Fit of Electroweak Parameters in Polarised Deep-Inelastic Scattering using data from the H1 experiment

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Deep-inelastic scattering

Kinematic variables

- virtuality of exchanged boson

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

- Bjorken scaling variable

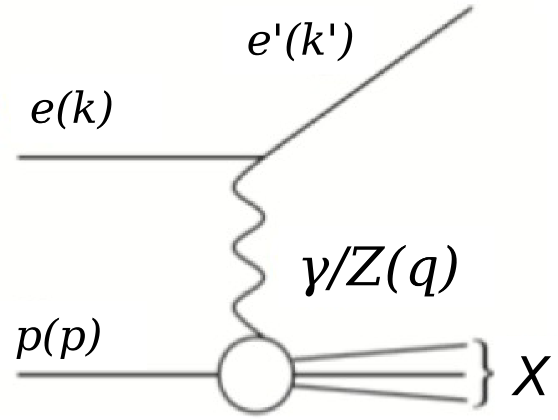
$$x = \frac{Q^2}{2\, p \cdot q}$$

- Inelasticity

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

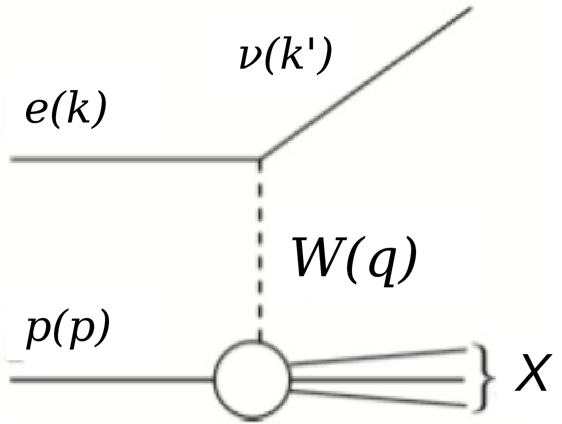
Neutral current scattering

$ep \rightarrow e'X$



Charged current scattering

$ep \rightarrow \nu_e X$



Factorization in ep collisions

Hard scattering coefficients and parton distribution functions (PDFs)

$$\sigma_{ep \to eX} = f_{p \to i} \otimes \hat{\sigma}_{ei \to eX}$$

PDFs are not observables – only cross sections are

PDFs are largely determined from DIS data

Polarised deep-inelastic ep scattering

Neutral and charged current at tree level

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

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

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

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

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

Generalised structure functions

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

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

Z⁰-exchange

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

Structure functions in QPM

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

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

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

HERA Operation

HERA-I operation 1993-2000

- E_e = 27.6 GeV
- E_p = 820 / 920 GeV
- √s = 301 & 318 GeV
- int. Lumi. ~ 110 pb^{-1}

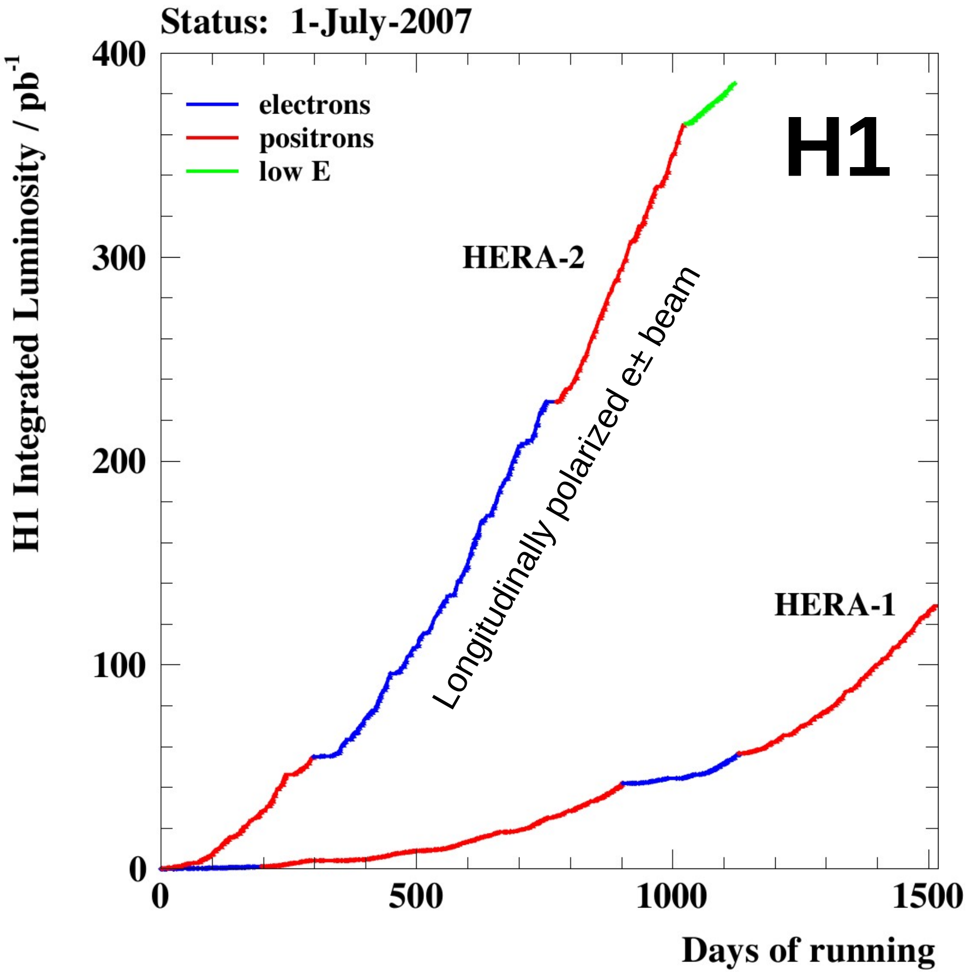
HERA-II operation 2003-2007

- E_e = 27.6 GeV
- E_p = 920 GeV
- √s = 318 GeV
- int. Lumi. ~ 330 pb^{-1}
- Longitudinally polarised leptons

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

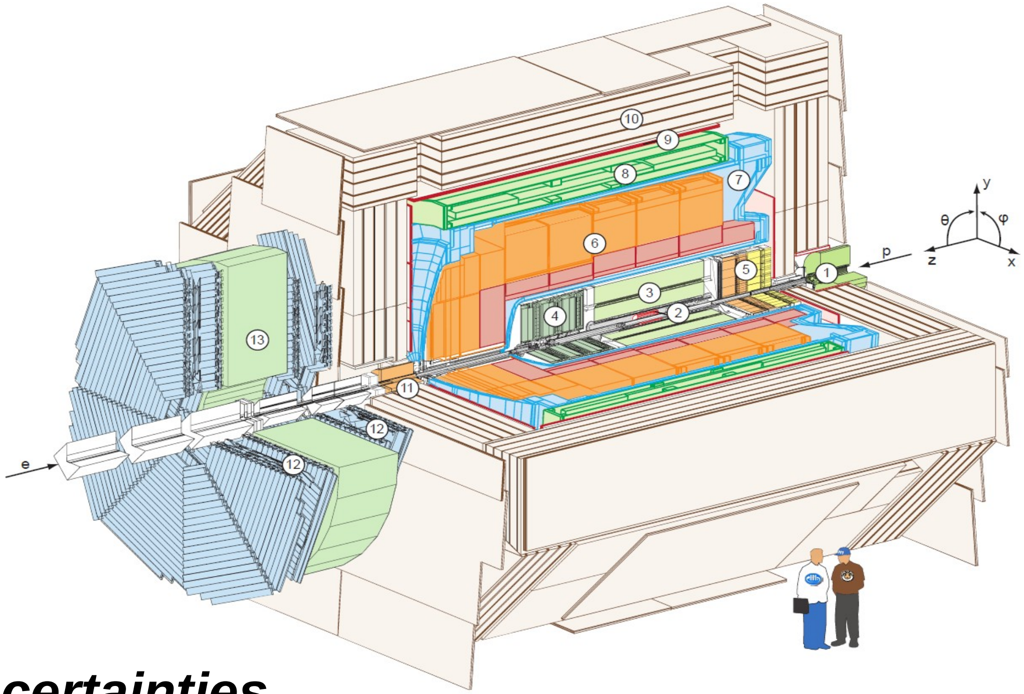
Low-Energy Run 2007

- E_e = 27.6 GeV
- E_p = 575 & 460 GeV
- √s = 225 & 251 GeV
- Dedicated F_L measurement



The H1 Detector

Drawing of the H1 experiment



H1 multi-purpose detector

Asymmetric design

Trackers

- Silicon tracker
- Jet chambers
- Proportional chambers

Calorimeters

- Liquid Argon sampling calorimeter
- SpaCal: scintillating fiber calorimeter

Superconducting solenoid

- 1.15T magnetic field

Muon detectors

Excellent control over experimental uncertainties

- Overconstrained system in NC DIS
- Electron measurement: 0.5 – 1% scale uncertainty
- Jet energy scale: 1%
- Luminosity: 1.5 - 2.5%
- Continuous upgrades with time

H1 Structure Function Data

Dataset	Q^2 min	Q2 max	No. Points	Polarisation [%]	Reference
e+ Combined low-Q^2	12 [0.5]	150	81 [262]		EPJ C71 (2011) 1579 arXiv:1012.4355
e+ Combined low-E_p	12 [1.5]	90	118 [136]		
e+ NC 94-97	150	30000	130		EPJ C13 (2000) 609 hep-ex/9908059
e+ CC 94-97	300	15 000	25		
e− NC 98-99	150	30 000	126		EPJ C19 (2001) 269 hep-ex/0012052
e− CC 98-99	300	15 000	28		
e− NC 98-99 high y	100	800	13		EPJ C30 (2003) 1 hep-ex/0304003
e+ NC 99-00	150	30 000	147		
e+ CC 99-00	300	15 000	28		
e+ NC high y	60	800	11		JHEP 1209 (2012) 061 arXiv:1206.7007
e− NC high y	60	800	11		
e+ NC L	120	30 000	137	-37.0 ± 1.0	
e+ CC L	300	15 000	28	-37.0 ± 1.0	
e+ NC R	120	30 000	137	+32.5 ± 0.7	
e+ CC R	300	15 000	28	+32.5 ± 0.7	
e− NC L	120	50 000	138	-25.8 ± 0.7	
e− CC L	300	30 000	29	-25.8 ± 0.7	
e− NC R	120	30 000	139	+36.0 ± 0.7	
e− CC R	300	15 000	28	+36.0 ± 0.7	

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

Light quark couplings

Couplings of light quarks to Z-boson

- χ^2 / ndf = 1370.5 / (1388 – 21)
- *u*-type coupling better constrained than *d*-type coupling
  -> sensitivity from valence quarks
- Results compatible with SM expectation
- PDF uncertainties are small

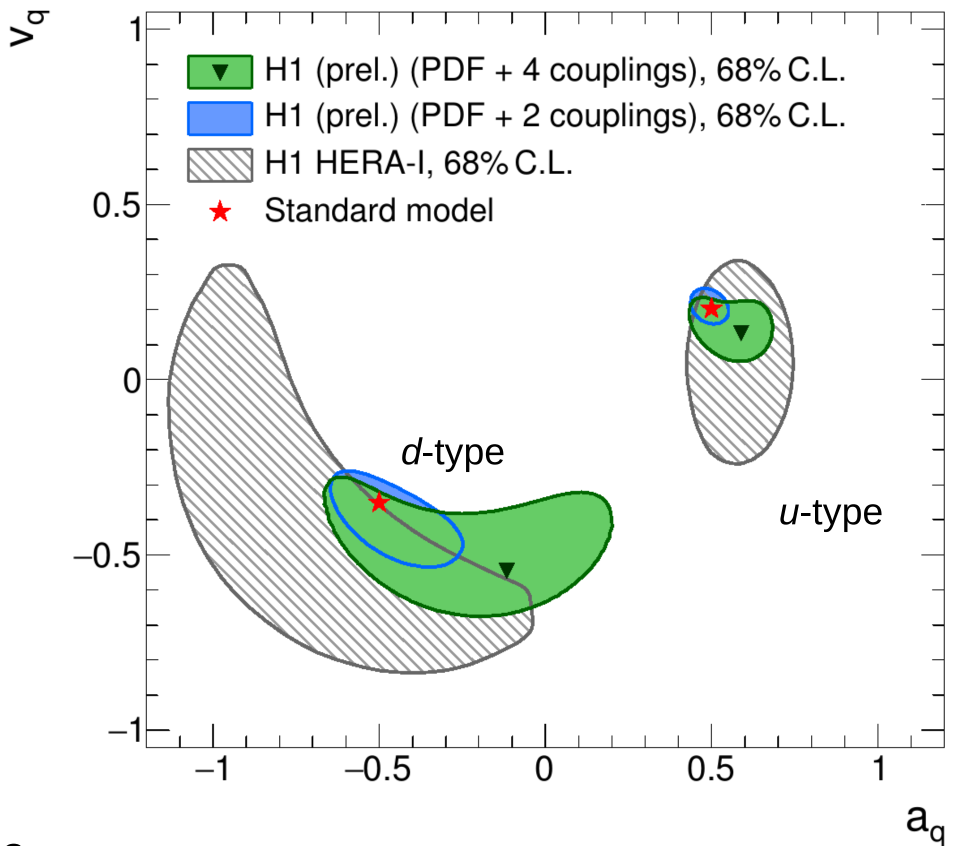
Comparison to H1 HERA-I

Phys.Lett.B 632 (2006) 35

- Considerably improved sensitivity using final H1 HERA-II data
- Polarisation in HERA-II important vor vector couplings

Fit: PDF + 2 couplings

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

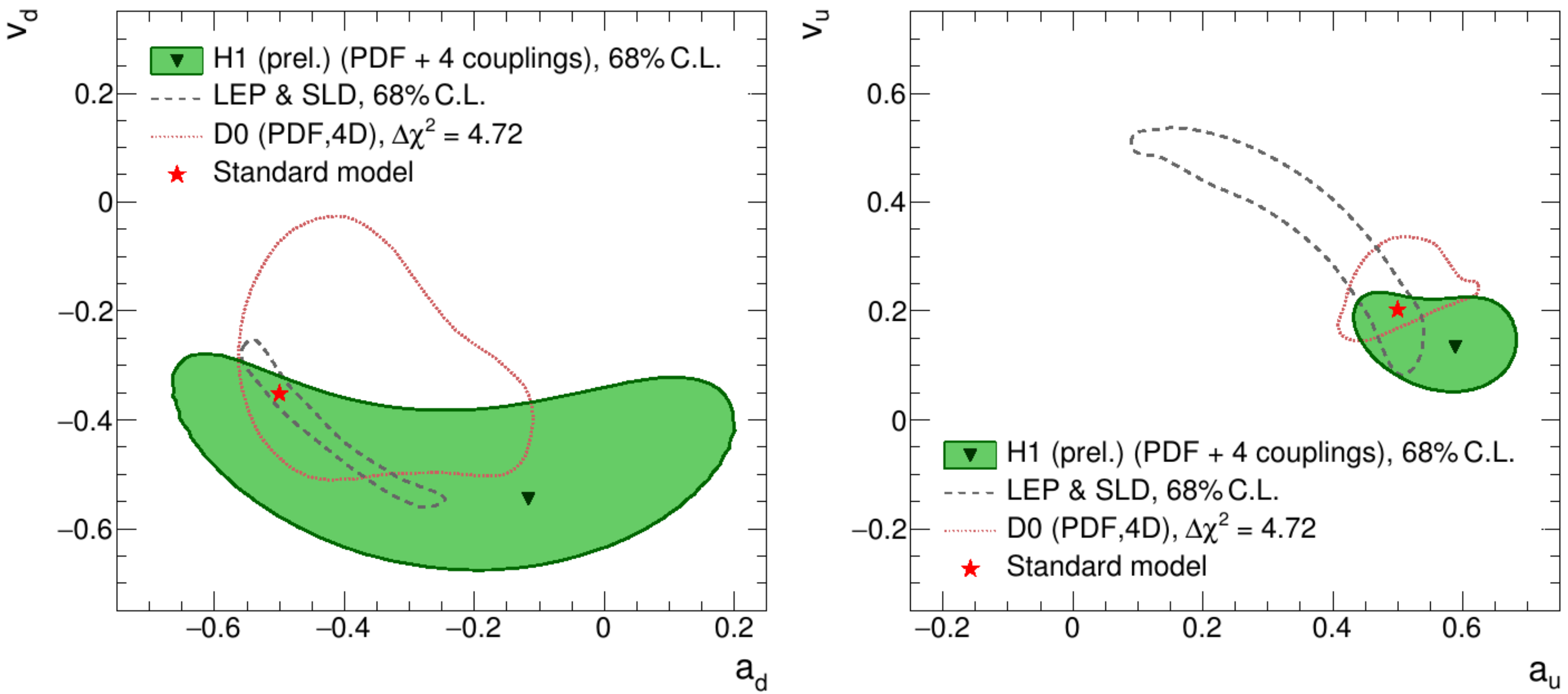


Light quark couplings

Couplings of light quarks to Z-boson

- LEP&SLD [Phys. Rept. 427 (2006) 257]
  Effective couplings from asymmetry at Z-pole
- D0 [Phys. Rev. D 84 (2011) 012007]
  Forward-backward charge asymmetry

Comparable precision of complementary processes



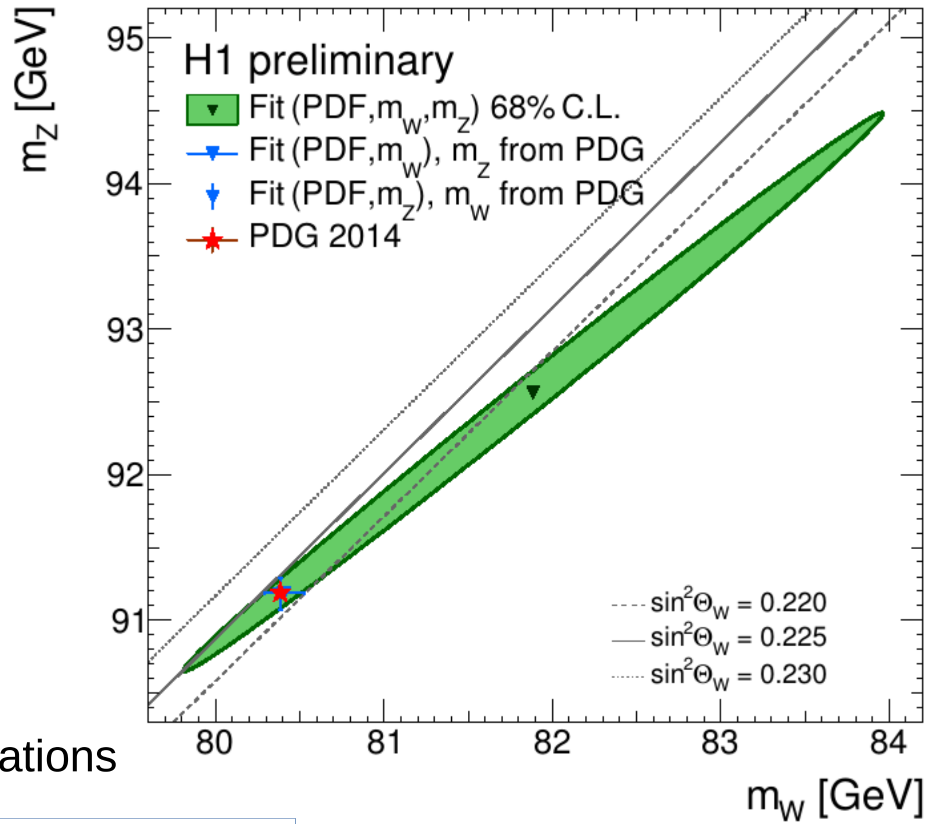
Study of Standard Model Parameters

Standard Model is now overconstrained

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

(m_W – m_Z) + PDF fits

- Assume α is known
- on-shell masses m_W and m_Z are only free EW parameters
- Agreeement within PDG14 SM values
- Large correlation between m_W and m_Z



Mass of W-boson

Take other masses (m_Z) as external input to calculations

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

Approx. half the exp. uncertainty may be attributed to PDFs

Compare to H1 HERA-I: $m_W = 80.786 \pm 0.205$ (exp) $^{+0.063}_{-0.098}$ (th) GeV

$m_{W,PDG} = 80.385 \pm 0.015$ 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

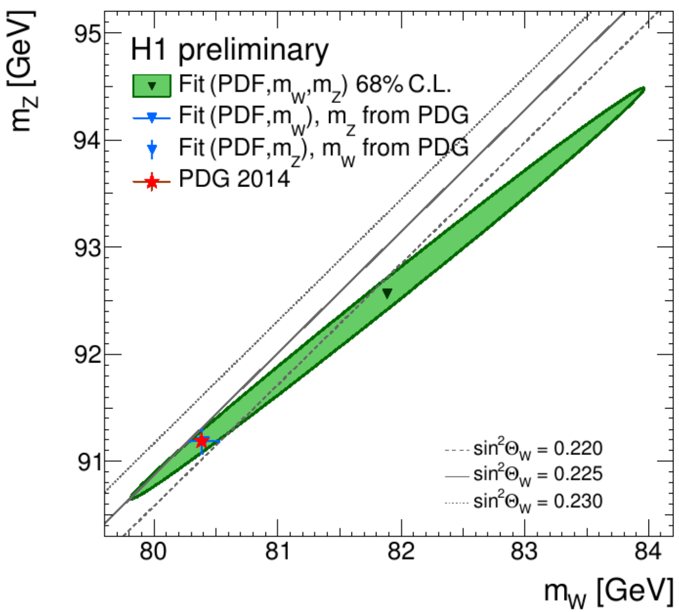
$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$$

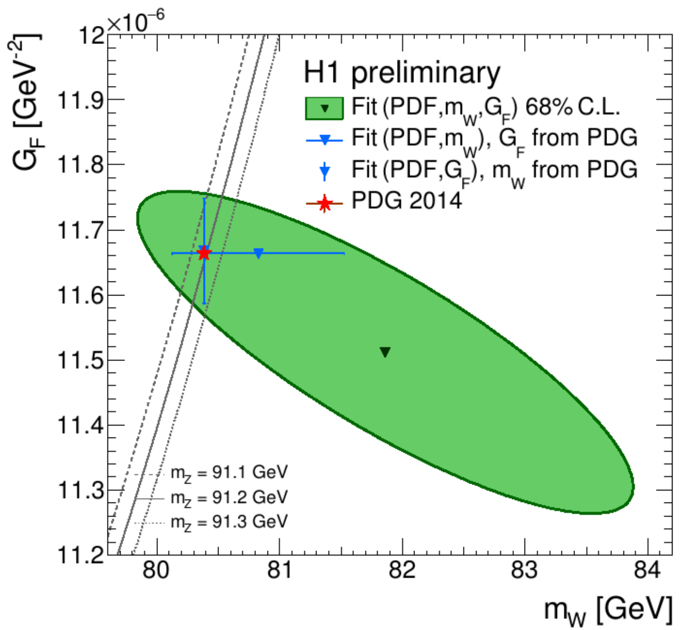
Perform calculations consistently in on-shell scheme (α,m_Z,m_W)

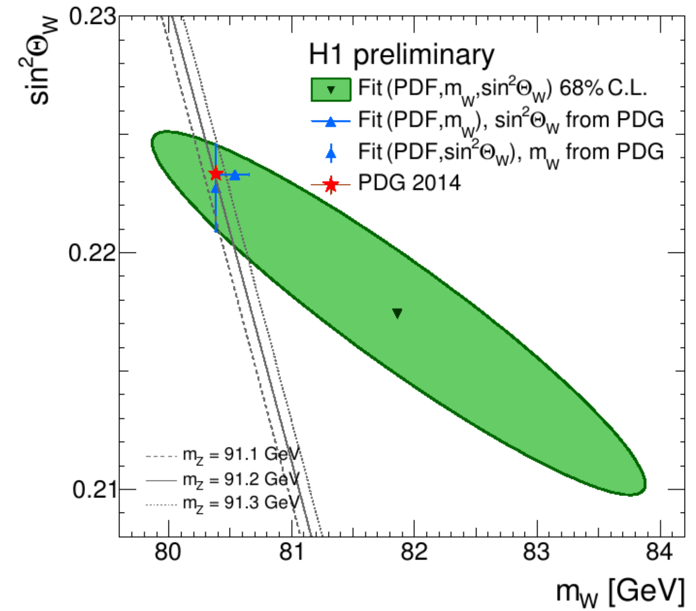
- Calculate m_Z (iteratively) from G_F or $\sin^2\theta_W$

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



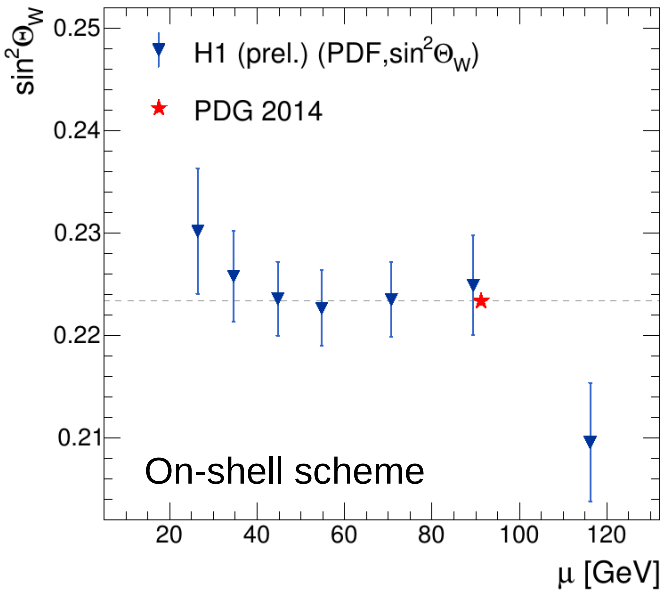




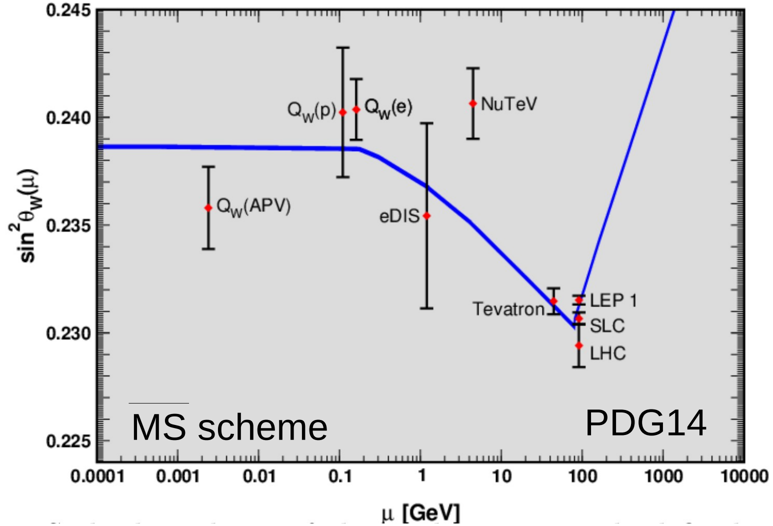
Exploit Q^2 dependence of data

Virtually exchanged bosons allow for SM tests at various energy scales

- Weak mixing angle is extracted for different scales $\mu=\sqrt{Q^2}$
- Simultaneous fit of PDF and values of $\sin^2\theta_W$
- Data are subdivided into different Q^2 regions each with independent $\sin^2\theta_W(Q^2)$



Compare to $\overline{\text{MS}}$ values



Results

- Results compatible with precise value from Z-pole measurements
- Unique measurement of weak mixing angle at different scales
- Comparison to MSbar values straight forward

Summary and Outlook

H1prelim-16-041

Light quark couplings to Z-boson

- Couplings determined from all H1 inclusive NC and CC data
- Longitudinal polarisation improves significantly H1 HERA-I result
- Values are consistent with SM expectations and compatible with other collider data

Standard model tests

- SM parameters are tested in deep-inelastic scattering
- Good consistency is found for m_Z, m_W, G_F and $\sin^2\Theta_W$
- Weak mixing angle is determined at different scales in a single experiment

W-boson mass

- W-boson mass determined with an experimental precision of 118 MeV
- Fitted value consistent with precise direct measurements
- Significantly improves H1 HERA-I results ($\Delta m_W \sim 200$ MeV)

Outlook

- Calculations to be supplemented with full 1-loop EW corrections at lepton vertex

-> NNLO-QCD + NLO-EW fit to H1 data

Comparison H1 vs. H1+ZEUS data

ZEUS Collaboration

- Fit of PDF + Electroweak parameters to H1 and ZEUS data
  Phys. Rev. D 93 (2016) 092002
  - All ZEUS data (incl. HERA-II polarised)
  - H1 HERA-I data
  - H1 HERA-II data (unpolarised, i.e. corrected for lepton beam polarisation)

- Results from ZEUS Collaboration taking H1 data and ZEUS data compatible with H1 results alone
  Both for HERA-I and HERA-II

- Results from both experiments with somewhat higher precision than H1 alone
- H1 data alone very constraining for u-type quarks
- 'Including' ZEUS data constains better d-type axial coupling