Determination of electroweak parameters in polarised deep-inelastic scattering at HERA

D. Britzger

for the H1 collaboration

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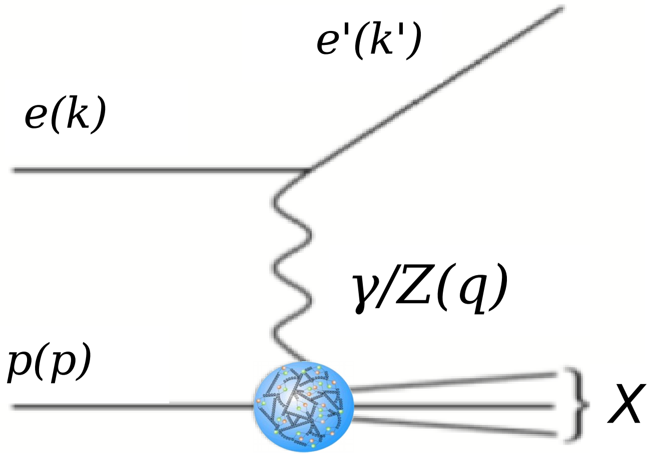
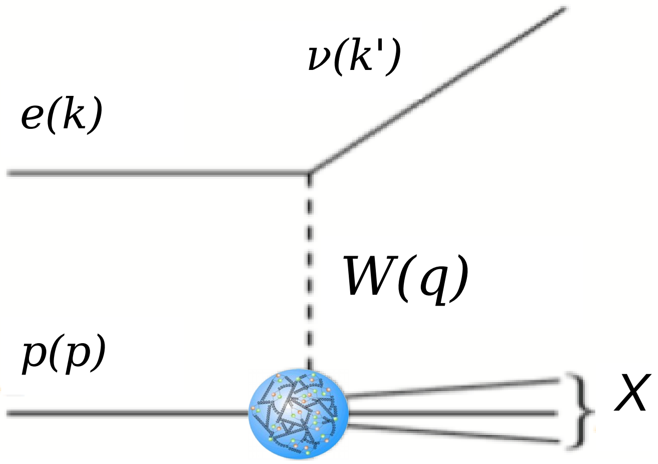
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Deep-inelastic scattering

Neutral current scattering
$ep \rightarrow e'X$



Charged current scattering
$ep \rightarrow \nu_e X$



- Study the structure of the proton -> bound together by QCD dynamics
- Probe electroweak structure of SM and unification of electromagnetic and weak force

-> Extract fundamental QCD and EW parameters

Electroweak effects in DIS at HERA

H1+ZEUS, Eur.Phys.J.C75 (2015) 12

Inclusive DIS as a function of Q^2

Lower values of Q^2

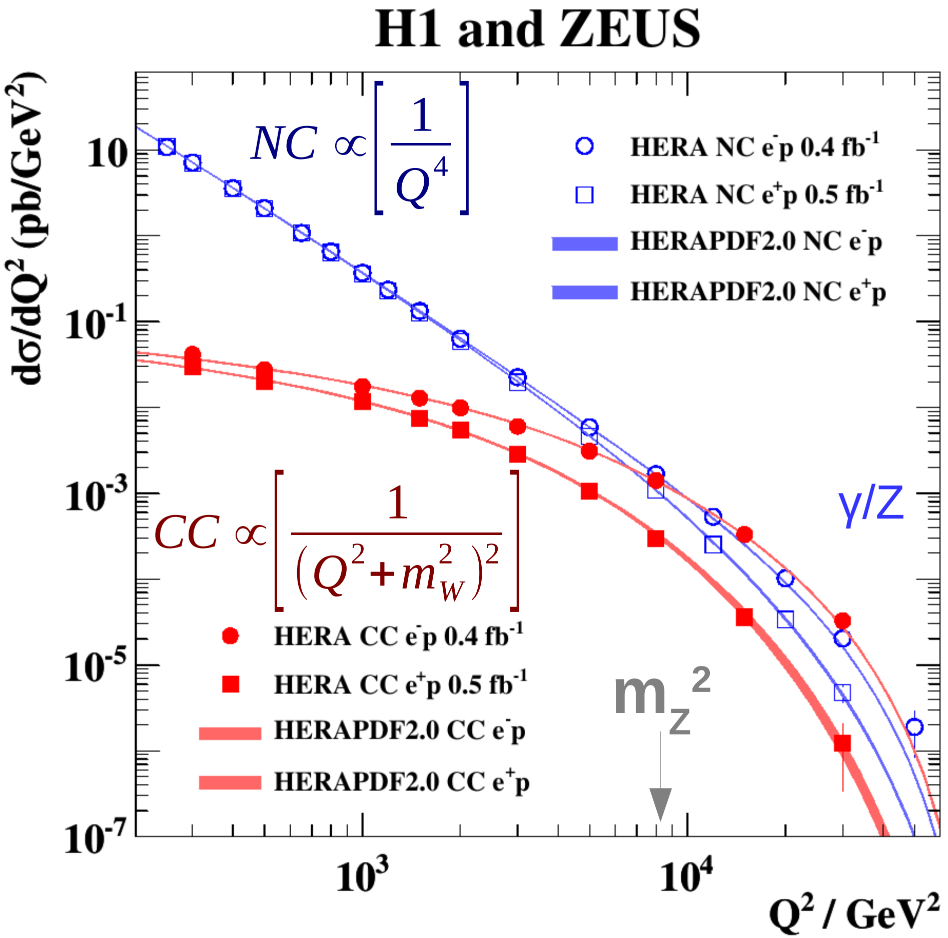
- NC mediated by γ
- CC is mediated by massive W-boson

Around EW unification scale

- NC and CC of similar size
- Z exchange becomes important for NC

W and Z-exchange: e^+p and e^-p differ

- NC: γ/Z-interference differ for e^+ and e^-
- For CC e^+:
  Helicity factor $(1-y)^2$ applies to d-quarks



Electroweak effects in DIS

CC DIS: *purely weak*

$$\frac{d\sigma^{\pm}_{CC}}{dQ^2\,dx} = \frac{1 \pm P}{2}\,\frac{G_F^2}{4\pi x}\left[\frac{m_W^2}{m_W^2 + Q^2}\right]^2 \left(Y_+ \boldsymbol{W}_2^{\pm} \pm Y_- x \boldsymbol{W}_3^{\pm} - y^2 \boldsymbol{W}_L^{\pm}\right)$$

NC DIS: *γγ, γZ, ZZ exchange*

- *axial-vector & vector couplings (a,v)*

$$\frac{d\sigma^{\pm}_{NC}}{dQ^2\,dx} = \frac{2\pi\alpha^2}{x}\left[\frac{1}{Q^2}\right]^2 \left(Y_+ \boldsymbol{F}_2 \pm Y_- x \boldsymbol{F}_3 \mp y^2 \boldsymbol{F}_L\right)$$

NC generalised structure functions:

$$\boldsymbol{F}_2 = F_2^{\gamma} + \kappa_Z(-v_e \mp P a_e) F_2^{\gamma Z} + \kappa_Z^2 (v_e^2 + a_e^2 \pm P v_e a_e) F_2^Z$$

$$x\boldsymbol{F}_3 = +\kappa_Z(\pm a_e + P v_e) F_3^{\gamma Z} + \kappa_Z^2 \left(\mp 2 v_e a_e - P(v_e^2 + a_e^2)\right) x F_3^Z$$

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

$$G_F = \frac{\pi\alpha}{\sqrt{2} m_W^2}\left[1 - \frac{m_W^2}{m_Z^2}\right]^{-1}(1 + \Delta r)$$

$$\Delta r = \Delta r(\alpha, m_W, m_Z, m_t, m_h, \cdots)$$

Quark-parton model

$$\left[F_2, F_2^{\gamma Z}, F_2^Z\right] = x \sum_q \left[Q_q^2, 2Q_q g_V^q, g_V^q g_V^q + g_A^q g_A^q\right]\{q + \bar{q}\},$$

$$x\left[F_3^{\gamma Z}, F_3^Z\right] = x \sum_q \left[2Q_q g_A^q, 2 g_V^q g_A^q\right]\{q - \bar{q}\}.$$

EW higher orders: ρ, κ

$$g_A^q = \sqrt{\rho_{\mathrm{NC},q}}\, I_{\mathrm{L},q}^3,$$

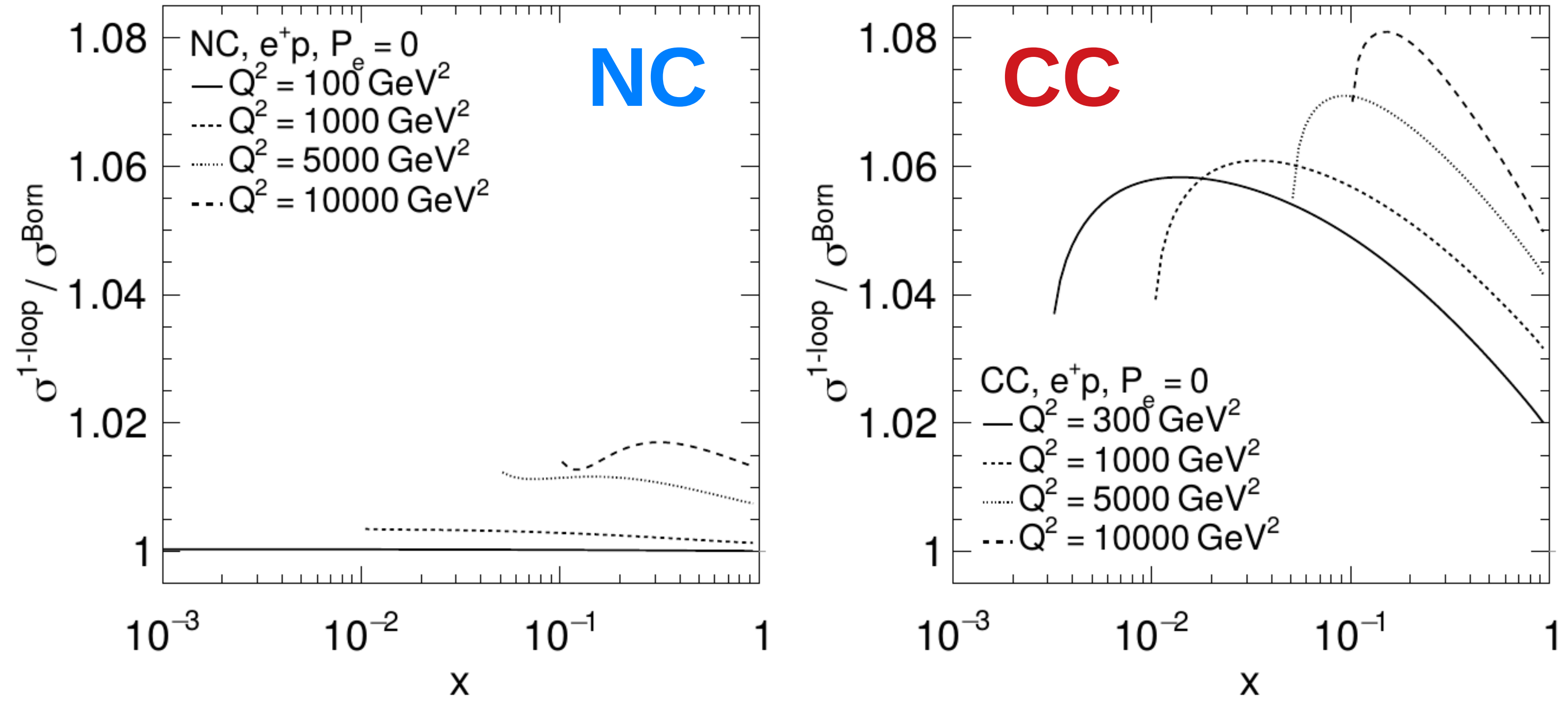
$$g_V^q = \sqrt{\rho_{\mathrm{NC},q}}\left(I_{\mathrm{L},q}^3 - 2Q_q \kappa_{\mathrm{NC},q} \sin^2\theta_W\right)$$

3 independent variables at born-level in DIS, e.g on-mass shell scheme: (α, m_W, m_Z, Δr)

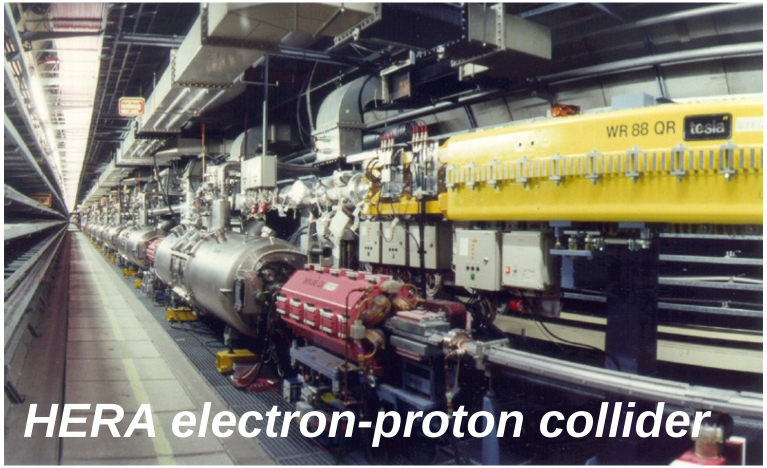
Higher order EW effects

Size of the purely weak 1-loop EW corrections for unpolarised NC and CC

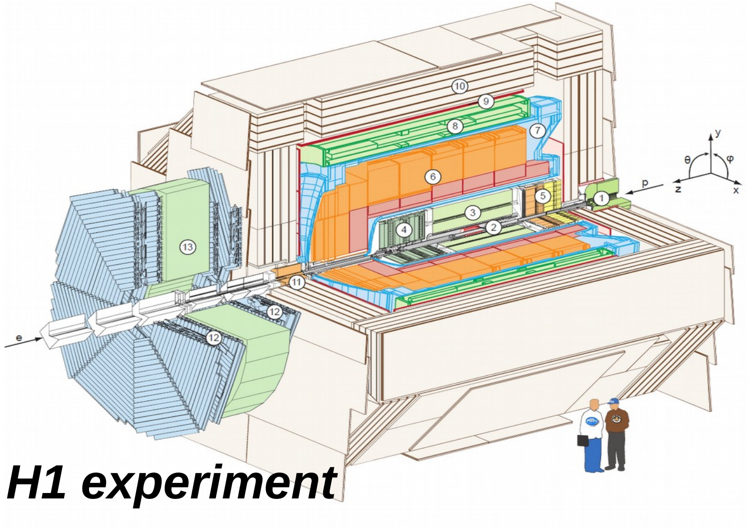
- (excl. vacuum polarisation & virtual photon corrections)
- Corrections vary by < 0.1% for polarised case, or for e- scattering



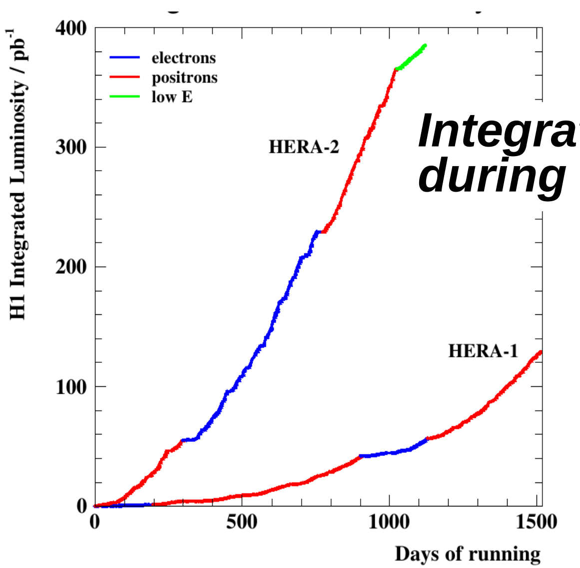
HERA and H1 experiment



HERA electron-proton collider

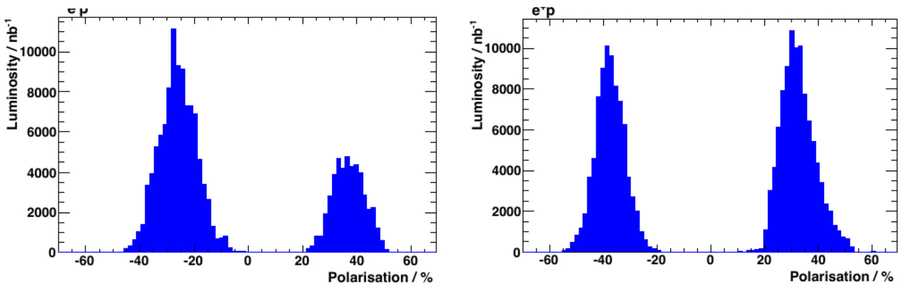


H1 experiment



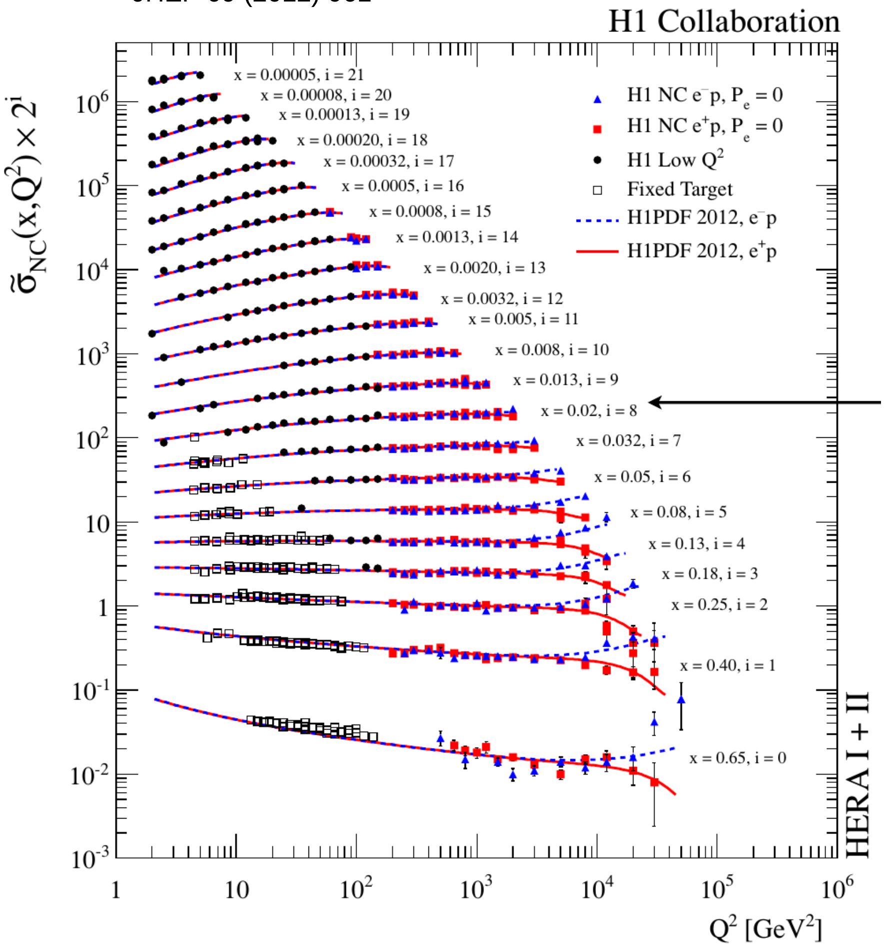
Integrated luminosity during HERA-I and -II

Lepton longitudinal beam polarisation in HERA-II



Input data

JHEP 09 (2012) 061



All H1 inclusive NC and CC DIS data

- HERA-I & HERA-II
- HERA-II high-Q^2 data
- Data well-described by (N)NLO QCD

	Data set	Q^2-range [GeV^2]	$\sqrt{s}$ [GeV]	$\mathcal{L}$ [pb^{-1}]	No. of data points	Polarisation [%]	Ref.
1	e^+ combined low-Q^2	(0.5) 8.5 – 150	301,319	20, 22, 97.6	94 (262)	–	[56]
2	e^+ combined low-E_p	(1.5) 8.5 – 90	225,252	12.2, 5.9	132 (136)	–	[56]
3	e^+ NC 94–97	150 – 30 000	301	35.6	130	–	[32]
4	e^+ CC 94–97	300 – 15 000	301	35.6	25	–	[32]
5	e^- NC 98–99	150 – 30 000	319	16.4	126	–	[33]
6	e^- CC 98–99	300 – 15 000	319	16.4	28	–	[33]
7	e^- NC 98–99 high-y	100 – 800	319	16.4	13	–	[57]
8	e^+ NC 99–00	150 – 30 000	319	65.2	147	–	[57]
9	e^+ CC 99–00	300 – 15 000	319	65.2	28	–	[57]
10	e^+ NC L HERA-II	120 – 30 000	319	80.7	136	−37.0 ± 1.0	[58, 59]
11	e^+ CC L HERA-II	300 – 15 000	319	80.7	28	−37.0 ± 1.0	[58, 59]
12	e^+ NC R HERA-II	120 – 30 000	319	101.3	138	+32.5 ± 0.7	[58, 59]
13	e^+ CC R HERA-II	300 – 15 000	319	101.3	29	+32.5 ± 0.7	[58, 59]
14	e^- NC L HERA-II	120 – 50 000	319	104.4	139	−25.8 ± 0.7	[58, 59]
15	e^- CC L HERA-II	300 – 30 000	319	104.4	29	−25.8 ± 0.7	[58, 59]
16	e^- NC R HERA-II	120 – 30 000	319	47.3	138	+36.0 ± 0.7	[58, 59]
17	e^- CC R HERA-II	300 – 15 000	319	47.3	28	+36.0 ± 0.7	[58, 59]
18	e^+ NC HERA-II high-y	60 – 800	319	182.0	11	–	[58, 59]
19	e^- NC HERA-II high-y	60 – 800	319	151.7	11	–	[58, 59]

Fit strategy

Electroweak parameters are determined in a fit of predictions to data

→ their correlations are properly taken into account

→ the final uncertainties include those arising from the PDFs

PDFs are parameterised at low scale with 13 'free' fit parameters

- NNLO QCD and DLGAP evolution; similar to H1PDF2017 or HERAPDF2.0

Fits performed with normal-distributed realative uncertainties

$$\chi^2 = \sum_{ij} \log \frac{\varsigma_i}{\tilde{\sigma}_i} V_{ij}^{-1} \log \frac{\varsigma_j}{\tilde{\sigma}_j}$$

Very good data/theory agreement (PDF fit alone)

$\chi^2/n_{dof} = 1435 / (1415\text{-}17) = 1.03$

Determination of the W-boson mass

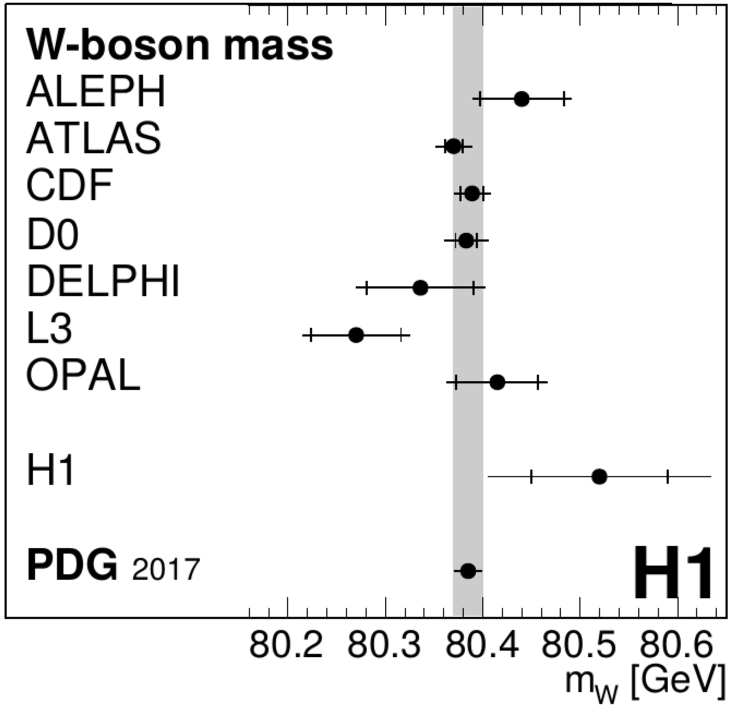
Determination performed in on-shell scheme

$$m_W = 80.520 \pm 0.070_{\rm stat} \pm 0.055_{\rm syst} \pm 0.074_{\rm PDF} = 80.520 \pm 0.115_{\rm tot}\ \rm GeV$$

- to be compared with HERA-I result

$$M_W = 80.786 \pm 0.205(\exp)^{+0.063}_{-0.098}(\rm th)\ GeV$$

→ factor of 2 improvement



Sensitivity 'breakedown'

- Dominant sensitivity (~120 MeV) from the normalisation of the CC cross sections
- The quark and electron couplings to the Z (in NC DIS) provides additional sensitivity of ~225 MeV
- The W propagator term in CC DIS provides a sensitivity of ~800MeV

W and Z mass – with G_F as additional input

m_W + m_Z + PDF fit

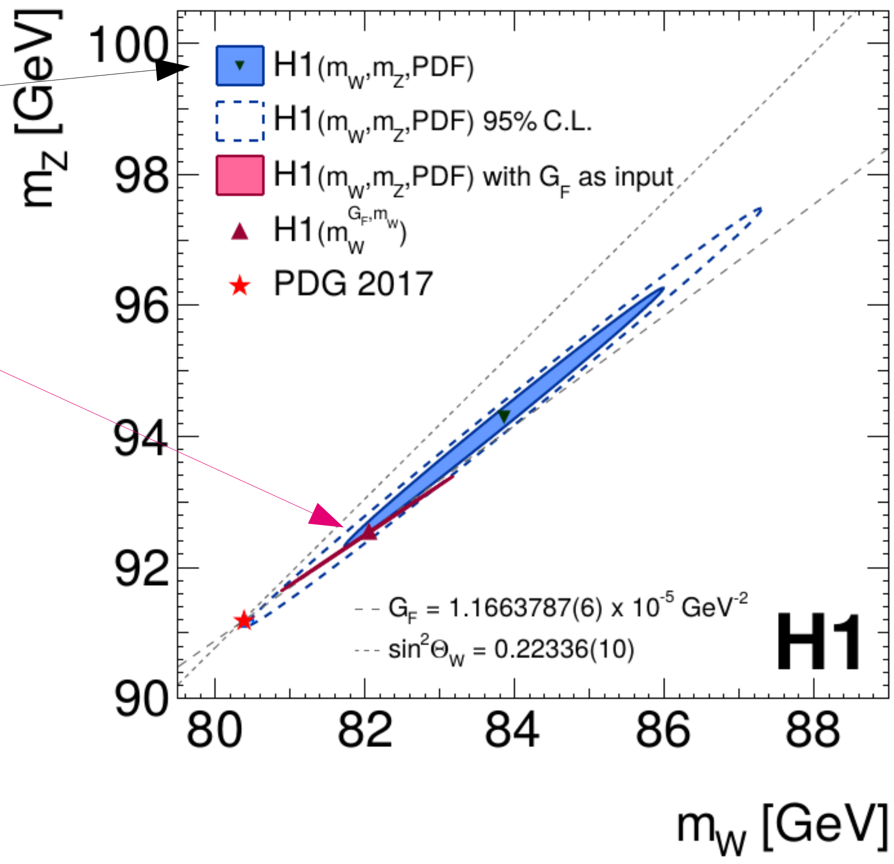
- Moderate precision
- Large correlation between masses

with G_F as additional external input

- Only low-scale parameters used as input (α, G_F)
- H1 data simultaneously constrain and test EW theory
- Result: shallow ellipse in m_W-m_Z space, due to high precision of G_F
- Unique test with a single data set

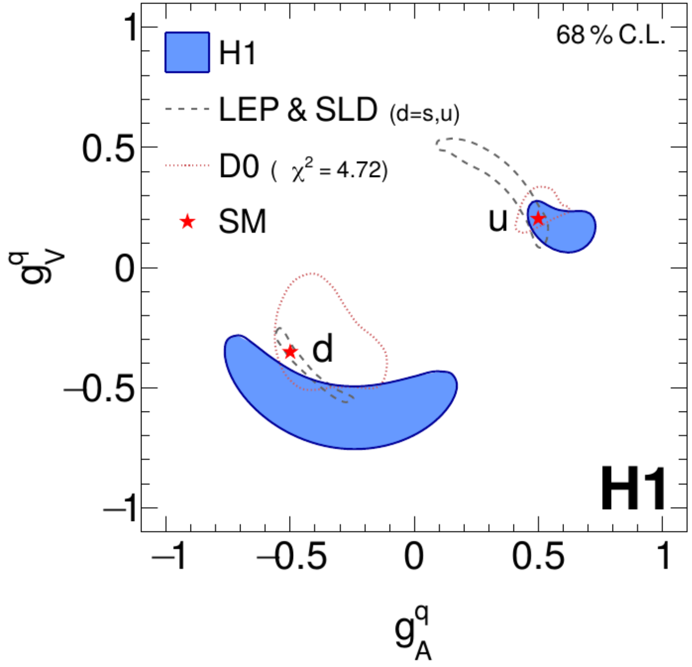
Consistency with precise Z-pole measurements found

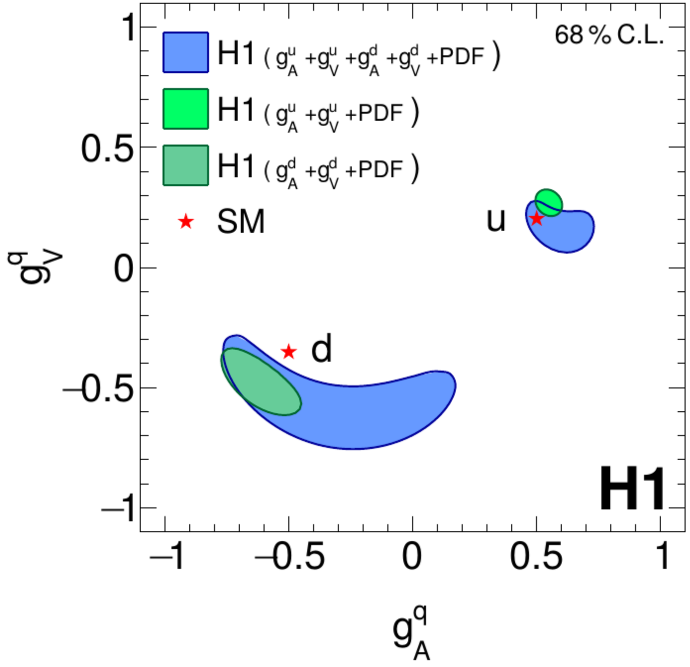
- albeit with moderate precision only



Light quark weak neutral current couplings to Z

- Results are competitive and consistent with other determinations
  Also, reasonable consistency with expectation





SM born-level expectation

$$g_A^q = I_{L,q}^3\,,$$
$$g_V^q = I_{L,q}^3 - 2Q_q \sin^2\theta_W$$

- Significant improvement over HERA-I determination
- 2-coupling fit is more precise due to the reduced correlation

Study BSM NC form factors

Probe (BSM) higher-order corrections to weak NC couplings

Introduce modification (ρ', κ')
to form factors (ρ, κ)

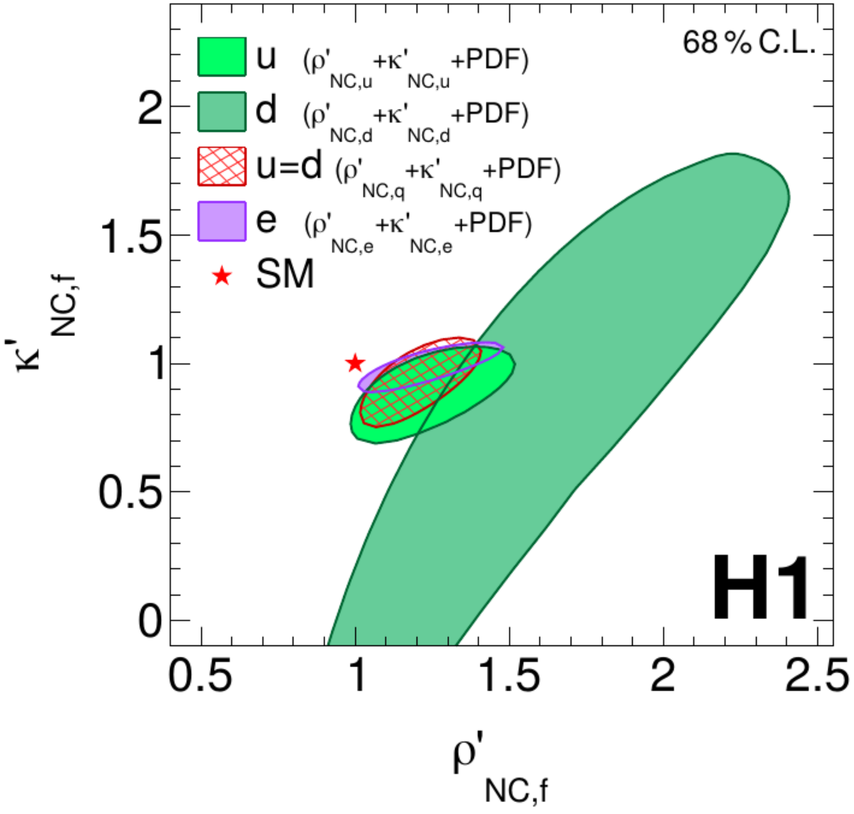
$$g_A^q = \sqrt{\rho_{\mathrm{NC},q}} I^3_{\mathrm{L},q} \, , \qquad \rho_{\mathrm{NC}} \rightarrow \rho'_{\mathrm{NC}} \rho_{\mathrm{NC}}$$

$$g_V^q = \sqrt{\rho_{\mathrm{NC},q}} \left(I^3_{\mathrm{L},q} - 2 Q_q \kappa_{\mathrm{NC},q} \sin^2\theta_W \right) \qquad \kappa_{\mathrm{NC}} \rightarrow \kappa'_{\mathrm{NC}} \kappa_{\mathrm{NC}}$$

Perform 4 fits for NC form factors

- u-type, d-type, (light) quarks, electrons
  (the latter for comparison with precise LEP results)

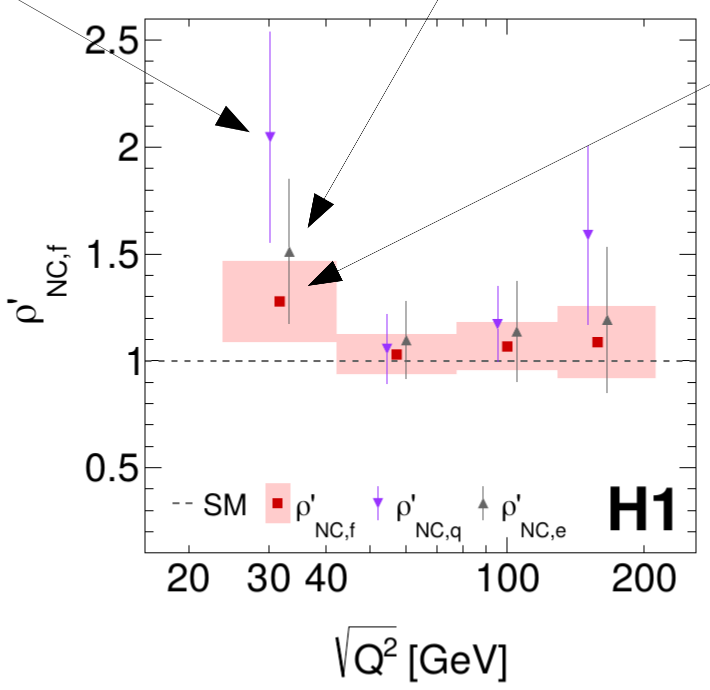
Results consistent with SM expectation (unity)

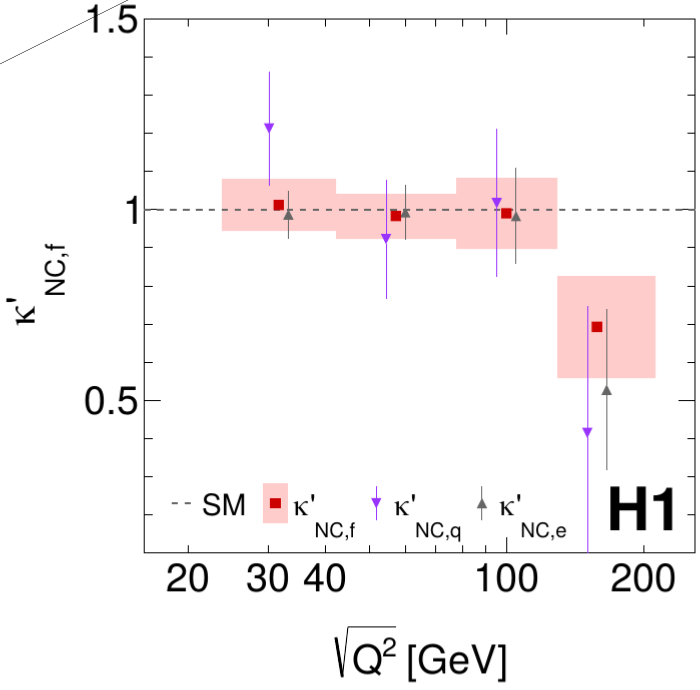


Scale dependence

Three fits of 'form-factor modifications' (ρ',κ') + PDFs *(set other parameters to their SM values)*

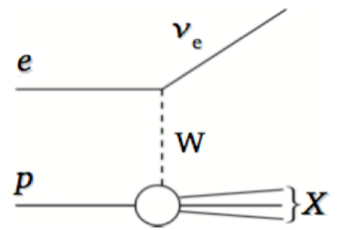
1) **quark** form factors, 2) **electron** form factors 3) **common fermion** (e+q) form factors



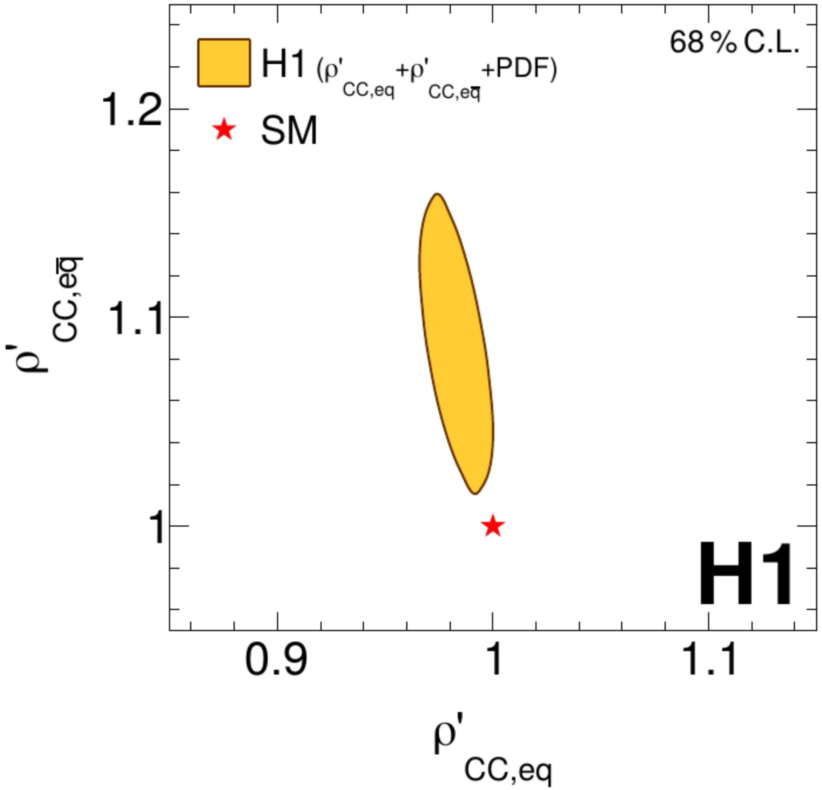


κ' is (about) the famous $\sin^2\theta_w^{eff}(Q)$

→ ***No significant scale dependence and deviation from SM***



Form factors in charged currents



CC cross section

$$\frac{d^2\sigma^{\pm}_{\rm CC}}{dxdQ^2} \simeq (1 \pm P_e)\frac{G_{\rm F}^2}{4\pi x}\left[\frac{m_W^2}{m_W^2+Q^2}\right]^2 \left(Y_+ W_2^{\pm} \mp Y_- x W_3^{\pm}\right)$$

CC form factors

- SM: CC form factors incorporate higher-order EW corrections

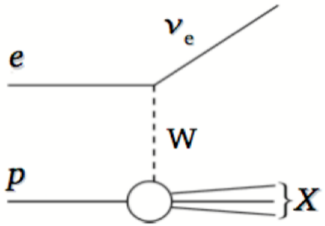
$$W_2^- = x\left(\rho^2_{\rm CC,\mathit{eq}} U + \rho^2_{\rm CC,\mathit{e\bar{q}}}\overline{D}\right)$$
$$W_2^+ = x\left(\rho^2_{\rm CC,\mathit{eq}} \overline{U} + \rho^2_{\rm CC,\mathit{e\bar{q}}} D\right)$$

- Introduce (non-SM) modifications

$$\rho_{\rm CC} \to \rho'_{\rm CC}\rho_{\rm CC}$$

→ No significant devitions from SM

→ Unique test of CC sector
(actually better than NC form factor of d-type quarks)



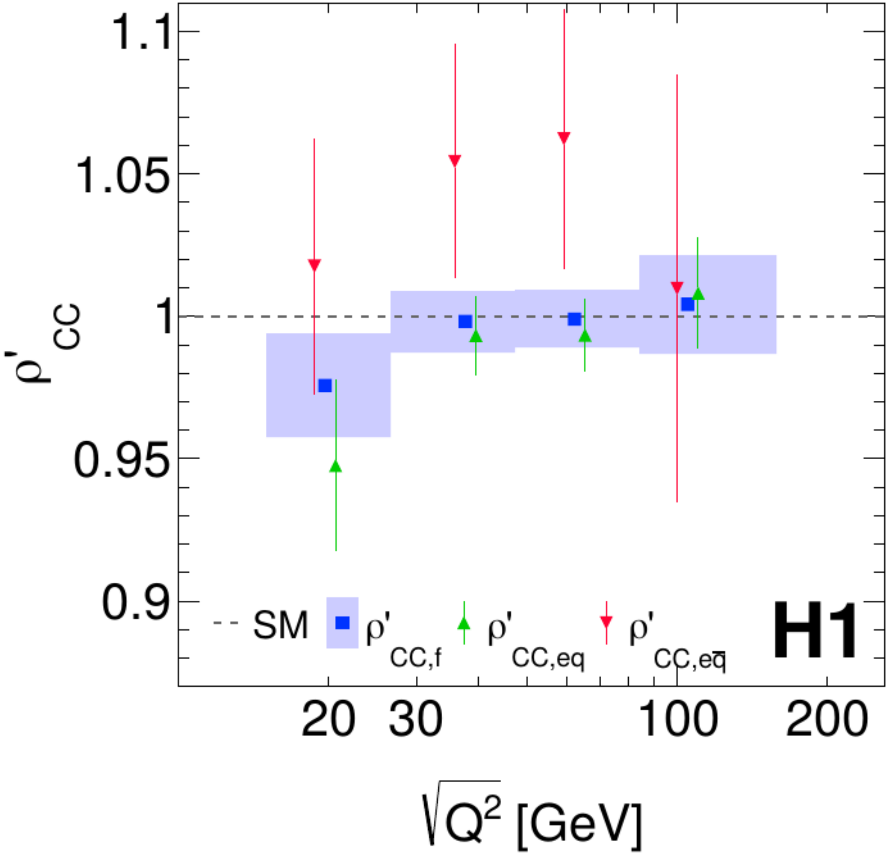
Charged currents (CC)

Scale dependence of CC form factors

- Three fits:
  - eqbar + PDF
  - eq + PDF
  - f (eq=eqbar) + PDF

No significant scale dependence and deviation from SM

First scale dependence study for CC



All HERA-I and HERA-II data taken by H1 used to determine EW parameters together with PDFs

- Precision w.r.t. HERA-I results improved by a factor of ~2

Thanks to increased statistics and longitudinal polarised lepton beams

W-boson mass determined with reasonable precision

- Complementary test between space-like and time-like regimes

The light quark couplings to the Z boson are competitive to other determinations

BSM-like modification of the SM form factors and their scale dependence studied

- First such study for CC
- Unique test of scale dependence of EW theory
- Within the uncertainties, no significant deviations from SM