Electroweak Parameters determined from inclusive DIS data together with PDFs

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PDF uncertainties in EW analyses

PDF uncertainties are (among) the largest uncertainties in precision EW studies in Run-I, Run-II, and beyond…

m_W

LHCb, JHEP 2201 (2022) 036

$$m_W = 80362 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\ \text{MeV}, \quad \text{NNPDF3.1}$$
$$m_W = 80350 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 12_{\text{PDF}}\ \text{MeV}, \quad \text{CT18}$$
$$m_W = 80351 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 7_{\text{PDF}}\ \text{MeV}, \quad \text{MSHT20}$$

$\sin^2\theta_{eff}$

LHCb, JHEP 1511(2015) 190

Uncertainty	average $\Delta\lvert A_{\text{FB}}^{\text{pred}}\rvert$
PDF	0.0062
scale	0.0040
α_s	0.0030
FSR	0.0016

m_W

ATLAS, EPJ C 78 (2018) 110

Channel	$m_{W^+} - m_{W^-}$ [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.
$W \to e\nu$	−29.7	17.5	0.0	4.9	0.9	5.4	0.5	0.0	24.1	30.7
$W \to \mu\nu$	−28.6	16.3	11.7	0.0	1.1	5.0	0.4	0.0	26.0	33.2
Combined	−29.2	12.8	3.3	4.1	1.0	4.5	0.4	0.0	23.9	28.0

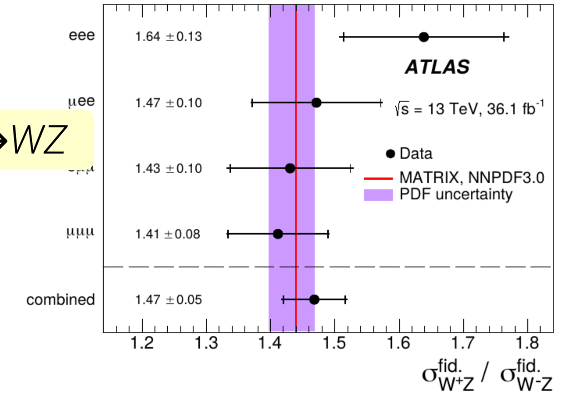
$\sin^2\theta_{eff}$

CMS, EPJ C 78 (2018) 701

$$\sin^2\theta^{\ell}_{\text{eff}} = 0.23101 \pm 0.00036\,(\text{stat}) \pm 0.00018\,(\text{syst}) \pm 0.00016\,(\text{theo}) \pm 0.00031\,(\text{PDF})$$

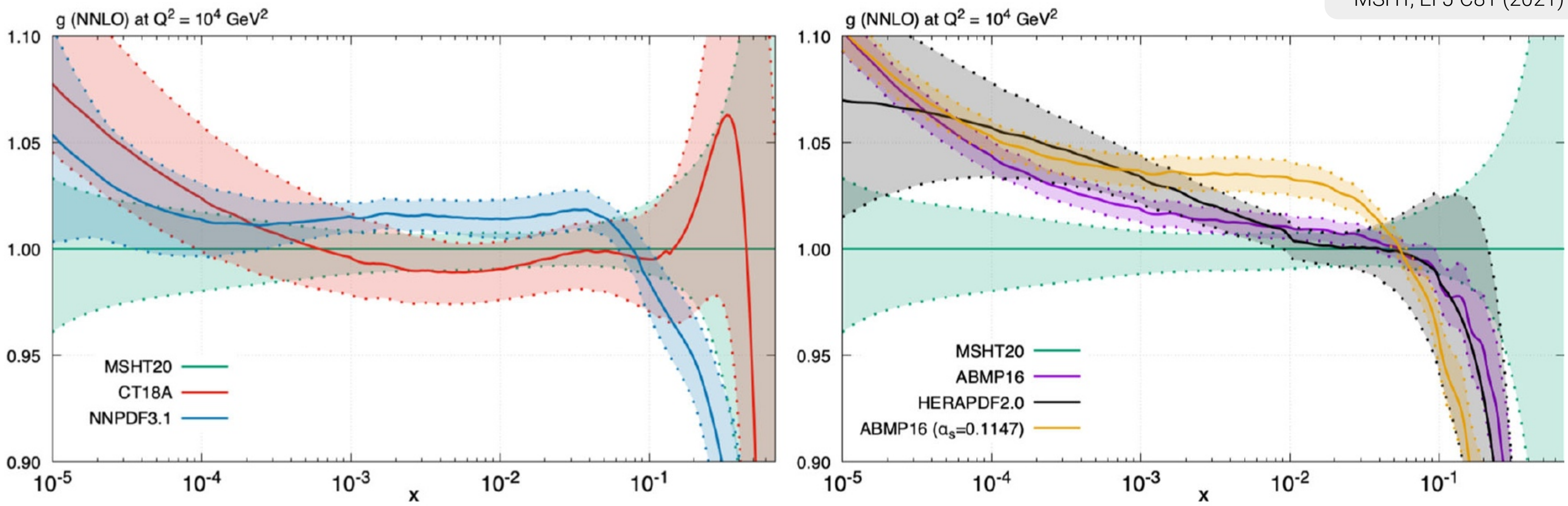
$pp \to WZ$

ATLAS, EPJ C79 (2019)



PDFs are determined from data

MSHT, EPJ C81 (2021) 341



Can PDF uncertainties be reduced in the future?

Are PDFs correlated with EW parameters, or are the data used in PDF fits themselves sensitive to EW parameters?

Is there sensitivity to EW parameters in the PDF?

Neutral and charged current DIS

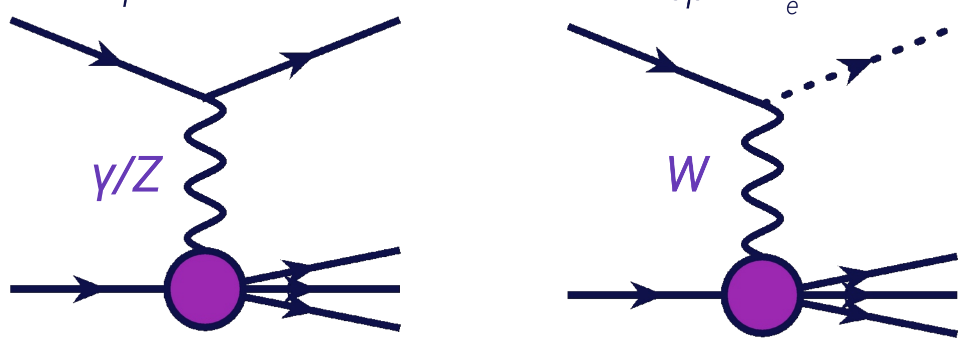
Inclusive NC and CC DIS data from HERA

→ backbone of any PDF fit

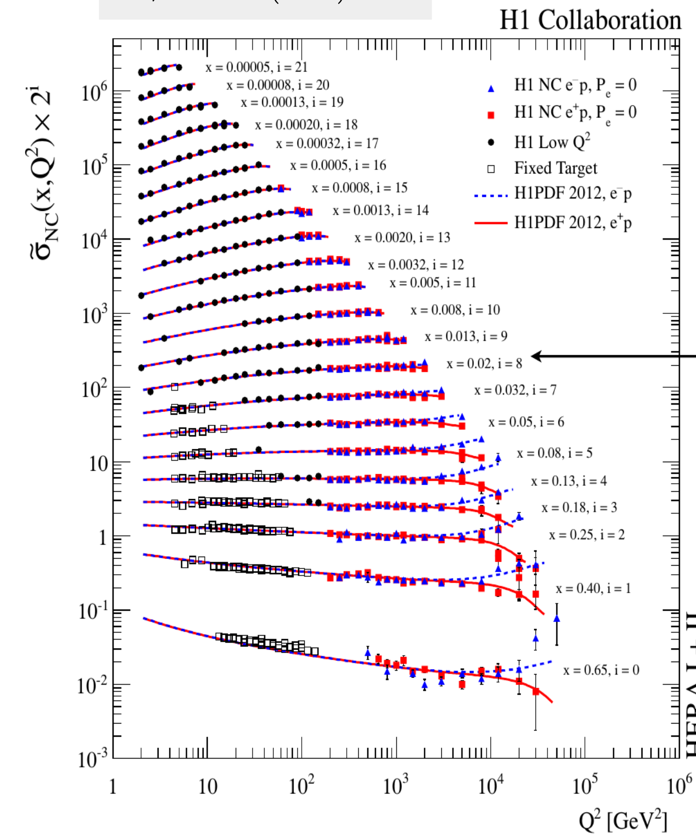
→ PDFs can be determined from HERA data alone

Neutral current scattering
$ep \rightarrow e' + X$

Charged current scattering
$ep \rightarrow \nu_e + X$



H1, JHEP 09 (2012) 061



To which extent are these data sensitive to EW parameters ?

How to do a PDF+EW fit?

NB: the following studies are performed with dedicated data from H1, while otherwise the inclusive DIS data are not accurate beyond LO EW theory

$$\frac{d^2\sigma^{\pm}_{NC}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}(Y_+\tilde{F}_2^{\pm} \mp Y_- x\tilde{F}_3^{\pm} - y^2\tilde{F}_L^{\pm}) \cdot (1 + \Delta^{weak}_{NC})$$

H1, JHEP 09 (2012) 061

Electroweak effects in DIS

CC DIS: *purely weak*

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

NC DIS: *γγ, γZ, ZZ exchange*

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

NC generalised structure functions

$$\boldsymbol{F}_2=F_2^{\gamma}+\kappa_Z\left(-g_V^e\mp Pg_A^e\right)F_2^{\gamma Z}+\kappa_Z^2\left(g_V^{e\,2}+g_A^{e\,2}\pm Pg_V^e g_A^e\right)F_2^Z$$

$$x\boldsymbol{F}_3=+\kappa_Z\left(\pm g_A^e+Pg_V^e\right)F_3^{\gamma Z}+\kappa_Z^2\left(\mp 2g_V^e g_A^e-P\left(g_V^{e\,2}+g_a^{e2}\right)\right)xF_3^Z$$

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

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

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

Quark-parton model

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

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

EW higher orders: ρ, κ

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

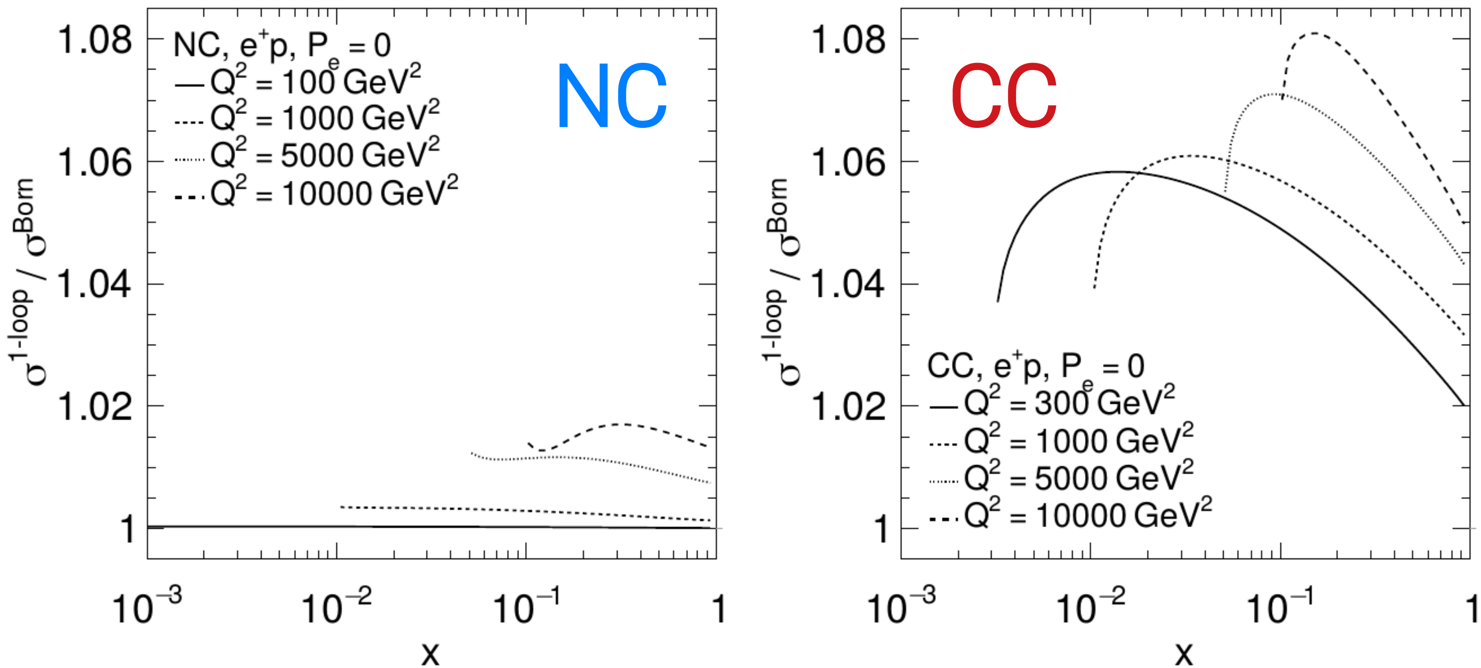
$$g_V^q=\sqrt{\rho_{\mathrm{NC},q}}\left(I^3_{\mathrm{L},q}-2Q_q\kappa_{\mathrm{NC},q}\sin^2\theta_W\right)$$

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



Simultaneous fit of PDFs and EW parameters

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

- NNLO QCD and DLGAP evolution;

→ similar to H1PDF2012, H1PDF2017 or HERAPDF2.0

Electroweak parameters are determined simultaneously with PDFs

→ their correlations are properly taken into account

→ the final uncertainties include those arising from the PDFs

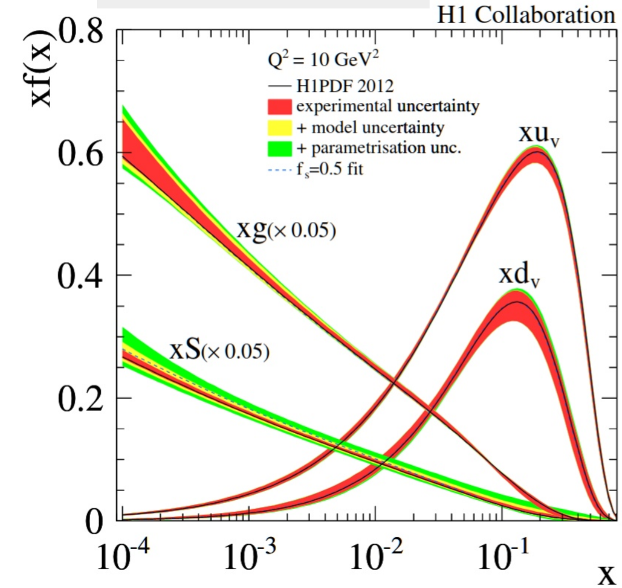
- χ^2 minimization are performed with normal-distributed relative uncertainties

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

- Very good data/theory agreement (PDF fit alone)

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

H1, JHEP 09 (2012) 061



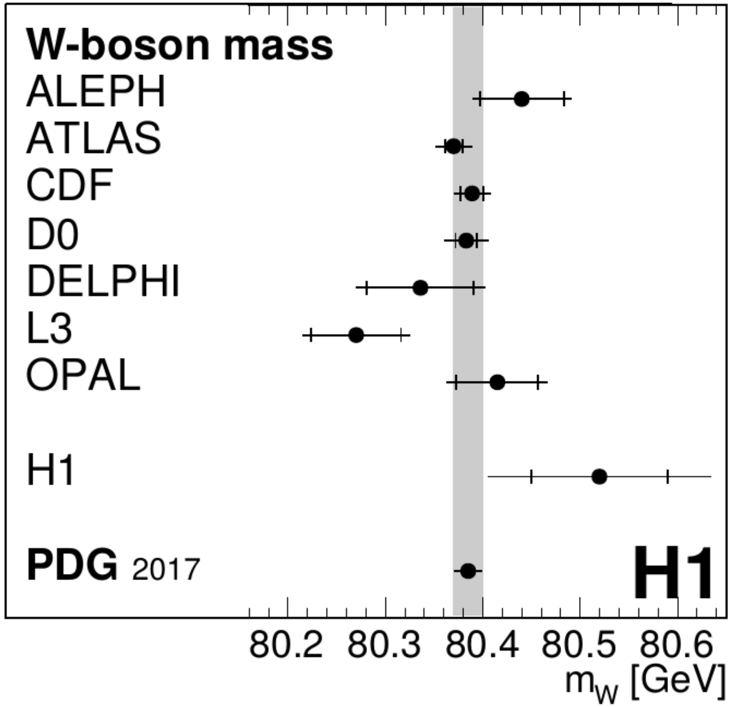
Determination of the W-boson mass

W-mass determination in on-shell scheme

- Simultaneous PDF+m_W fit

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

- *W*-mass in on-shell scheme difficult to interpret → consistency test of EW theory, when compared to direct W-mass measurements



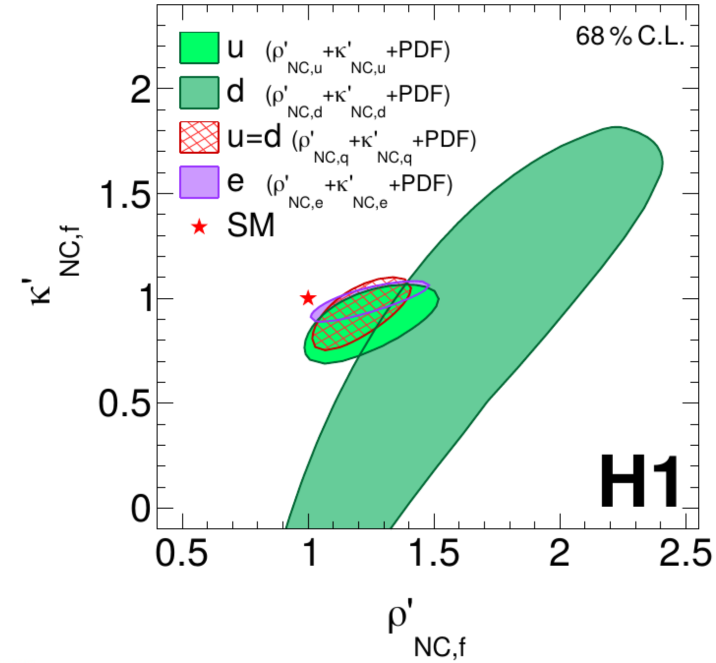
H1, Eur.Phys.J.C78 (2018), 777

Sensitivity 'breakdown'

- Dominant sensitivity (~120 MeV) from normalization of the CC cross sections
- The quark and electron couplings to the Z (in NC DIS) provides sensitivity of ~225 MeV
- W-propagator term $m_{W,prop}$ in CC DIS has a sensitivity of ~800MeV

NC form factors

H1, Eur.Phys.J.C78 (2018), 777



Probe higher-order corrections to weak NC couplings

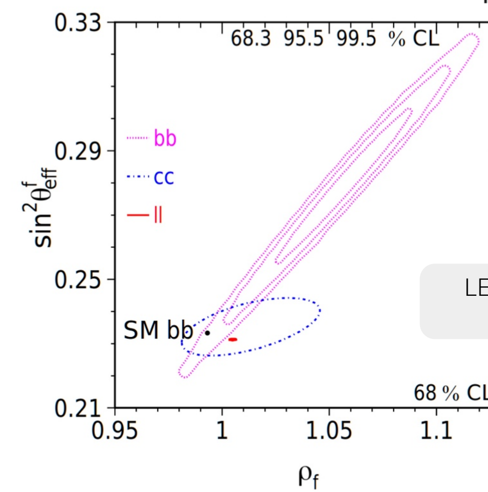
- Introduce anomalous form factors (ρ', κ')

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

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

- 4 independent determinations of NC form factors:
  → u-type, d-type, (light) quarks, electrons

- Results consistent with SM expectation
- With some calculation, results could be compared with LEP+SLD → but much larger uncertainties



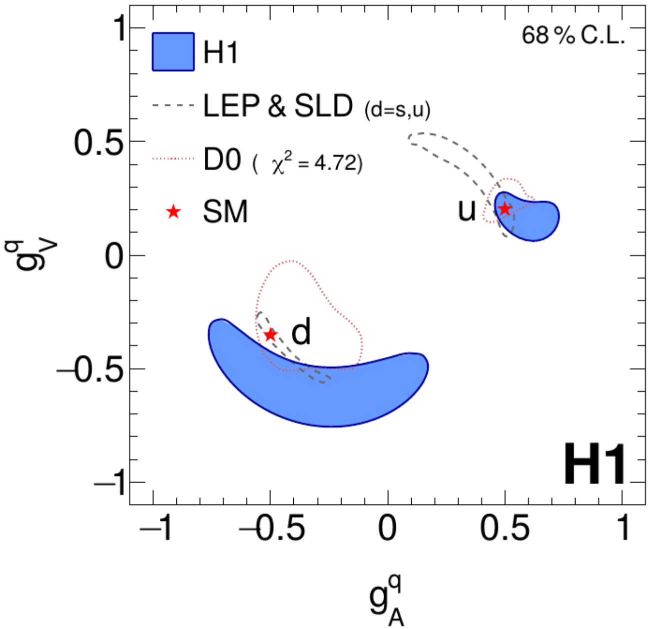
LEP+SLD, Phys.Rept.427 (2006) 257

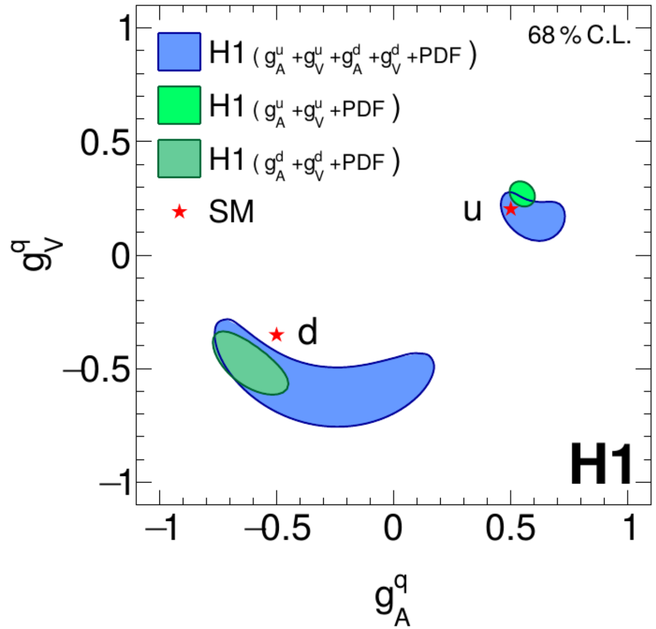
Light quark weak neutral current couplings to Z

- Results are competitive and consistent with other determinations
  Reasonable consistency with expectation

SM born-level expectation

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





All values enter PDG21

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{-0.527^{+0.040}_{-0.028}}$	OUR AVERAGE				
-0.619 ± 0.108		[1] ANDREEV	2018A	H1	$e^\pm p$
-0.497 ± 0.165	156k	[2] ABAZOV	2011D	D0	$E_{\mathrm{cm}}^{p\bar{p}}$ = 1.97 TeV
$-0.52\ ^{+0.05}_{-0.03}$		[3] LEP-SLC	2006		E_{cm}^{ee} = 88 – 94 GeV
$-0.016\ ^{+0.346}_{-0.536} \pm 0.091$	5026	[4] ACOSTA	2005M	CDF	$E_{\mathrm{cm}}^{p\bar{p}}$= 1.96~TeV

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.519^{+0.028}_{-0.033}}$	OUR AVERAGE				
0.548 ± 0.036		[1] ANDREEV	2018A	H1	$e^\pm p$
0.501 ± 0.110	156k	[2] ABAZOV	2011D	D0	$E_{\mathrm{cm}}^{p\bar{p}}$ = 1.97 TeV
$0.47\ ^{+0.05}_{-0.33}$		[3] LEP-SLC	2006		E_{cm}^{ee} = 88 – 94 GeV
$0.441\ ^{+0.207}_{-0.173} \pm 0.067$	5026	[4] ACOSTA	2005M	CDF	$E_{\mathrm{cm}}^{p\bar{p}}$= 1.96~TeV

VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{-0.38^{+0.04}_{-0.05}}$	OUR AVERAGE				
-0.488 ± 0.092		[1] ANDREEV	2018A	H1	$e^\pm p$
-0.351 ± 0.251	156k	[2] ABAZOV	2011D	D0	$E_{\mathrm{cm}}^{p\bar{p}}$ = 1.97 TeV
$-0.33\ ^{+0.05}_{-0.07}$		[3] LEP-SLC	2006		E_{cm}^{ee} = 88 – 94 GeV
$-0.226\ ^{+0.635}_{-0.290} \pm 0.090$	5026	[4] ACOSTA	2005M	CDF	$E_{\mathrm{cm}}^{p\bar{p}}$= 1.96~TeV

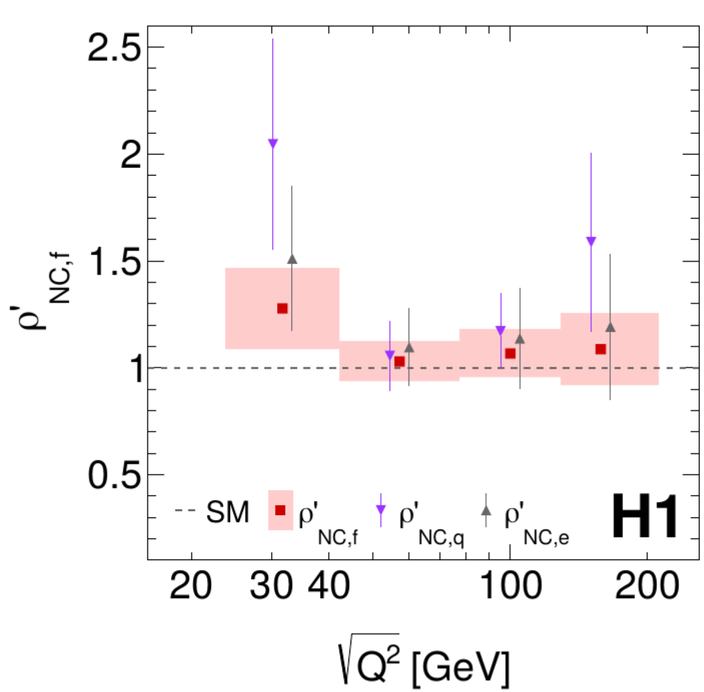
VALUE	EVTS	DOCUMENT ID		TECN	COMMENT
$\mathbf{0.266 \pm 0.034}$	OUR AVERAGE				
0.270 ± 0.037		[1] ANDREEV	2018A	H1	$e^\pm p$
0.201 ± 0.112	156k	[2] ABAZOV	2011D	D0	$E_{\mathrm{cm}}^{p\bar{p}}$ = 1.97 TeV
$0.24\ ^{+0.28}_{-0.11}$		[3] LEP-SLC	2006		E_{cm}^{ee} = 88 – 94 GeV
$0.399\ ^{+0.152}_{-0.188} \pm 0.066$	5026	[4] ACOSTA	2005M	CDF	$E_{\mathrm{cm}}^{p\bar{p}}$= 1.96~TeV

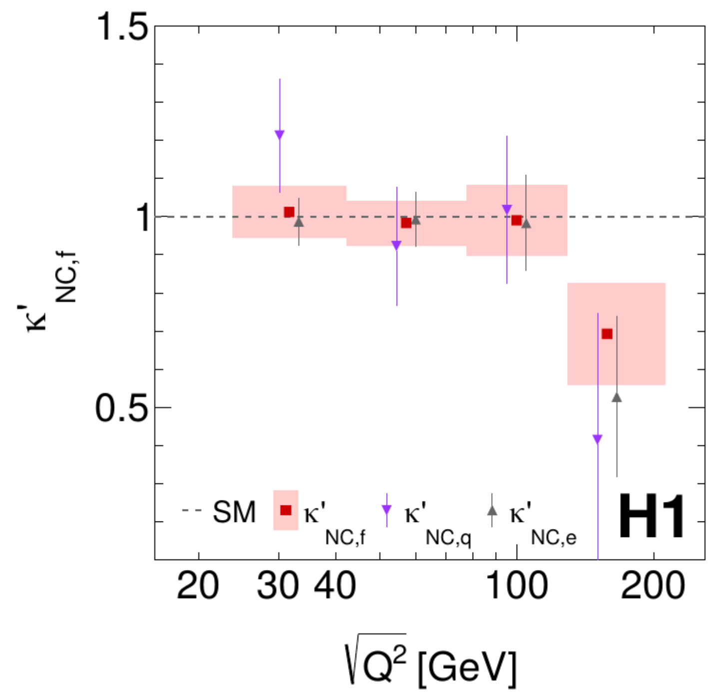
- 2-coupling fit is more precise due to the reduced correlation
- Among most precise measurements to date

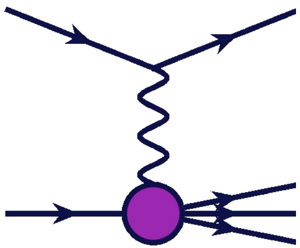
Scale dependence

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' can be translated to $\sin^2\theta_w^{eff}(Q)$

→ No significant scale dependent deviation from SM

H1, Eur.Phys.J.C78 (2018), 777

Charged currents effective couplings

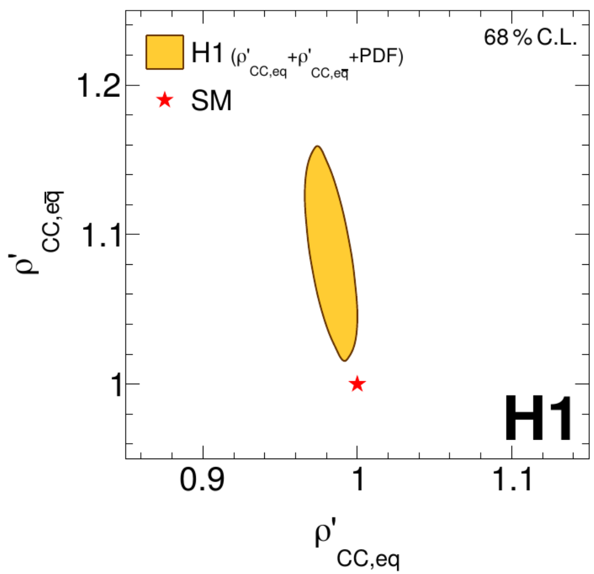
Charged current cross section

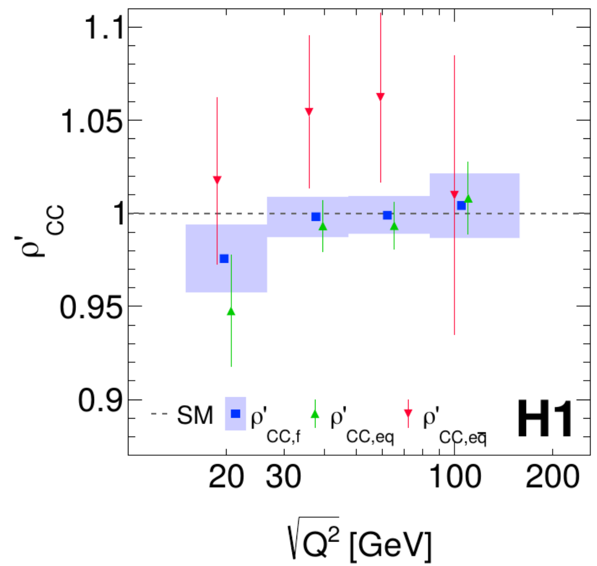
$$\frac{d^2\sigma^{\pm}_{CC}}{dxdQ^2} \simeq (1 \pm P_e)\frac{G_F^2}{4\pi x}\left[\frac{m_W^2}{m_W^2+Q^2}\right]^2 (Y_+W_2^{\pm} \mp Y_-xW_3^{\pm})$$

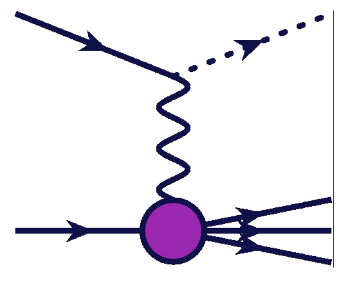
Charged current form factors

- SM: CC form factors incorporate higher-order EW corrections
- Introduce (non-SM) modifications $\rho_{CC} \rightarrow \rho'_{CC}\rho_{CC}$

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







→ No significant devitions from SM
→ Unique test of CC sector
(actually better than NC form factor of d-type quarks)

H1, Eur.Phys.J.C78 (2018), 777

Conclusions on HERA data

HERA inclusive DIS data have only (very) little sensitivity to EW parameters

→ No impact from EW parameters on PDFs to be expected

→ HERA inclusive data are accurate to LO EW only, while no relevant sensitivity to higher-order EW effects

Though, there are some interesting aspects

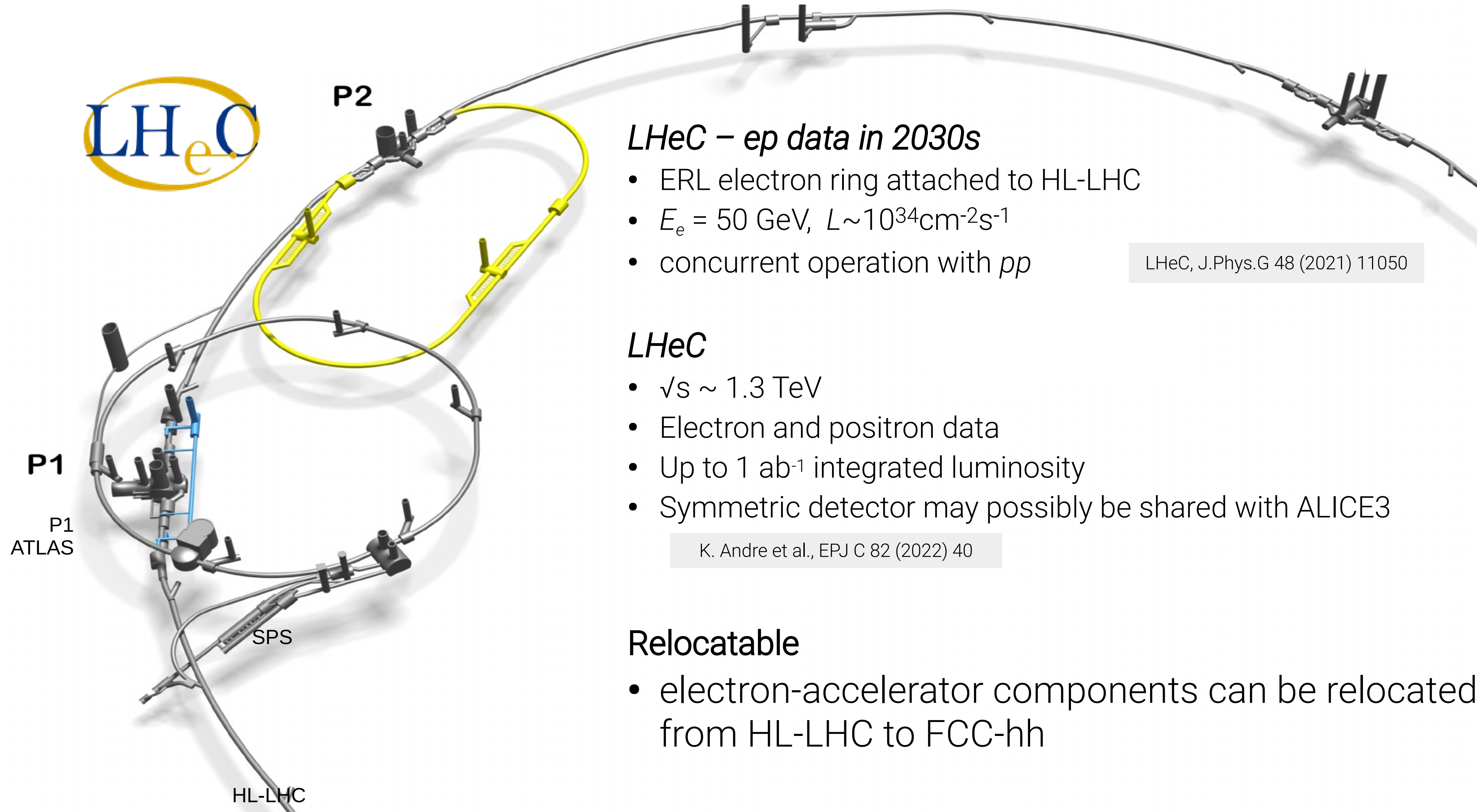
→ Competitive sensitivity for EW effects of 1st generation quarks

→ Sensitivity to EW effects in charged currents

→ Moderate sensitivity to scale-dependent effects (space-like)

How to reduce the (dominant) PDF uncertainties in future LHC analyses ??

Electron-proton collisions at the HL-LHC ?



LHeC – ep data in 2030s

- ERL electron ring attached to HL-LHC
- E_e = 50 GeV, $L \sim 10^{34} cm^{-2} s^{-1}$
- concurrent operation with *pp*

LHeC, J.Phys.G 48 (2021) 11050

LHeC

- √s ~ 1.3 TeV
- Electron and positron data
- Up to 1 ab^{-1} integrated luminosity
- Symmetric detector may possibly be shared with ALICE3

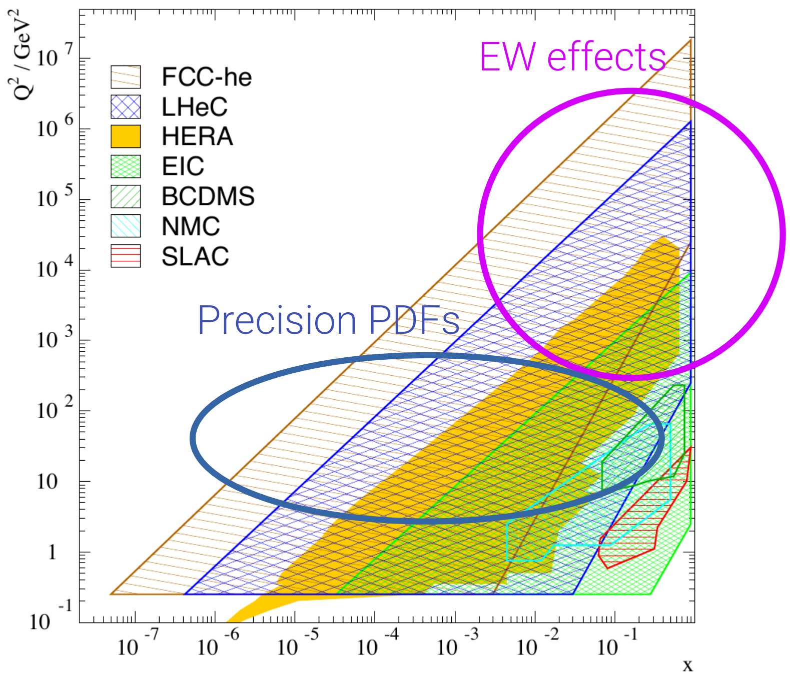
K. Andre et al., EPJ C 82 (2022) 40

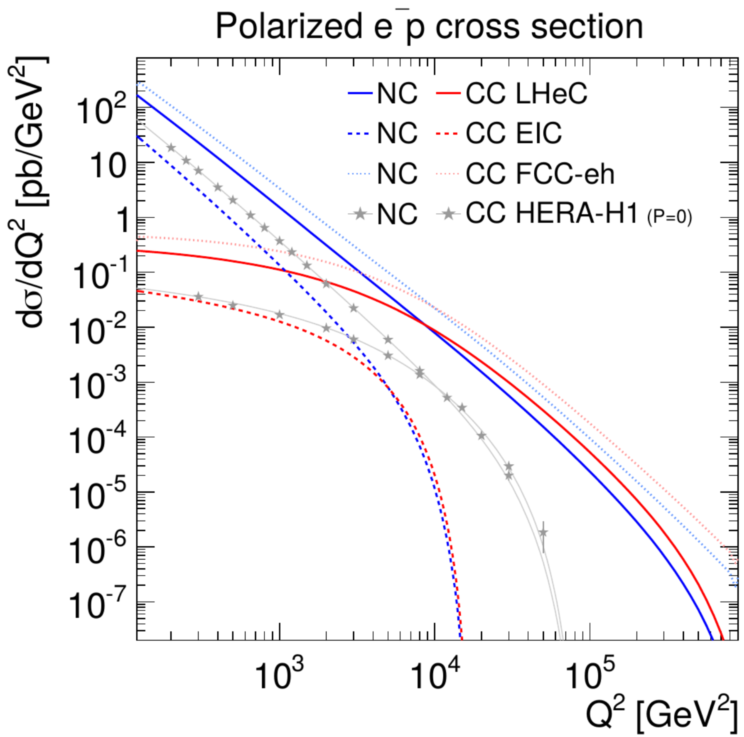
Relocatable

- electron-accelerator components can be relocated from HL-LHC to FCC-hh

LHeC kinematic reach

LHeC: greatly increased kinematic reach ($\sqrt{s}$~1.3 TeV and L~1 ab^{-1})





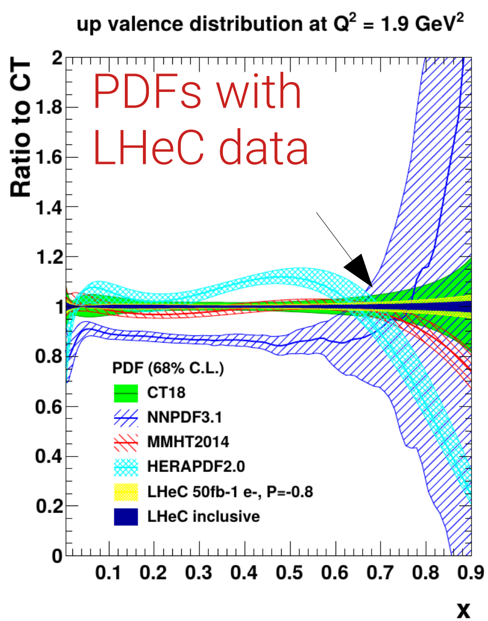
1. Superior sensitivity to PDFs
2. Enhanced sensitivity to EW effects

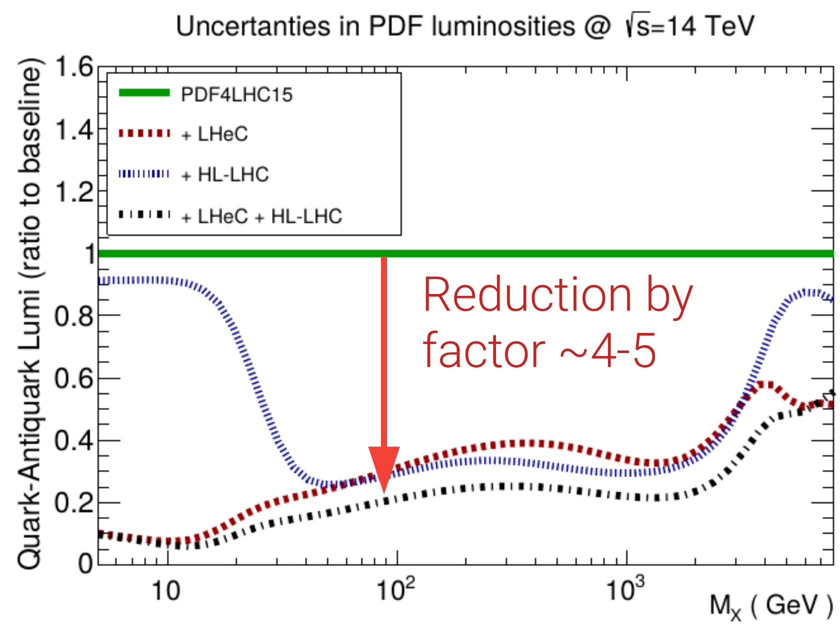
LHeC PDFs

Khalek et al., SciPost Phys. 7 (2019) 051

LHeC, J.Phys.G 48 (2021) 11050

Prospects for PDFs determinations with LHeC inclusive DIS data
→ greatly reduced PDF uncertainties



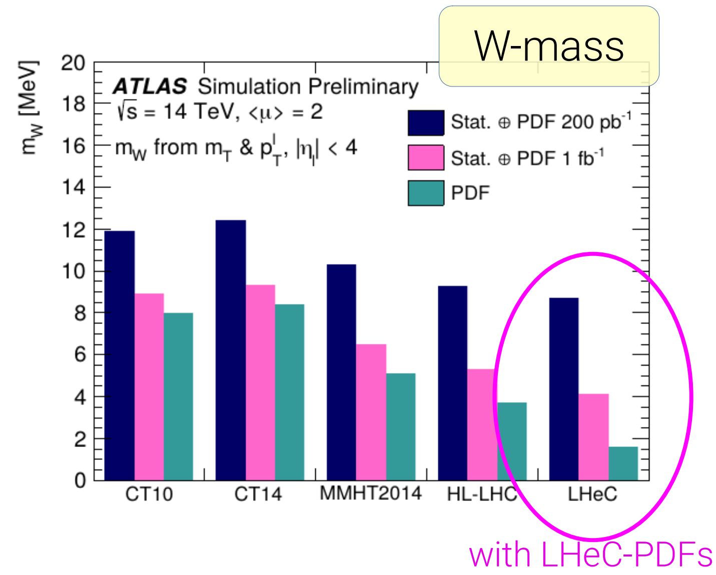


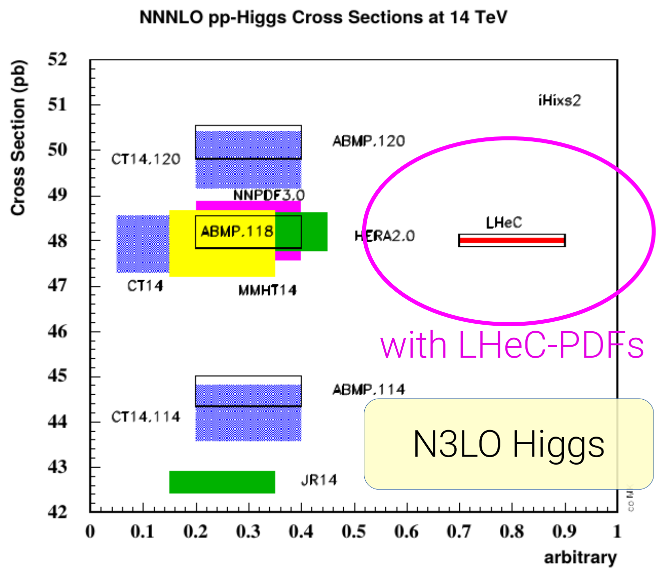
→ greatly reduced PDF uncertainties
→ Independent determination of PDFs (no shared syst. uncertainties)

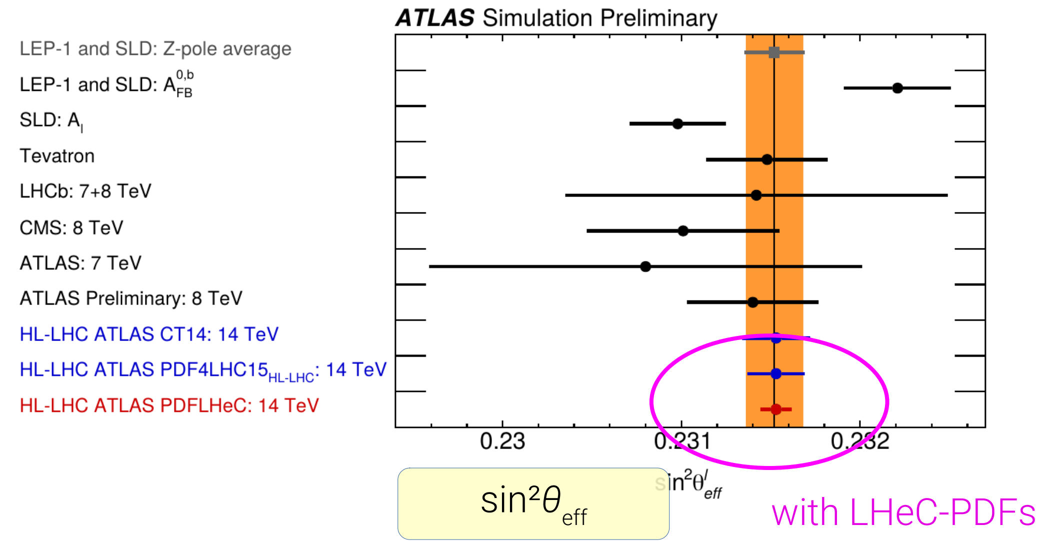
pp physics with LHeC PDFs

Significantly improved PDFs will reduce uncertainties in m_W or $\sin^2\theta_{eff}$

Improved PDFs are crucial to reach current precision (LEP or theory)





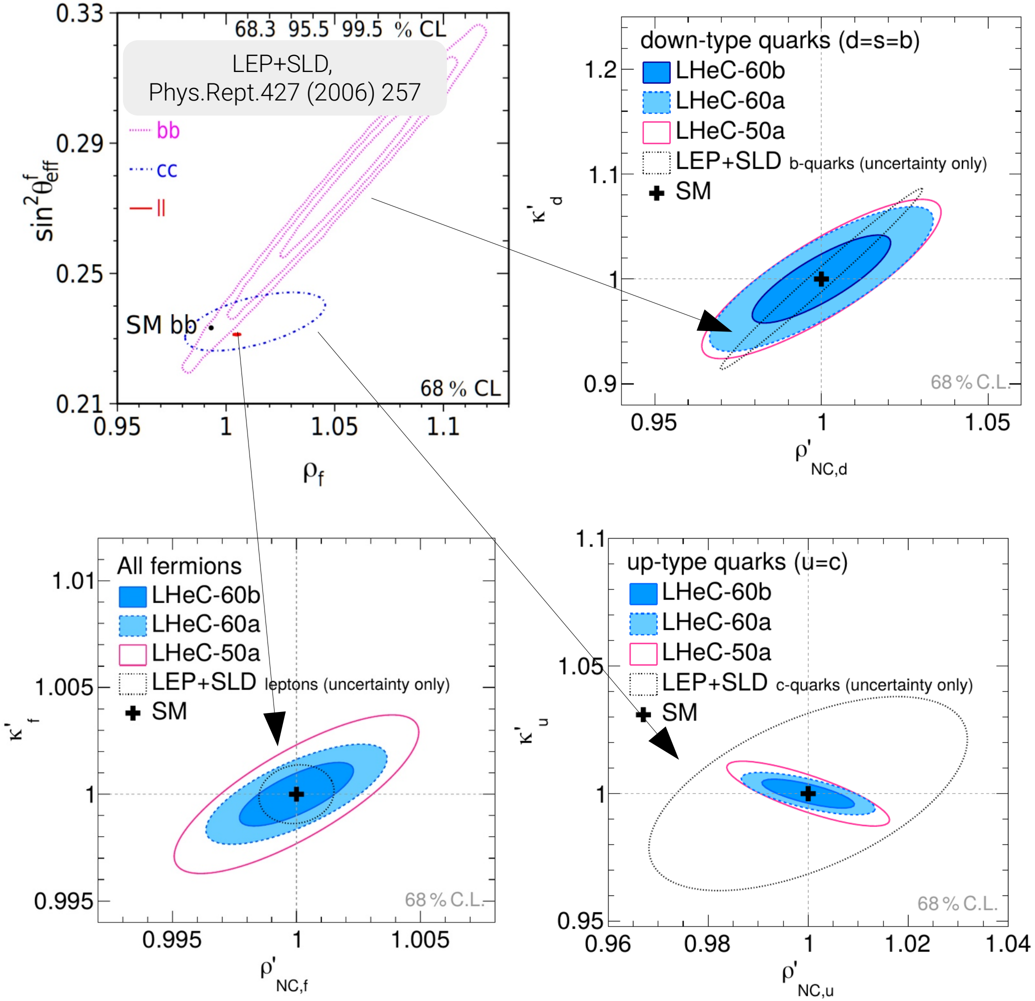


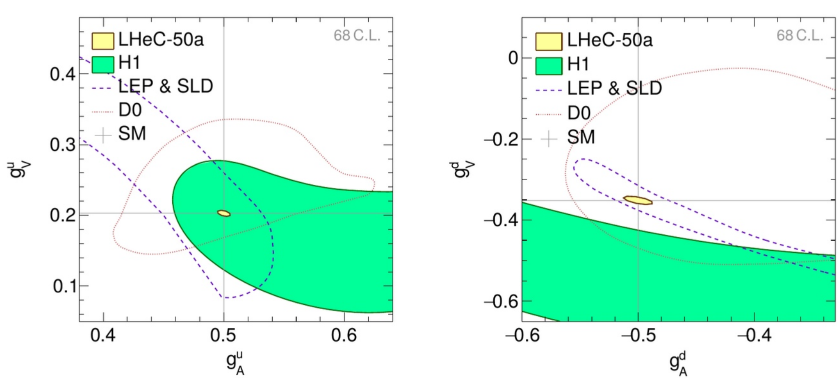
LHeC vs. LEP+SLD

2D determinations of κ and ρ

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

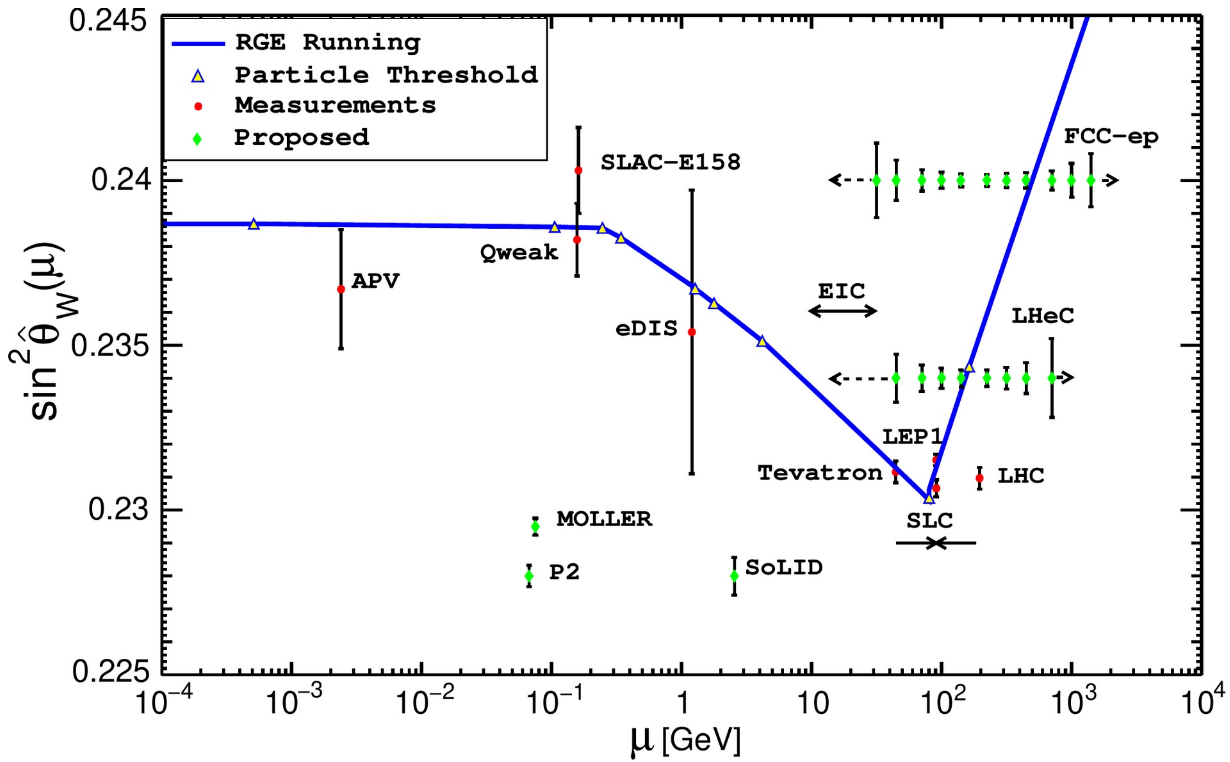
- Competitive sensitivity to LEP+SLD (albeit a single detector only)
- Complementary with pp/ee
  - c-quark vs. u-quarks
  - b-quarks vs. d-quarks
- highest precision for 1st gen. quark couplings





DB, Spiesberger, Klein,
EPJ C 80 (2020) 831

Running of the weak mixing angle



Proposed future experiments (green) have arbitrary vertical offsets

Present Z-pole measurements have horizontal offset

- Simultaneous determination of multiple values of $\sin^2\theta_W$ together with PDFs at different Q^2
- Per mille uncertainties in 20 < Q < 2000 (700) GeV in spacelike regime
- Unique measurement of 'running' at high scales

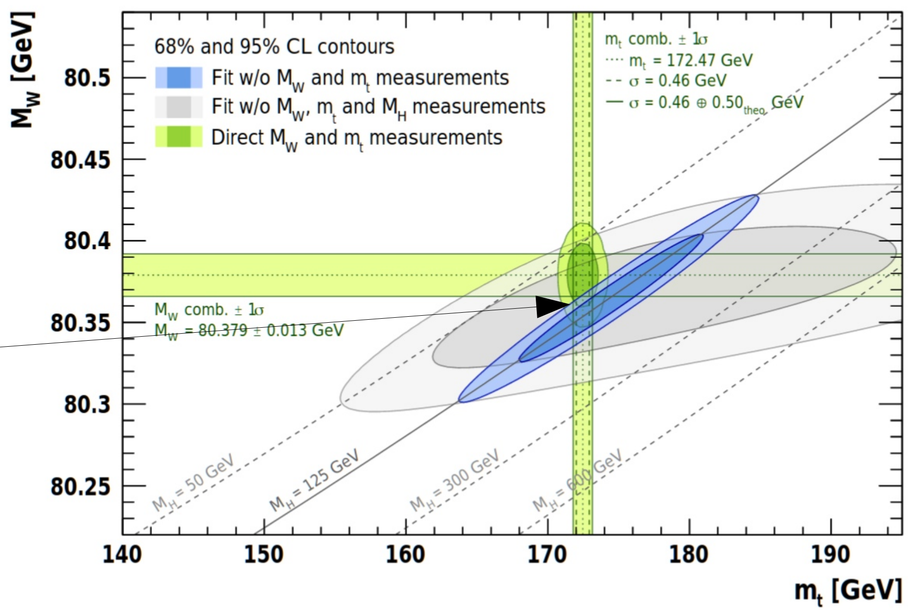
DB, Spiesberger, Klein, PoS EPS-HEP2021 (2022) 367

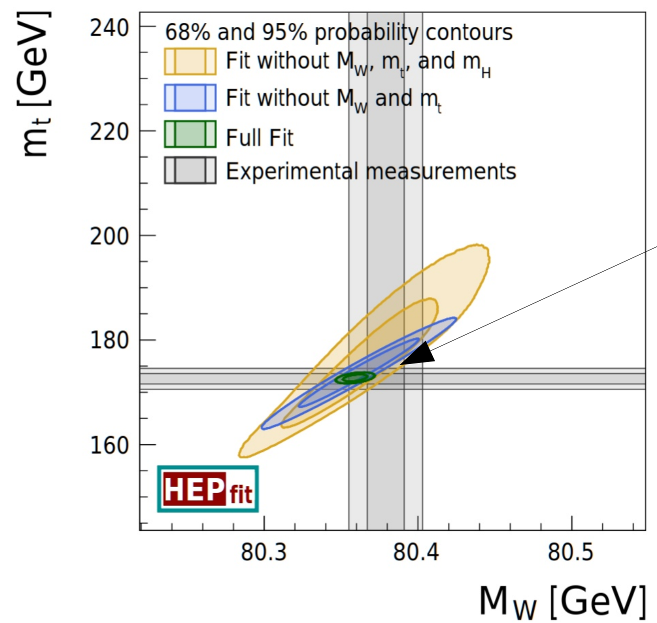
(The) global electroweak fit – with LHeC

Global electroweak fit

- Many precision observables fitted together
- Full fit with m_W & m_t, where ρ_t defines correlation → Overconstrained test of the SM

'Full fit' not displayed here





'Full fit'

arXiv:2112.07274

HEPfit, JHEP 12 (2016) 135
GFitter, EPJ C78 (2018) 675
PDG20, PTEP 2020 (2020) 083C01
arXiv:2112.07274

(The) global electroweak fit – with LHeC

(simplified) global electroweak fit

- Free EW parameters:
  G_F, m_Z, m_t, m_H
- Constraints from direct measurements:
  G_F, m_Z, m_t, m_H, m_W

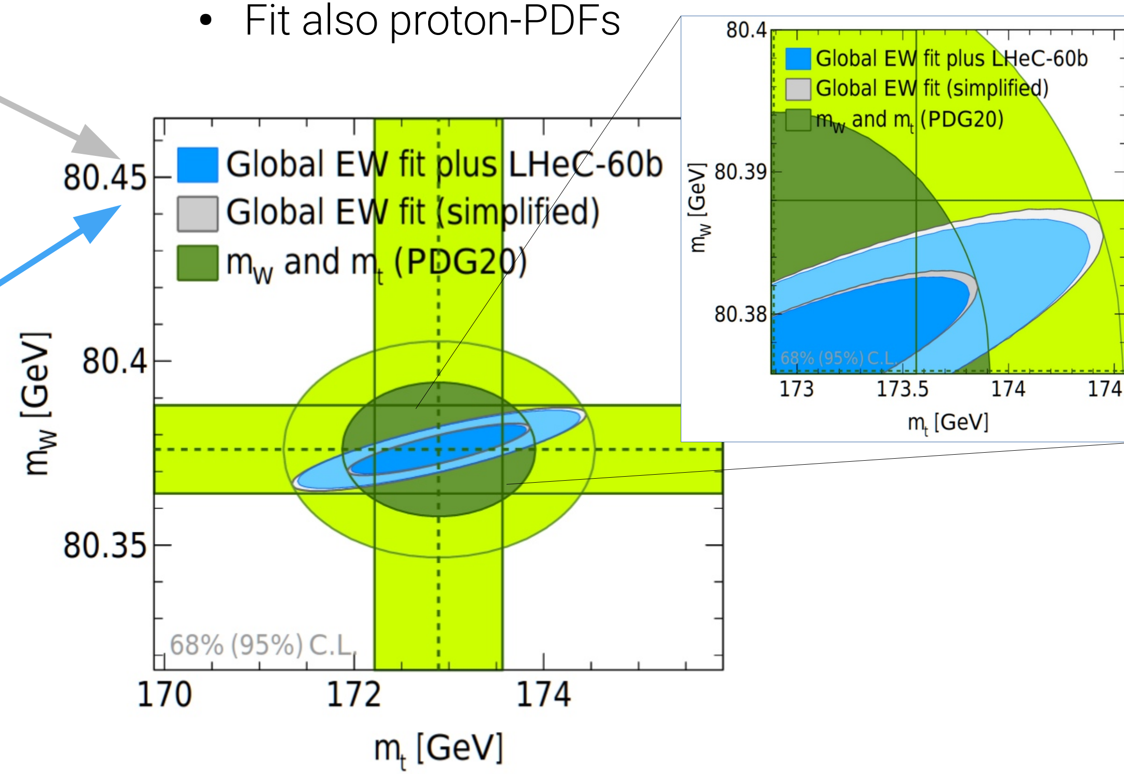
→ Good agreement of expct'd uncertainties with global fitters

Include inclusive DIS data

- Free fit parameters:
  G_F, m_Z, m_t, m_H, 13*PDFs
  → Fit also proton-PDFs
- Constraints from measurements:
  G_F, m_Z, m_t, m_H, m_W, 1200 NC/CC DIS data
  → DIS predictions: NNLO QCD + 1-loop EW

Global electroweak fit with LHeC inclusive DIS data

- m_W−m_t relation domainated by ρ_t
- Fit also proton-PDFs



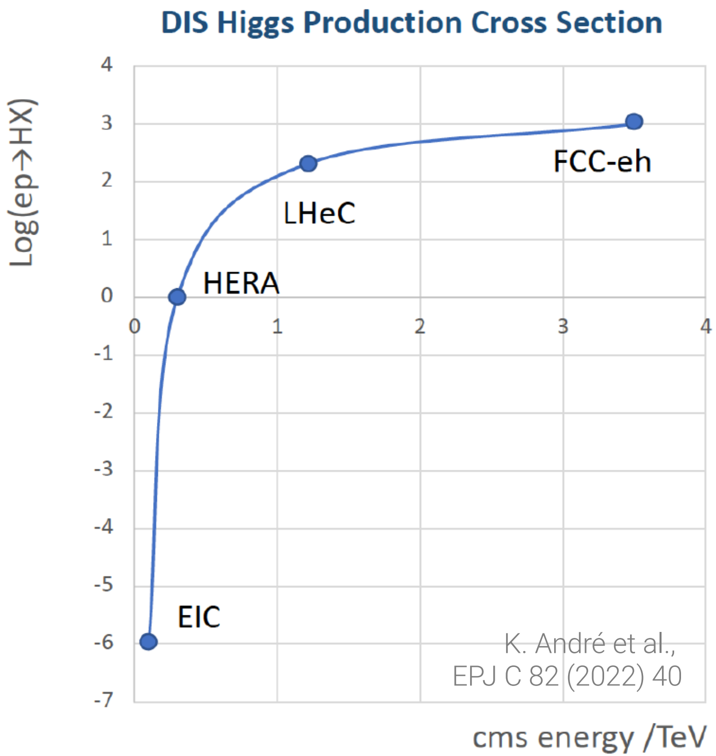
→ Only tiny impact of DIS data observed on m_t-m_W correlation

Conclusions

- Precision physics at the LHC becomes successively limited by PDF uncertainties
- Deep-inelastic scattering is sensitive to PDFs and has sensitivity to electroweak effects
- A simultaneous determination of PDFs and electroweak parameters exhibit some moderate sensitivity to EW parameters, with some highlights:
  → NC couplings of 1^{st} gen. quarks, scale-dependent parameters, EW effects in charged-currents
  → Exact treatment of EW effects in DIS predictions will (very likely) not affect the PDFs
- Future high-luminosity TeV-scale DIS experiments (LHeC) could reduce PDF uncertainties in proton-proton analyses, and enable to achieve uncertainties at a competitive level
  → These LHeC data would also be highly sensitive to EW effects themselves, and being complementary to *pp* or e^+e^- data (and being highly sensitive to Higgs-couplings)
- Full 'global EW-fit' together with a PDF determination is possible, but DIS data will not contribute to the m_t-m_W relation

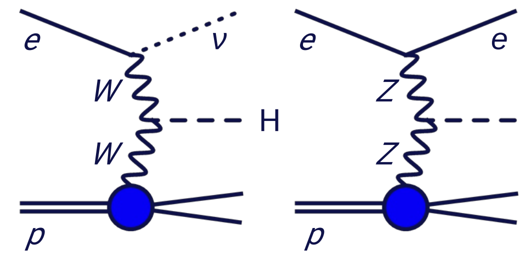
Backup

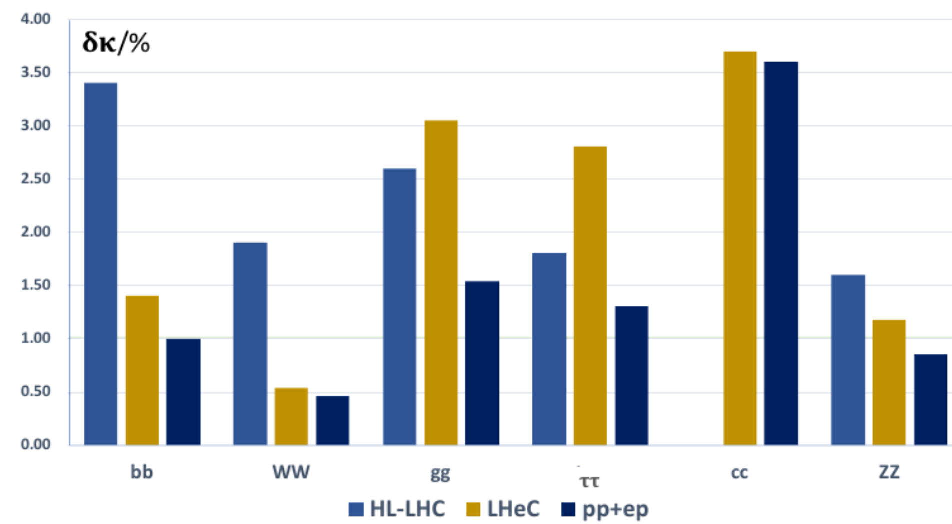
Higgs physics at LHeC



- Higgs prodcution in CC and NC DIS

Higgs couplings in kappa-framework





- Higgs-production cross section ~ 200pb
- Sensitivity to six decay channels

  bb, WW, gg, ττ, cc, ZZ

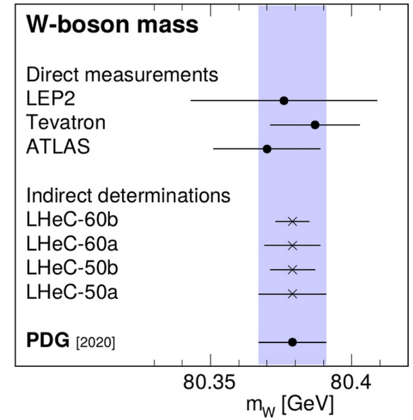
LHeC provides most precise measurements of

1. H → ff (in bb channel)
2. H → VV (in WW channel)

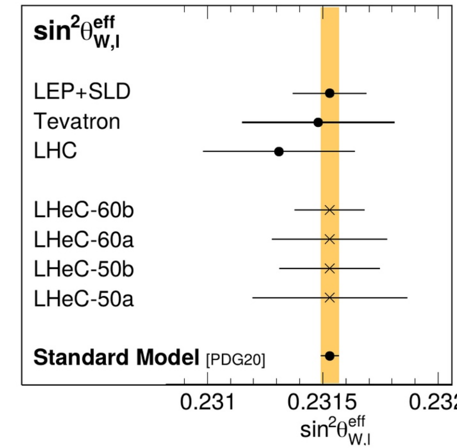
EW physics with LHeC inclusive DIS data

LHeC inclusive DIS data would come with an interesting sensitivity to EW effects

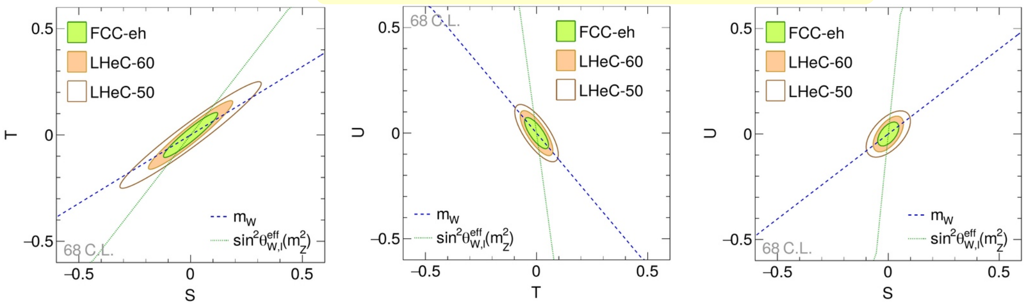
indirect W-mass



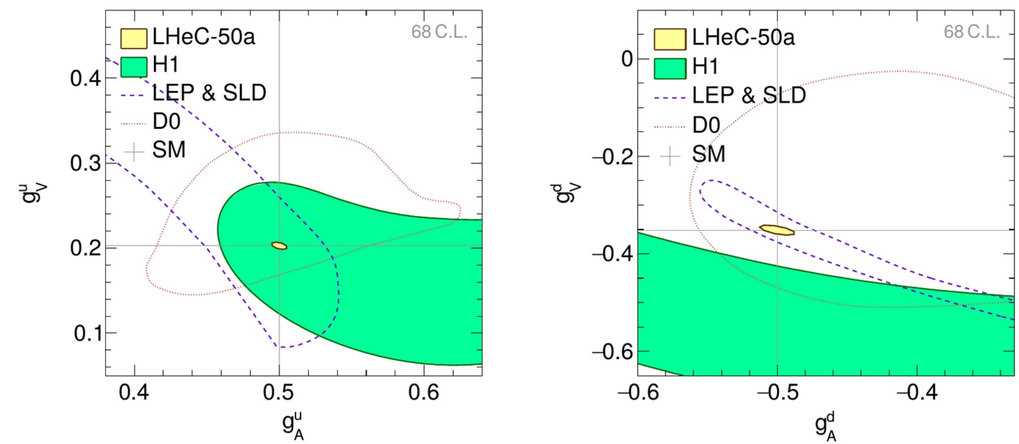
$\sin^2\theta_{l,eff}$



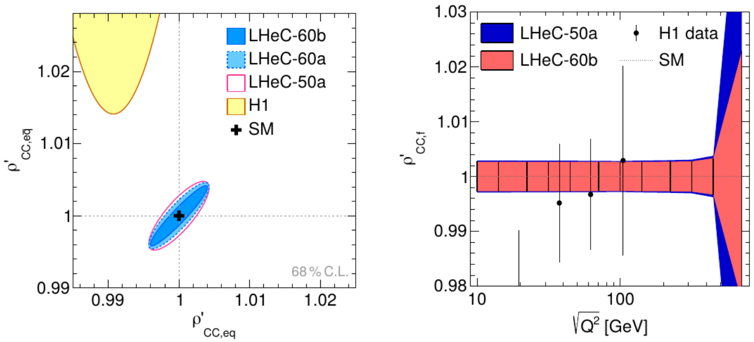
STU parameters



1st gen. NC quark couplings



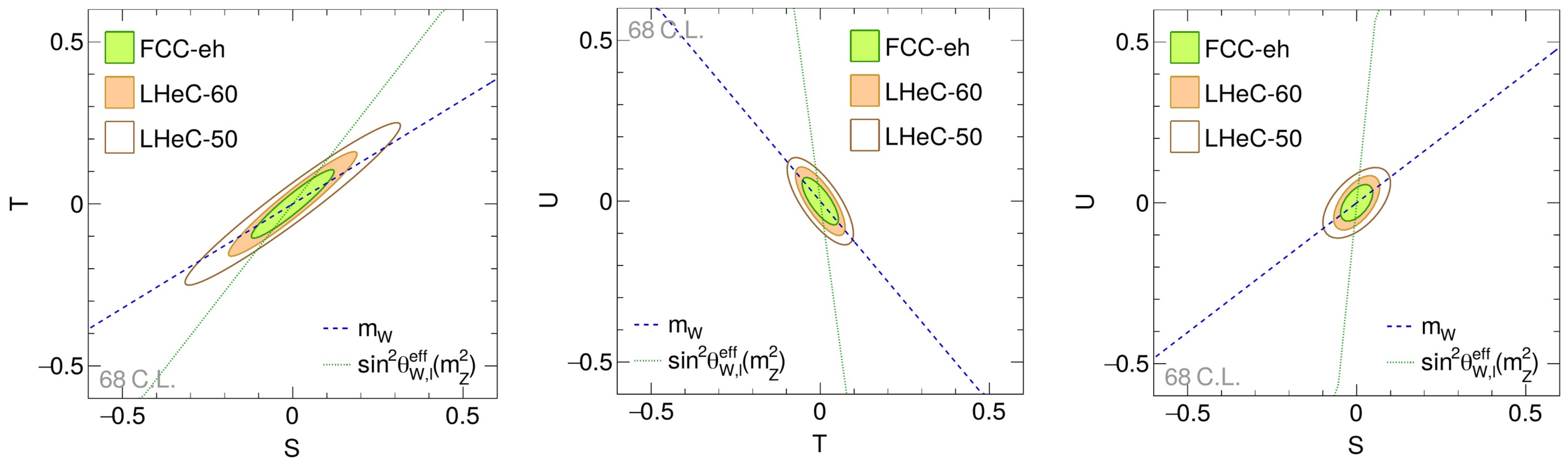
Charged current couplings



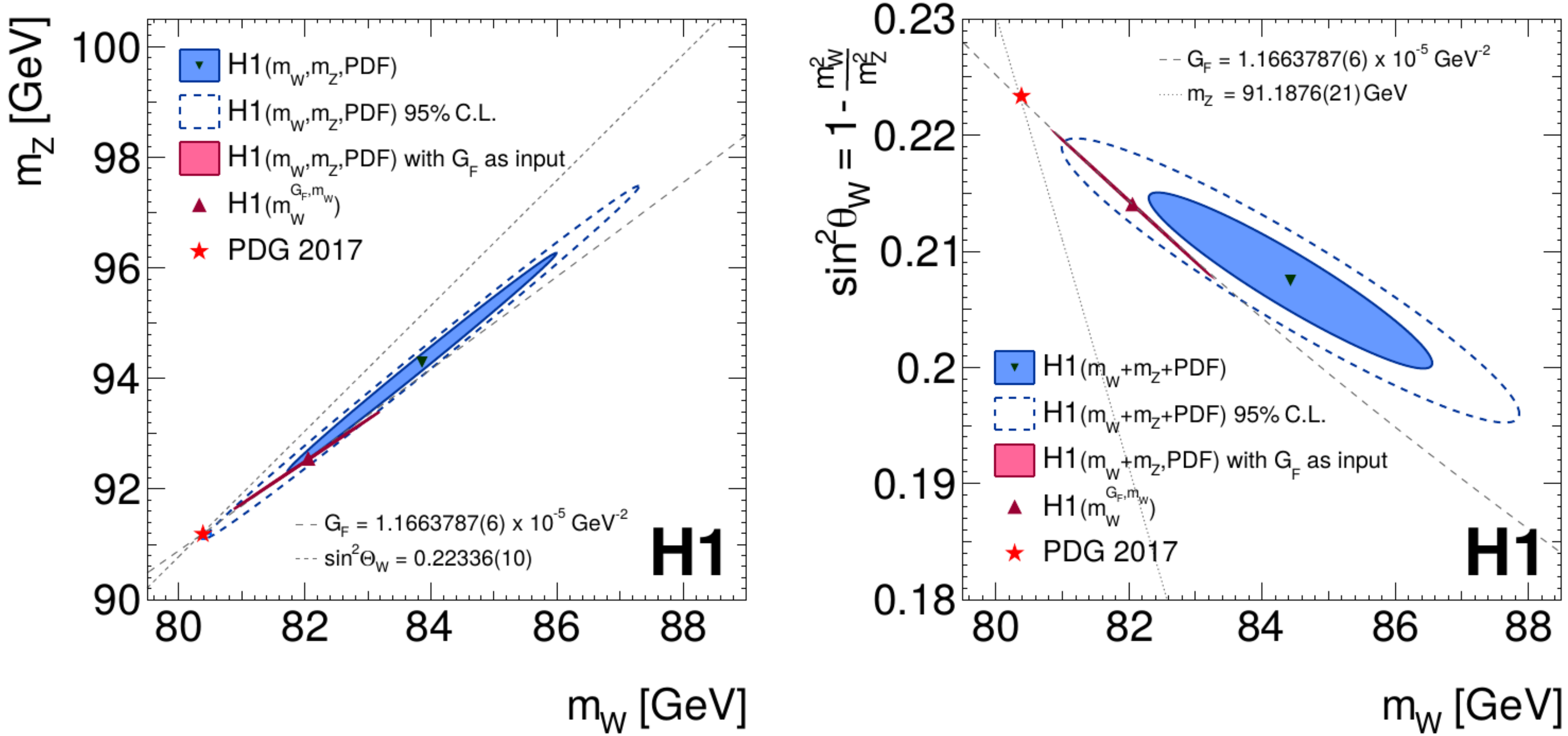
STU parameters from inclusive DIS

S, T, U parameters are non-SM contributions to Z & W-boson self-energies

- Studied here: 2-parameter fits incl. PDF fit
- Scheme dependence: Modified on-shell (MOMS)
- With inclusive NC&CC DIS: Possible to disentangle S, T and U
  → Complementary to Z-pole



W and Z mass – with G_F as additional input



W-mass in other PDF+EW analyses using HERA data

H1 – HERA-I data

H1, Phys.Lett.B632 (2006) 35

$$M_W = 80.786 \pm \underline{0.205_{\text{exp}}} \,{}^{+0.048}_{-0.029}\Big|_{\text{model}} \pm 0.025_{\delta m_t} - 0.084_{\delta M_H} \pm 0.033_{\delta(\Delta r)}\ \text{GeV}\,.$$

[47]

H1 – HERA-I + HERA-II data

H1, Eur.Phys.J.C78 (2018), 777

$$m_W = 80.520 \pm 0.070_{\text{stat}} \pm 0.055_{\text{syst}} \pm 0.074_{\text{PDF}} = 80.520 \pm \underline{0.115_{\text{tot}}}\ \text{GeV}\,.$$

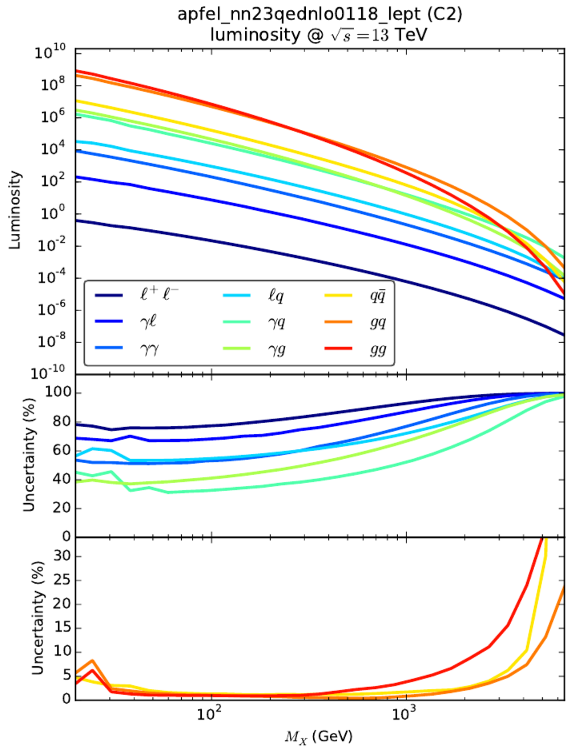
ZEUS Collab. – H1-HERA-I + H1-HERA-II + ZEUS-HERA-I + ZEUS-HERA-II data

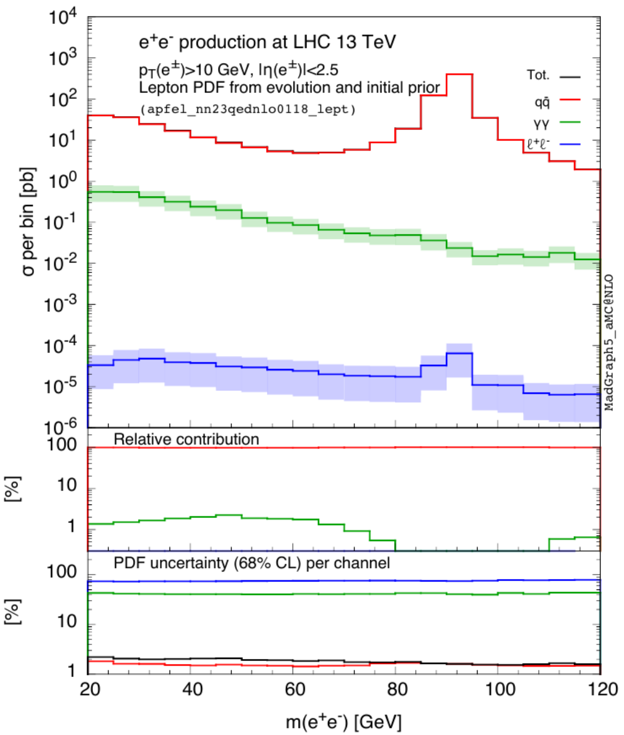
$$M_W = 80.68 \ \pm \underline{0.28\,(\text{experimental/fit})} \ {}^{+0.12}_{-0.01}\,(\text{model}) \ {}^{+0.23}_{-0.01}\,(\text{parameterisation})\ \text{GeV}\ .$$

This t-channel determination is in agreement with the PDG14 value of 80.385±0.015 GeV, which is dominated by s-channel processes. The result presented here is a substantial improvement compared to a result published by H1 using HERA I data [47].

ZEUS, Phys. Rev. D 93 (2016) 092002

PDFs with photons and leptons





Physics Letters B 820 (2021) 136534

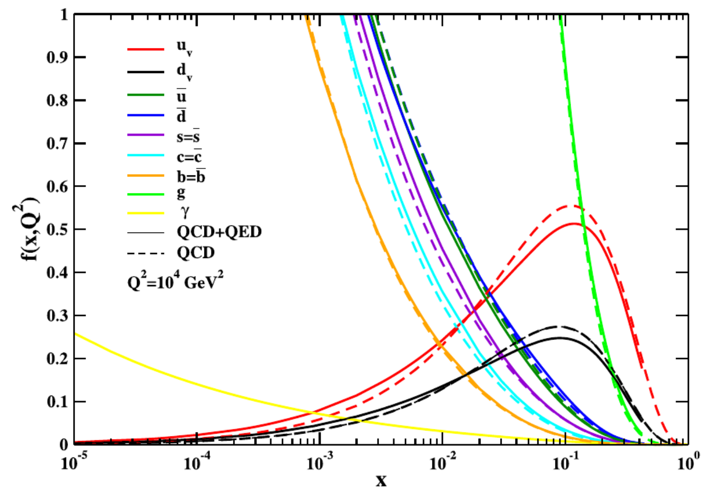


Fig. 1. The parton distribution functions at $Q^2 = 10^4$ GeV^2 with and without QED corrections.

$$P^{(0)}_{\gamma\gamma}(x) = -\frac{4}{3}\delta(1-x)$$