

# Simultaneous QCD & Electroweak Fits to HERA Inclusive DIS data

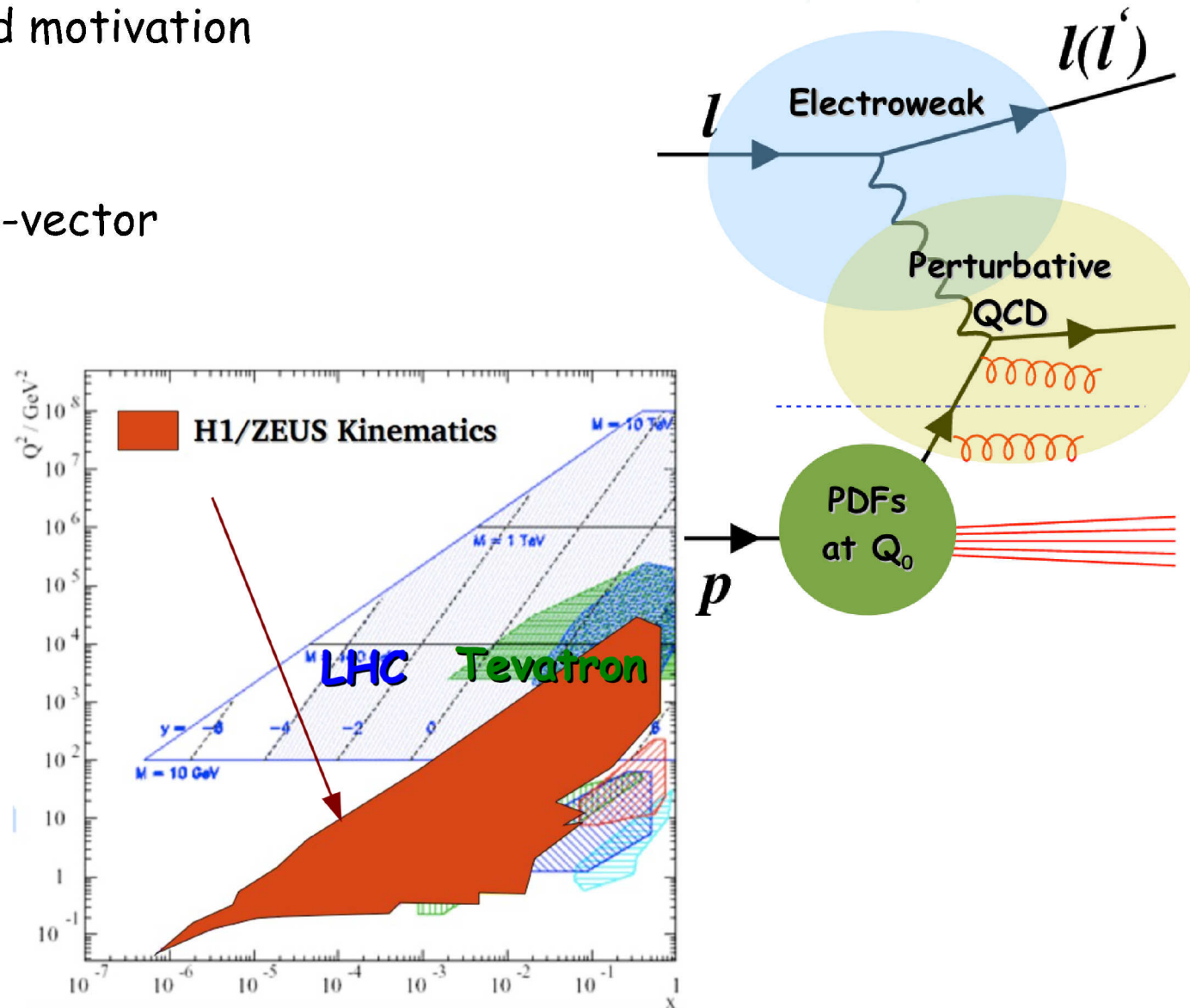
U.Schneekloth on behalf of H1 & ZEUS collaborations

# Outline

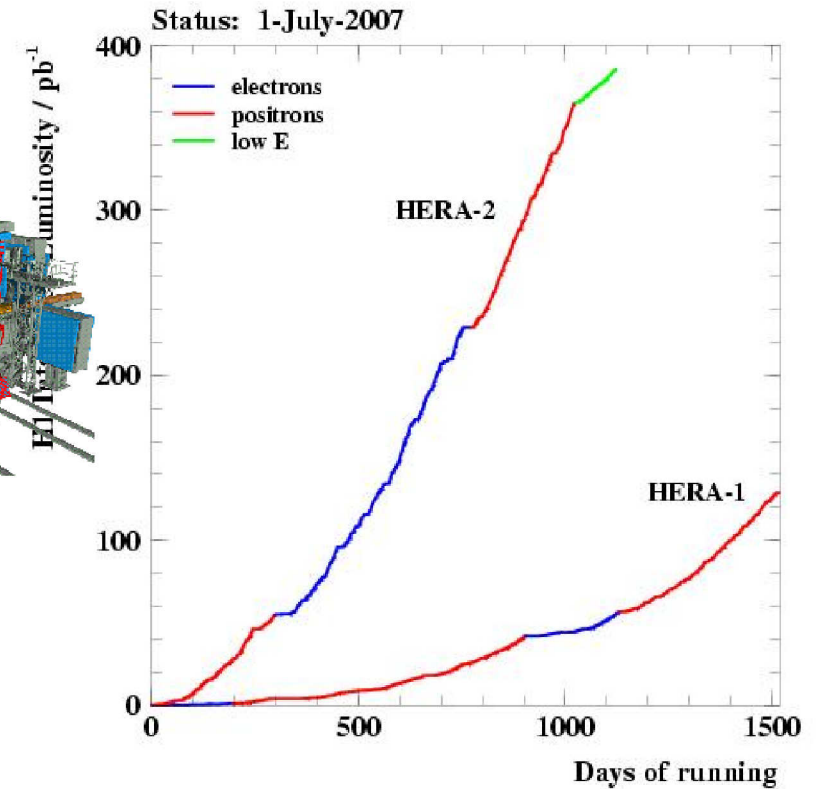
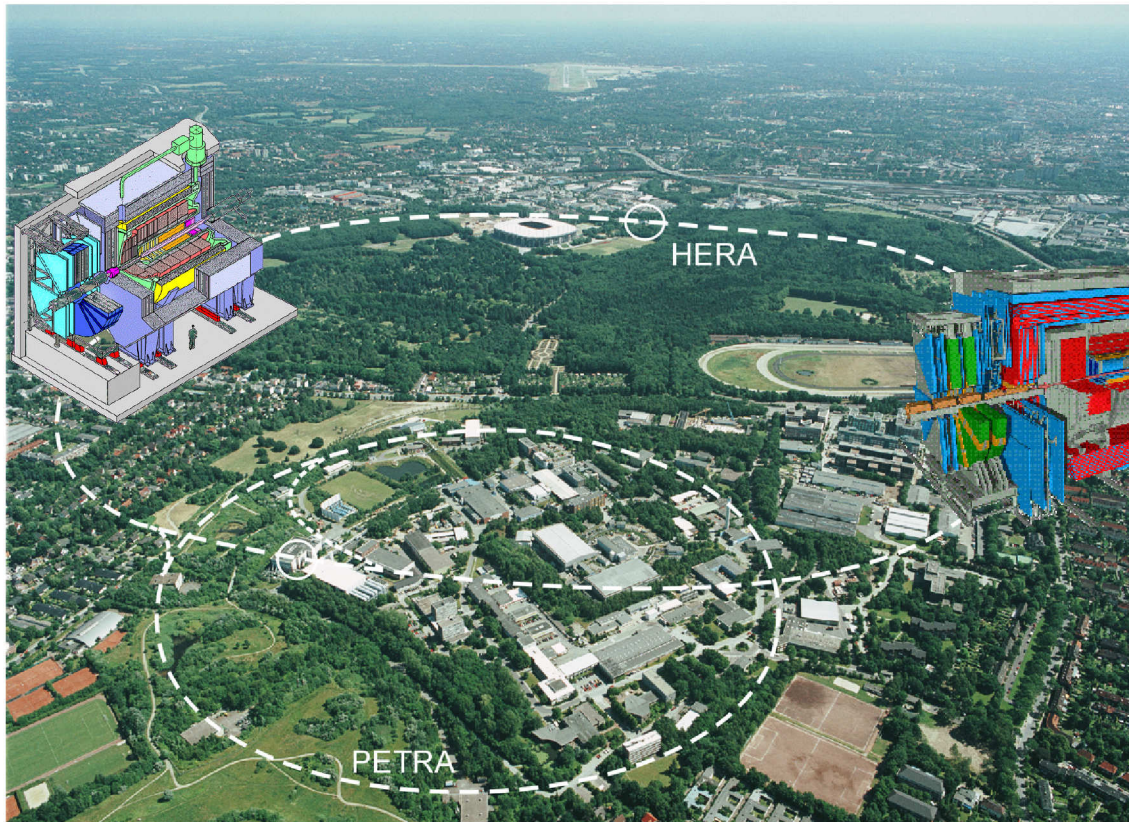
## Deep Inelastic Scattering at HERA

- 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



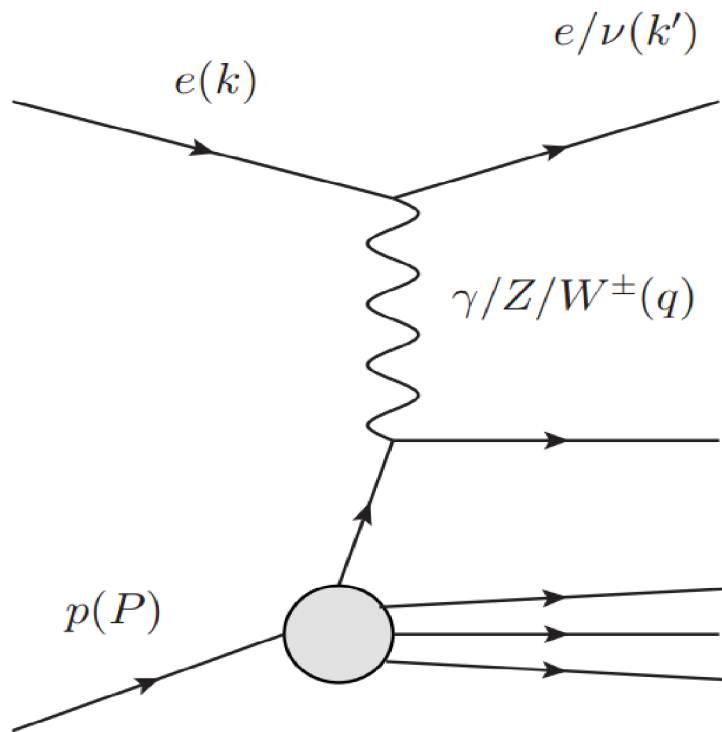
# HERA: the only ep Collider



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

$$X(P') \quad E_p = 920(820, 460, 575) \text{ GeV}$$

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

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

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

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

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

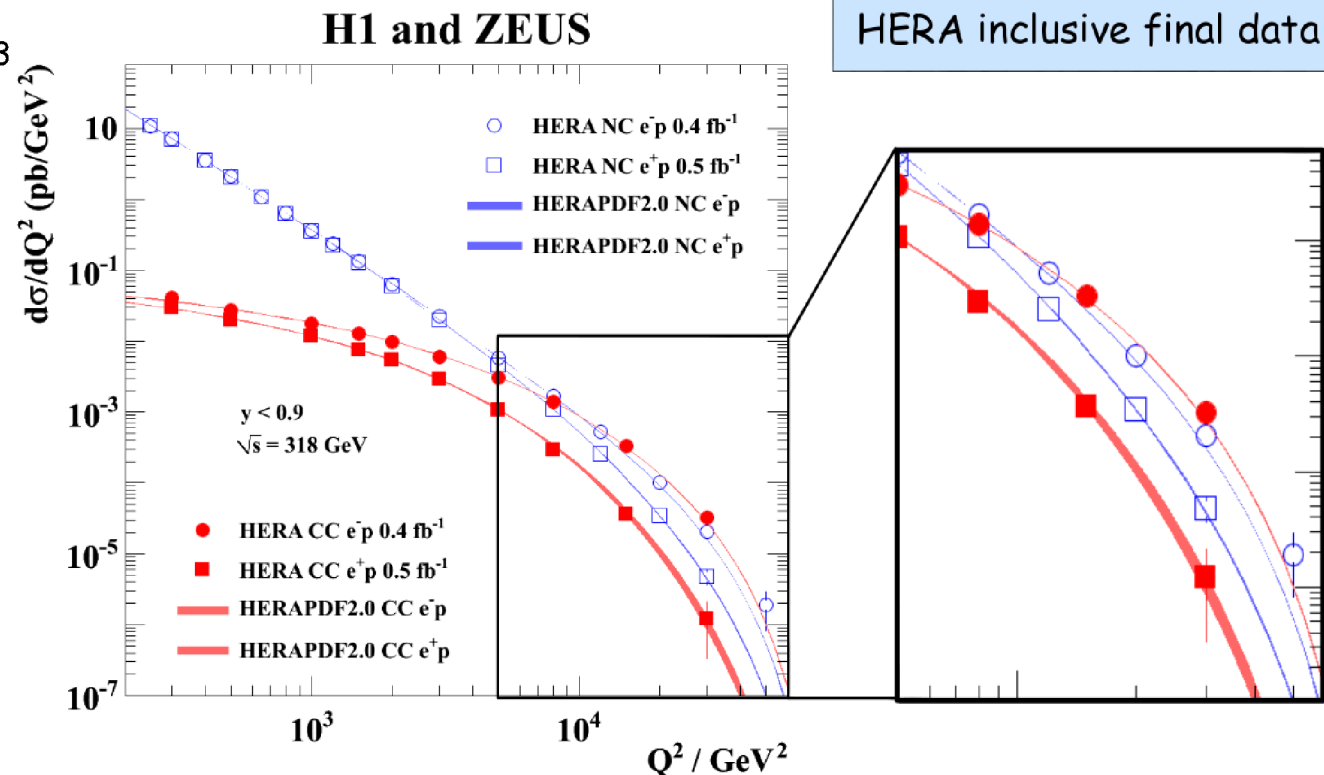
Experimental luminosity (H1 & ZEUS):

$\sim 0.5 \text{ fb}^{-1}$  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

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

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

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

- Structure functions in QP model

**NC**

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)

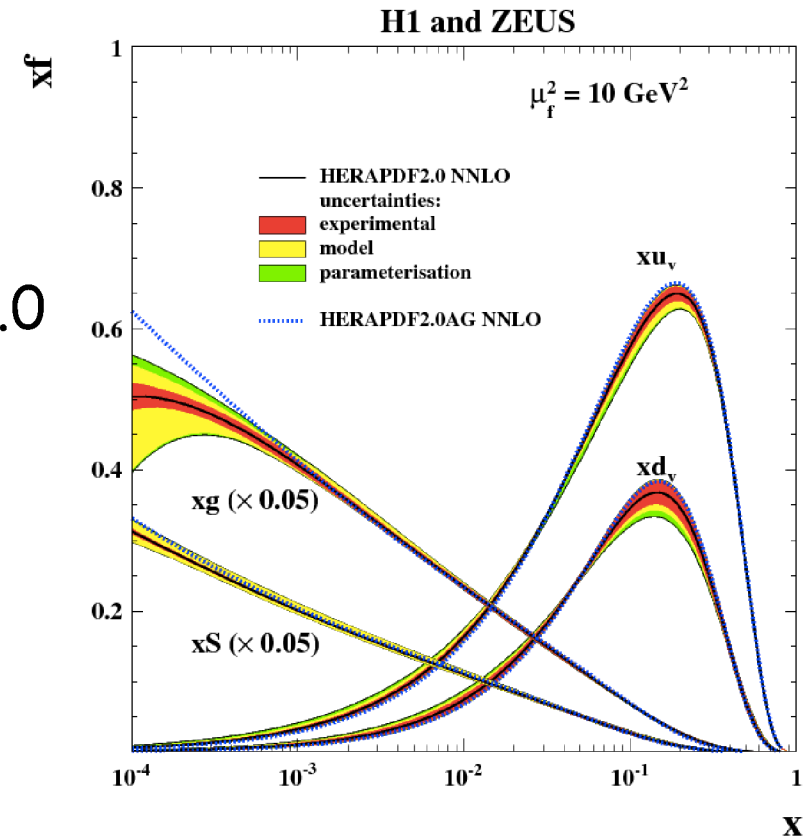
$$xf(x) = Ax^B(1-x)^C(1+Dx+Ex^2)$$

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

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

[desy.de/~hspiesb/eprc.html](http://desy.de/~hspiesb/eprc.html)

- No ISR/FSR corrections





# Vector and axial-vector couplings

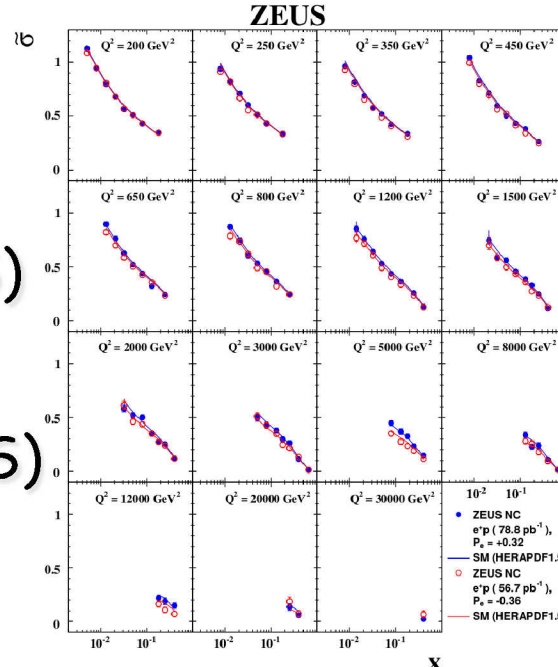


## Uncombined data sets

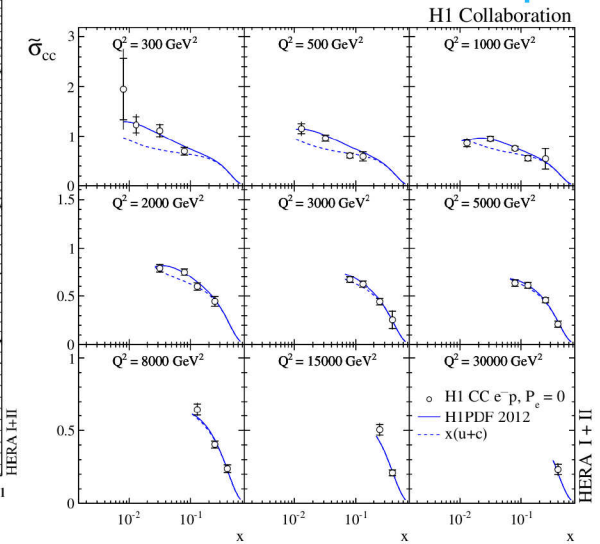
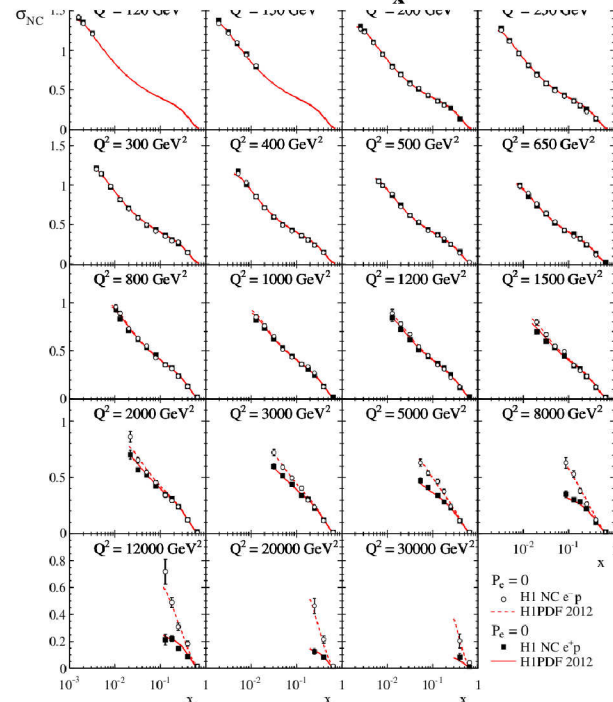
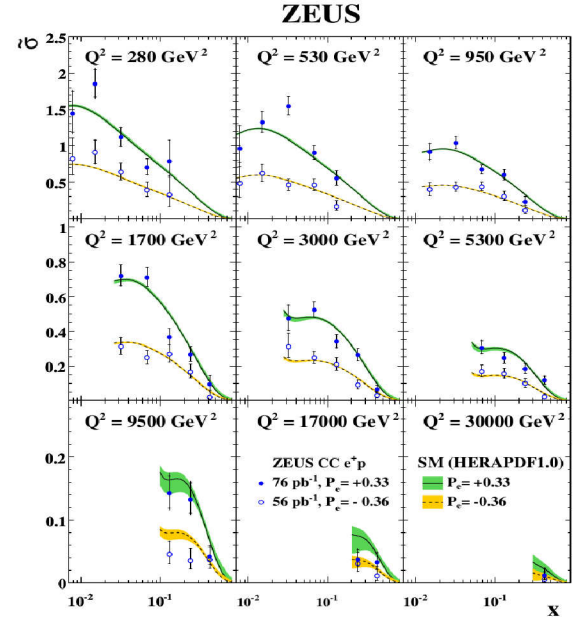
- All HERAI data (H1 & ZEUS)
  - unpolarised
- Reduced  $E_p$  data (H1 & ZEUS)
- HERAII
  - H1 unpolarized data
  - ZEUS polarized data

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

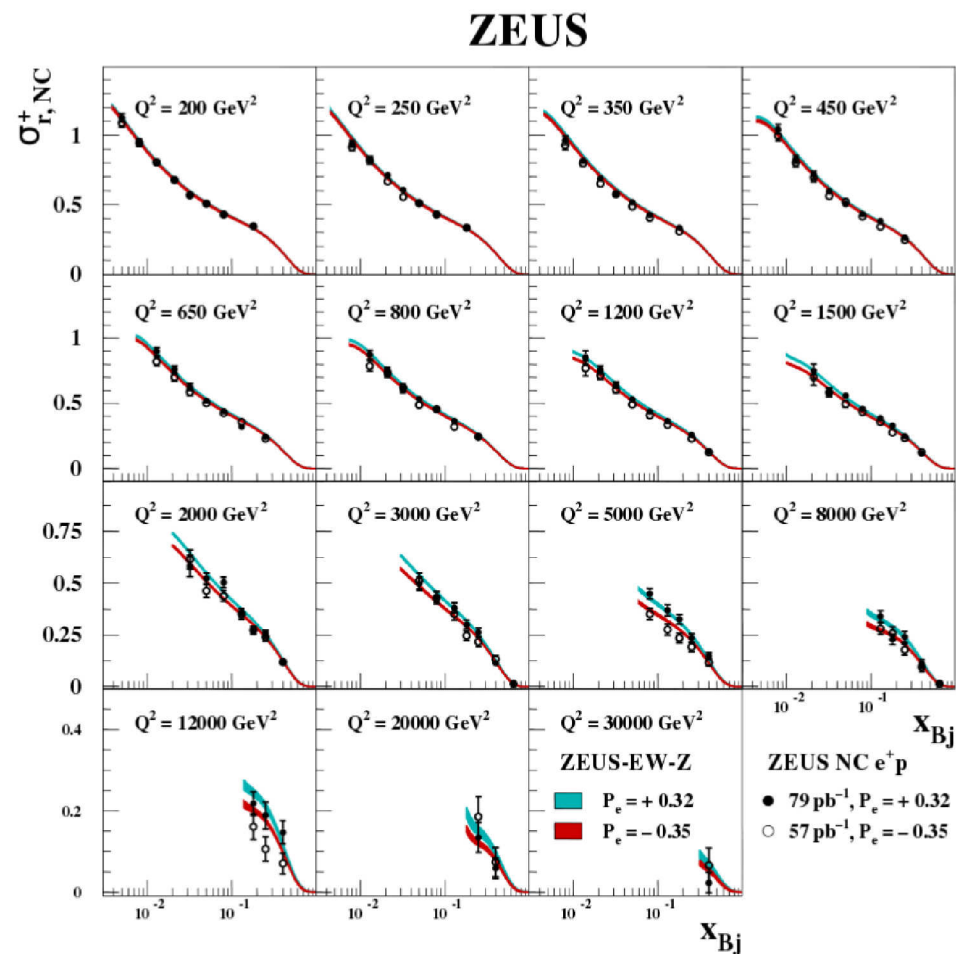
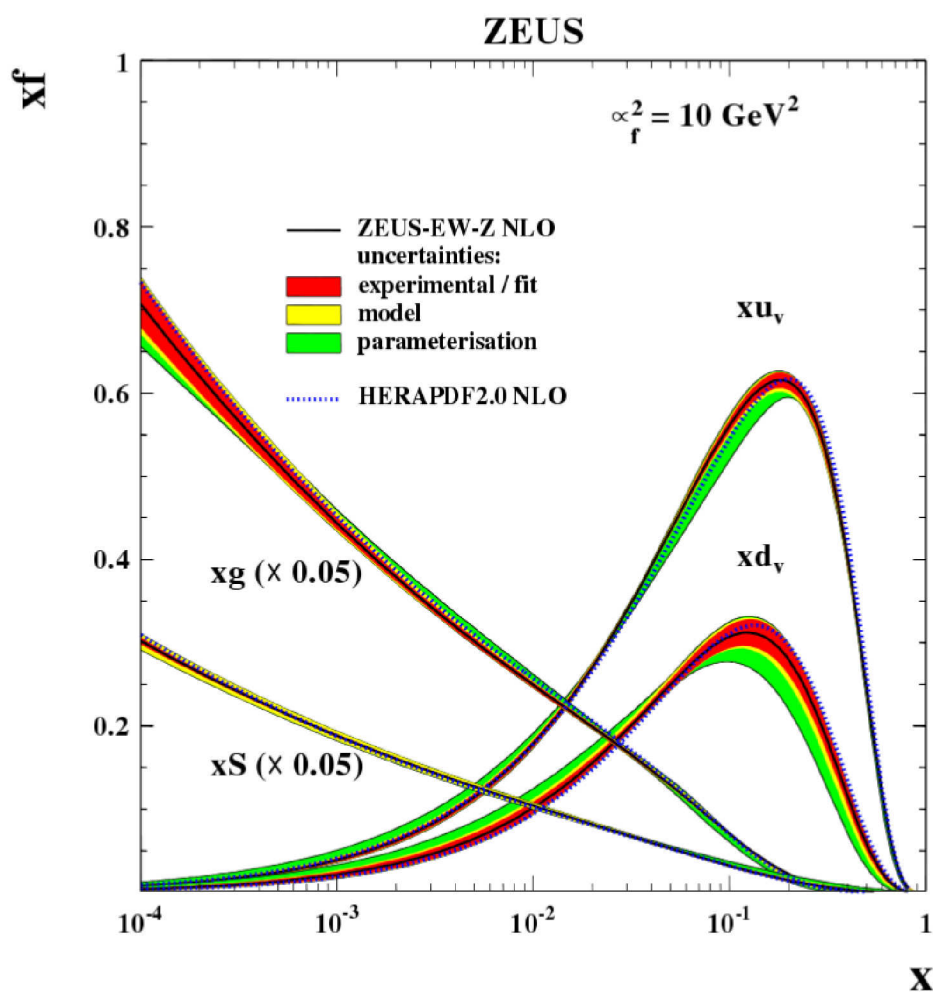
- DGLAP evolution @ NLO
- HF scheme - GN VFNS NLO



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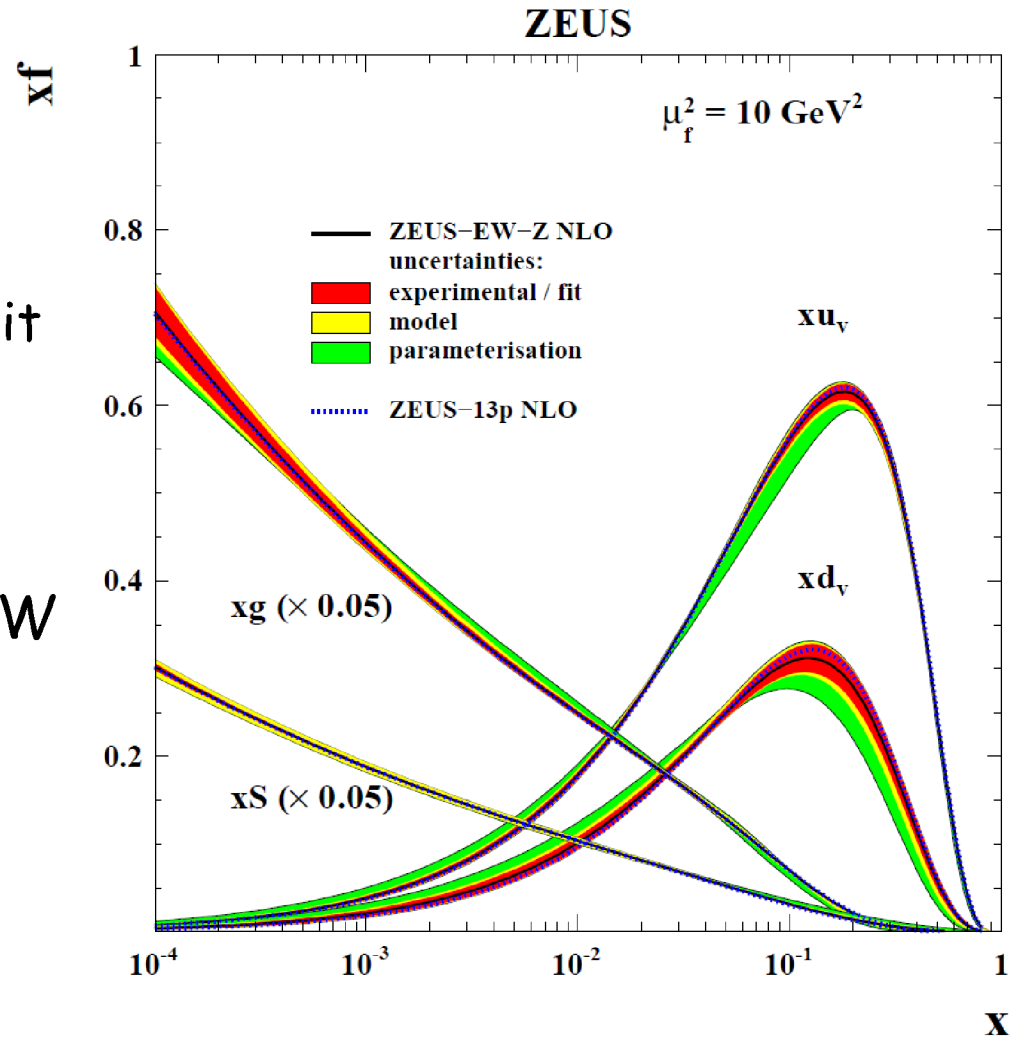
- Simultaneous QCD and EW fit:
  - 13 QCD parameters + 4 EW couplings





# 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



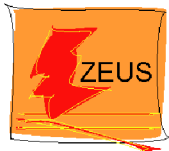


# QCD & EW parameters uncorrelated

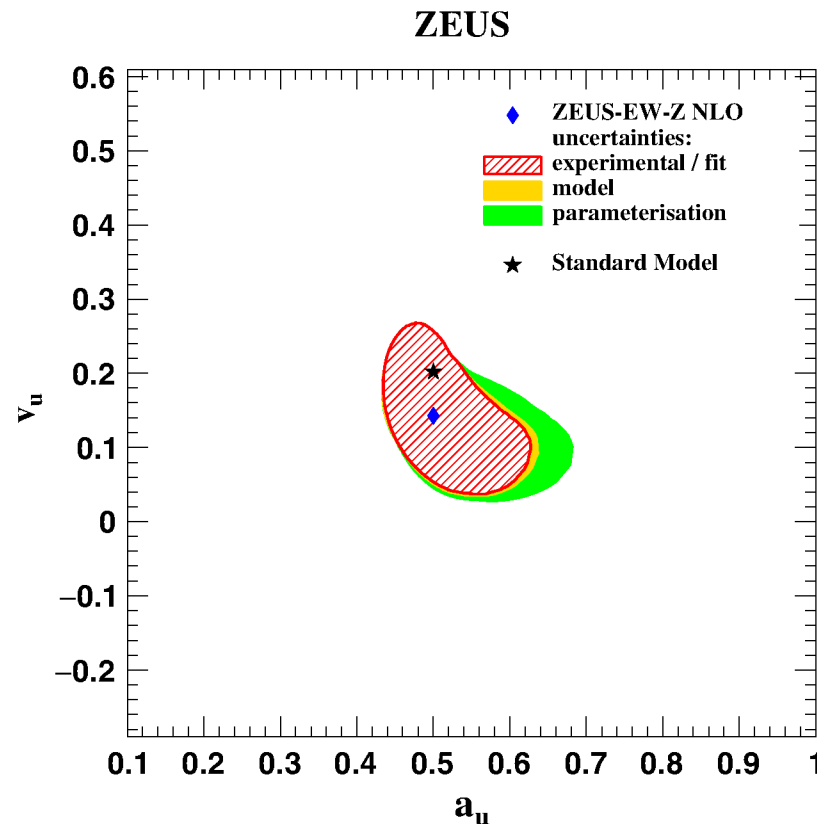
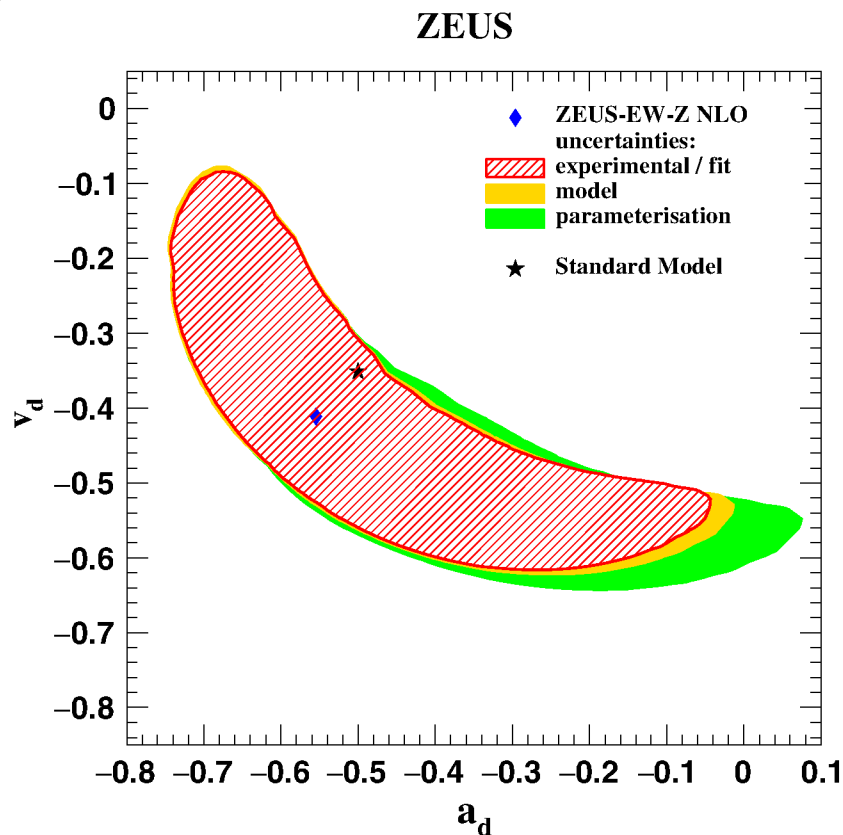
- Detailed studies performed to check stability of EW couplings with respect to various QCD parameters
  - HPDF1: QCD parameters and all constants fixed to HERAPDF2.0
  - HPDF2: QCD parameters fixed to HERAPDF2.0 + on-shell value of  $\sin^2 q_w$
  - 13p - reference fit described before

→ 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



$$a_u = 0.50^{+0.09}_{-0.05}(\text{exp/fit}) \quad +0.04_{-0.02}(\text{mod}) \quad +0.08_{-0.01}(\text{par}) = \mathbf{0.50^{+0.12}_{-0.05}(\text{tot})} \quad \mathbf{0.5}$$

$$a_d = -0.56^{+0.34}_{-0.14}(\text{exp/fit}) \quad +0.11_{-0.05}(\text{mod}) \quad +0.20_{-0.00}(\text{par}) = \mathbf{-0.56^{+0.41}_{-0.15}(\text{tot})} \quad \mathbf{-0.5}$$

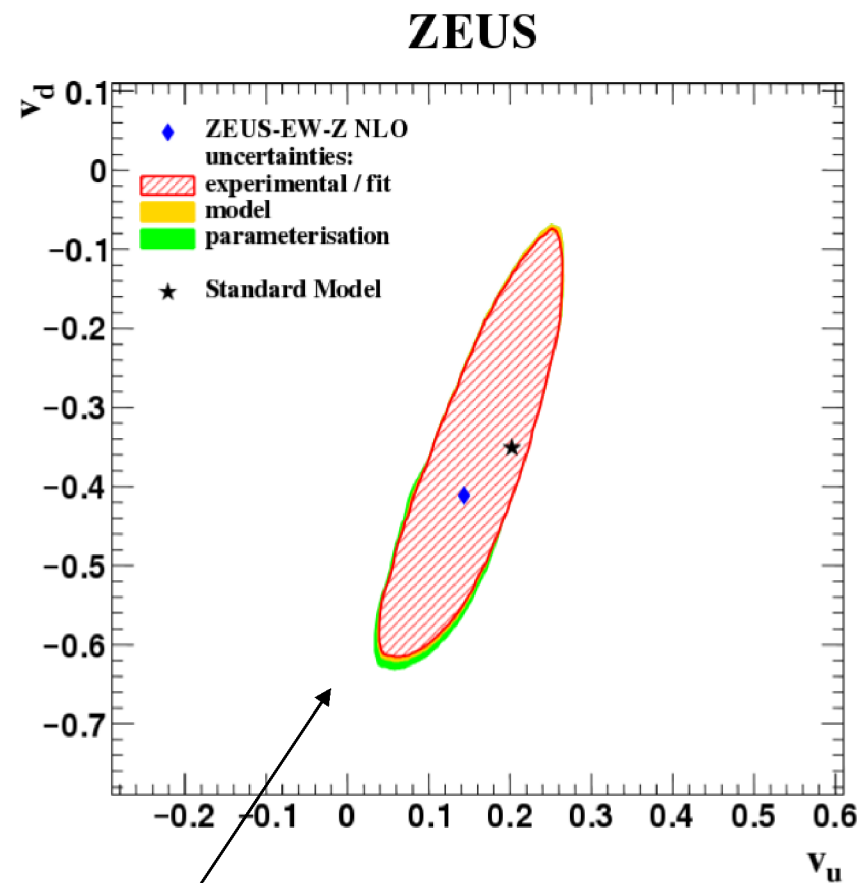
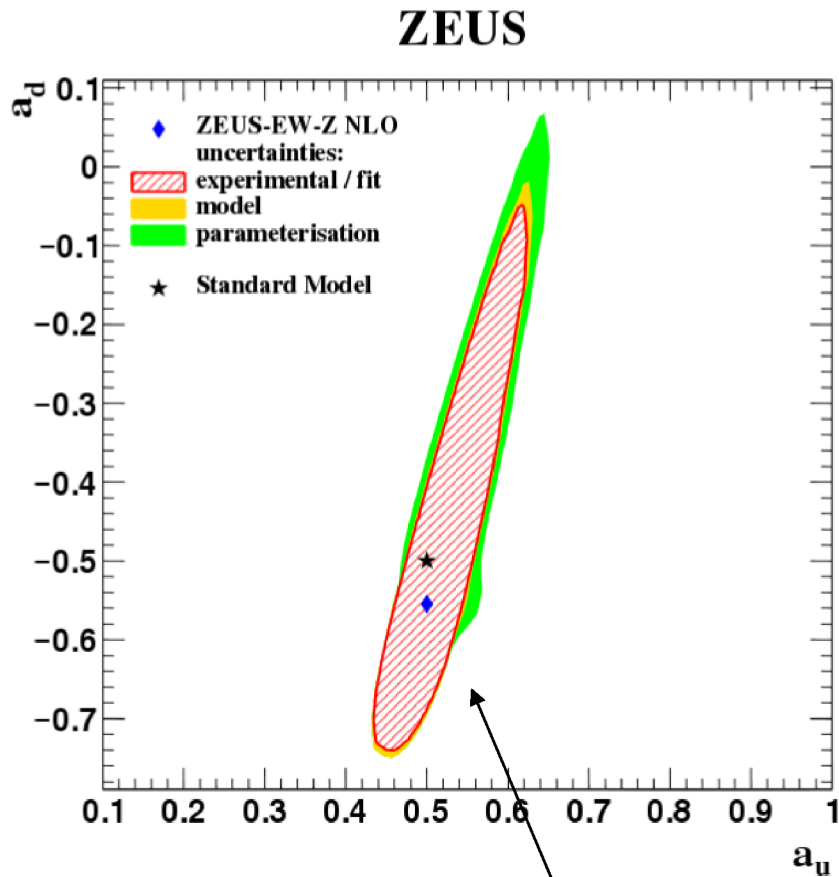
$$v_u = 0.14^{+0.08}_{-0.08}(\text{exp/fit}) \quad +0.01_{-0.00}(\text{mod}) \quad +0.03_{-0.01}(\text{par}) = \mathbf{0.14^{+0.09}_{-0.09}(\text{tot})} \quad \mathbf{0.202}$$

$$v_d = -0.41^{+0.24}_{-0.16}(\text{exp/fit}) \quad +0.04_{-0.07}(\text{mod}) \quad +0.00_{-0.08}(\text{par}) = \mathbf{-0.41^{+0.25}_{-0.20}(\text{tot})} \quad \mathbf{-0.351}$$

Standard Model

# Correlations

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



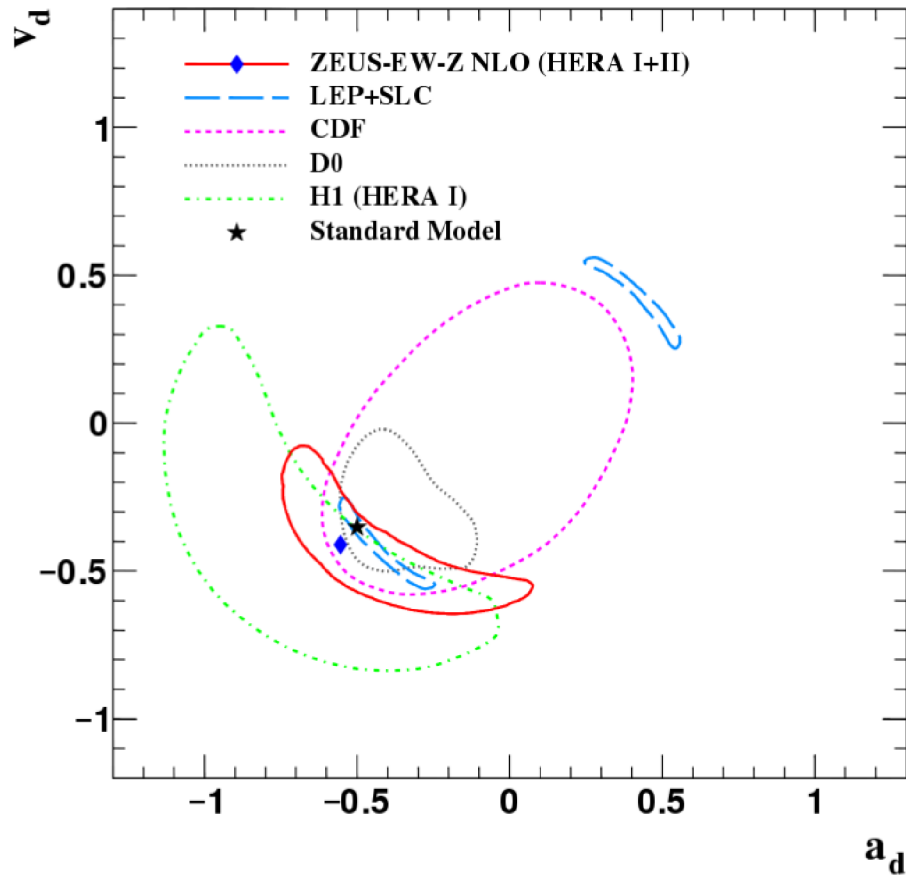
	$a_u$	$a_d$	$v_u$	$v_d$
$a_u$	1.000	0.861	-0.555	-0.729
$a_d$	0.861	1.000	-0.636	-0.880
$v_u$	-0.555	-0.636	1.000	0.851
$v_d$	-0.729	-0.880	0.851	1.000

Insignificant correlations of couplings to PDF parameters

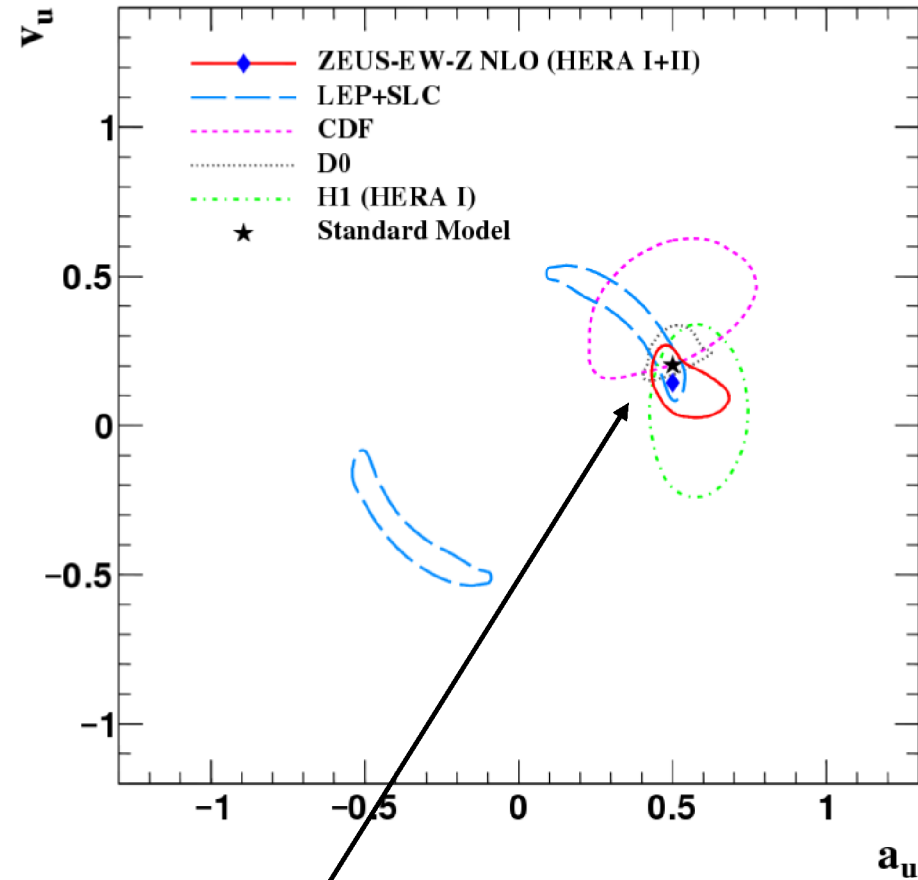


# Comparison with other Measurements

## ZEUS



## ZEUS



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



# H1 Fit Methodology

H1prelim-16-041



U.Schneekloth

QCD+EW fit

- 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

## $\chi^2$ 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

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

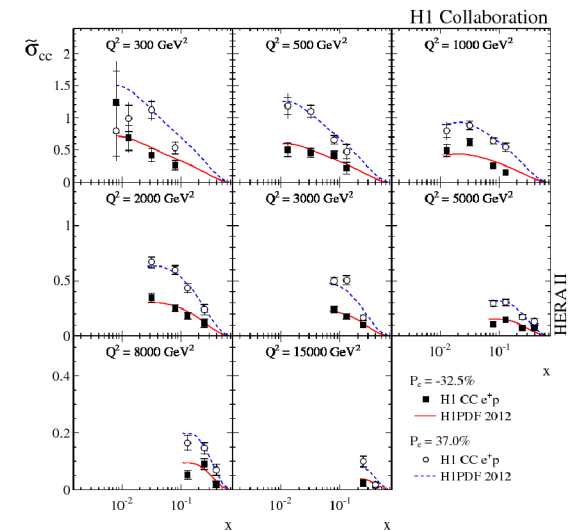
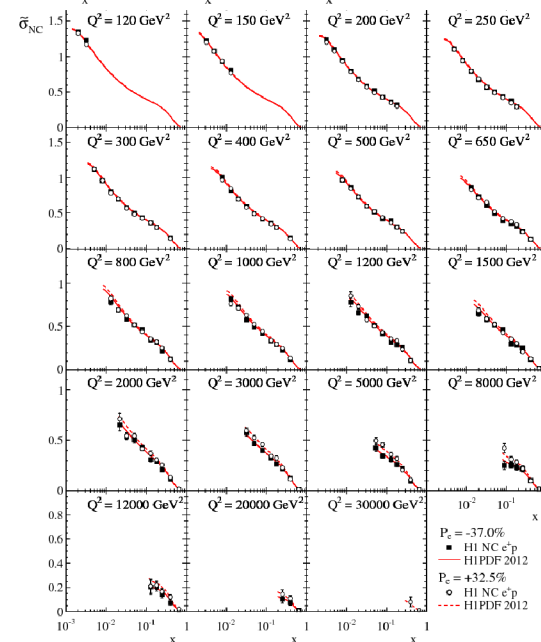
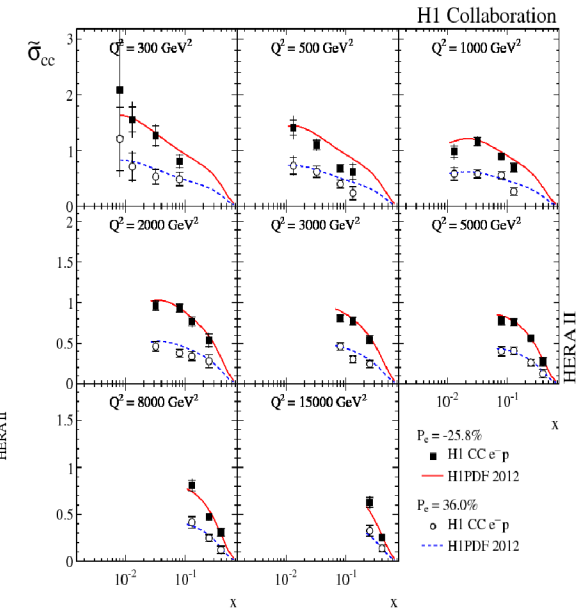
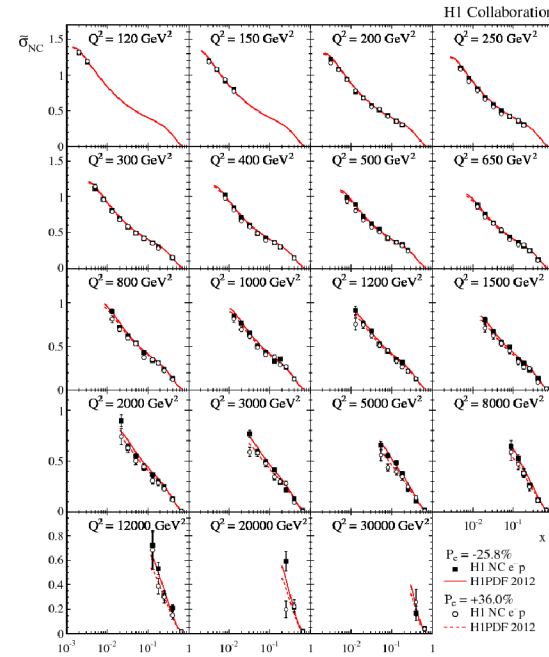
## Fit parameters

- 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  $Q^2 = 12 \text{ GeV}^2$

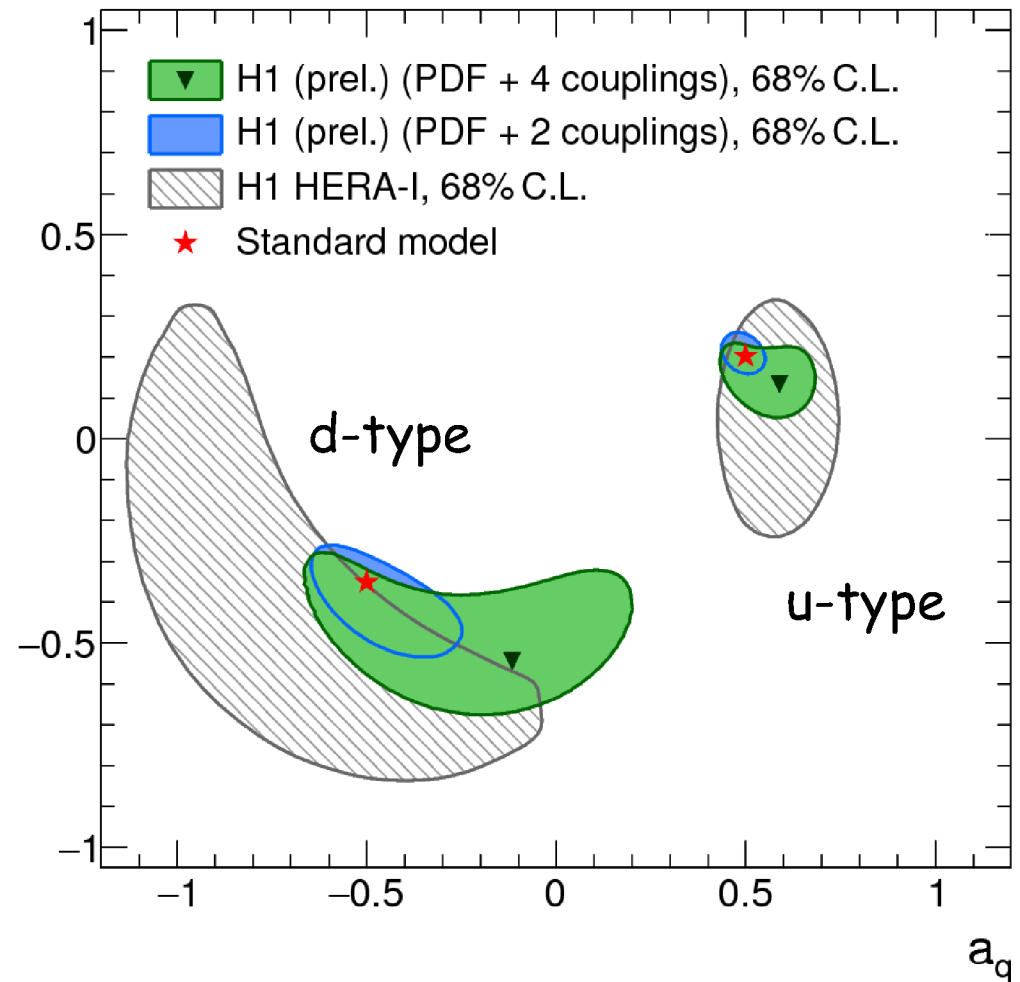


## Fit: PDF + 4 couplings

- $c^2 / \text{ndf} = 1370.5 / (1388 - 21)$
- 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

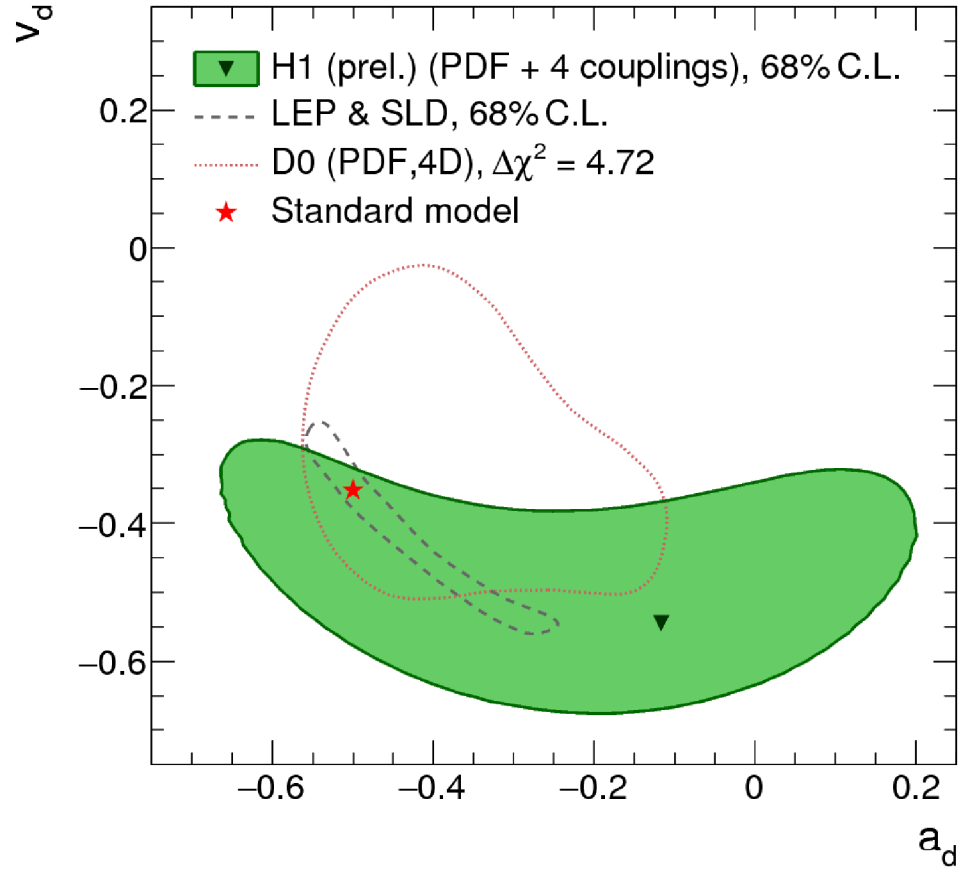
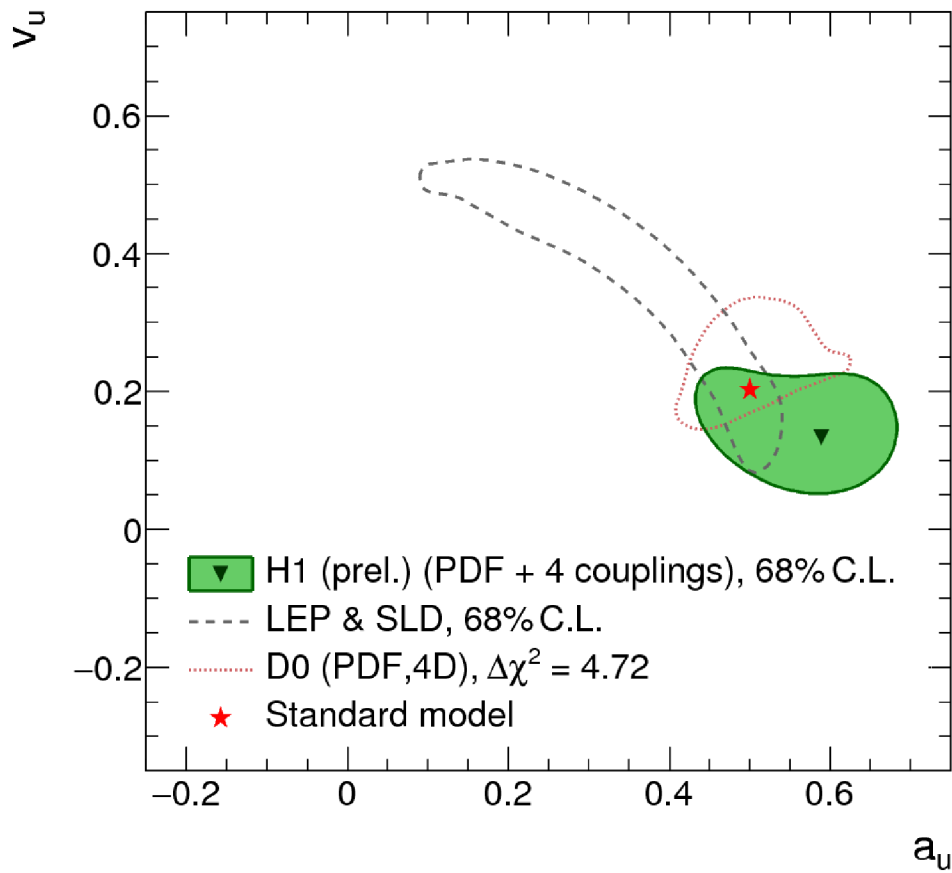
## Fit: PDF + 2 couplings

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



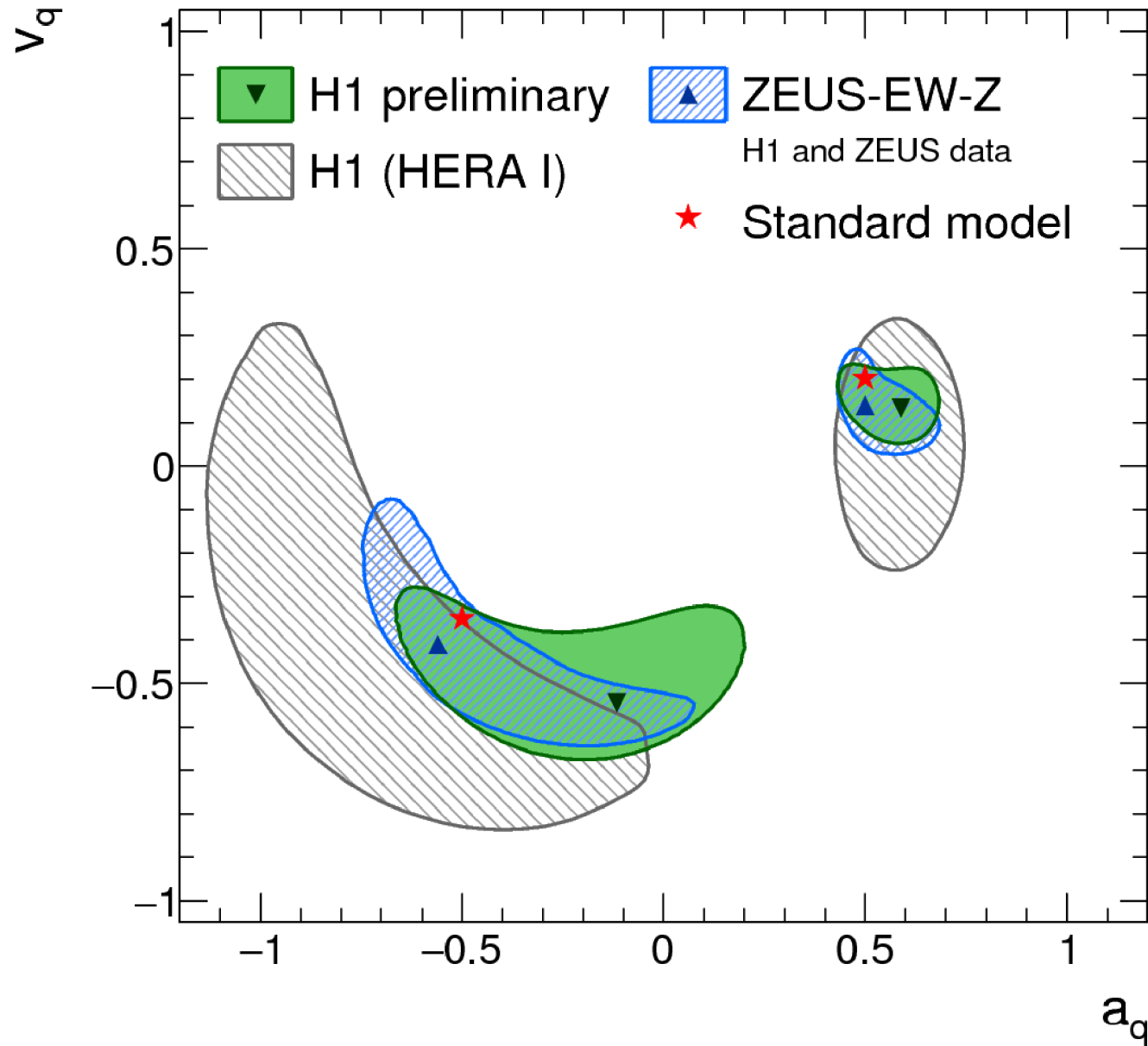


# Comparison with other Measurements



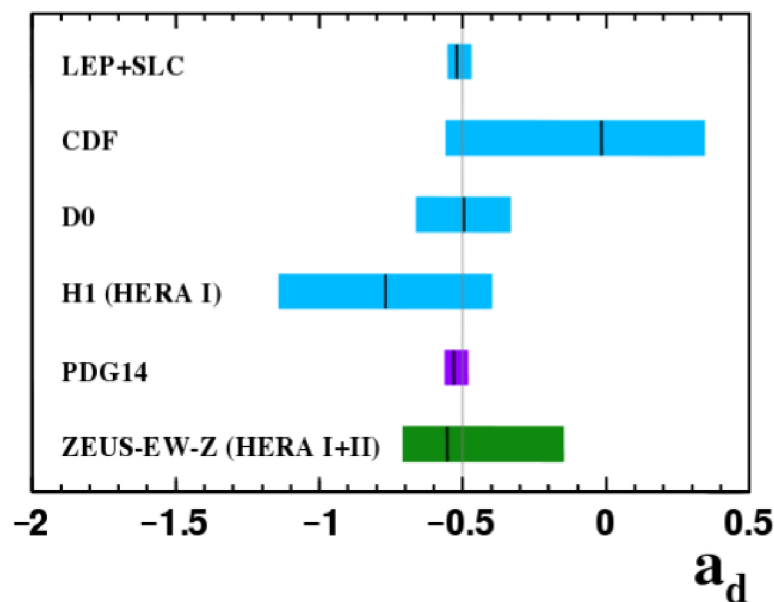
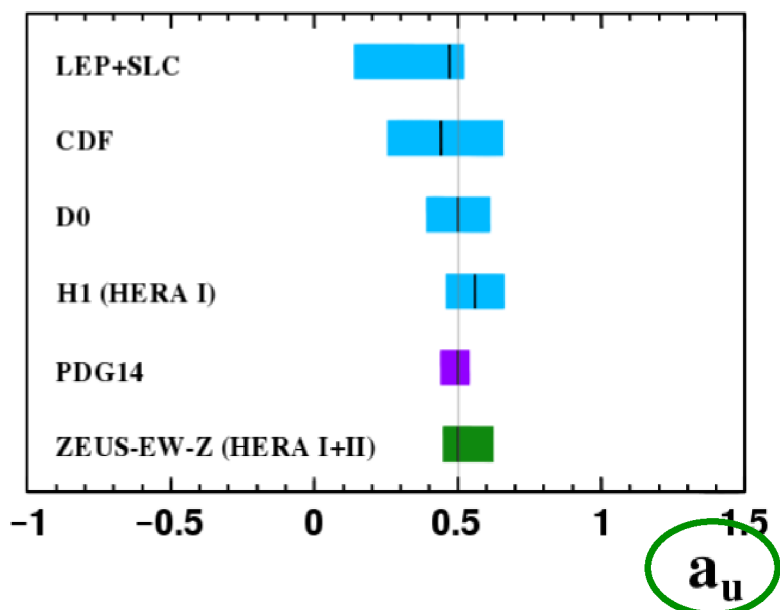
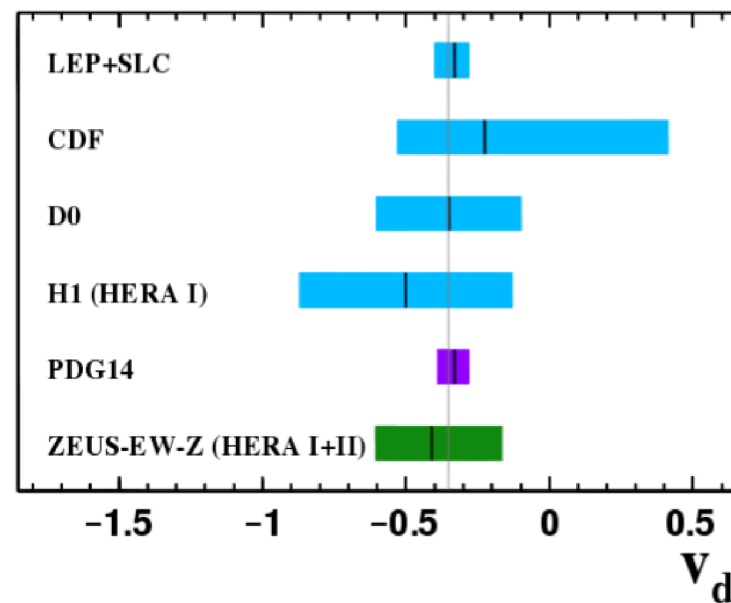
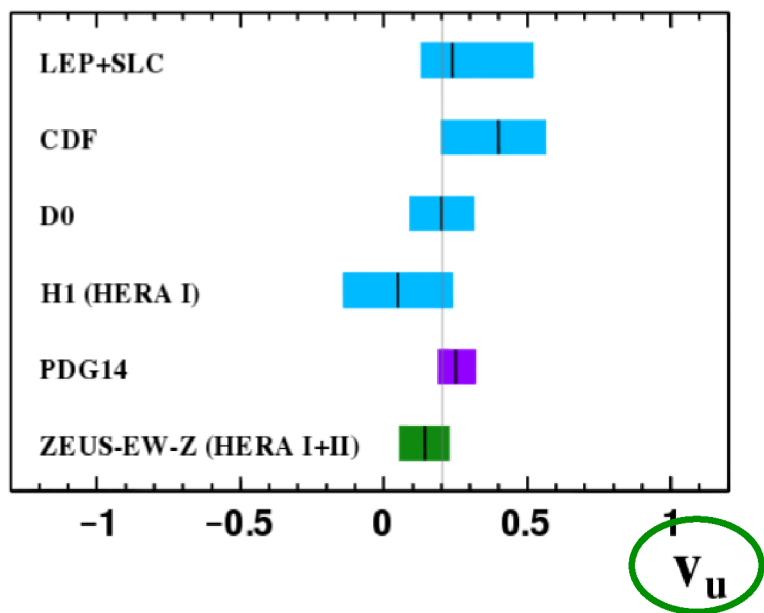
Comparable precision of complementary processes

# H1 and ZEUS Results Combined





# Comparison with other measurements



High sensitivity of HERA data to u-type quark couplings

# Probing Standard Model

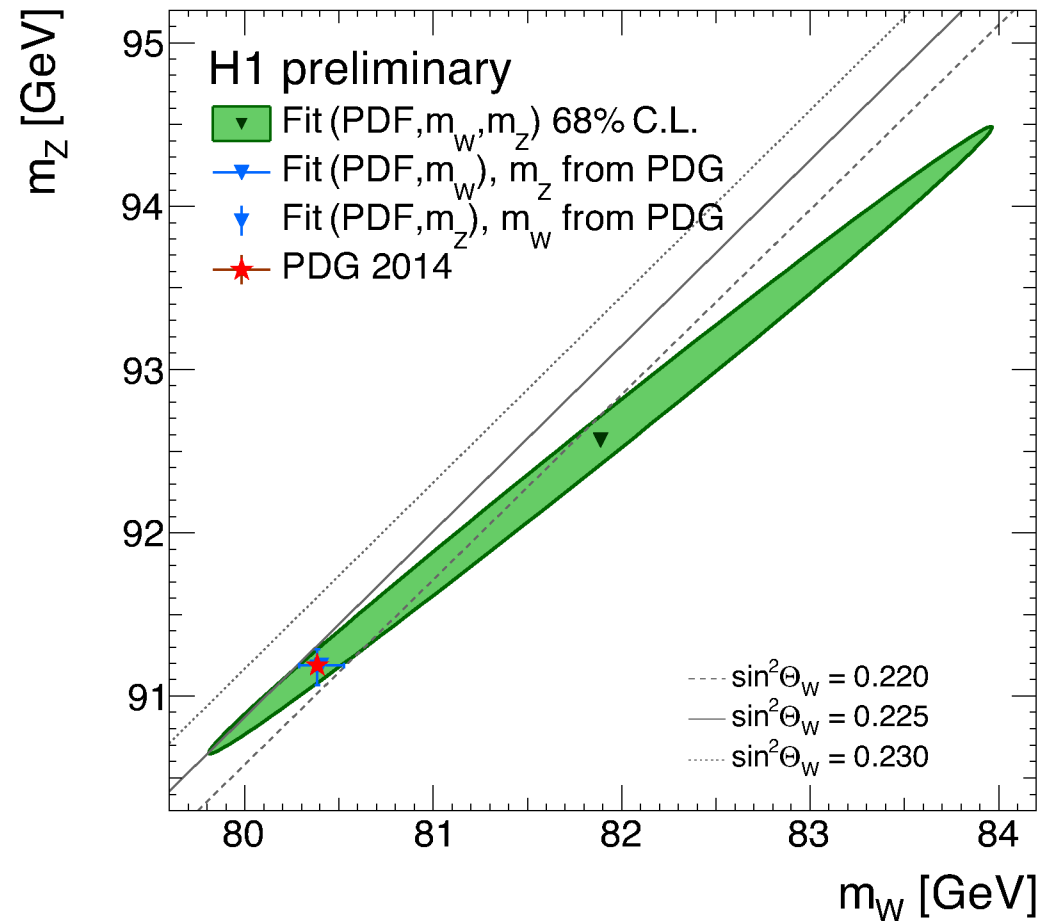
**Standard Model is now over constrained**

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

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



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

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



# 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

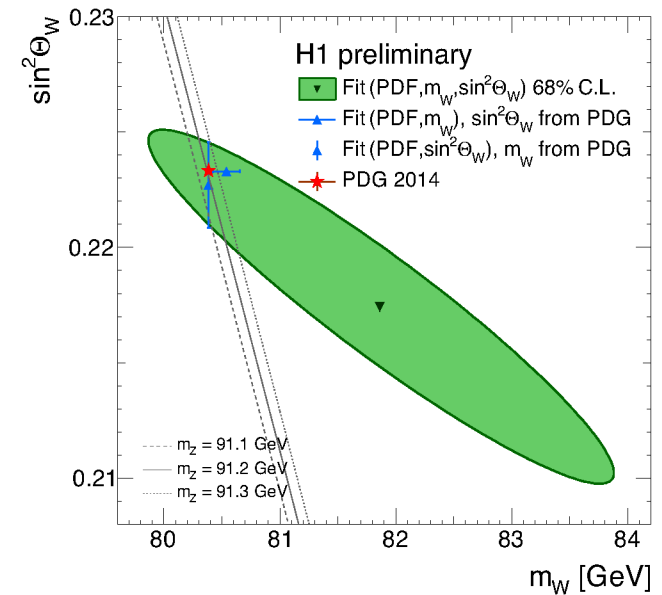
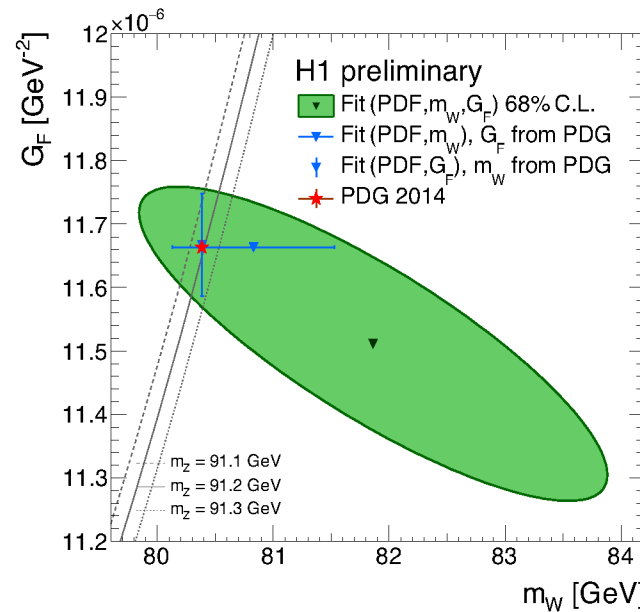
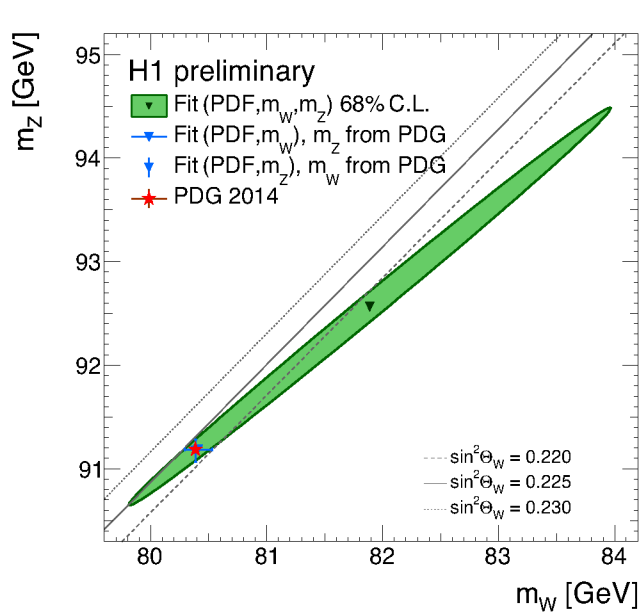
$$\sin^2 \theta_W = 1 - \frac{m_W^2}{m_Z^2}$$

## Perform calculations consistently in on-shell scheme ( $\alpha, m_Z, m_W$ )

- 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 $M_W$

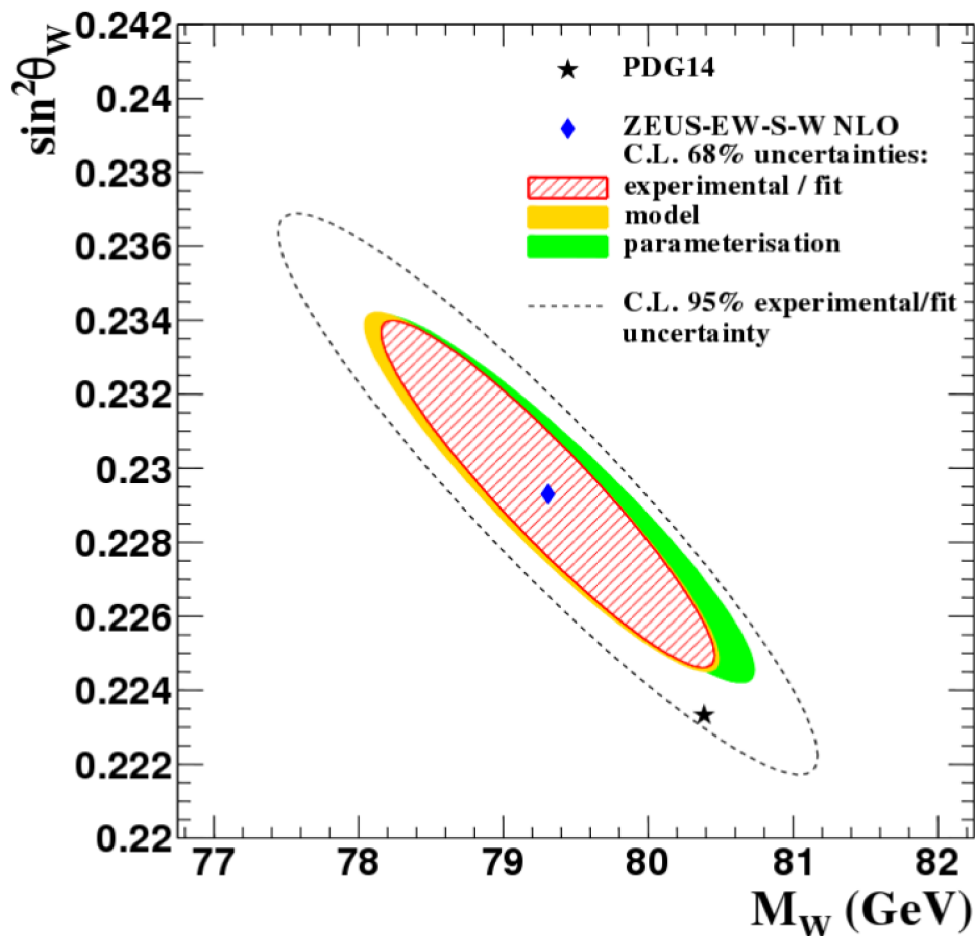
- Similar measurement by ZEUS

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

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

- All extracted quantities agree with world average values

## ZEUS



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

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

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

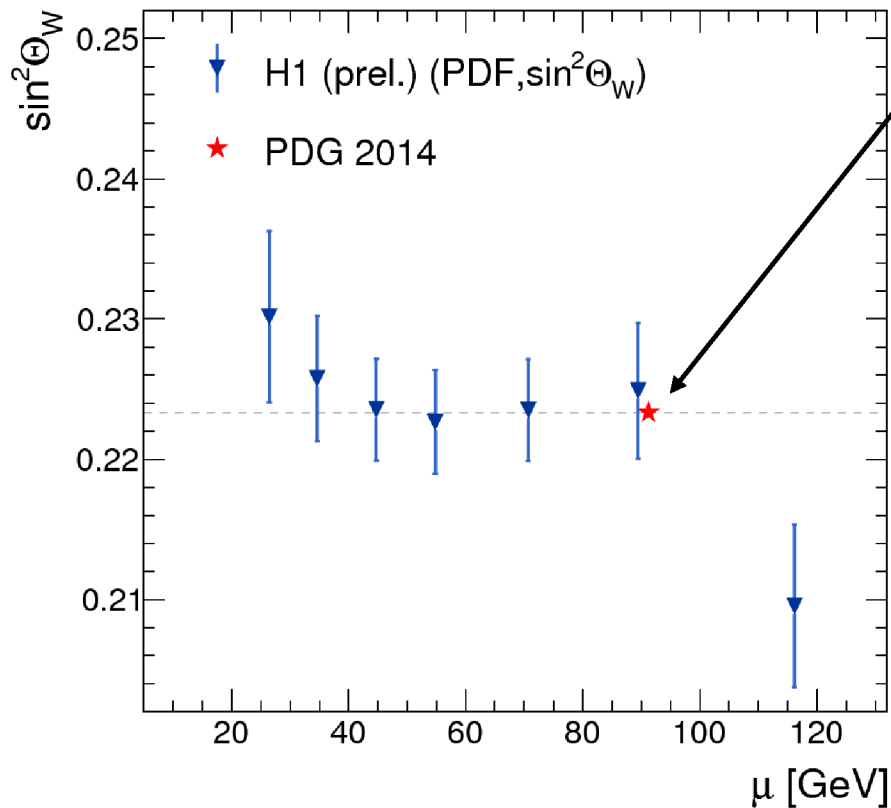
# On-shell $\sin^2\theta_W$

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

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

- Consistent with PDG14

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

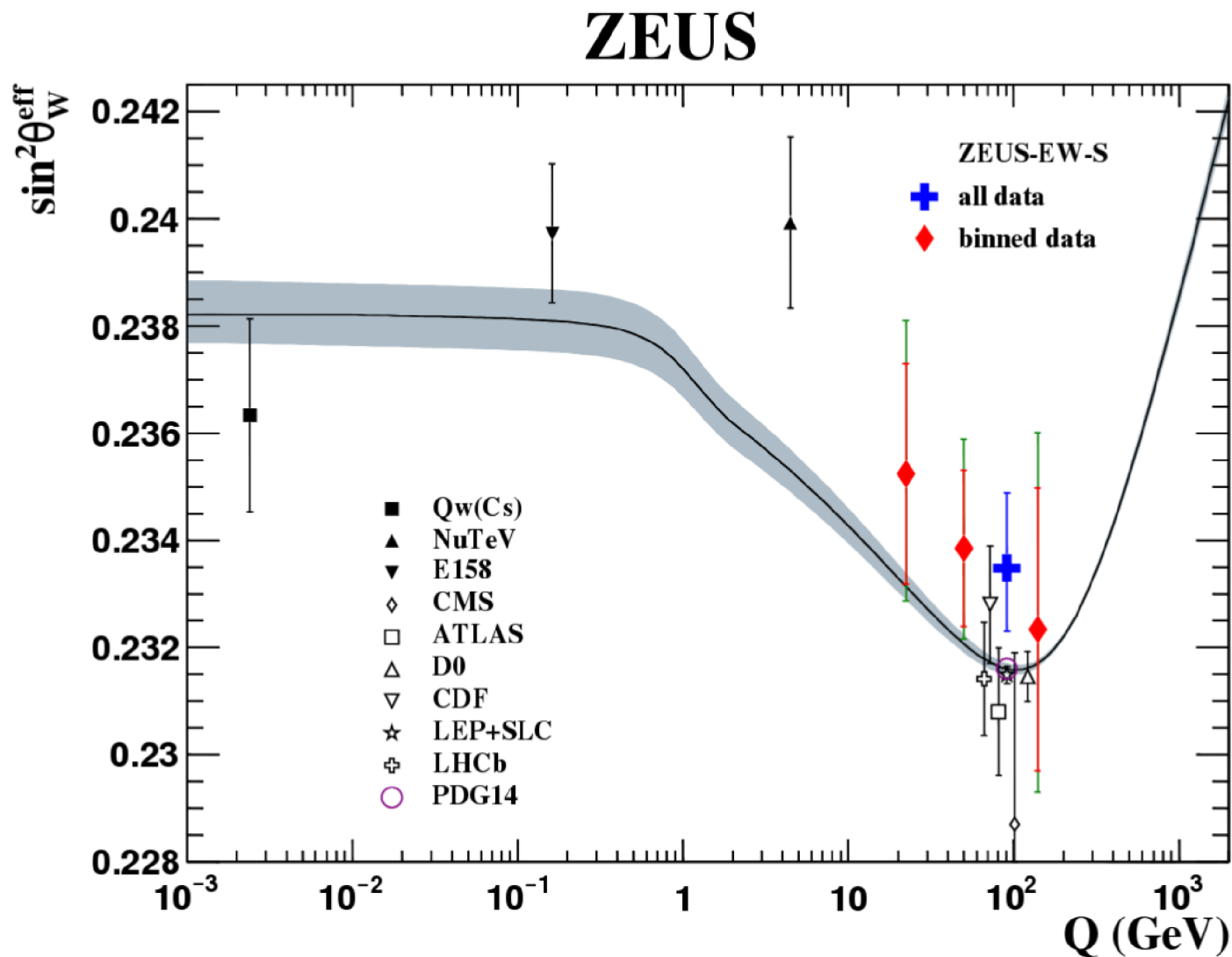


- $\sin^2\theta_W$  determined in  $Q^2$  bins
- Unique measurement of weak mixing angle at different scales
- Agreement with PDG14



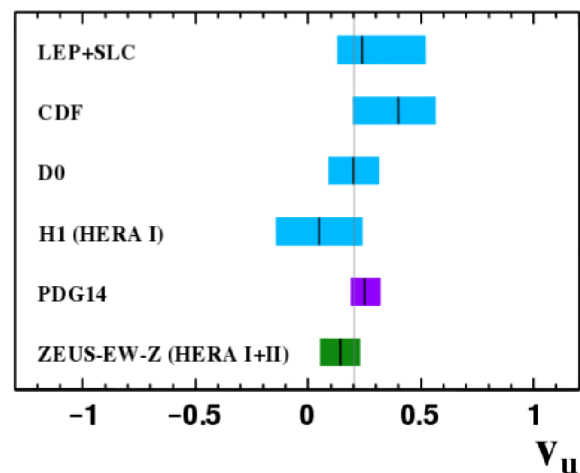
# Effective $\sin^2\theta_W$

- 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