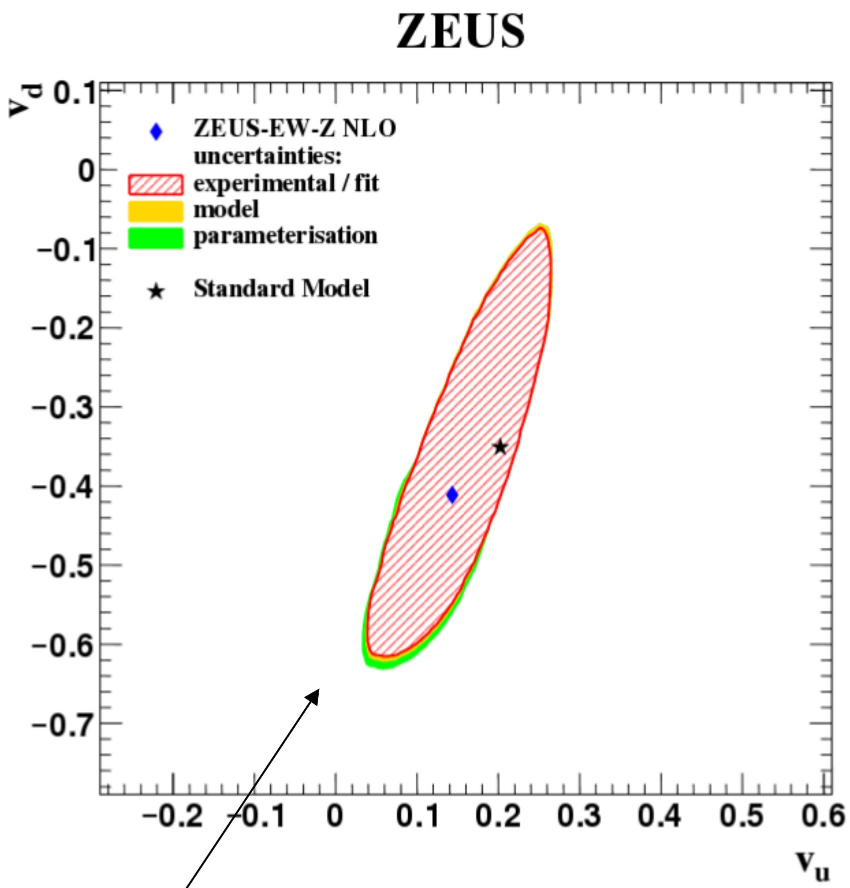


	Standard Model
$a_u = 0.50^{+0.09}_{-0.05}(\mathrm{exp/fit})\,^{+0.04}_{-0.02}(mod)\,^{+0.08}_{-0.01}(par) = \mathbf{0.50}^{+0.12}_{-0.05}(tot)$	0.5
$a_d = -0.56^{+0.34}_{-0.14}(\mathrm{exp/fit})\,^{+0.11}_{-0.05}(mod)\,^{+0.20}_{-0.00}(par) = \mathbf{-0.56}^{+0.41}_{-0.15}(tot)$	-0.5
$v_u = 0.14^{+0.08}_{-0.08}(\mathrm{exp/fit})\,^{+0.01}_{-0.00}(mod)\,^{+0.03}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

Correlations

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

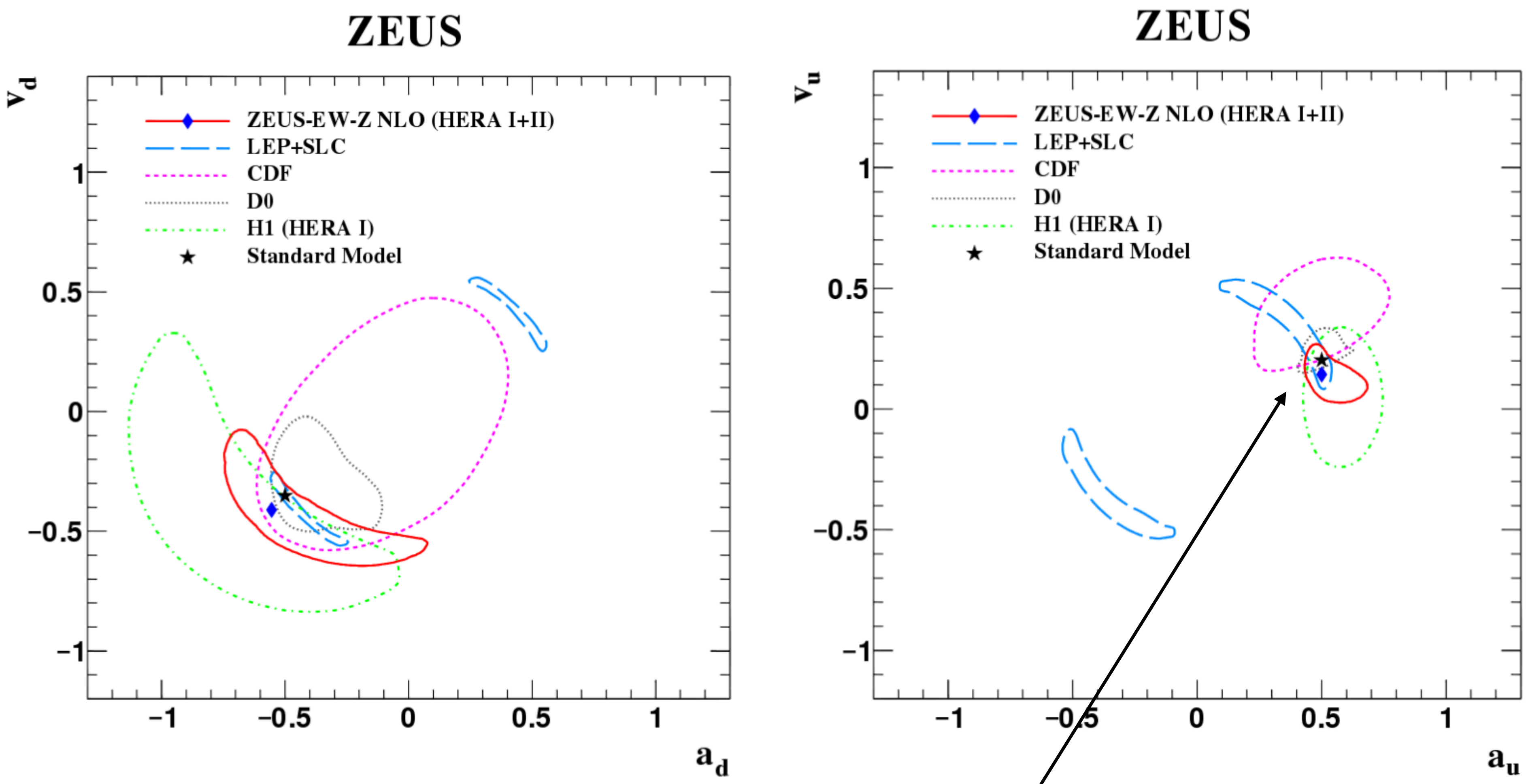




	a_u	a_d	v_u	v_d
a_u	1.000	0.861	−0.555	−0.729
a_d	0.861	1.000	−0.636	−0.880
v_u	−0.555	−0.636	1.000	0.851
v_d	−0.729	−0.880	0.851	1.000

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: a, 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

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

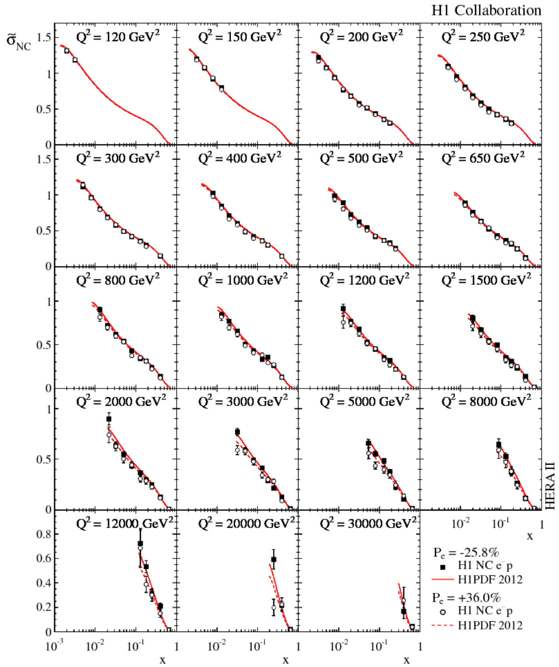
- 13 PDF parameters
- 4 polarisation values
- 4 Light-quark couplings (or other SM parameters)
- More general also 'nuisance parameters' of syst. uncertainties

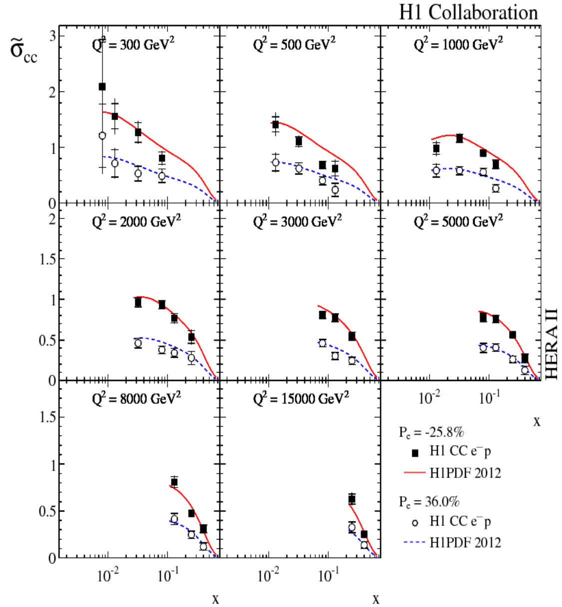
Data used

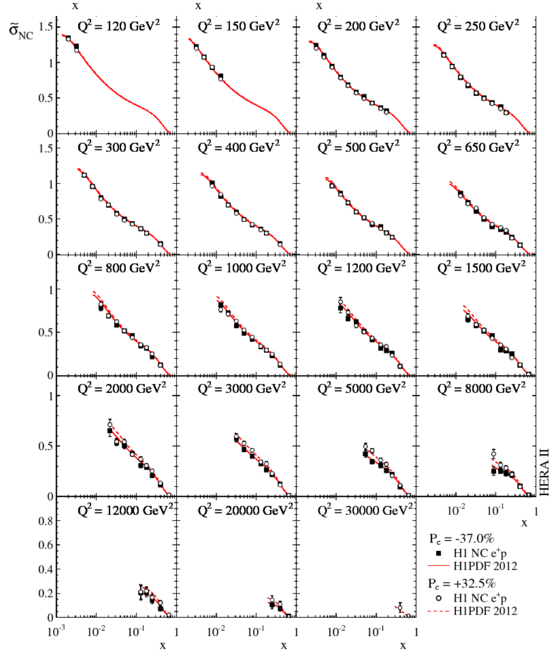
Uncombined data sets

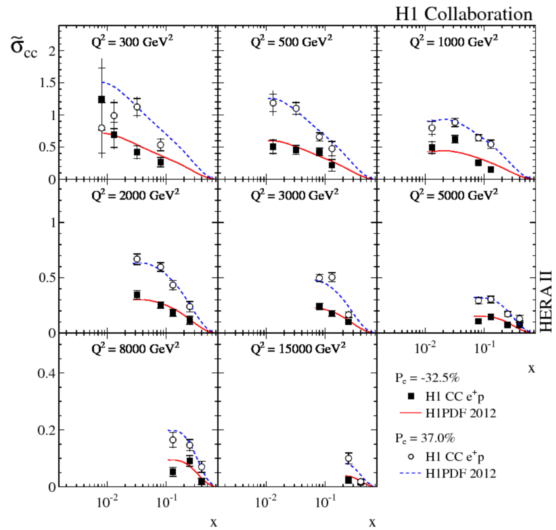
- H1 HERAI data
    - unpolarised
- Reduced E_p H1 data
- HERAII
    - H1 polarised data

Data from Q^2 = 12 GeV^2









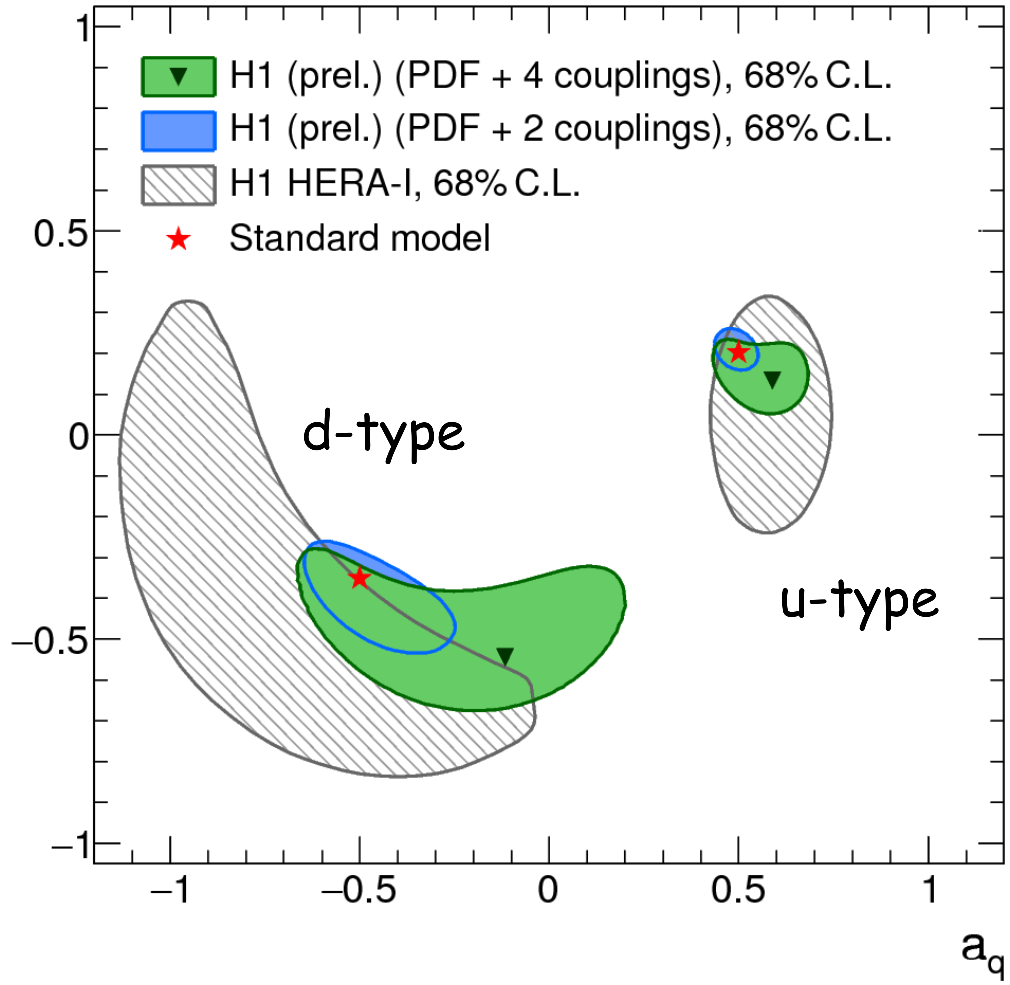
Light Quark Couplings

Fit: PDF + 4 couplings

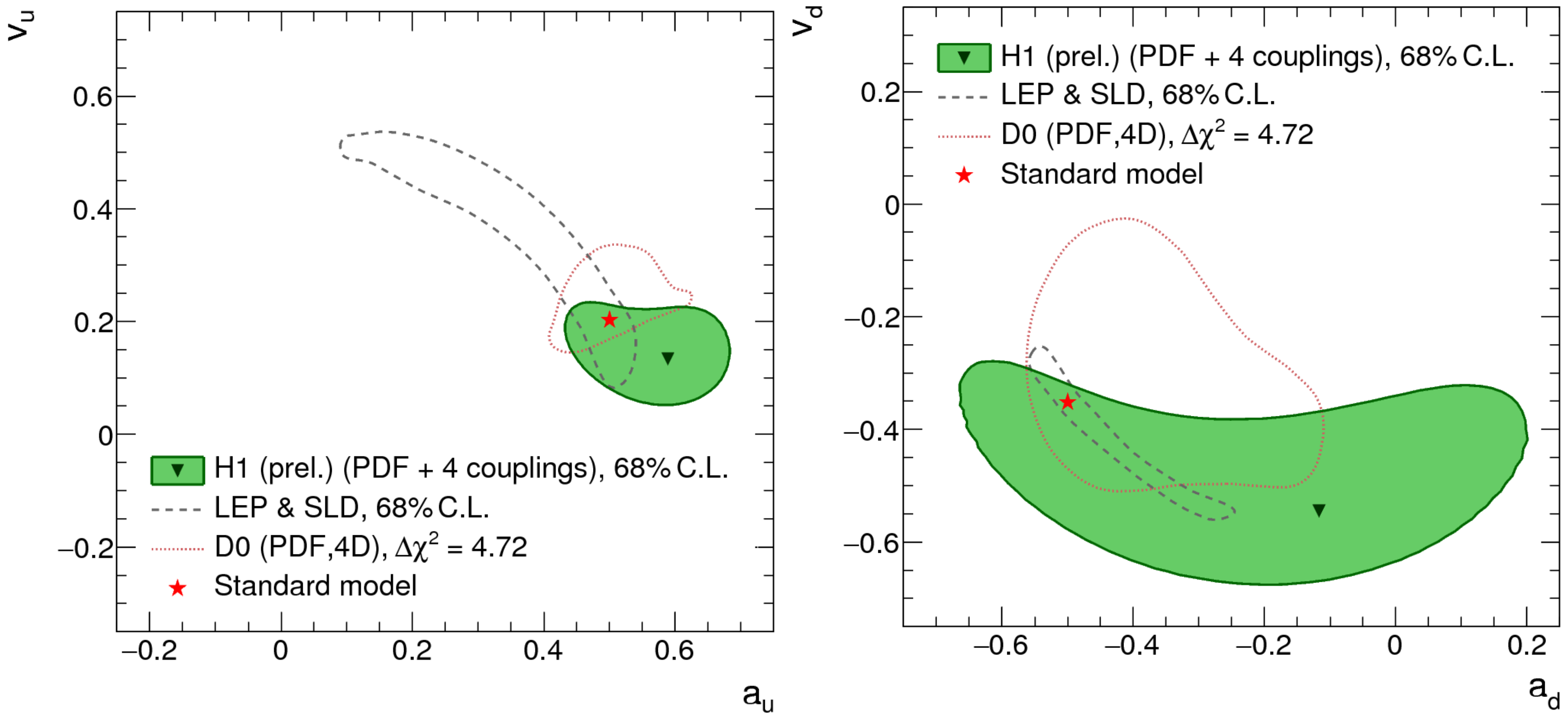
- c^2 / ndf = 1370.5 / (1388 – 21)
- u-type couplings constrained better then d-type
  → sensitivity from valence quarks
- Results compatible with SM
- PDF uncertainties small
- Considerably improved sensitivity using final H1 HERA-II data
- Polarisation in HERA-II important for vector couplings

Fit: PDF + 2 couplings

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

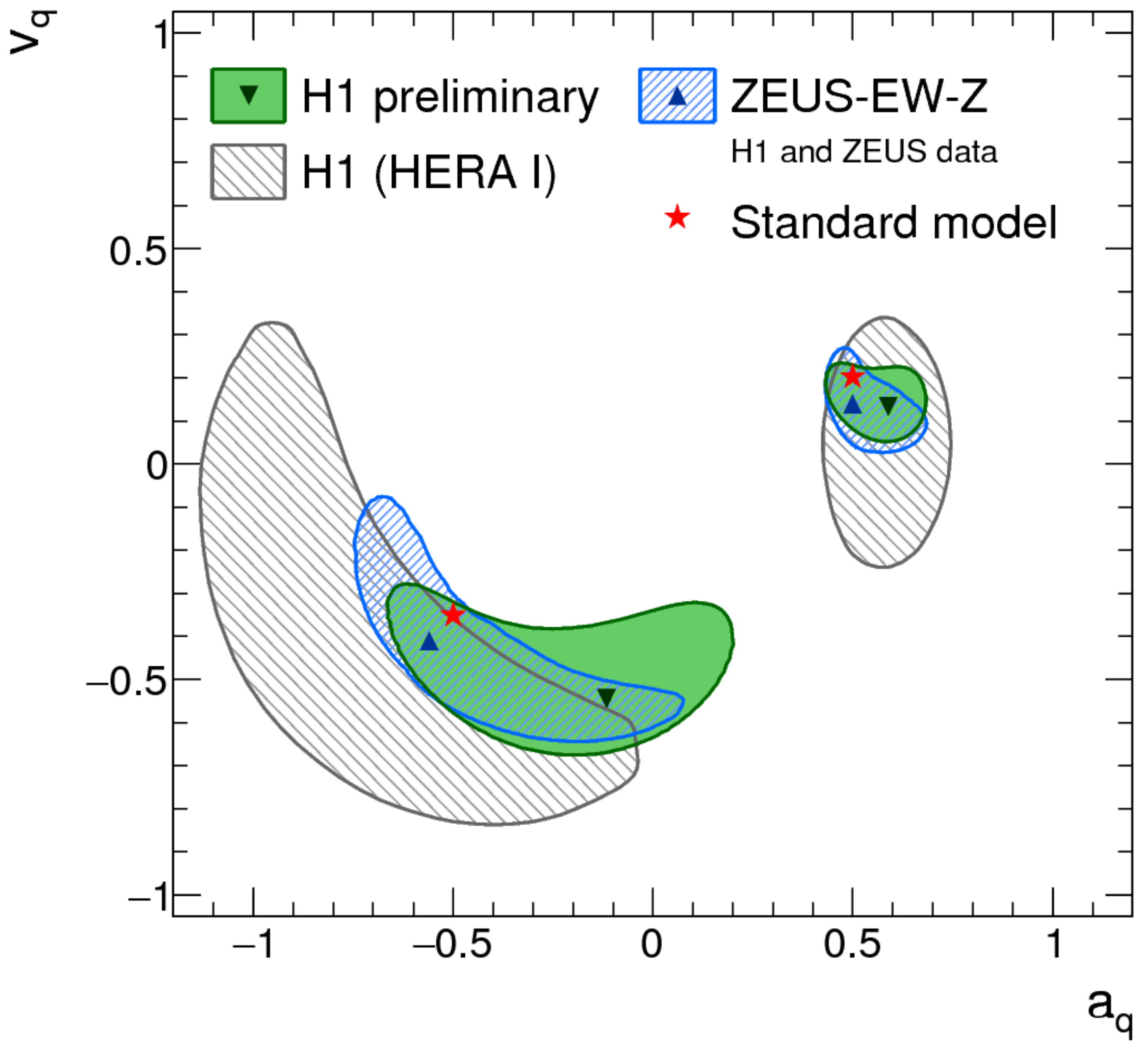


Comparison with other Measurements

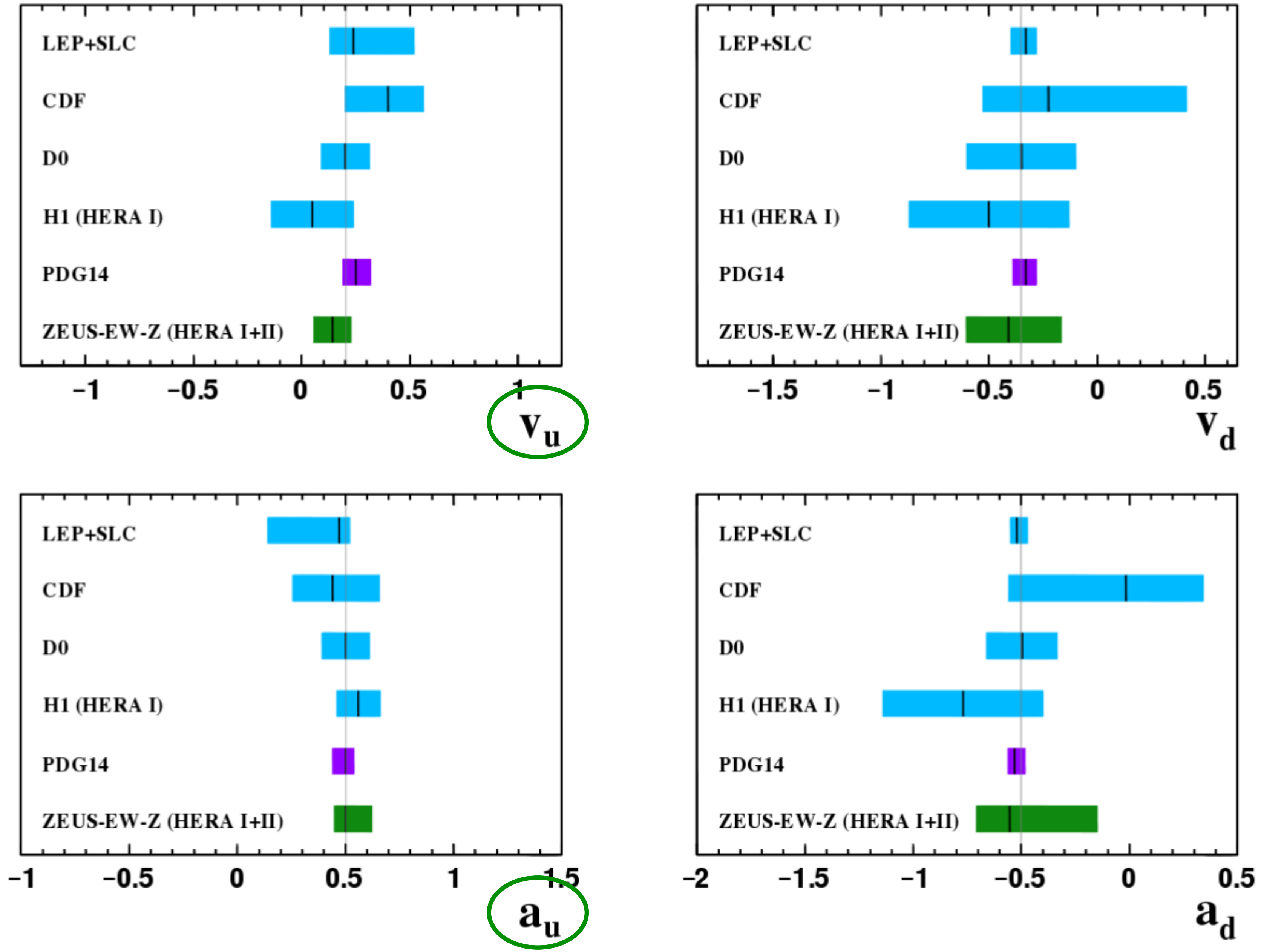


Comparable precision of complementary processes

H1 and ZEUS Results Combined



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

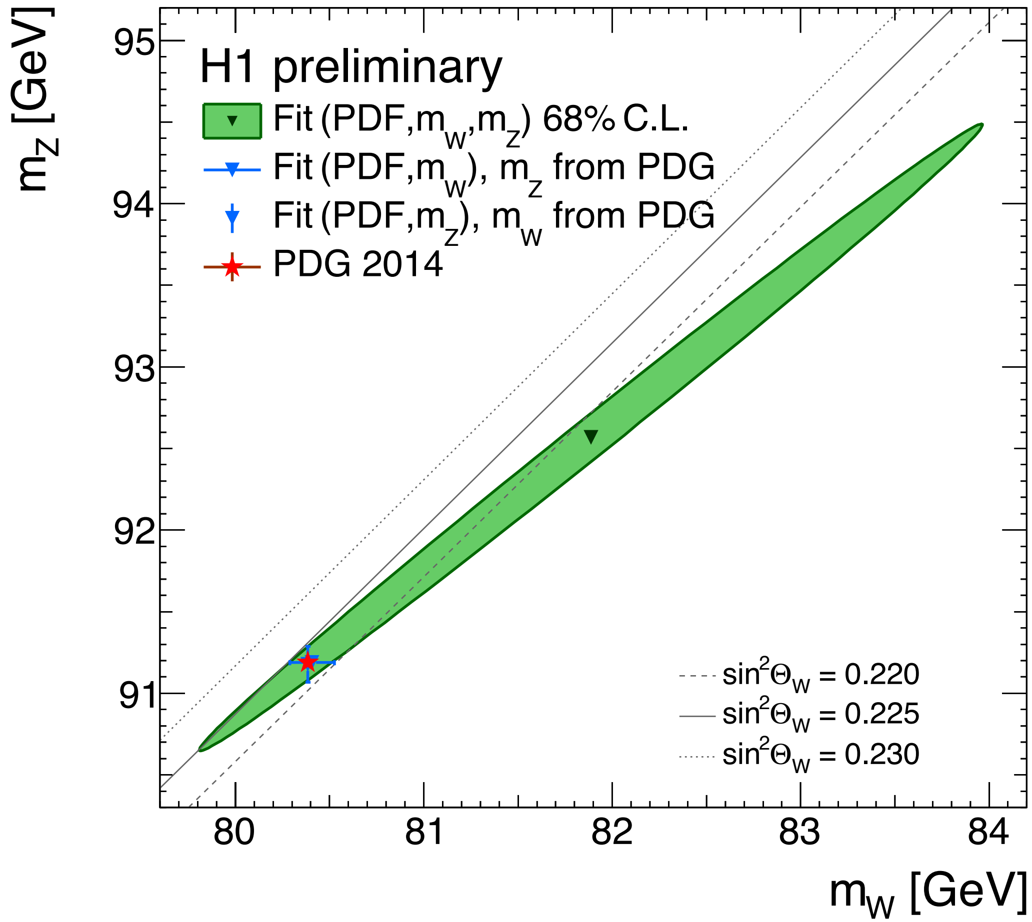
Boson Masses

$(m_W - m_Z)$ + 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 eternal 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

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

- Weak mixing angle

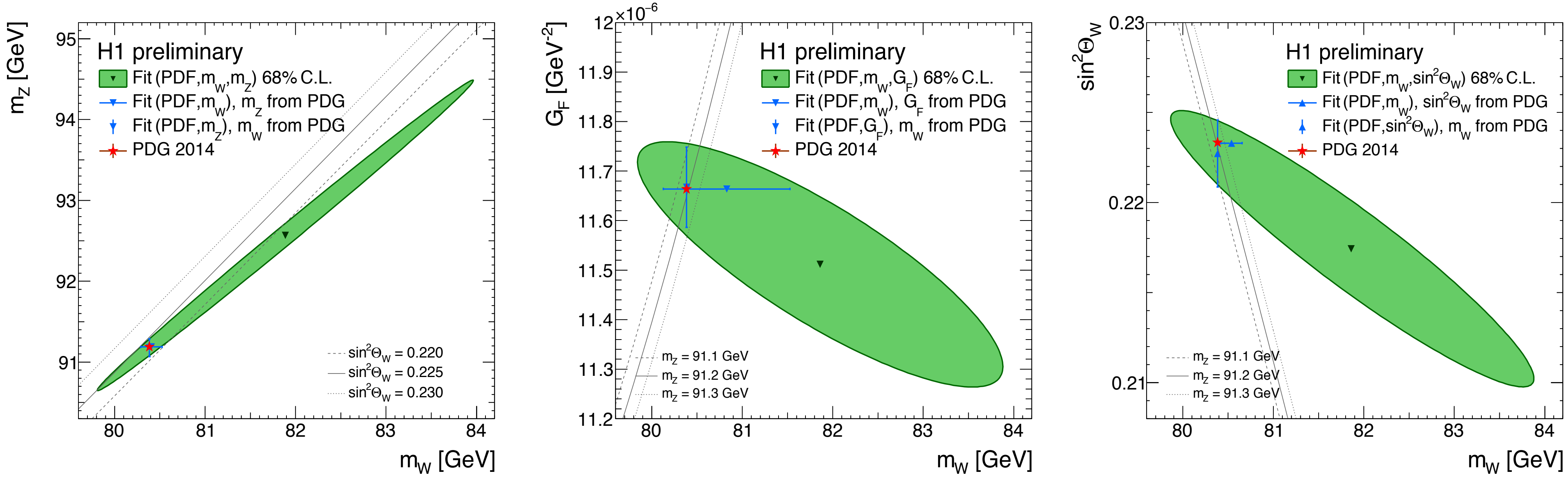
$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$$

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



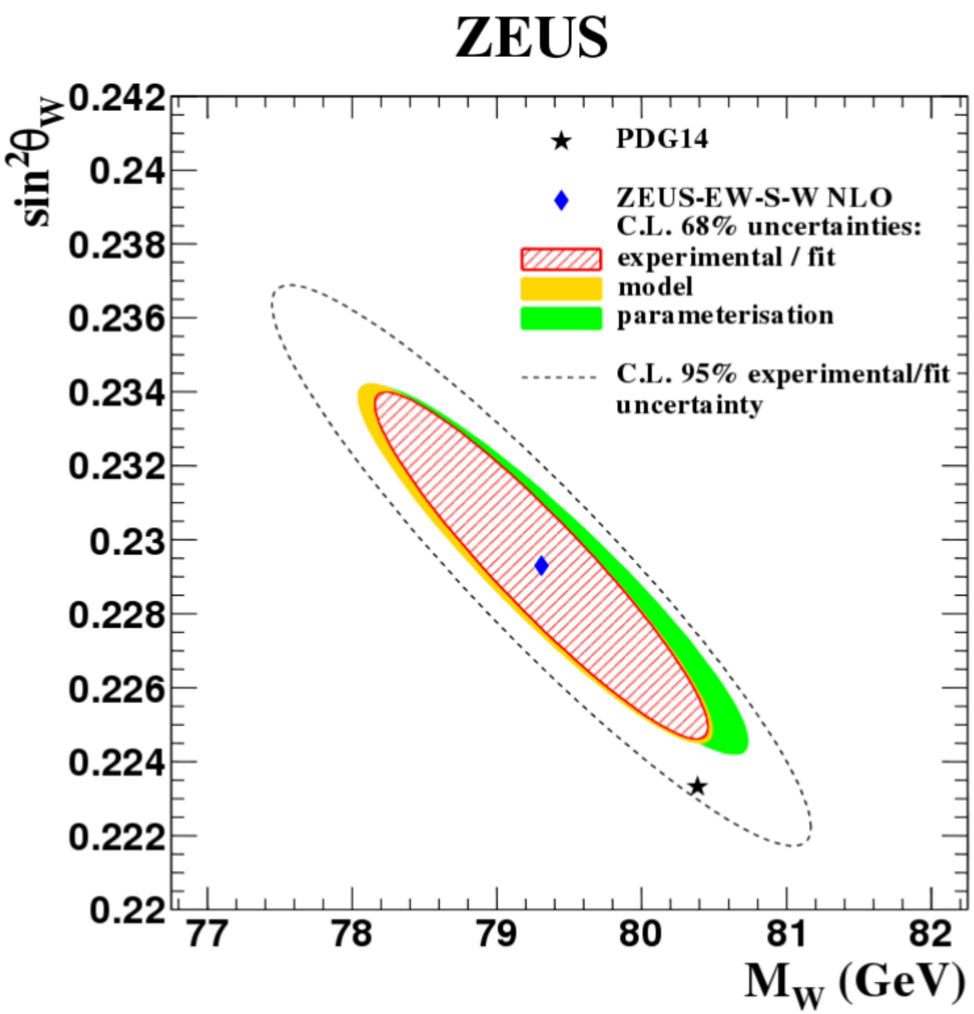
Simultaneous extraction of $\sin^2\theta_W$ and M_W

- Similar measurement by ZEUS

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

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

- All extracted quantities agree with world average values



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

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

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

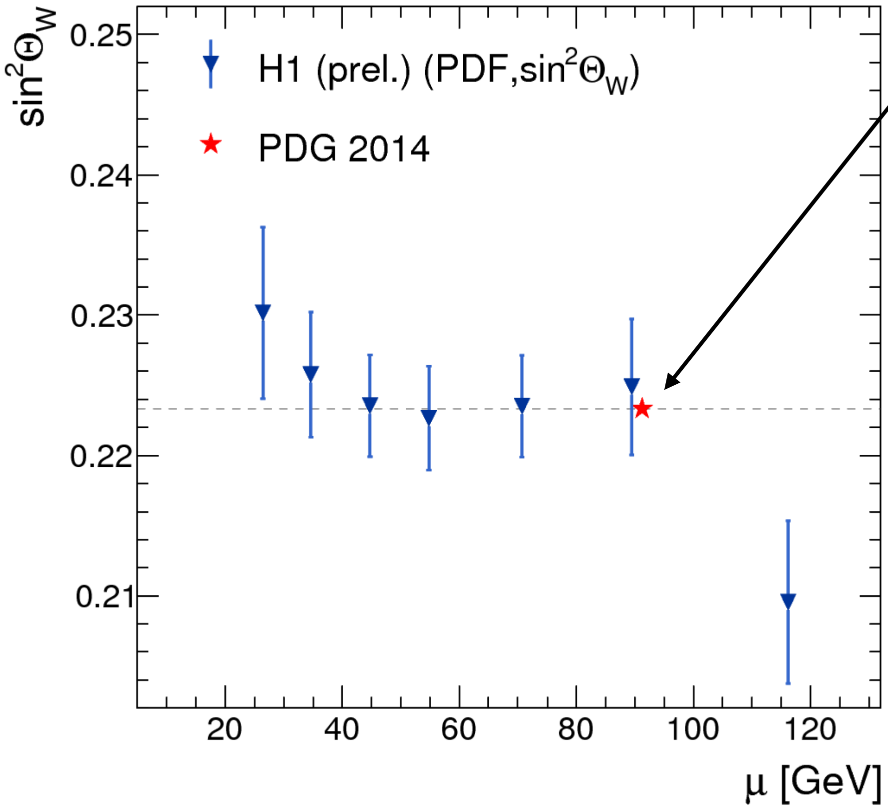
On-shell $\sin^2\theta_W$

- $\sin^2\theta_W$ 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

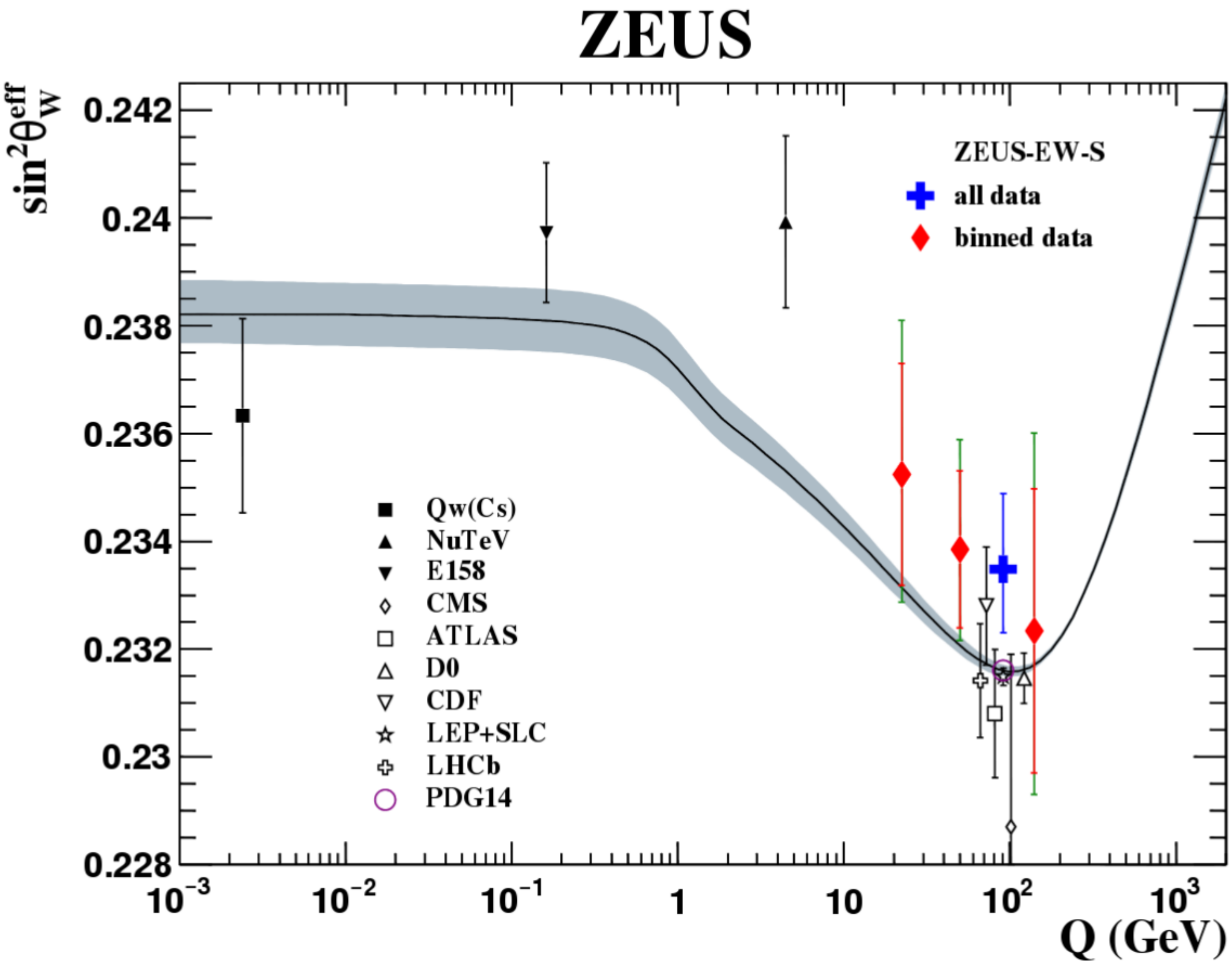
$$\sin^2\theta_W^{PDG\,14\,On-shell} = 0.22333 \pm 0.00011$$



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

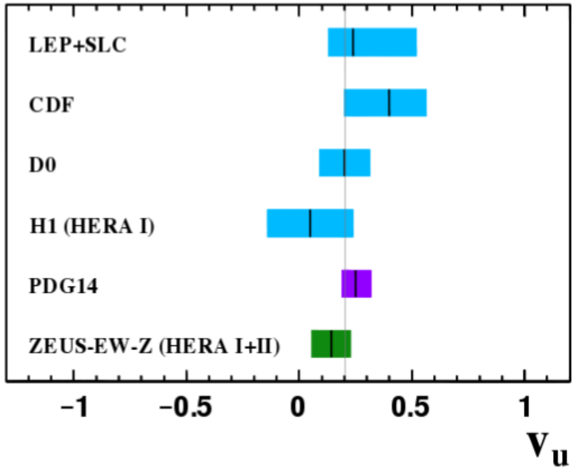
Effective $\sin^2\theta_W$

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