

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

Daniel Britzger for  
H1 Collaboration and H. Spiesberger

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# Deep-inelastic scattering

## Kinematic variables

- virtuality of exchanged boson

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

- Bjorken scaling variable

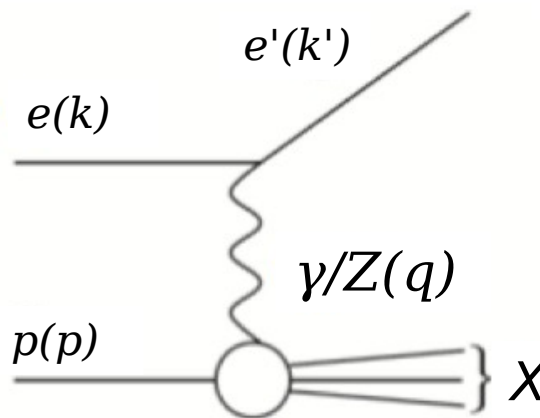
$$x = \frac{Q^2}{2p \cdot q}$$

- Inelasticity

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

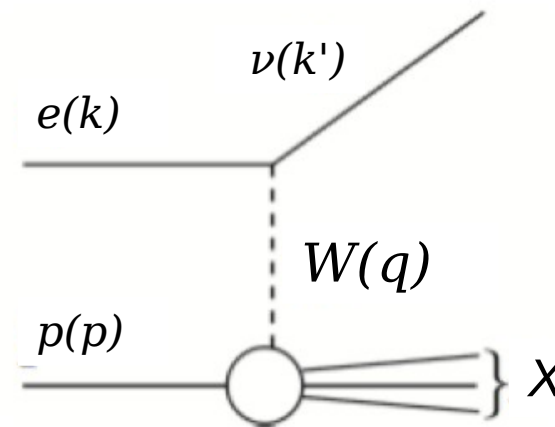
## Neutral current scattering

$$ep \rightarrow e'X$$



## Charged current scattering

$$ep \rightarrow \nu_e X$$



## Factorization in ep collisions

Hard scattering coefficients and parton distribution functions (PDFs)

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

## PDFs are not observables – only structure functions are

PDFs are largely determined from DIS data

# Polarised deep-inelastic ep scattering

## Neutral and charged current at tree level

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

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

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

## 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 $G_F$

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

## Generalised structure functions

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

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

## Z<sup>0</sup>-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

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

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

## Weak couplings to Z-boson

$$v_f = I_{f,L}^{(3)} - 2e_f \sin^2 \theta_W \quad (f = e, u, d, \dots)$$

$$a_f = I_{f,L}^{(3)}$$

## Parameters to calculations

Parameters to cross section calculation:  $\alpha, m_Z, m_W, (m_t, m_H, \dots)$

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
- $\sqrt{s} = 301$  &  $318$  GeV
- int. Lumi.  $\sim 110$  pb $^{-1}$

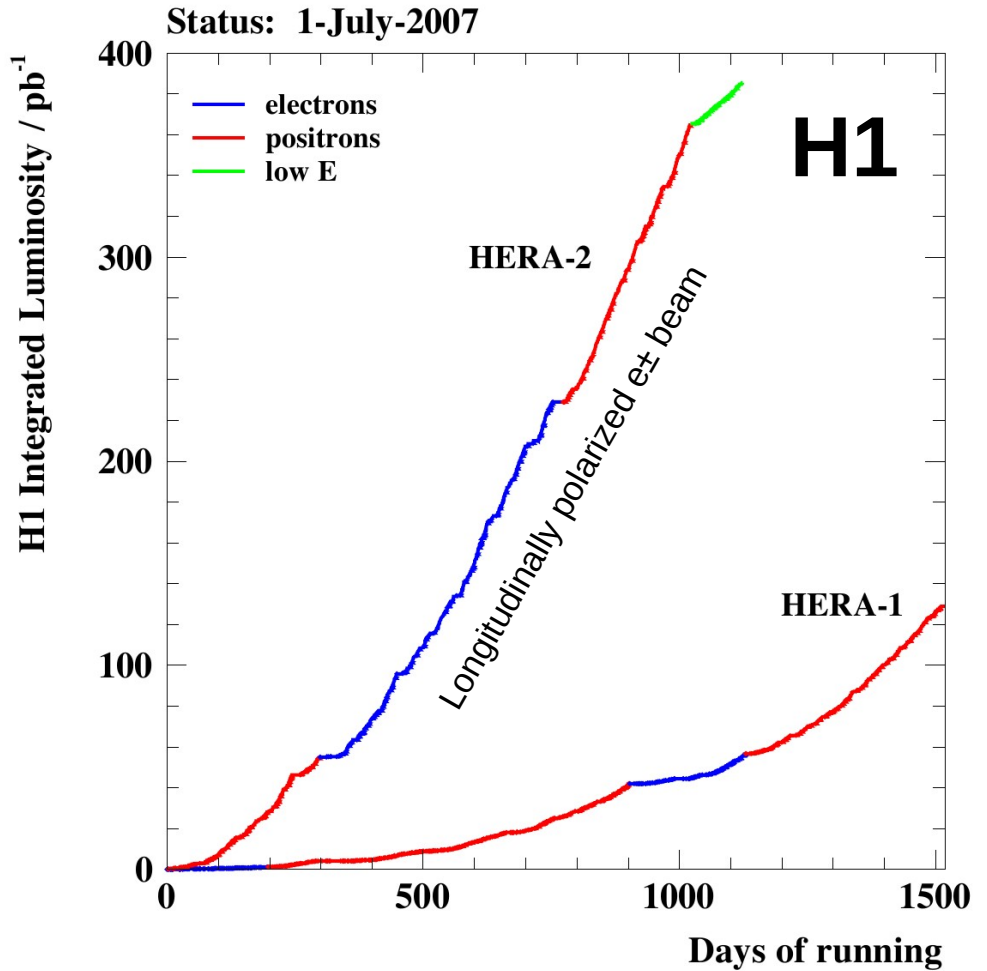
## **HERA-II operation 2003-2007**

- $E_e = 27.6$  GeV
- $E_p = 920$  GeV
- $\sqrt{s} = 318$  GeV
- int. Lumi.  $\sim 330$  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
- $\sqrt{s} = 225$  &  $251$  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

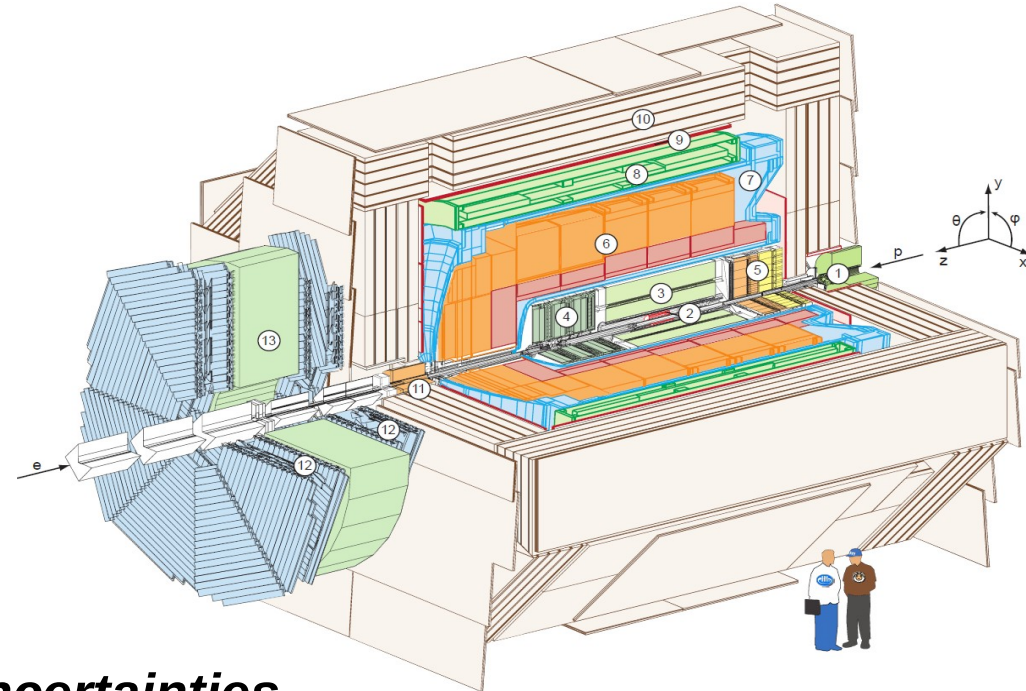
Calorimeters

- 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 <sup>2</sup> min	Q <sup>2</sup> max	No. Points	Polarisation [%]	Reference
e+ Combined low-Q <sup>2</sup>	12 [0.5]	150	81 [262]		EPJ C71 (2011) 1579 arXiv:1012.4355
e+ Combined low-E <sub>p</sub>	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 methodology 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:  $\alpha$ ,  $m_Z$ ,  $m_W$ ,  $(m_t, m_H, \dots)$

## ***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 methodology 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  $Q_0^2 = 1.9\text{GeV}^2$  (similar to HERAPDF2.0)

$xg$	$xg$	$xg(x) = A_g x^{B_g} (1-x)^{C_g} - A'_g x^{B'_g} (1-x)^{C'_g},$	
$xu_v$	$xU = xu + xc$	$xu_v(x) = A_{u_v} x^{B_{u_v}} (1-x)^{C_{u_v}} (1 + E_{u_v} x^2),$	fixed or constrained by sum-rules
$xd_v$	$xD = xd + xs$	$xd_v(x) = A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}},$	parameters set equal but free
$x\bar{U}$	$x\bar{U} = x\bar{u} + x\bar{c}$	$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}} (1-x)^{C_{\bar{U}}} (1 + D_{\bar{U}} x),$	
$x\bar{D}$	$x\bar{D} = x\bar{d} + x\bar{s}$	$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}} (1-x)^{C_{\bar{D}}},$	

- Use only data with  $Q^2 \geq 12 \text{ GeV}^2$

## $\chi^2$ 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



# Light quark couplings

## Couplings of light quarks to Z-boson

- $\chi^2 / \text{ndf} = 1370.5 / (1388 - 21)$
- $u$ -type coupling better constrained than  $d$ -type coupling  
-> sensitivity from valence quarks
- Results compatible with SM expectation
- PDF uncertainties are small

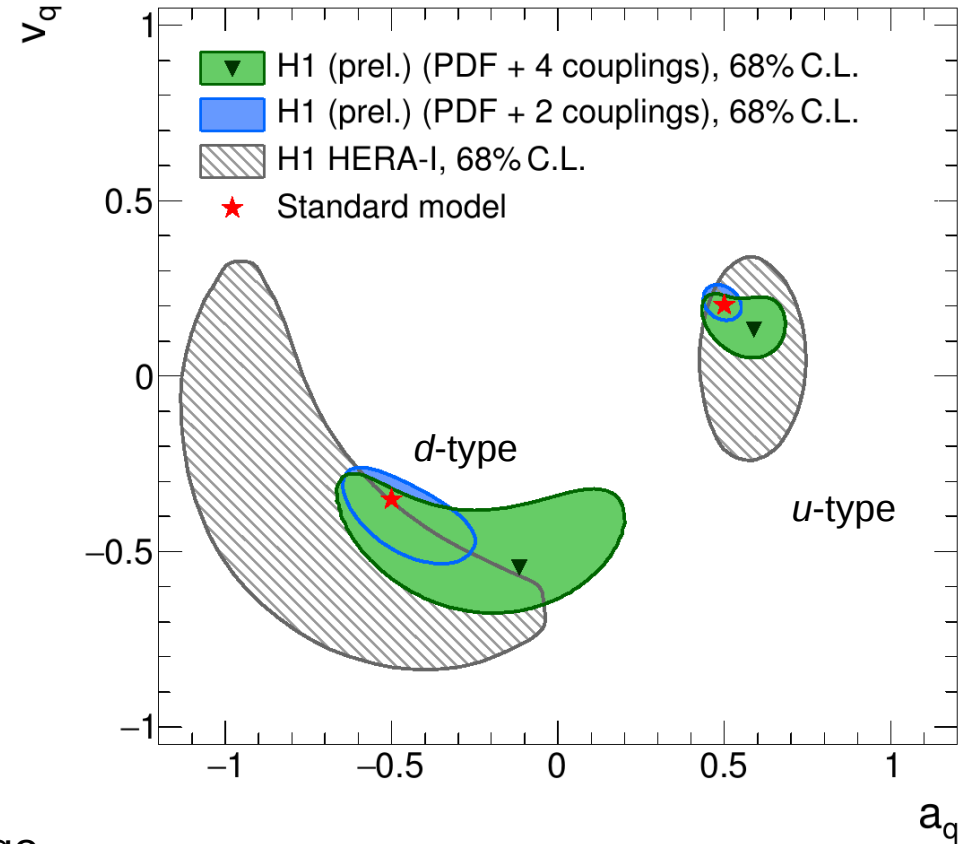
## Comparison to H1 HERA-I

Phys.Lett.B 632 (2006) 35

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

## Fit: PDF + 2 couplings

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

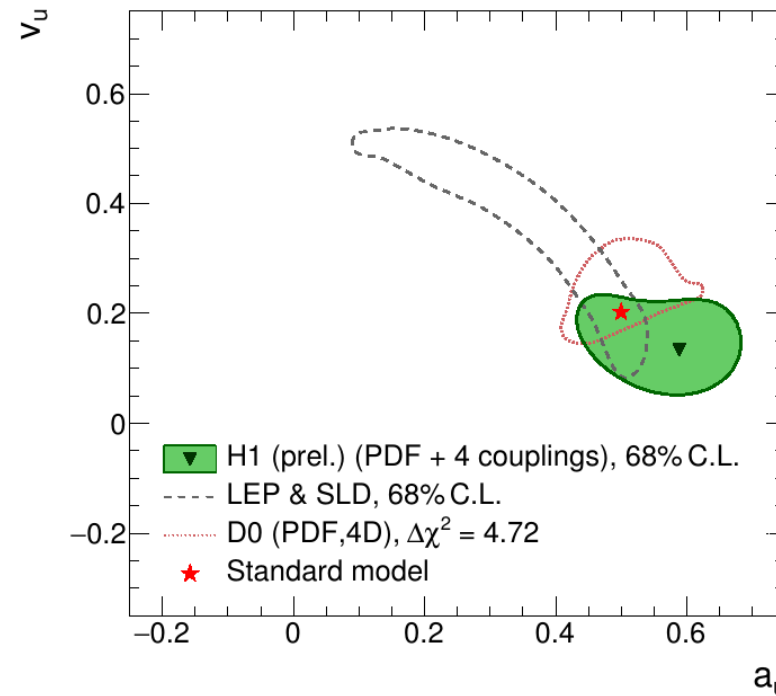
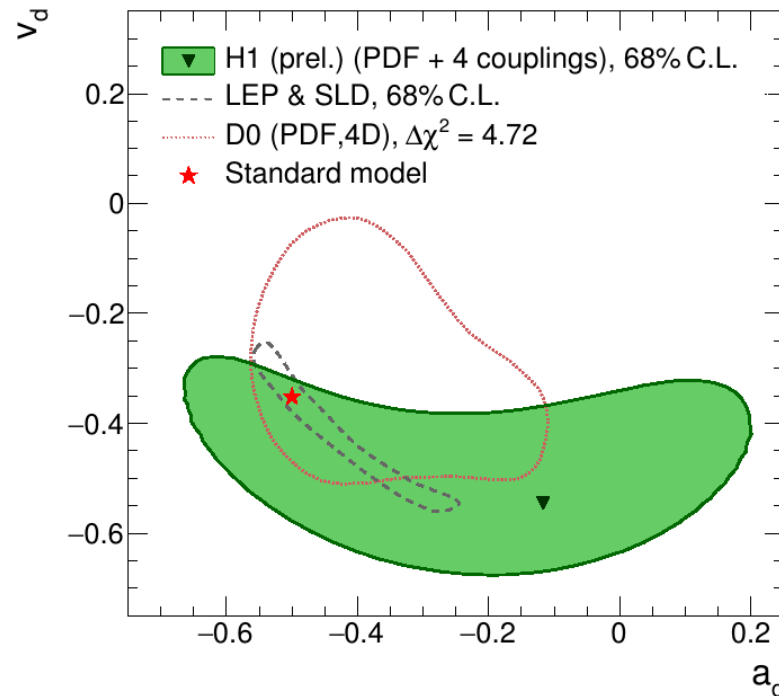


# Light quark couplings

## ***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

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

- Assume  $\alpha$  is known
- on-shell masses  $m_W$  and  $m_Z$  are only free EW parameters
- Agreement within PDG14 SM values
- Large correlation between  $m_W$  and  $m_Z$

## Mass of $W$ -boson

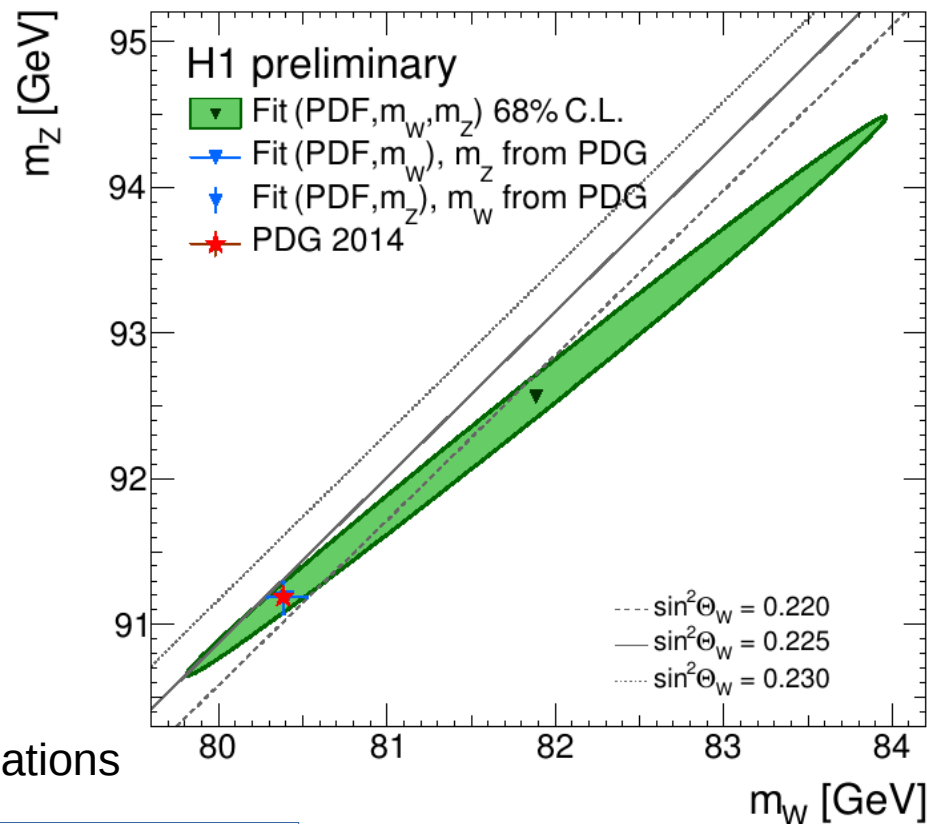
Take other masses ( $m_Z$ ) as external input to calculations

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

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

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

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



# 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

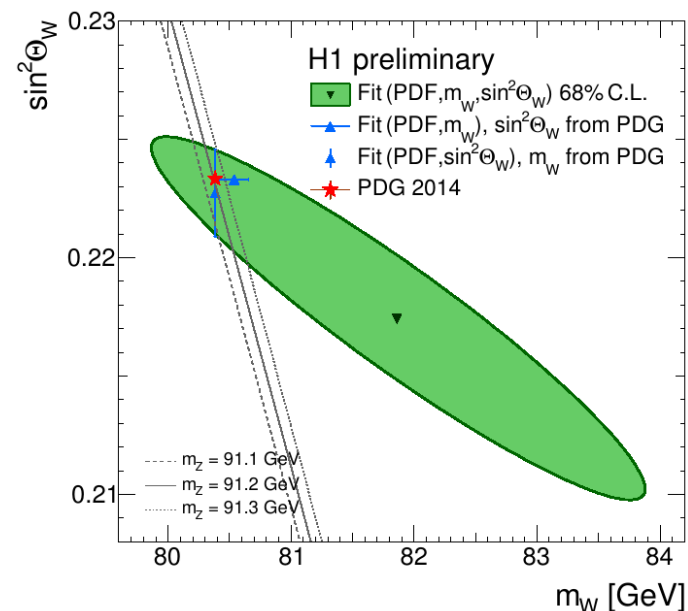
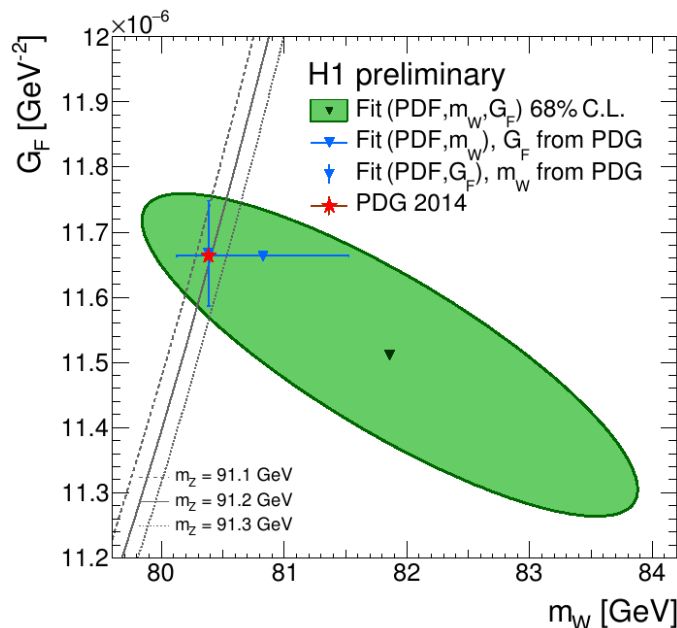
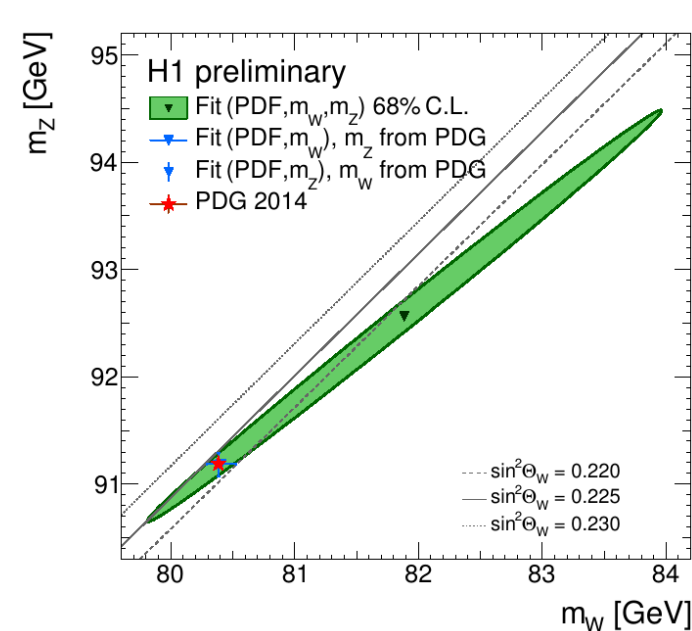
$$\sin^2 \theta_W = 1 - \frac{m_W^2}{m_Z^2}$$

## 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 $m_W$

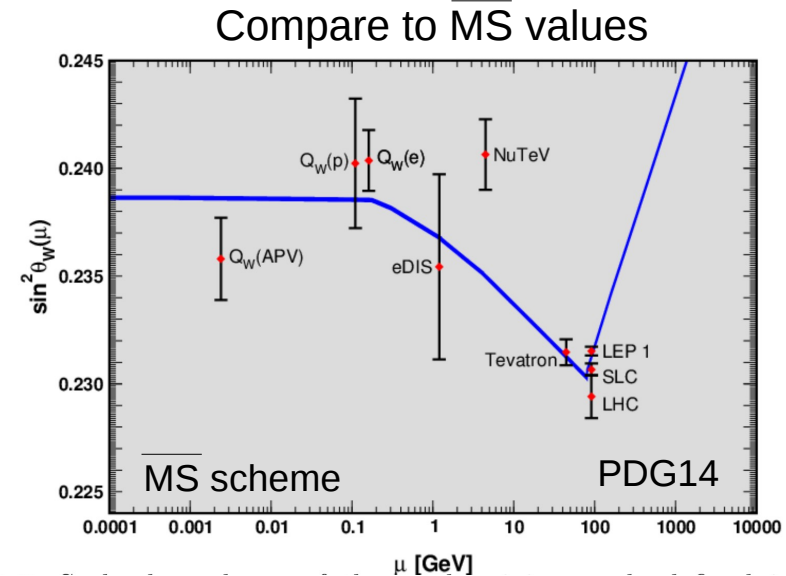
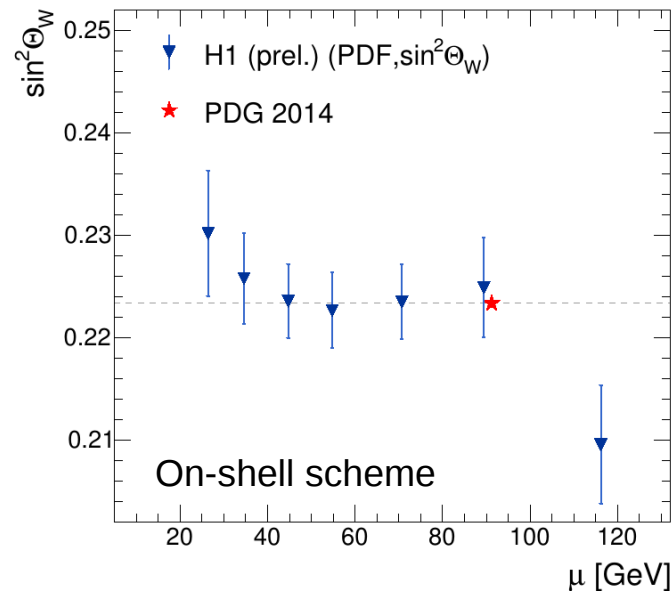
- H1 values consistent with precise values from PDG
- Correlation to  $m_W$  are different for  $m_Z$ ,  $\sin^2 \theta_W$  and  $G_F$



# 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  $\sin^2\theta_W(Q^2)$



## Results

- Results compatible with precise value from Z-pole measurements
- Unique measurement of weak mixing angle at different scales
- Comparison to  $\overline{\text{MS}}$  values straight forward

# Summary and Outlook

H1prelim-16-041

## ***Light quark couplings to Z-boson***

- Couplings determined from all H1 structure function 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
- > NNLO-QCD + NLO-EW fit to H1 data

