Electroweak and new physics fits to HERA DIS data

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On behalf of H1 and ZEUS Collaborations

- Inclusive data combination and HERAPDF2.0
- Electroweak physics at HERA
- Beyond Standard Model analysis using the simultaneous fit of BSM parameter and PDFs

HERA — world only $e^{\pm}p$ collider

HERA data provides unique opportunity to study the structure of the proton.

operated during 1992 - 2007,
2003 - 2007 — polarised lepton beams
➔ important for the **EW** measurements

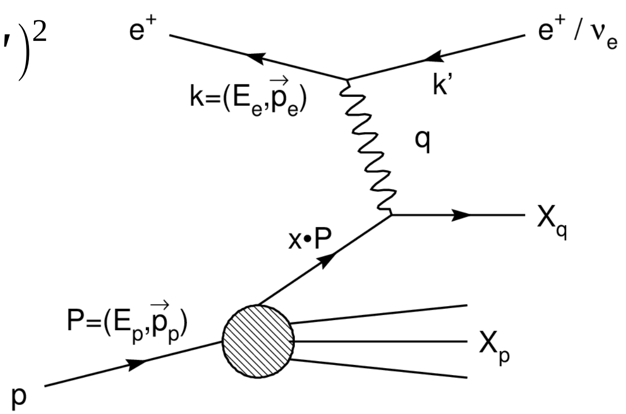
$e^{\pm}$ energy 27.5 GeV;
p energies 920, 820, 575 and 460 GeV.

Kinematics of the $e^{\pm}p$ collisions:

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

$$x_{Bj} = \frac{Q^2}{2P \cdot q}$$

$$y = \frac{P \cdot q}{P \cdot k}$$



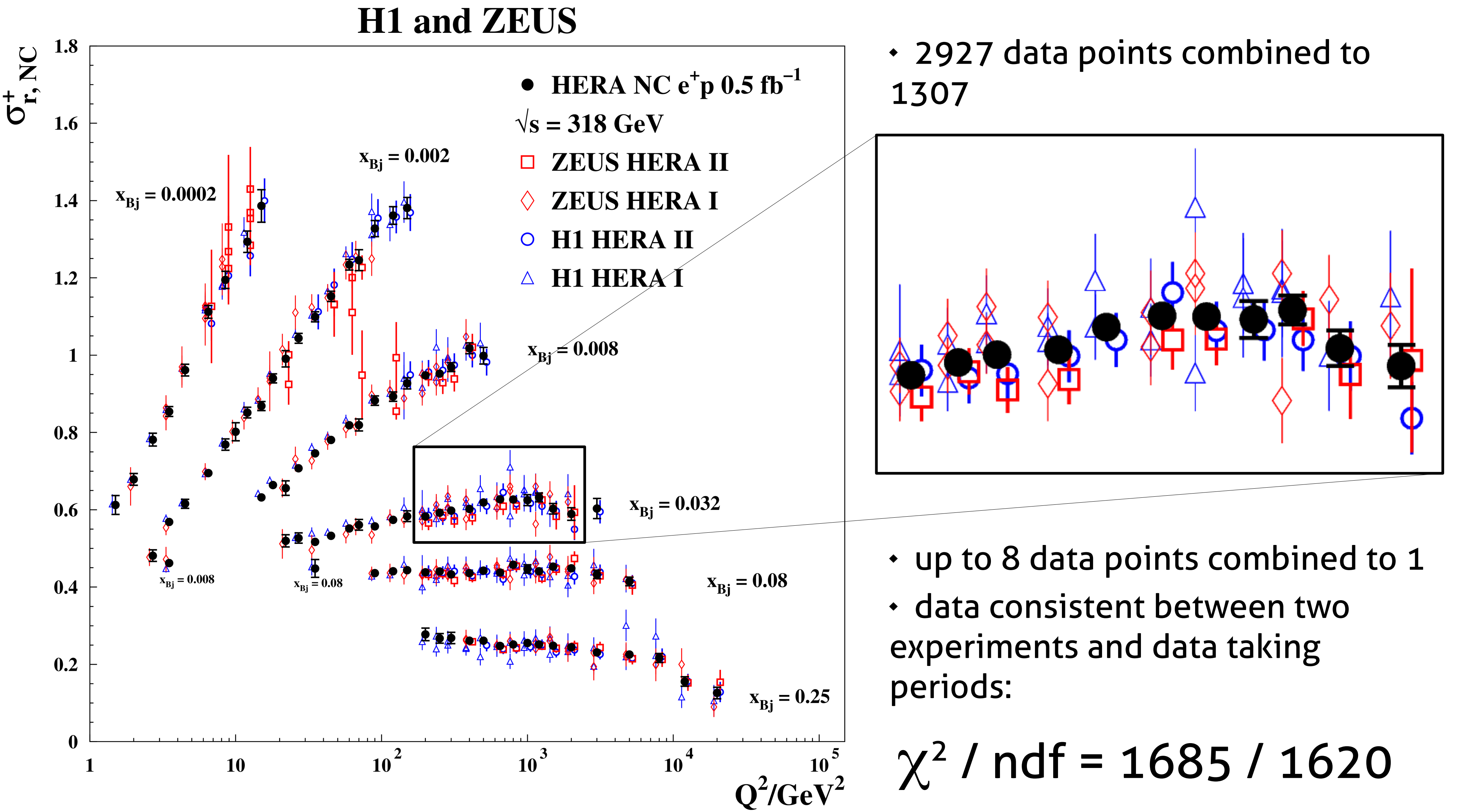
H1 and ZEUS — two collider experiments at HERA :

~ 0.5 fb^{-1} of luminosity recorded by each experiment.

Eur. Phys. J. C 75 (2015) 580
arXiv:1506.06042

Combined Inclusive DIS

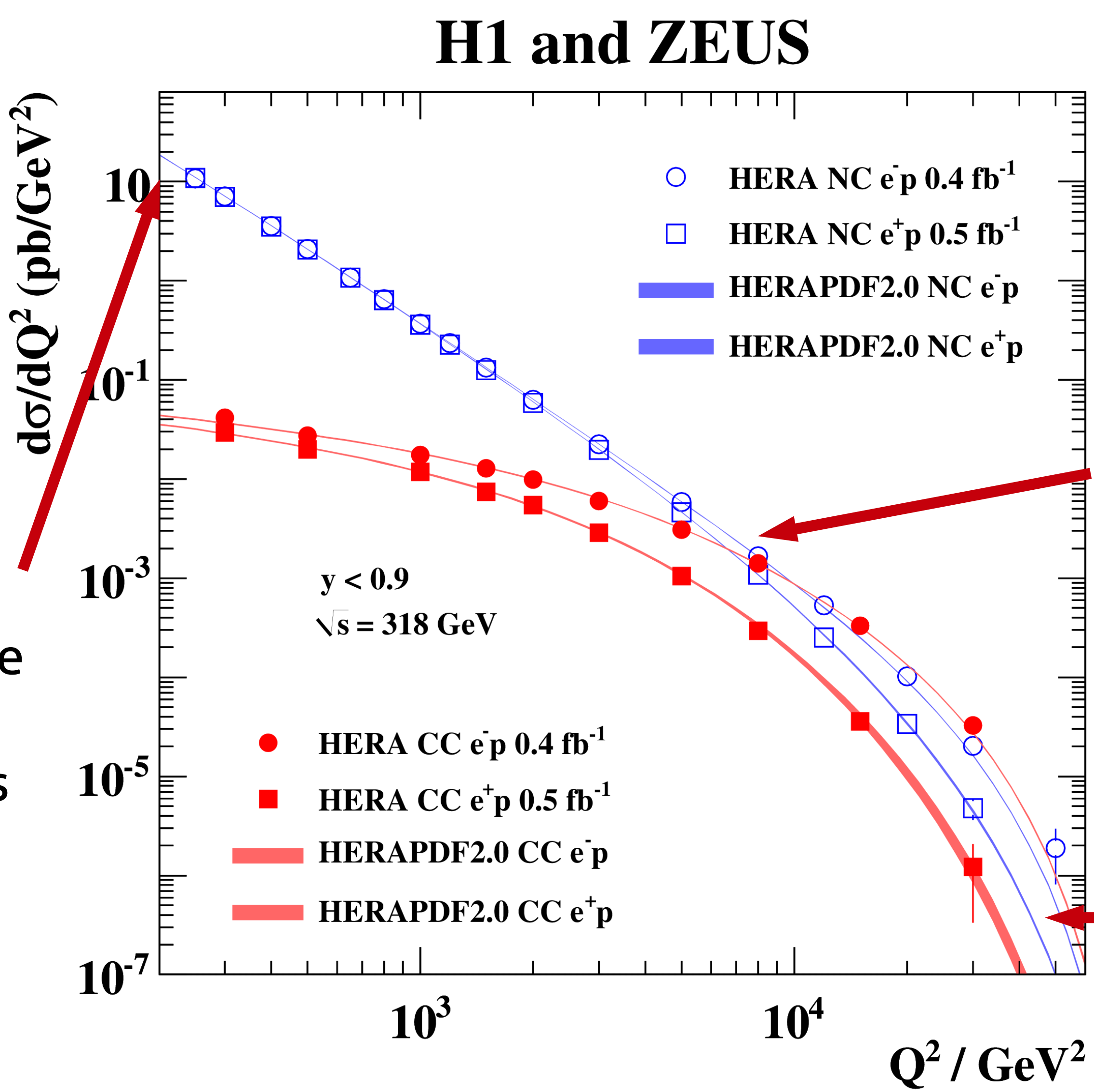
H1 and ZEUS have presented the combination of inclusive DIS measurements, but for zero beams polarisation.



- 2927 data points combined to 1307
- up to 8 data points combined to 1
- data consistent between two experiments and data taking periods:

$$\chi^2 \,/\, ndf = 1685 \,/\, 1620$$

Combined Inclusive DIS



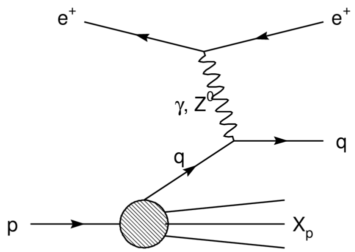
at low Q^2 γ exchange (NC DIS) dominates

NC and CC DIS cross sections become comparable at $Q^2 \sim M_Z^2$, M_W^2

γZ^0 interference
difference in NC e^+ and e^-

Effects of electroweak unification clearly seen.

QCD analysis of combined DIS data



Neutral Current :

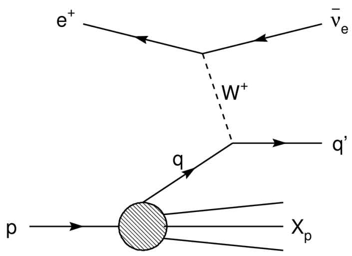
$$\frac{d^2\sigma_{NC}^{e\mp p}}{dx_{Bj}dQ^2}=\frac{2\pi\alpha^2}{x_{Bj}Q^4}\cdot\left(Y_+\cdot F_2\pm Y_-\cdot x\cdot F_3-y^2\cdot F_L\right)$$

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

$$F_2=\frac{4}{9}(xU+x\bar{U})+\frac{1}{9}(xD+x\bar{D})$$

$$x\cdot F_3\sim x u_v+x d_v$$

Similar equation for CC DIS.



Parton Density Functions parametrization at starting scale Q^2 = 1.9 GeV^2:

$$x g(x)=A_g x^{B_g}(1-x)^{C_g}-A'_g x^{B'_g}(1-x)^{C'_g}$$

$$x u_v(x)=A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}(1+D_{u_v}x+E_{u_v}x^2)$$

$$x d_v(x)=A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}$$

$$x\bar{U}(x)=A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}(1+D_{\bar{U}}x)$$

$$x\bar{D}(x)=A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}$$

fixed or calculated by sum-rules

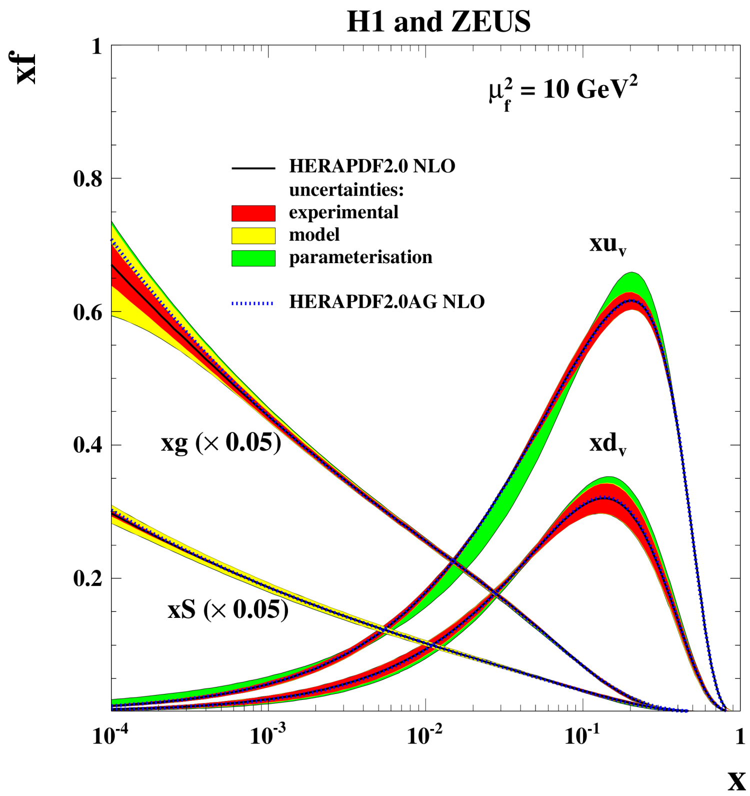
set equal

- Evolve to any Q^2 with DGLAP at NLO.
- Use Thorne-Roberts GMVFN scheme for Heavy quarks.

QCD analysis of combined DIS data

Eur. Phys. J. C 75 (2015) 580
arXiv:1506.06042

PDFs set **HERAPDF2.0** :



Combination of measurements of inclusive deep inelastic $e^{\pm}p$ scattering cross sections and QCD analysis of HERA data

This paper is dedicated to the memory of Professor Guido Altarelli who sadly passed away as it went to press. The results which it presents are founded on the principles and the formalism which he developed in his pioneering theoretical work on Quantum Chromodynamics in deep-inelastic lepton-nucleon scattering nearly four decades ago

H1 and ZEUS Collaborations

Polarised DIS

Phys. Rev. D 93 (2016) 092002
arXiv:1603.09628

In NC DIS polarisation affects γZ^0 interference and Z^0 exchange:

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

$$F_2^{\mp} = F_2^{\gamma} - (v_e \mp P_e a_e)\chi_Z F_2^{\gamma Z} + \\ + (v_e^2 + a_e^2 \mp 2 P_e v_e a_e)\chi_Z^2 F_2^Z$$

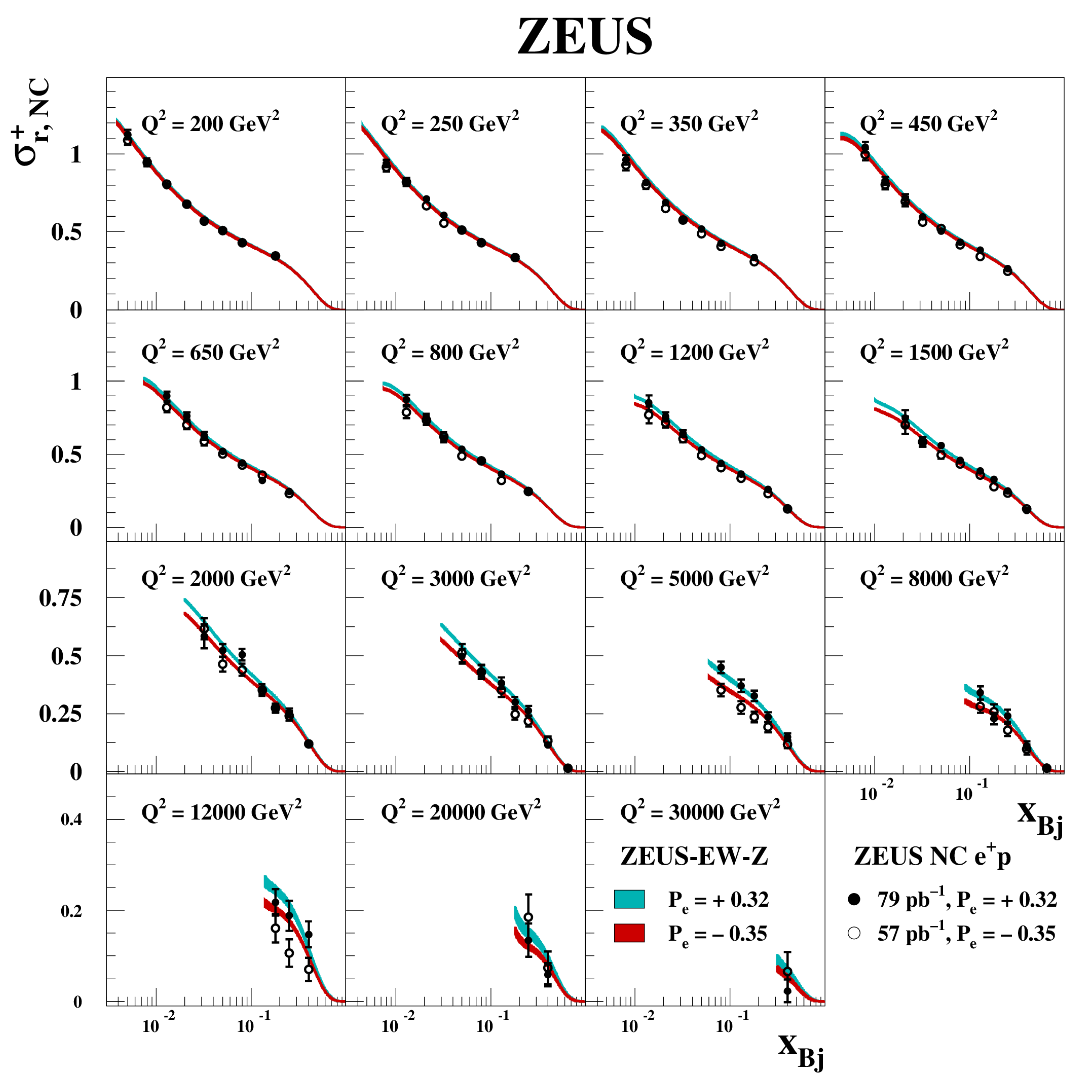
$$x F_3^{\mp} = -(a_e \mp P_e v_e)\chi_Z x F_3^{\gamma Z} + \\ + (2 v_e a_e \mp P_e (v_e^2 + a_e^2))\chi_Z^2 x F_3^Z$$

$$v_e = -\frac{1}{2} + 2\sin^2(\Theta_W) \qquad a_e = -\frac{1}{2}$$

In the on-shell scheme:

$$\sin^2(\Theta_W) = 1 - \frac{M_W^2}{M_Z^2}$$

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



Polarised DIS

In CC DIS polarisation scales the whole cross section:

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

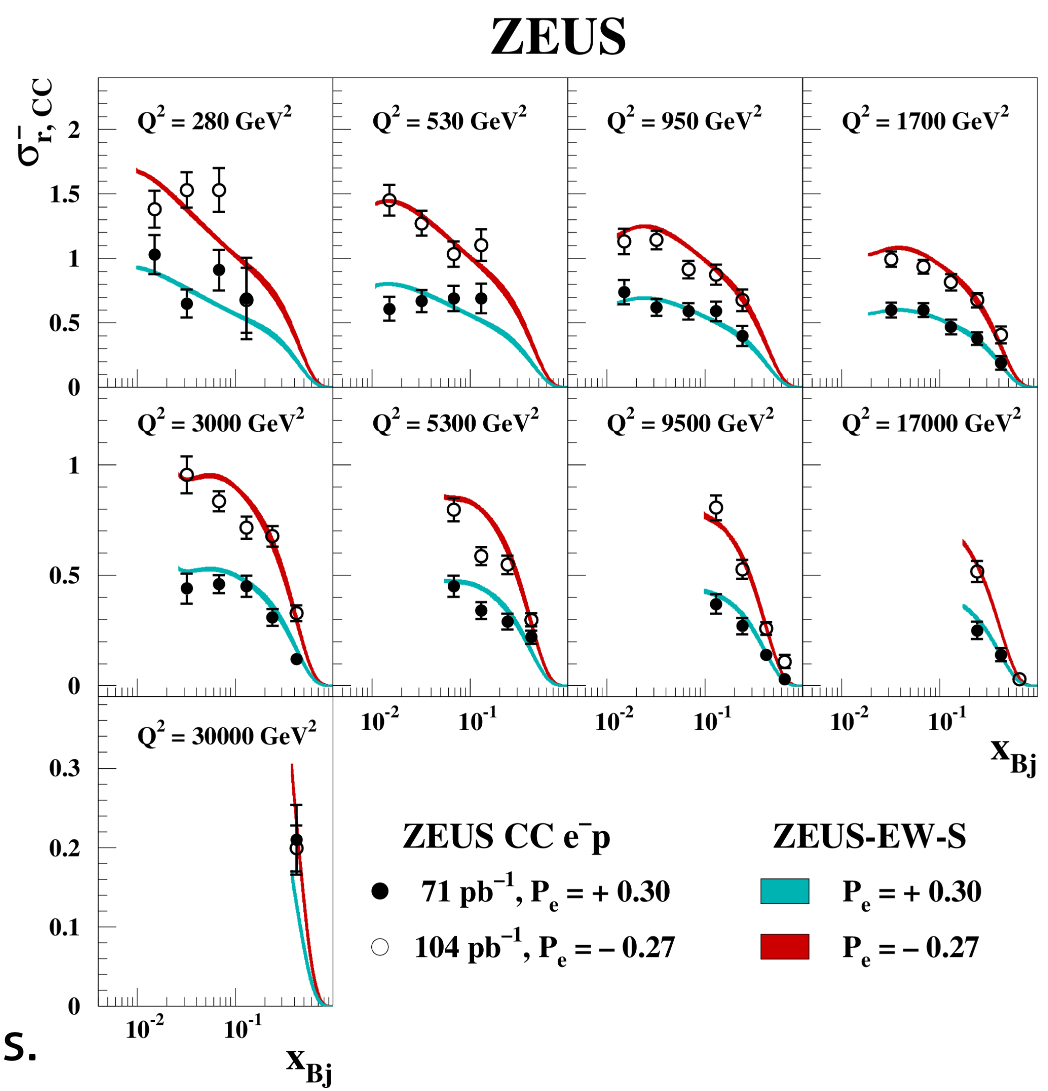
$$\frac{d^2\sigma_{CC}^{e+p}}{dx_{Bj}\,dQ^2} = (1+P_e)\frac{G_F^2 M_W^4}{2\pi x_{Bj}(Q^2+M_W^2)^2}\times$$
$$\times x[(\bar{u}+\bar{c})+(1-y)^2(d+s+b)]$$

In the on-shell scheme:

$$M_W = \frac{A_0}{\sin^2(\Theta_W)\sqrt{1-\Delta R}}$$

$$G_F = \frac{\pi\alpha_0}{\sqrt{2}\sin^2(\Theta_W)M_W^2}\frac{1}{1-\Delta R}$$

ΔR — radiative corrections.



ZEUS QCD + EW fits

Phys. Rev. D 93 (2016) 092002
arXiv:1603.09628

Used uncombined datasets:

- Same as in the data combination:
  - All HERA I data from H1 and ZEUS, unpolarised
  - Reduced E_p data from H1 and ZEUS
  - HERA II data from H1, unpolarised
- Different from the data combination:
  - HERA II data from ZEUS, **polarised**

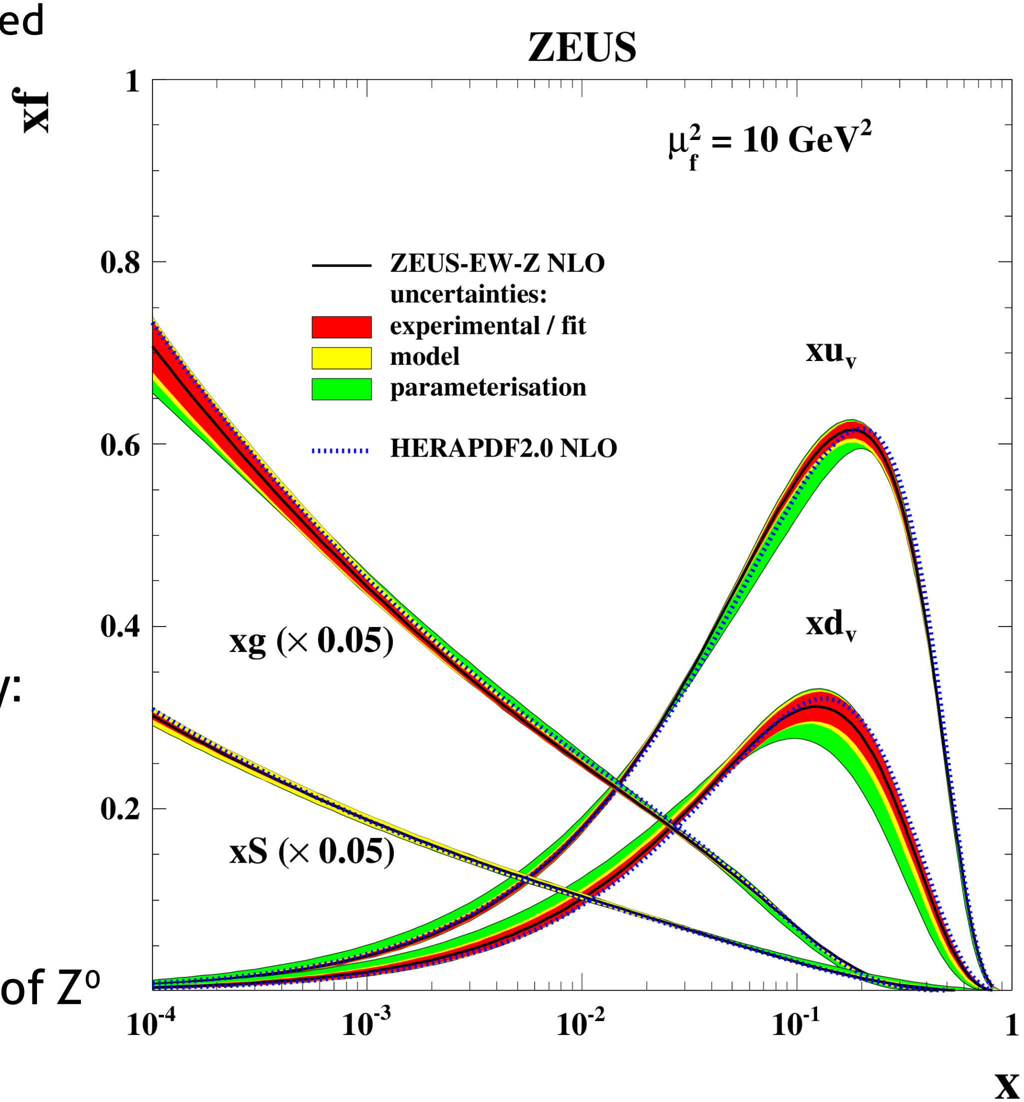
Data from Q^2 = 3.5 GeV^2

PDFs fits:

- Closely follow HERAPDF2.0
- One parameter less for better fit stability:

$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}} (1-x)^{C_{\bar{U}}}$$

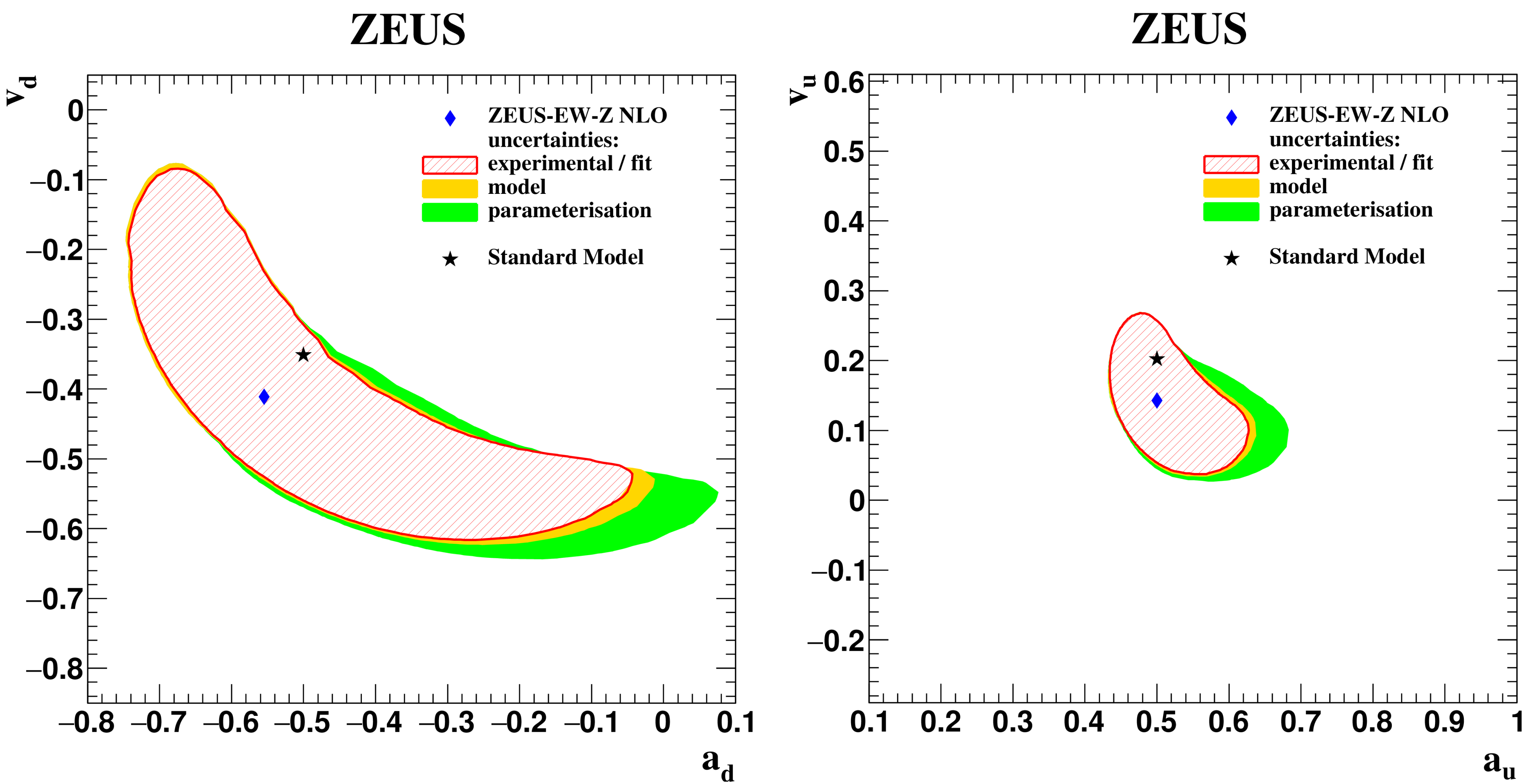
- ΔR calculated with EPRC code:
  desy.de/~hspiesb/eprc.html
- Simultaneous PDFs fits with 4 couplings of Z^0 to quarks, or $\sin^2(\Theta_W)$ and M_W



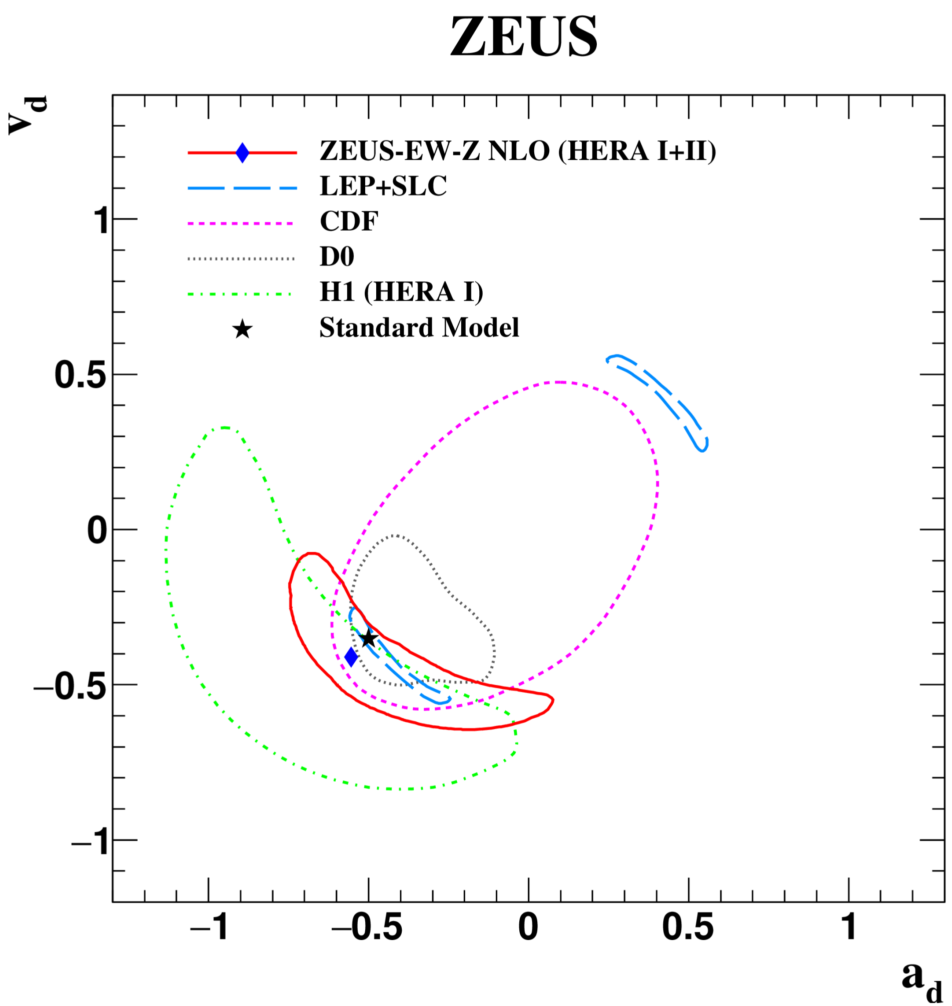
ZEUS light quark couplings

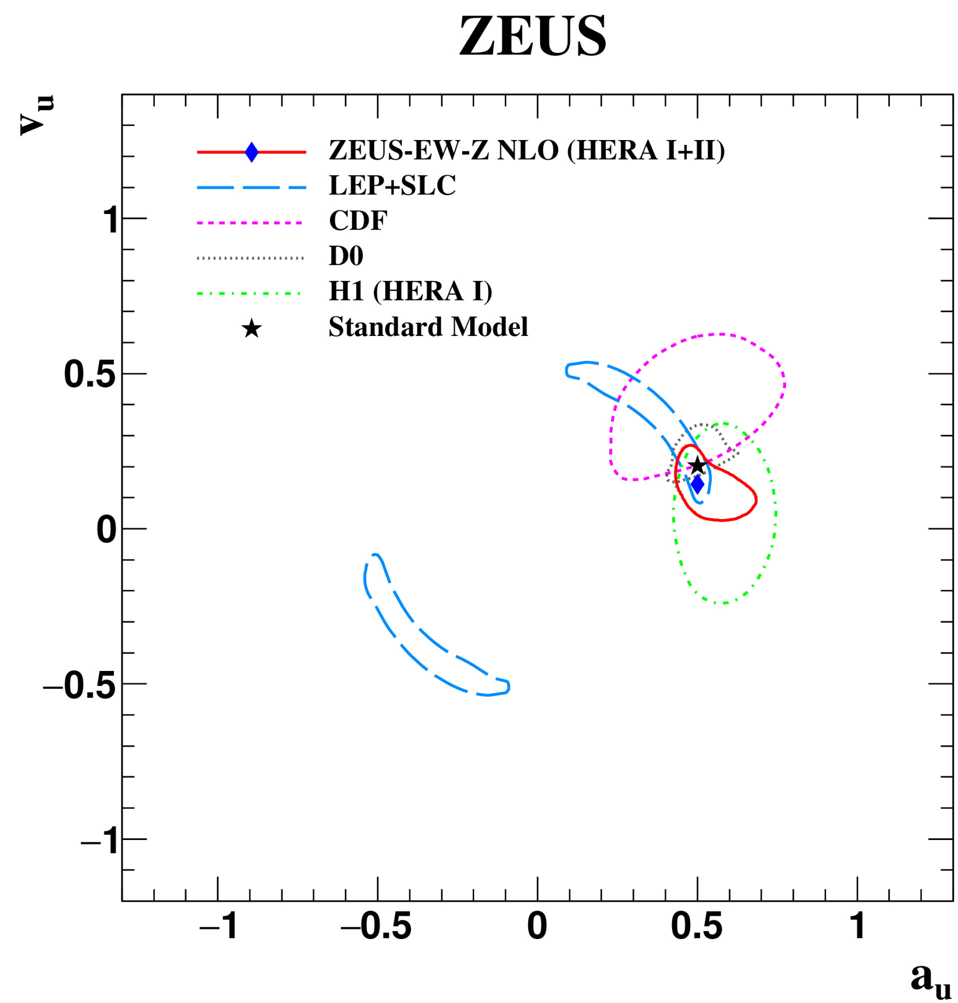
In quark parton model: $$[F_2^{\gamma}, F_2^{\gamma Z}, F_2^{Z}] = \sum_q [e_q^2, 2 e_q v_q, v_q^2 + a_q^2] x (q + \bar{q})$$

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



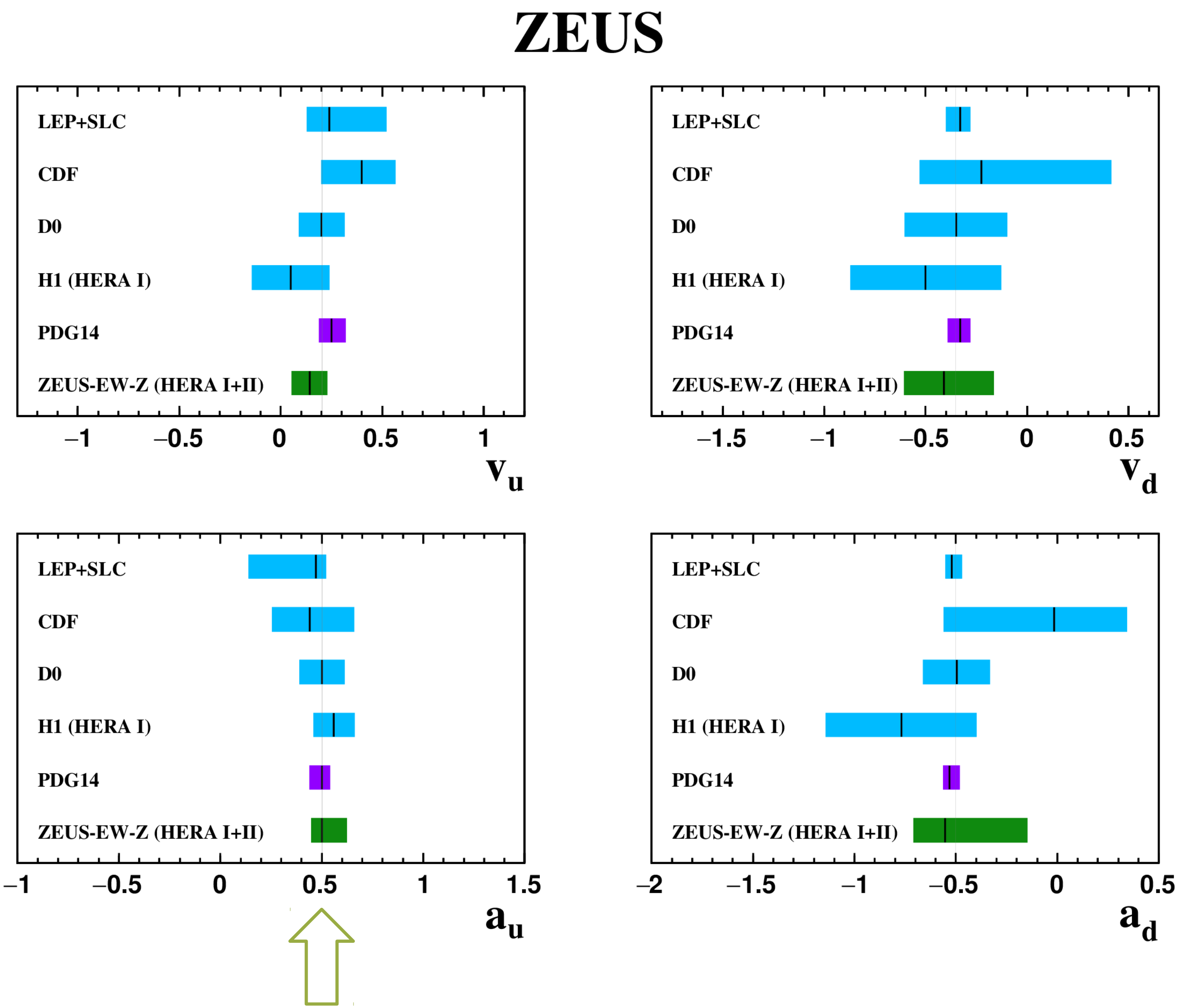
Comparison to other measurements





	SM		SM
$a_d = -0.56^{+0.34}_{-0.14}(\exp/fit)^{+0.11}_{-0.05}(mod)^{+0.20}_{-0.00}(param)$	-0.50	$a_u = 0.50^{+0.09}_{-0.05}(\exp/fit)^{+0.04}_{-0.02}(mod)^{+0.08}_{-0.01}(param)$	0.50
$v_d = -0.41^{+0.24}_{-0.16}(\exp/fit)^{+0.04}_{-0.07}(mod)^{+0.00}_{-0.08}(param)$	-0.351	$v_u = 0.14^{+0.08}_{-0.08}(\exp/fit)^{+0.01}_{-0.00}(mod)^{+0.03}_{-0.01}(param)$	0.202

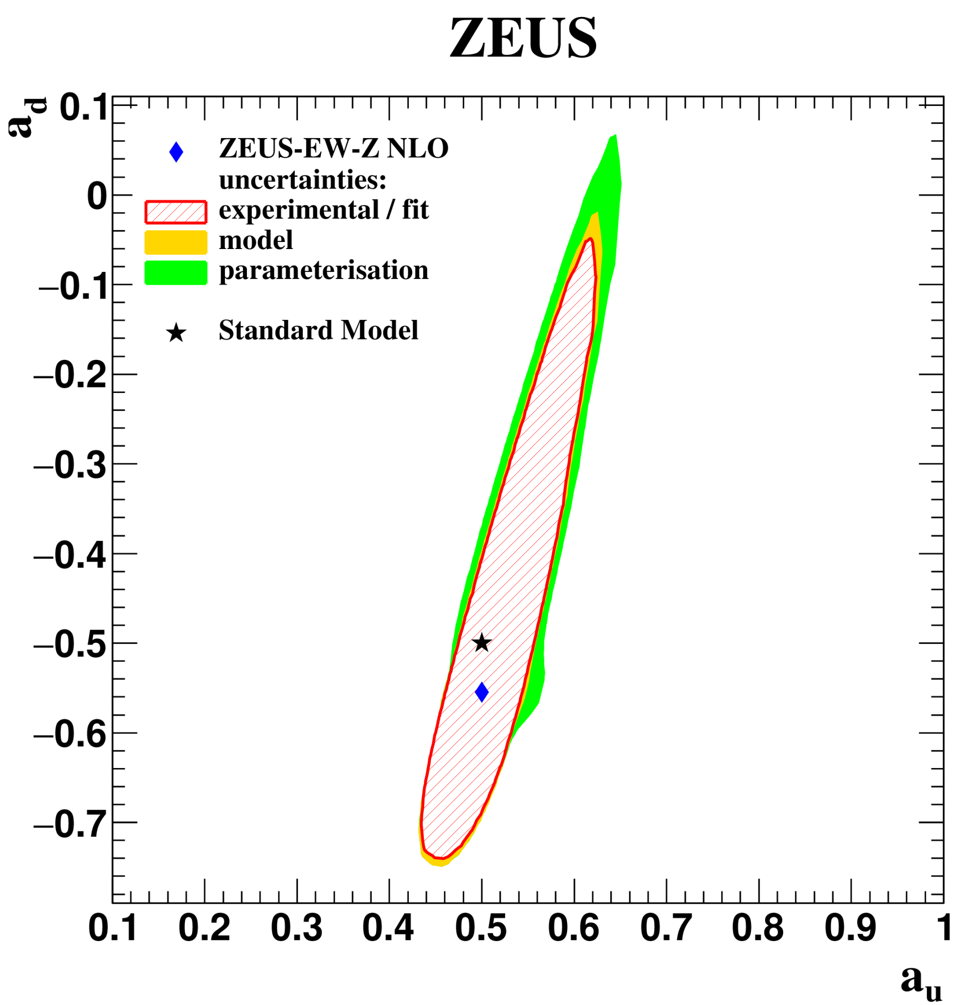
Comparison to other measurements

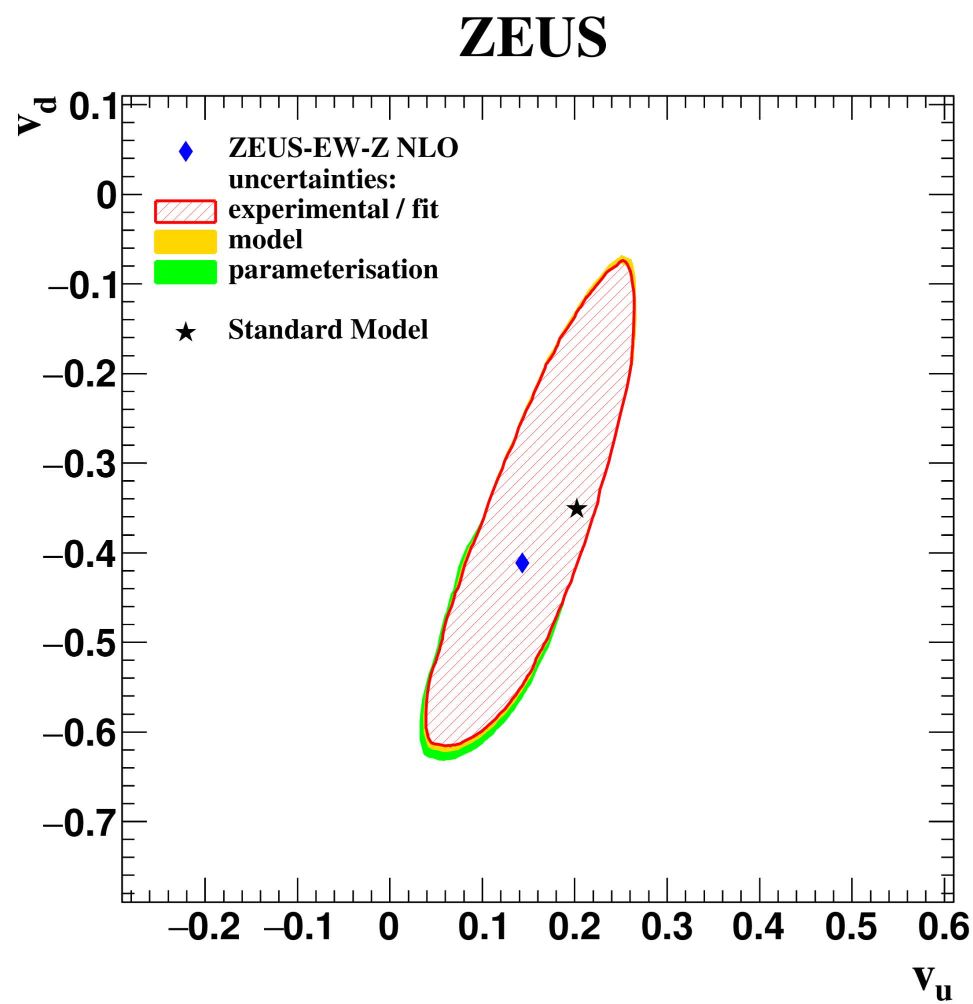


Remarkable sensitivity to **u-type** quark couplings

Correlations

Fit shows high correlation of axial-vector and vector couplings between quark types:

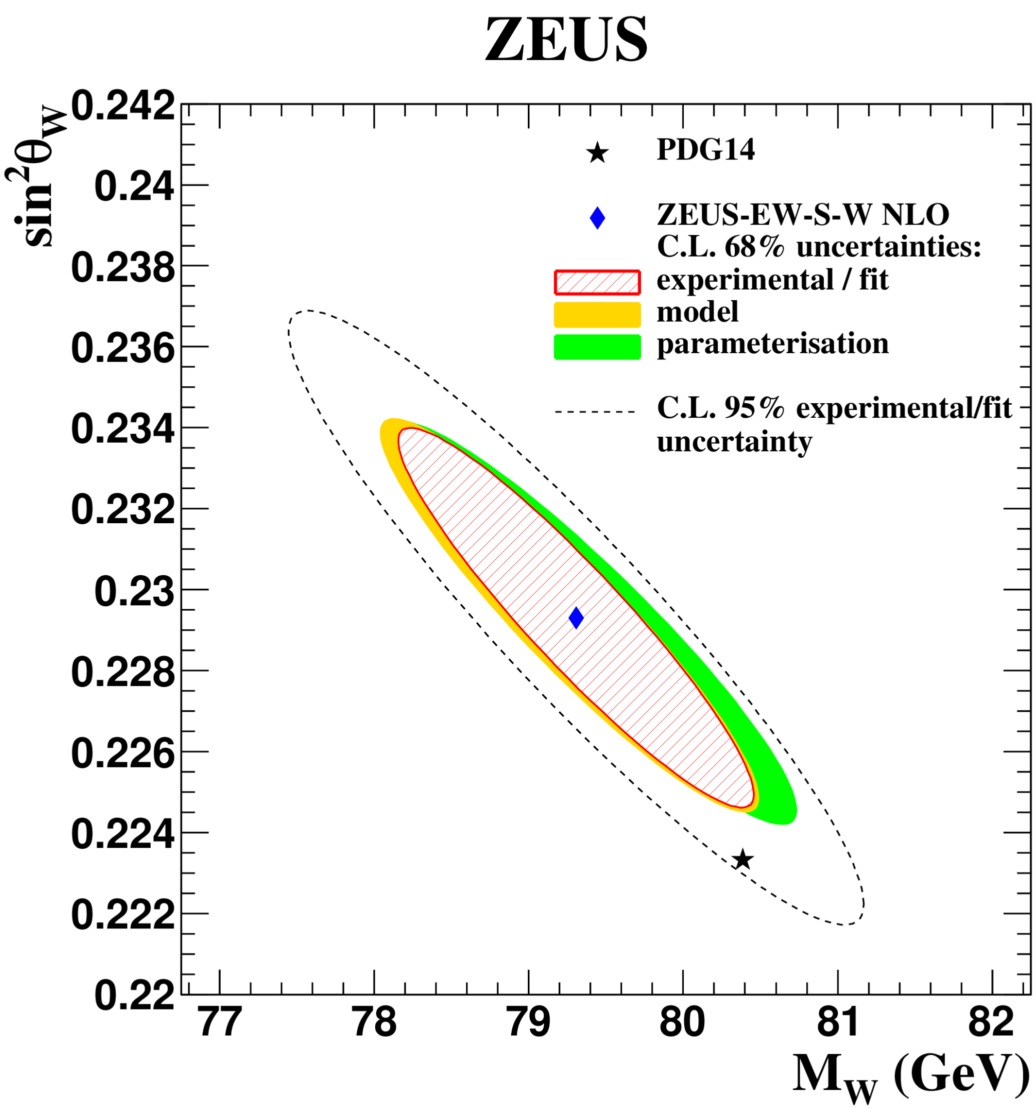




Their corelations to PDF parameters are small.

M_W and $\sin^2(\Theta_W)$

Simultaneous extraction of M_W and $\sin^2(\Theta_W)$:



$$\sigma_{NC}(\alpha, \sin^2(\Theta_W), M_Z)$$

$$\sigma_{CC}(G_F(\alpha, \sin^2(\Theta_W), M_W), M_W)$$

$$M_W = 79.30 \pm 0.76_{(\exp/fit)}{}^{+0.38}_{-0.08}{}_{(mod)}{}^{+0.48}_{-0.10}{}_{(param)}$$

$$\sin^2(\Theta_W) = 0.2293 \pm 0.0031_{(\exp/fit)}{}^{+0.005}_{-0.001}{}_{(mod)}{}^{+0.003}_{-0.001}{}_{(param)}$$

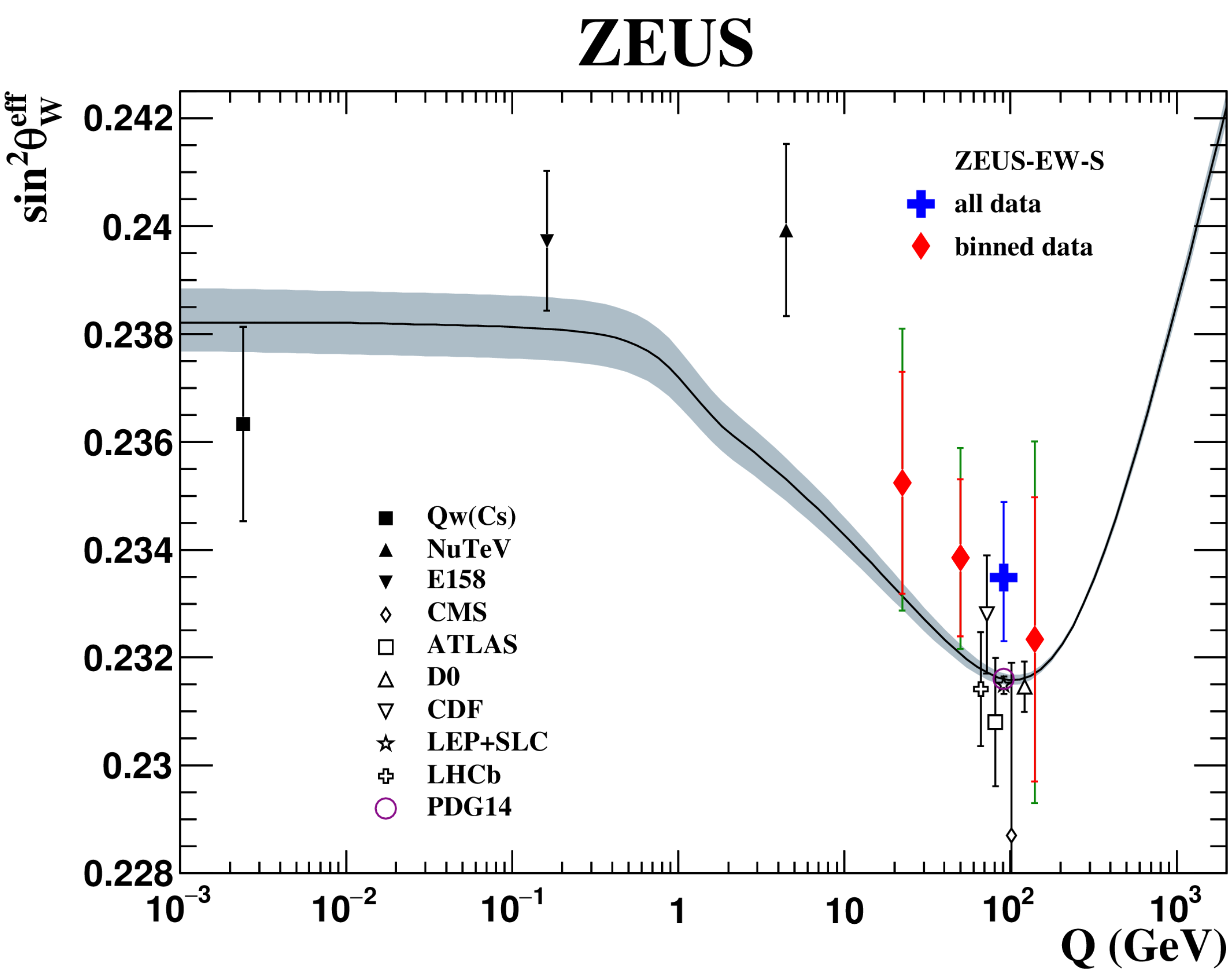
Good agreement with world average:

$$M_W^{DPG14} = 80.385 \pm 0.015$$

$$\sin^2(\Theta_W)^{PDG14\,on-shell} = 0.22333 \pm 0.00011$$

Effective $\sin^2(\Theta_W)$

On-shell measurements for the whole data and for three bins in Q^2 translated to effective $\sin^2(\Theta_W)$:



First observation of $\sin^2(\Theta_W)^{eff}$ running from one experiment.

H1 QCD + EW fits

H1prelim-16-041

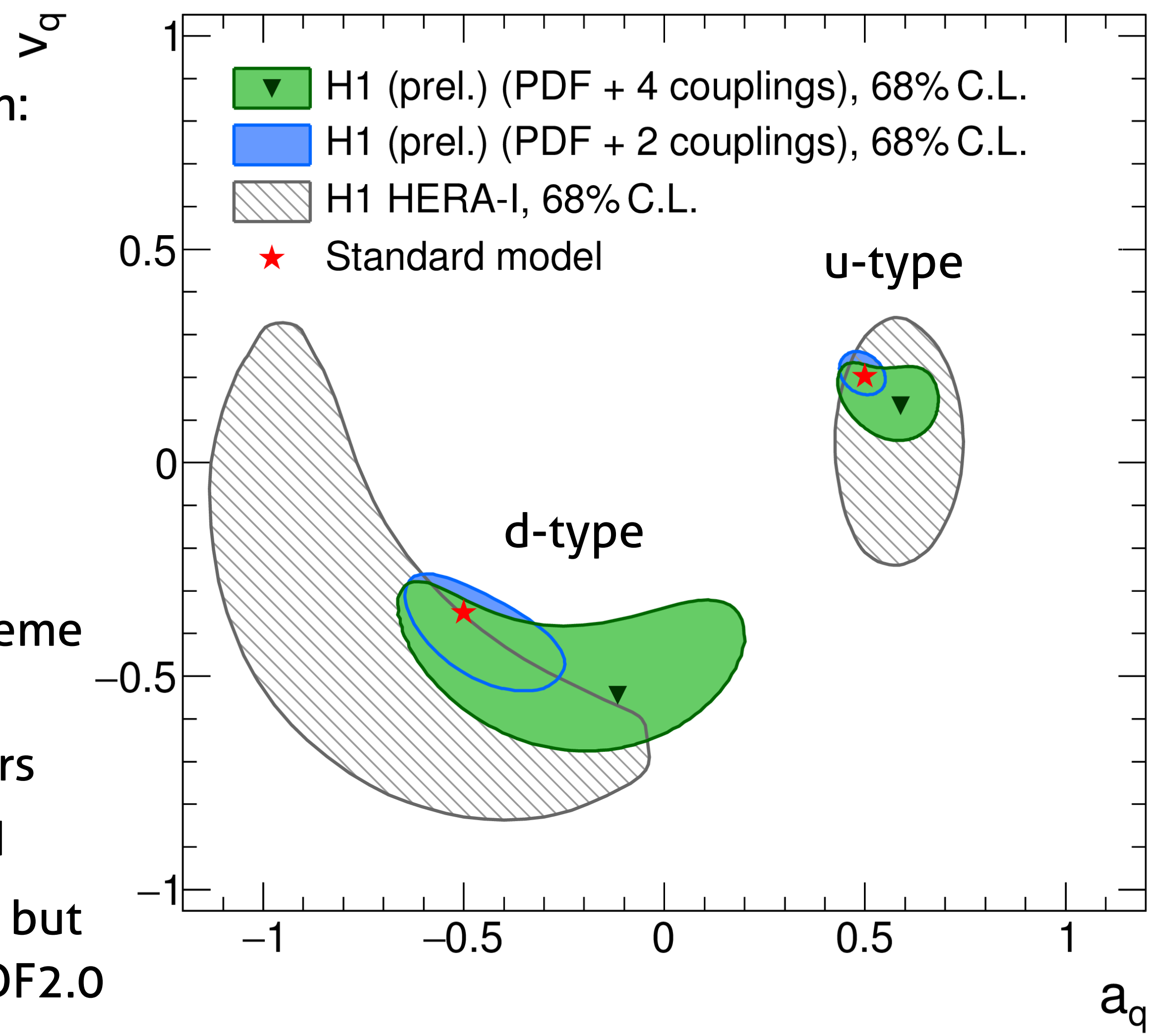
Used uncombined datasets:

- Same as in the data combination:
  - All HERA I data from H1, unpolarised
  - Reduced E_p data from H1
- Different from the data combination:
  - HERA II data from H1, **polarised**

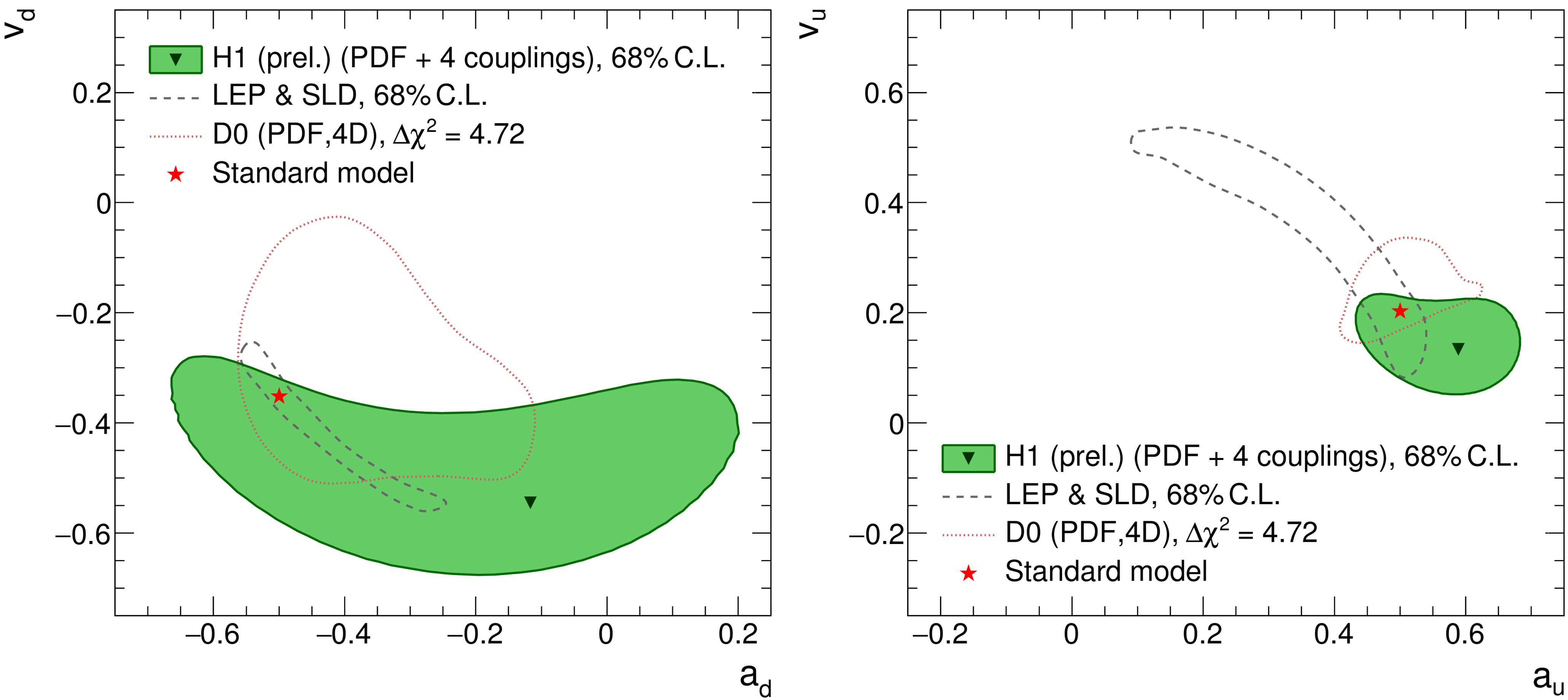
Data from Q^2 = 12 GeV^2

PDFs fits:

- Basics similar to ZEUS approach
- DGLAP evolution at NNLO
- Calculations strictly in on-shell scheme
- Polarisation values fitted within uncertainties as 4 additional parameters
- New C++ fitter and Alpos code used
- Different (log-normal) χ^2 definition, but results similar to using χ^2 from HERAPDF2.0

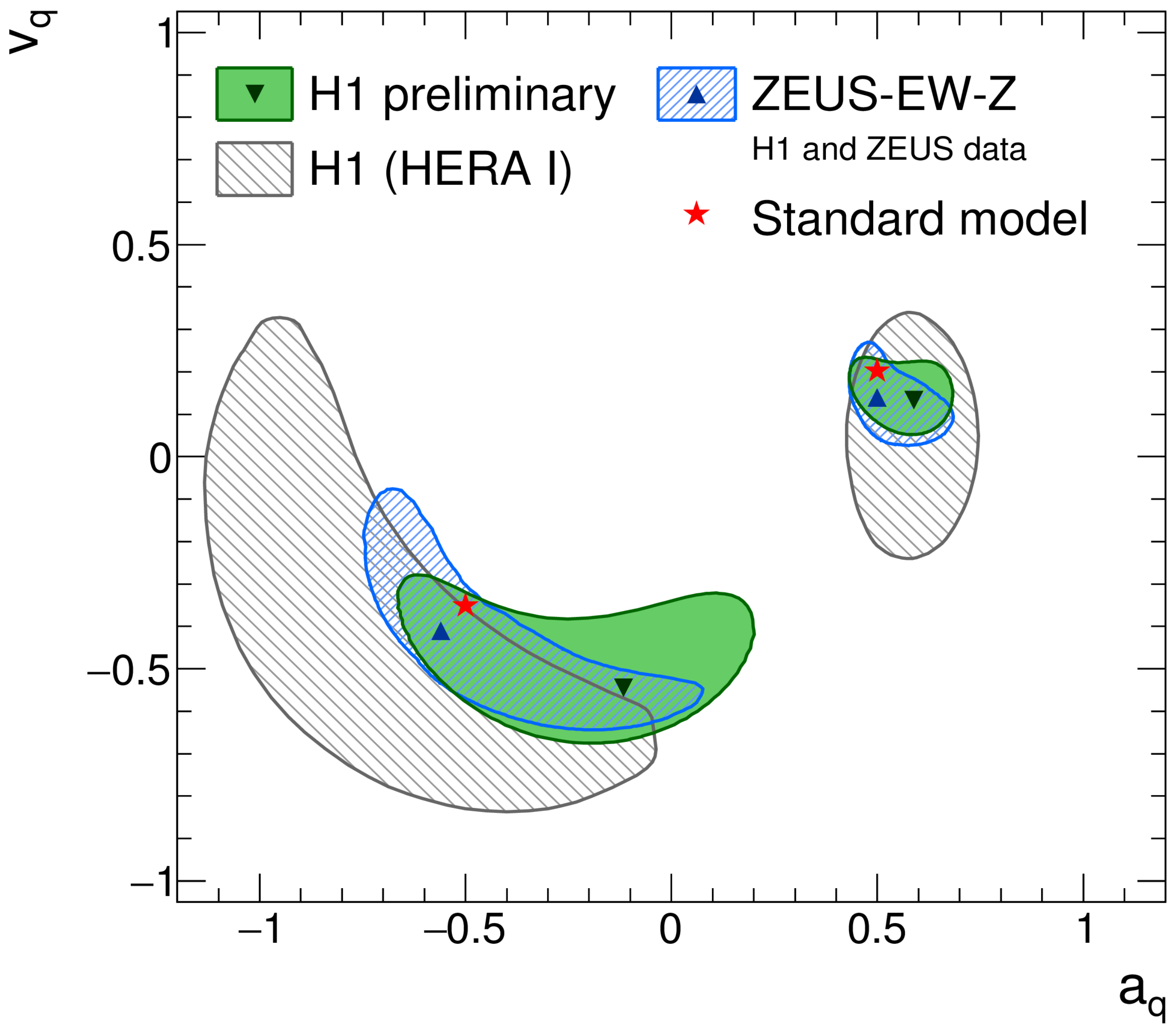


Comparison to other measurements



Comparable precision for **u-type** quark couplings

Comparison to ZEUS result

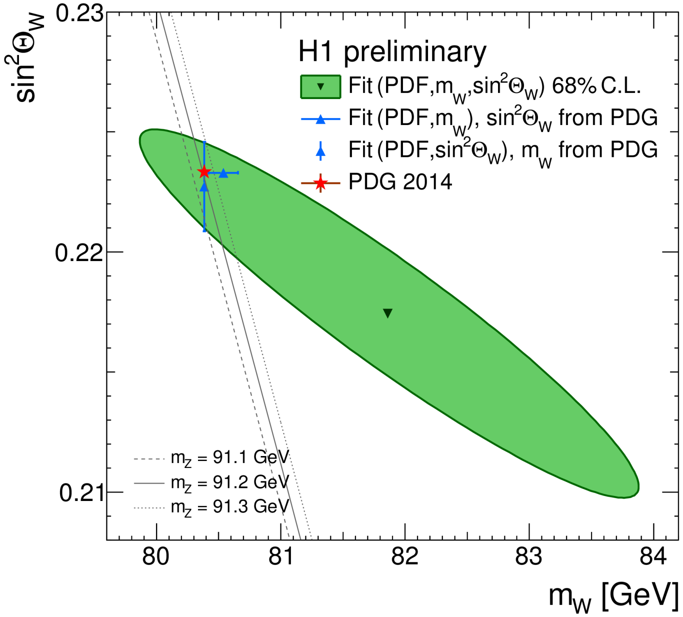


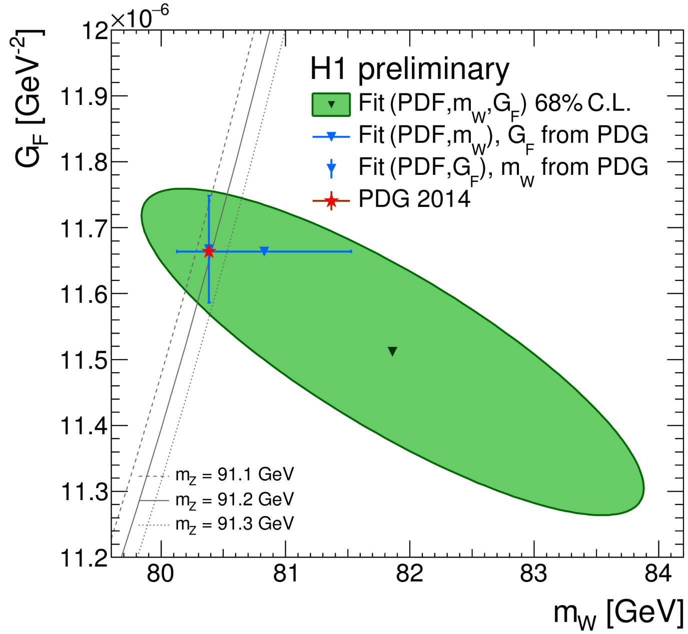
M_W and $\sin^2(\Theta_W)$, G_F, M_Z

Simultaneous extraction of pairs of parameters:

$$\sigma_{NC}(\alpha, \sin^2(\Theta_W), M_Z[\sin^2(\Theta_W), M_W])$$

$$\sigma_{CC}(G_F[\alpha, \sin^2(\Theta_W), M_W], M_W)$$



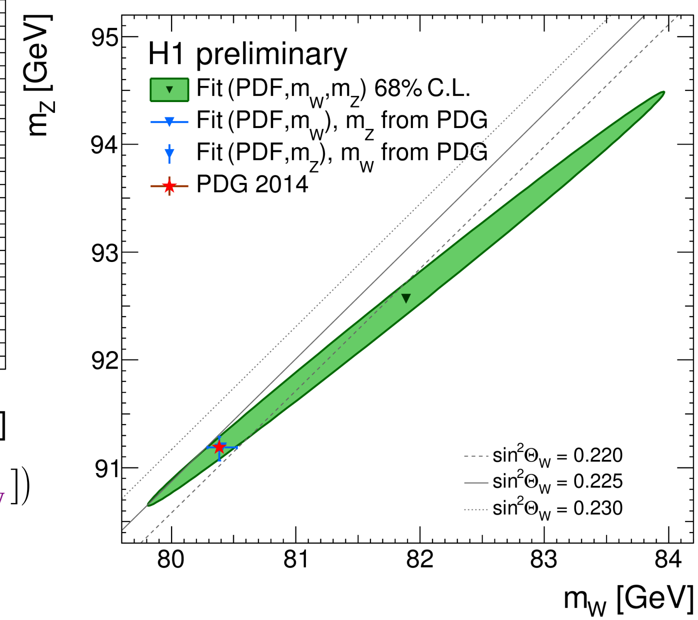


$$\sigma_{NC}(\alpha, \sin^2(\Theta_W)[G_F, M_W], M_Z[G_F, M_W])$$

$$\sigma_{CC}(G_F, M_W)$$

$$\sigma_{NC}(\alpha, \sin^2(\Theta_W)[M_Z, M_W], M_Z)$$

$$\sigma_{CC}(G_F[\alpha, M_Z, M_W], M_W)$$



Determined mass of W boson using external mass of Z⁰:

$$\sigma_{NC}(\alpha, \sin^2(\Theta_W)[M_Z, M_W], M_Z)$$

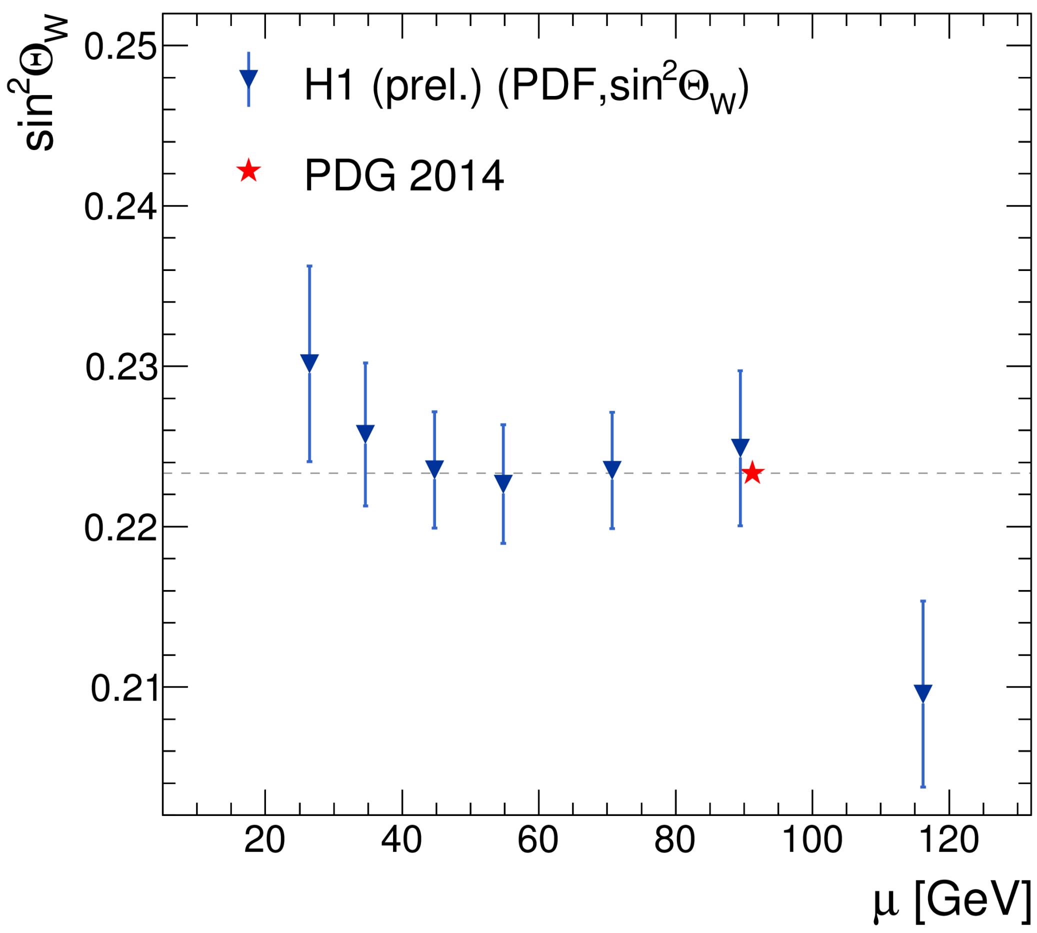
$$\sigma_{CC}(G_F[\alpha, M_Z, M_W], M_W)$$

$$m_W = 80.407 \pm 0.118_{(\exp, pdf)} \pm 0.005_{(m_Z, m_t, m_H)}$$

Result consistent with PDG2014: $M_W^{DPG14} = 80.385 \pm 0.015$

On-shell $\sin^2(\Theta_W)$

On-shell measurement for seven bins in Q^2:



$$\sin^2(\Theta_W) = 0.2252 \pm 0.0011_{(\exp/fit)}{}^{+0.0003}_{-0.0001}{}_{(mod)}{}^{+0.0007}_{-0.0001}{}_{(param)}$$

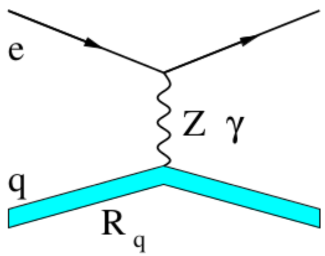
Good agreement with world average:

$$\sin^2(\Theta_W)^{PDG14\ on-shell} = 0.22333 \pm 0.00011$$

Unique measurement of $\sin^2(\Theta_W)$ at different scales.

BSM physics - quark form factor

One of the possible parameterisations of deviations from SM – spatial distribution or substructure of electrons and/or quarks:



$$\frac{d\sigma}{dQ^2} = \frac{d\sigma^{SM}}{dQ^2}\left(1 - \frac{R_e^2}{6}Q^2\right)^2\left(1 - \frac{R_q^2}{6}Q^2\right)^2$$

R_e, R_q – root mean square radii of the electroweak charge distributions in the electron and quark.

Same dependence expected for **NC** and **CC** e^+p and e^-p.

We assume **$R^2_e = 0$** and consider both, positive and negative values of R^2_q

HERA data is a core of any PDF extraction, and thus simultaneous fit, PDF+BSM, is necessary for any BSM analysis. For ***R^2_q*** such fit provide:

$$R^{2\ \mathrm{Data}}_q = -\,[0.14 \cdot 10^{-16}\ \mathrm{cm}]^2$$

in agreement with SM expectation of $R_q^{\mathrm{Data}} = 0$.

Frequentist approach

Monte Carlo replicas of the whole data set were generated as:

$$\mu^i = [m_0^i + \delta^i_{tot.uncor.} \cdot r^i_{tot.uncor.} \cdot \mu_0^i] \cdot (1 + \sum_j \gamma^j \cdot r^j_{sys.sh.})$$

r^i, r^j – Gaussian random numbers.

Previous method — And two different procedures were tested: — **New method**

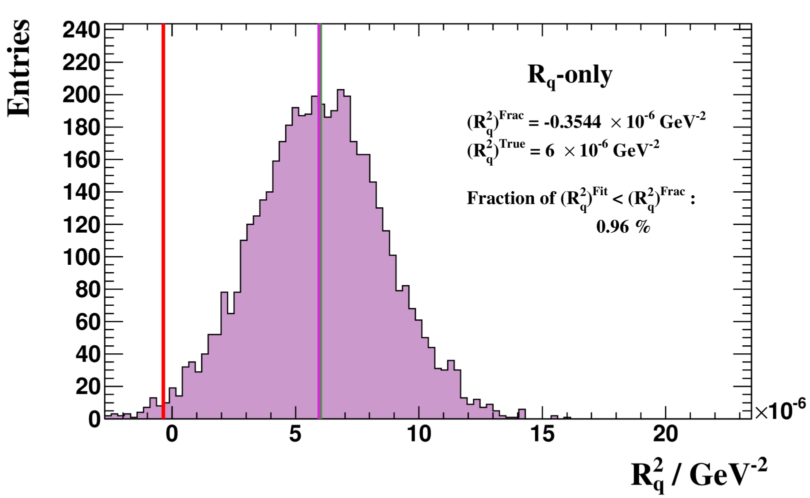
R_q-only

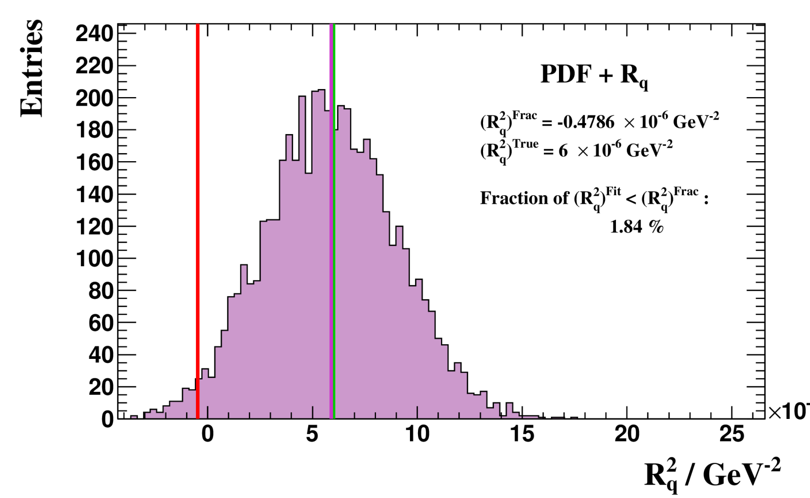
R^2_q parameter fited with PDFs fixed to SM PDFs.

PDF+R_q

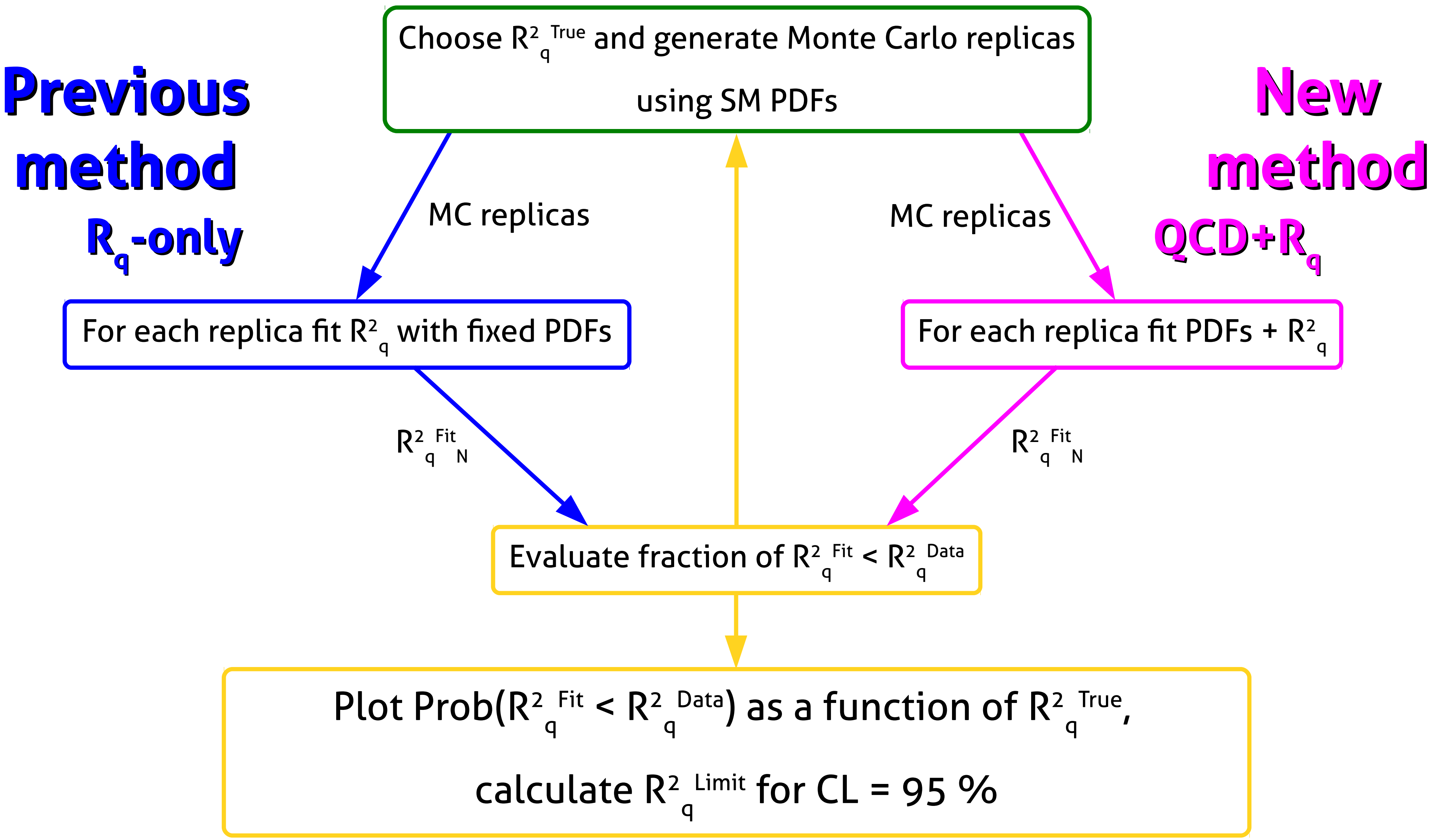
R^2_q parameter fited simultaneously with PDFs.

For example, for $R_q^{True} = 0.48 \cdot 10^{-16}$ cm:

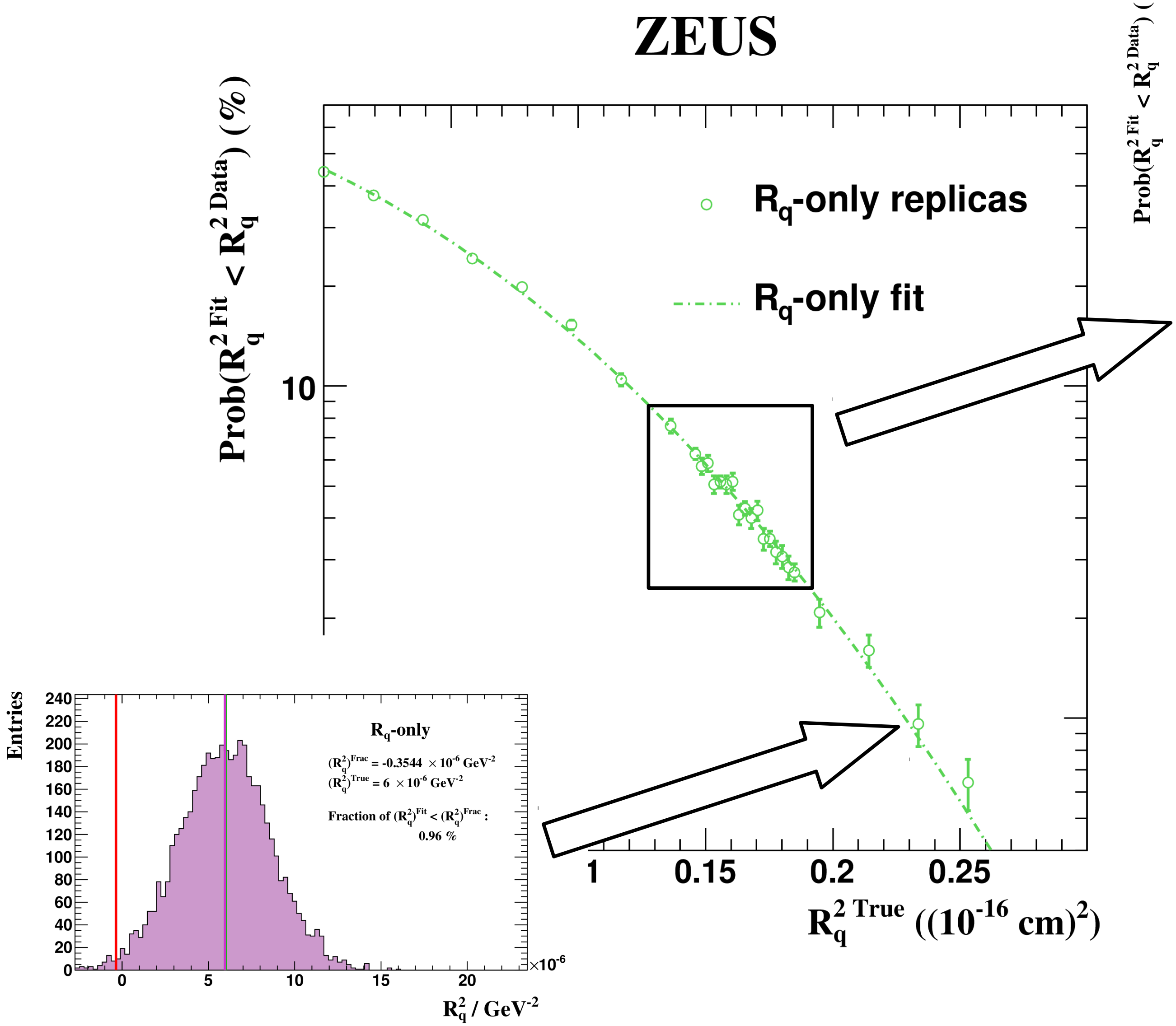


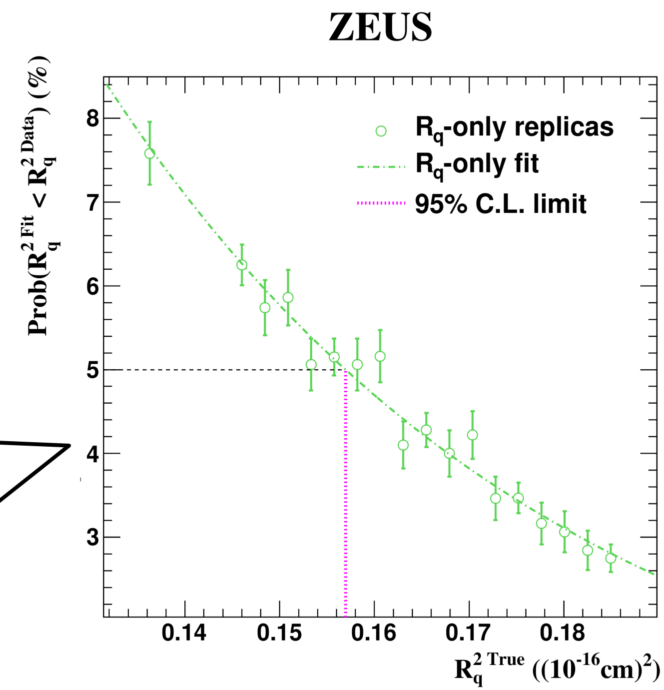


Analysis flowchart



R_q-only





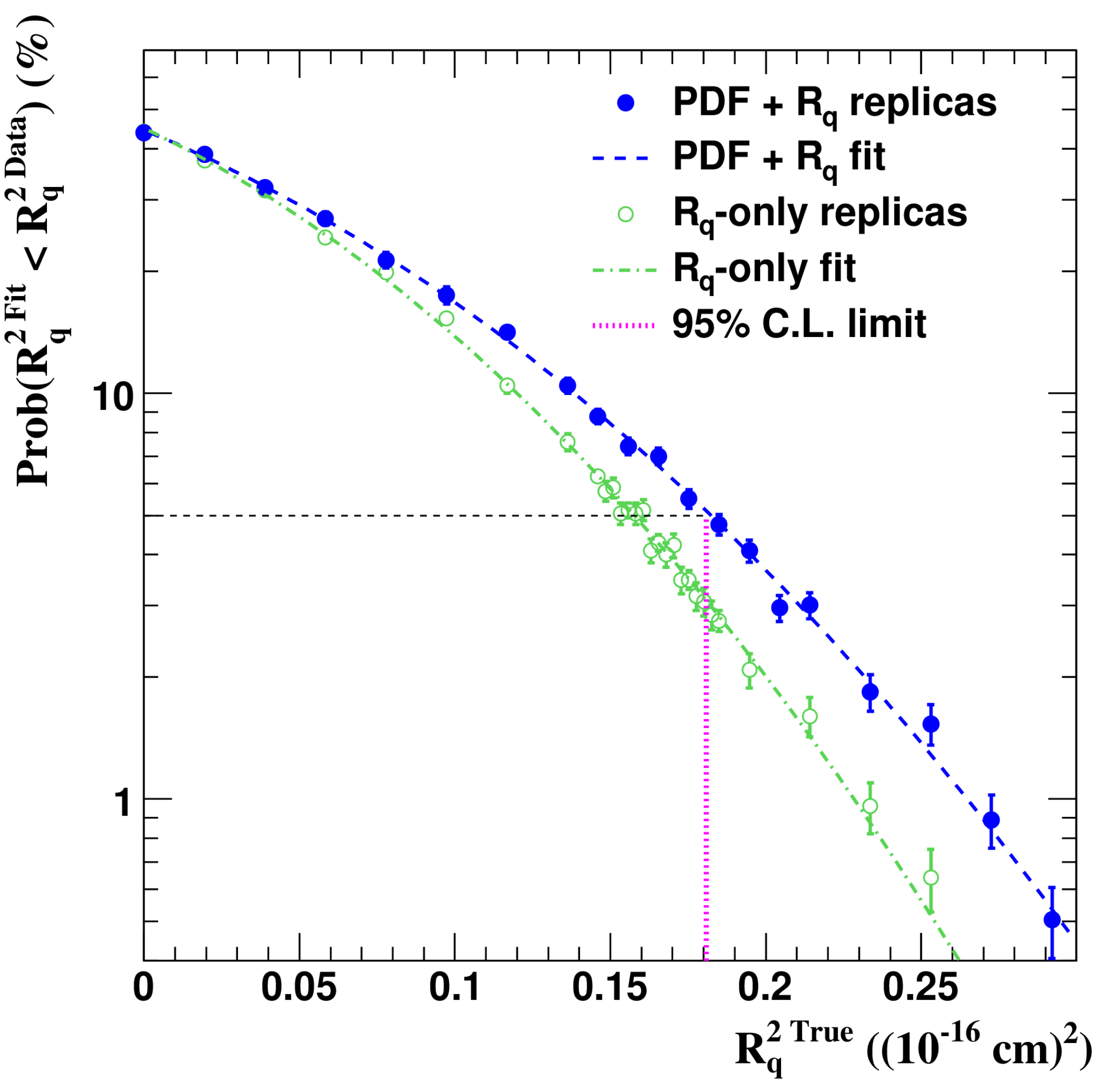
Fractions close to 5% fitted with:

$$f(x) = 5 \cdot \exp((x - A) \cdot B)$$

$$R_q^{\text{Limit}} = 0.40 \cdot 10^{-16}\ \text{cm}$$

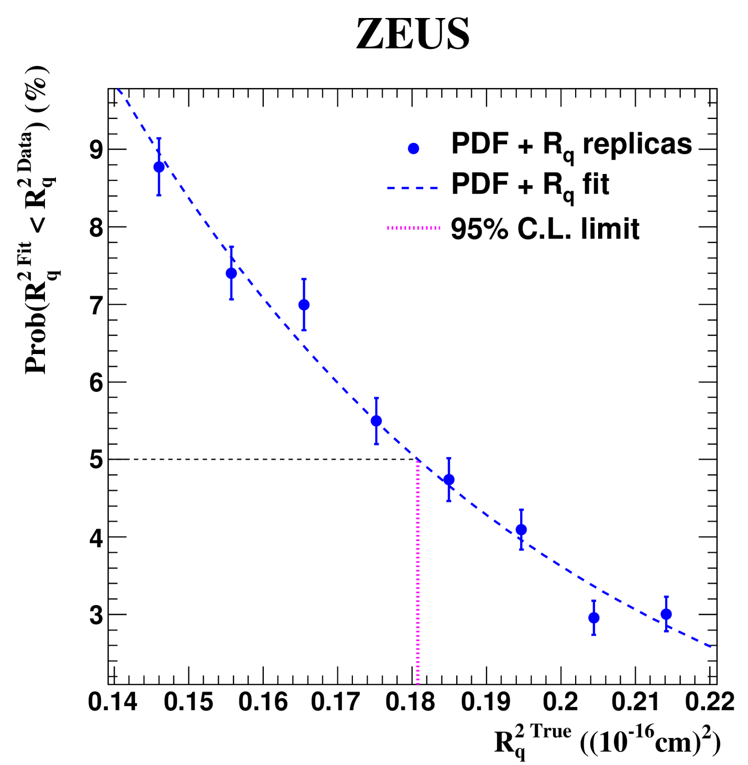
Phys. Lett. B 757 (2016) 468
arXiv:1604.01280

QCD+R_q



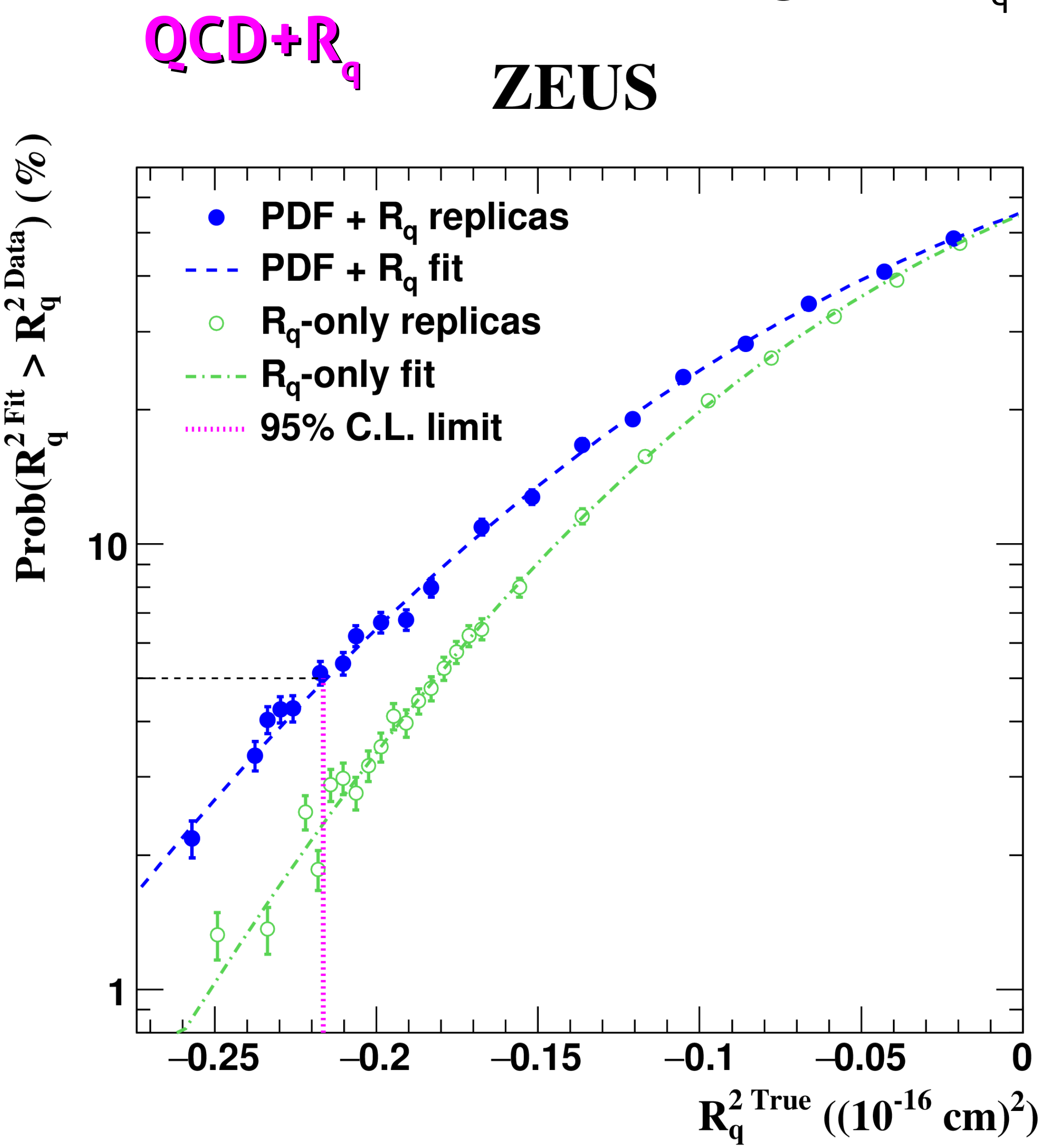
Fractions close to 5% fitted with:

$$f(x) = 5 \cdot \exp((x - A) \cdot B)$$



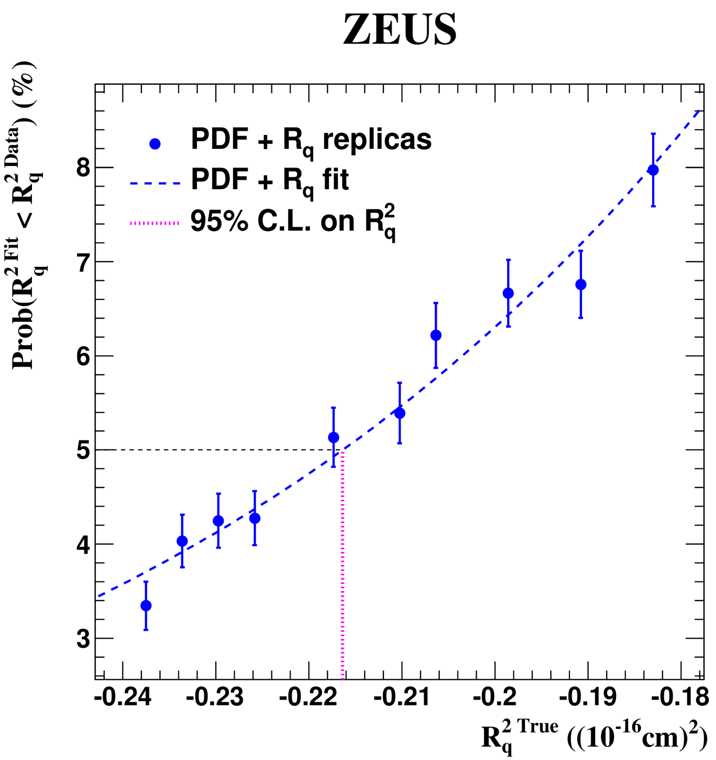
$$R_q^{Limit} = 0.43 \cdot 10^{-16}\ \mathrm{cm}$$

Negative R^2_q limit:

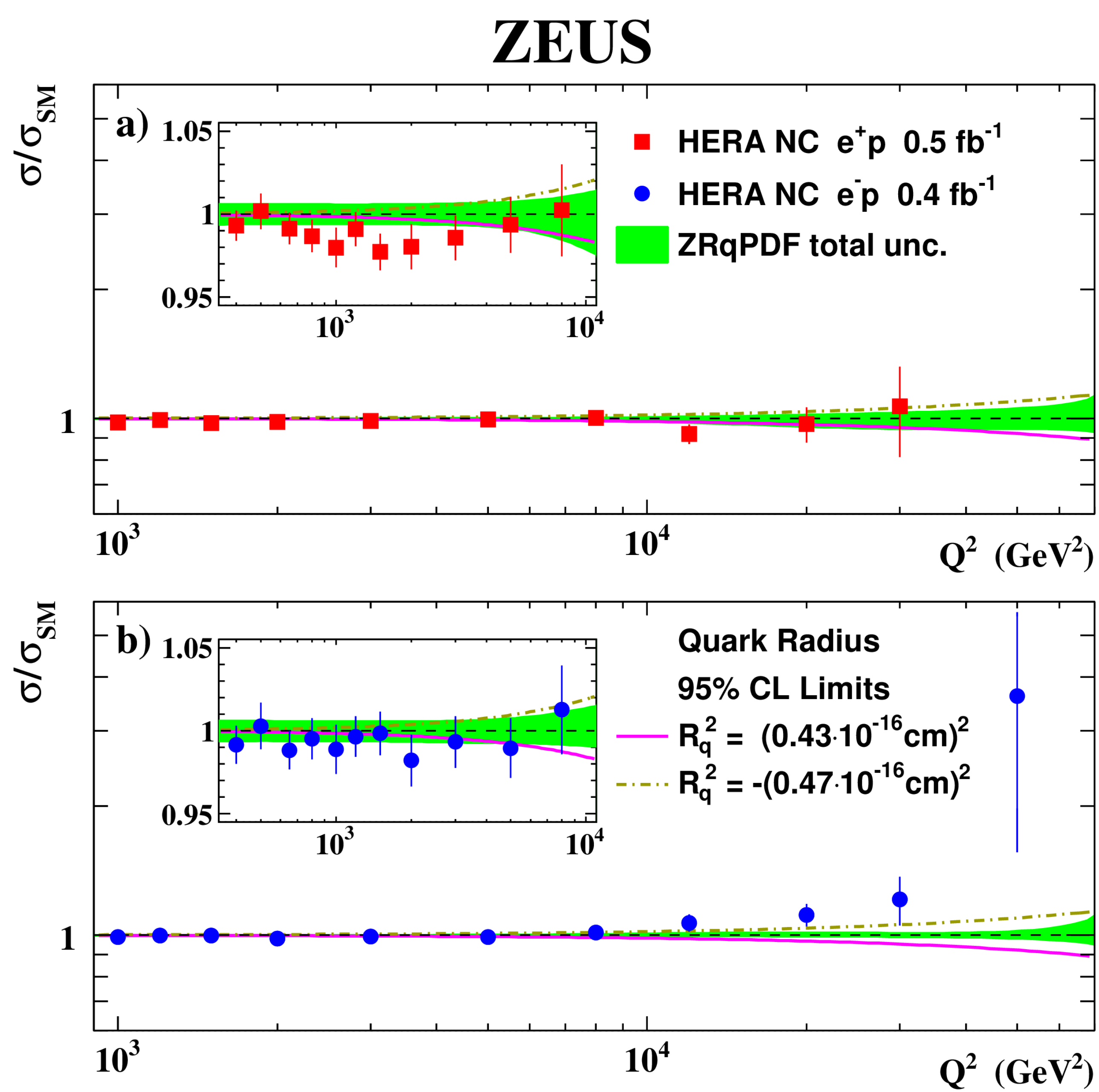


Fractions close to 5% fitted with:

$$f(x) = 5 \cdot \exp((x - A) \cdot B)$$



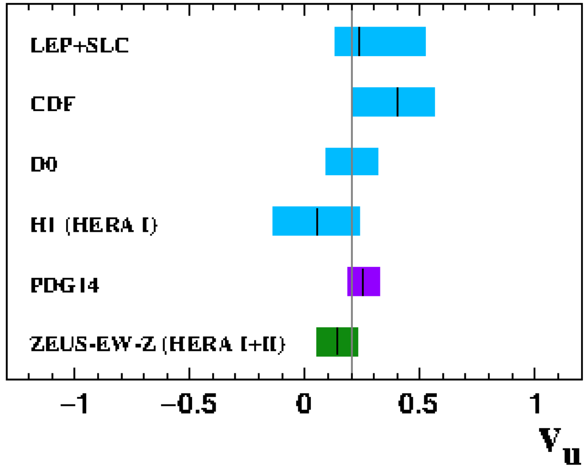
$$R^{2\ Limit}_q = -[0.47 \cdot 10^{-16}\ cm]^2$$

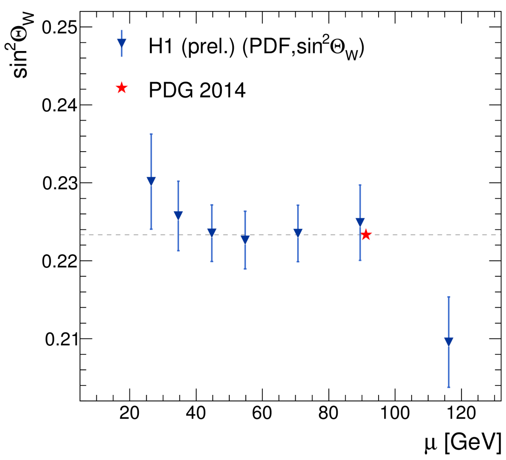


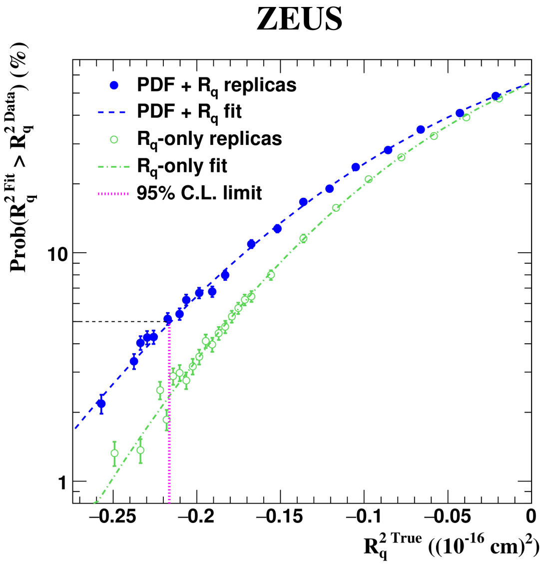
Comparison of R^2_q exclusion limits to HERA NC ep DIS data.

Summary

- HERA polarised inclusive data allows to determine electroweak parameters simultaneously with PDFs
- Couplings of u-type quarks among the most accurate in the world
- Unique observations of $\sin^2(\Theta_W)$ and $\sin^2(\Theta_W)^{eff}$ running from one experiment
- First BSM limits based on the new approach: simultaneous fit of PDF and BSM contribution; it shows that limits obtained with "previous" method ~10-20% too strong.

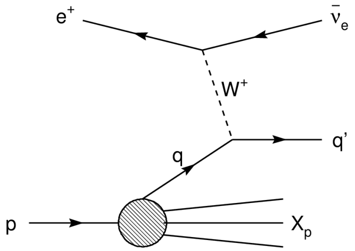






Backup

QCD analysis of combined DIS data



Charged Current :

$$\frac{d^2\sigma_{CC}^{e\mp p}}{dxdQ^2}=\frac{G_F^2}{4\pi x}\cdot\kappa^2\cdot\left(Y_+\cdot W_2^{\mp}\pm Y_-\cdot x\cdot W_3^{\mp}-y^2\cdot W_L^{\mp}\right)$$

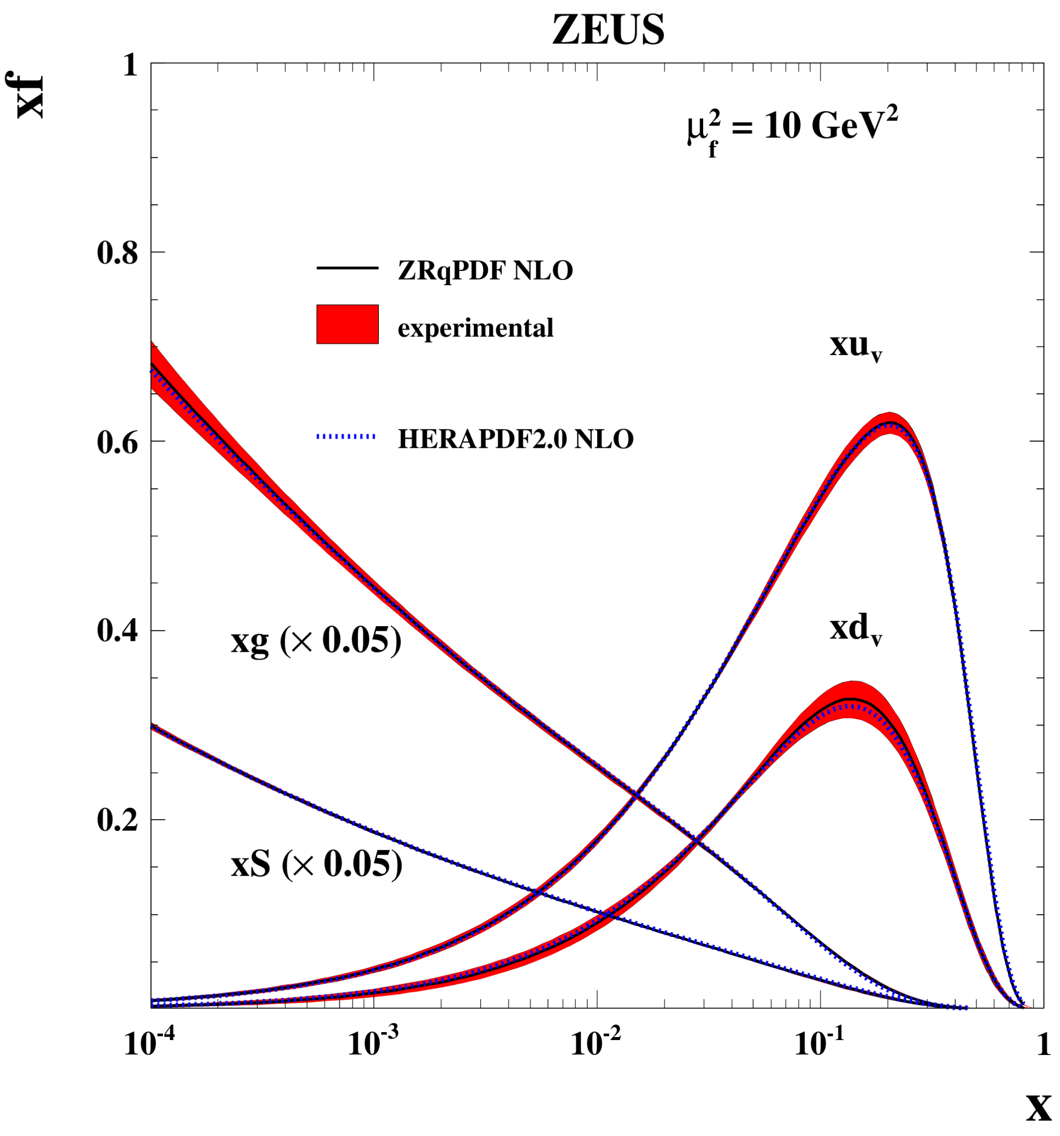
$$\kappa=\frac{M_W^2}{M_W^2+Q^2}$$

$$W_2^-=x\left(U+\bar{D}\right) \qquad W_2^+=x\left(D+\bar{U}\right)$$

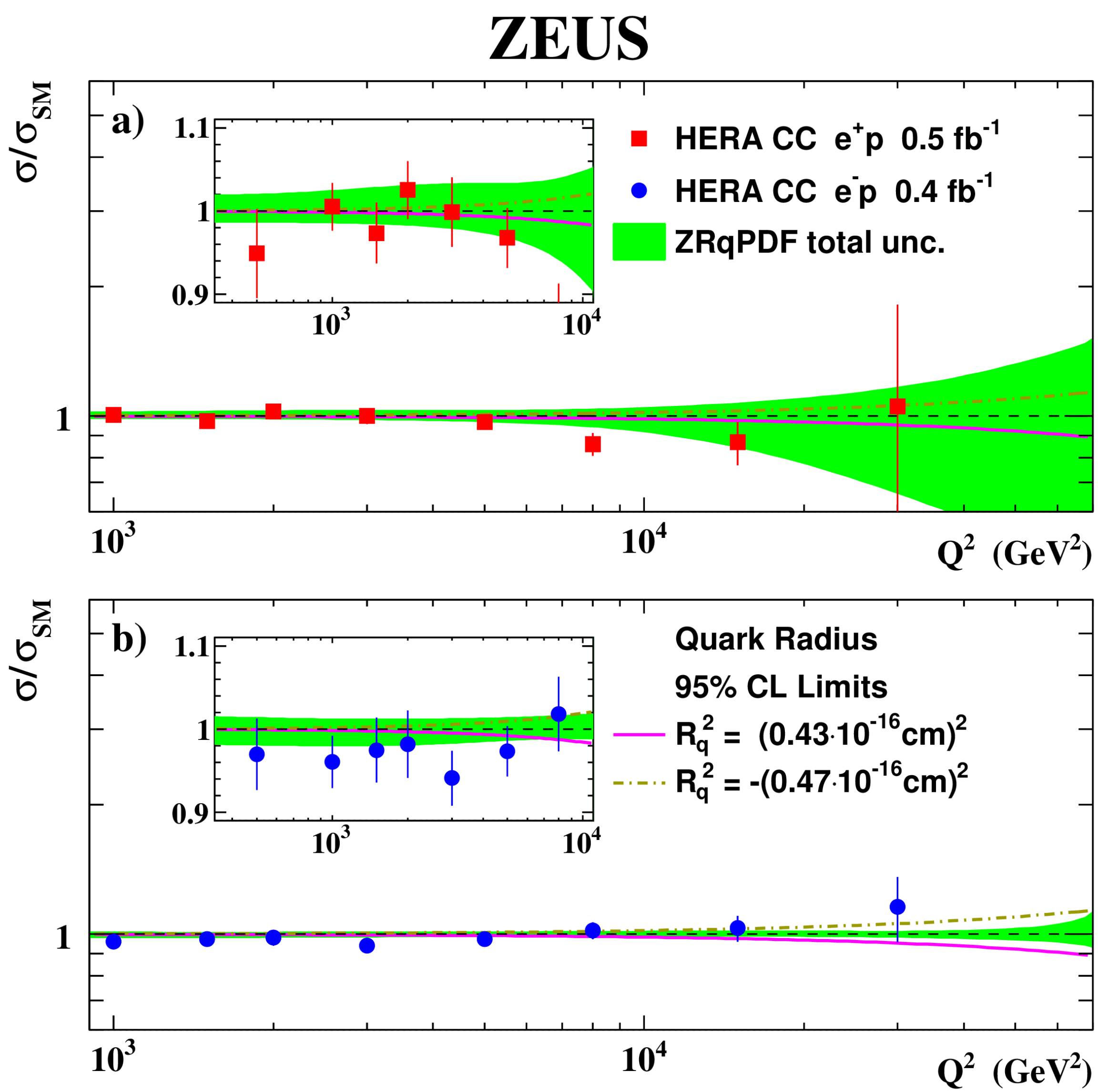
$$xW_3^-=x\left(U-\bar{D}\right) \qquad xW_3^+=x\left(D-\bar{U}\right)$$

BSM QCD analysis of combined DIS data

ZRqPDF set compared to HERAPDF2.0:



Quark form factor and CC DIS data



Comparison of R^2_q exclusion limits to HERA CC ep DIS data.