Electroweak physics at the FCC-eh (and LHeC)

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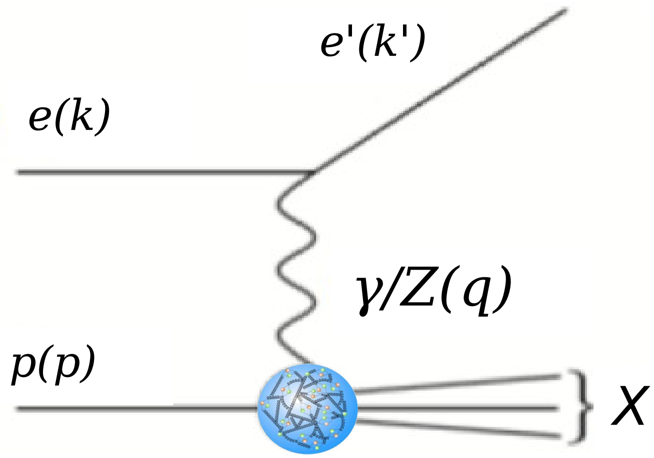
Snowmass EF04 meeting

10.09.2021

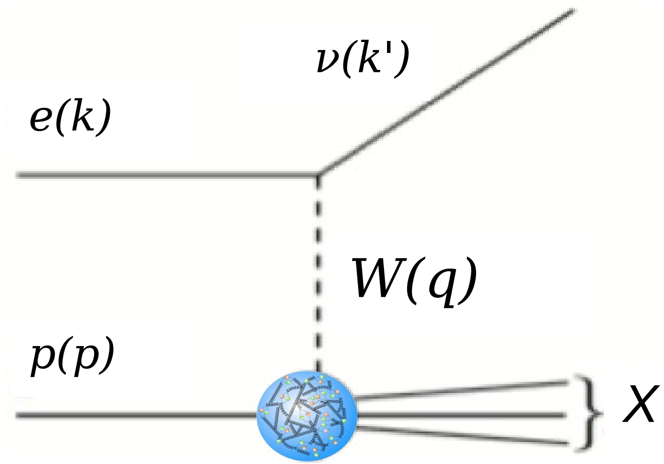
MAX-PLANCK-INSTITUT
FÜR PHYSIK

Deep-inelastic electron-proton scattering

Neutral current scattering
$ep \rightarrow e'X$



Charged current scattering
$ep \rightarrow \nu_e X$

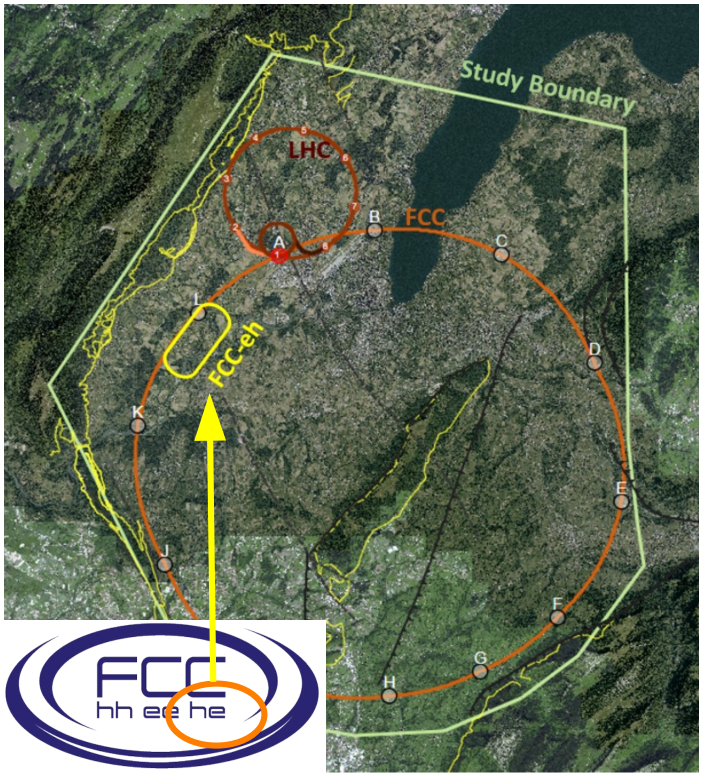


Deep-inelastic electron-proton scattering

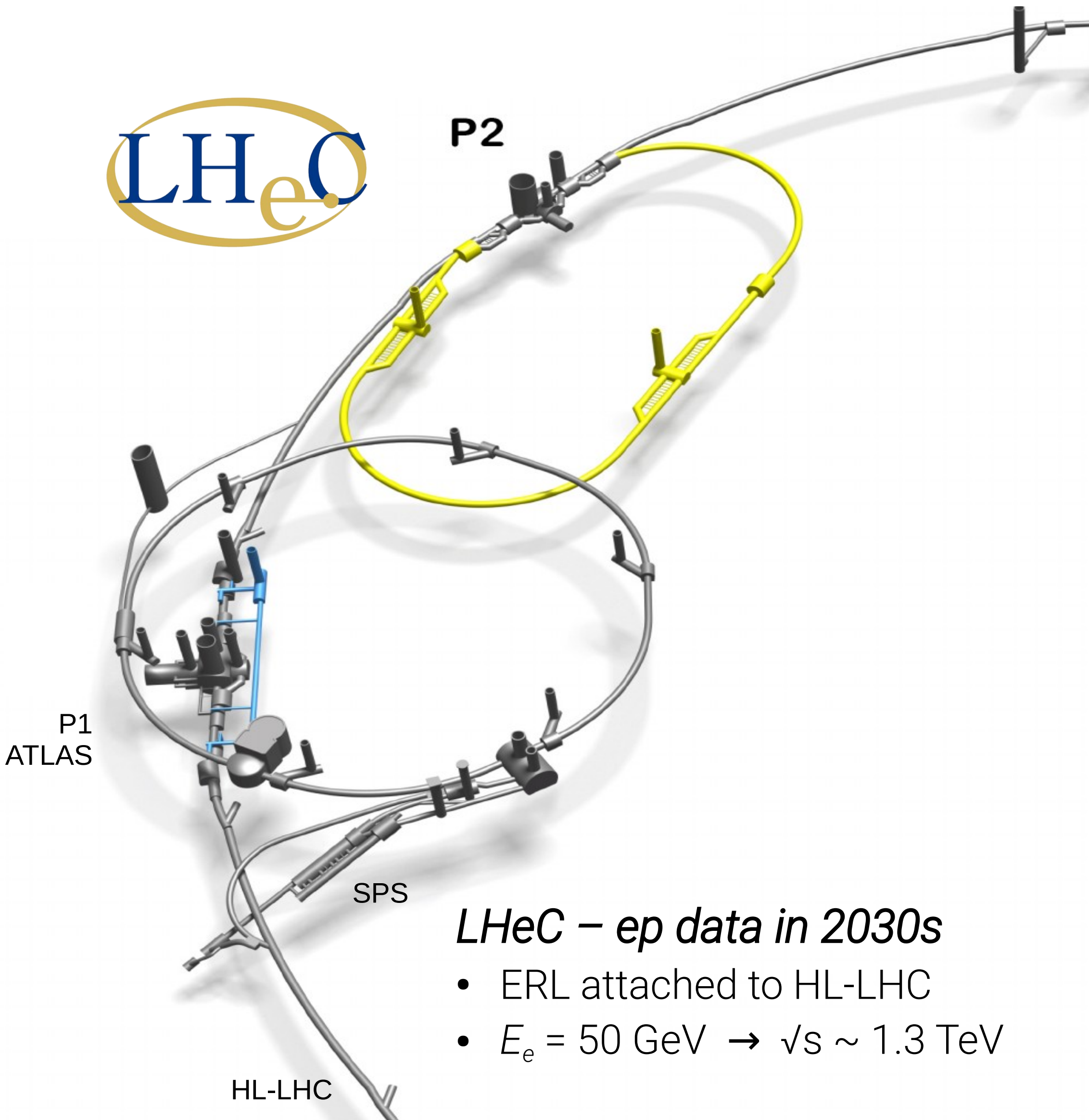
mediated in spacelike regime, by γ, γZ, Z or W-boson exchange

-> Ideal QCD and Electroweak laboratory

Future high-energy electron-proton experiments



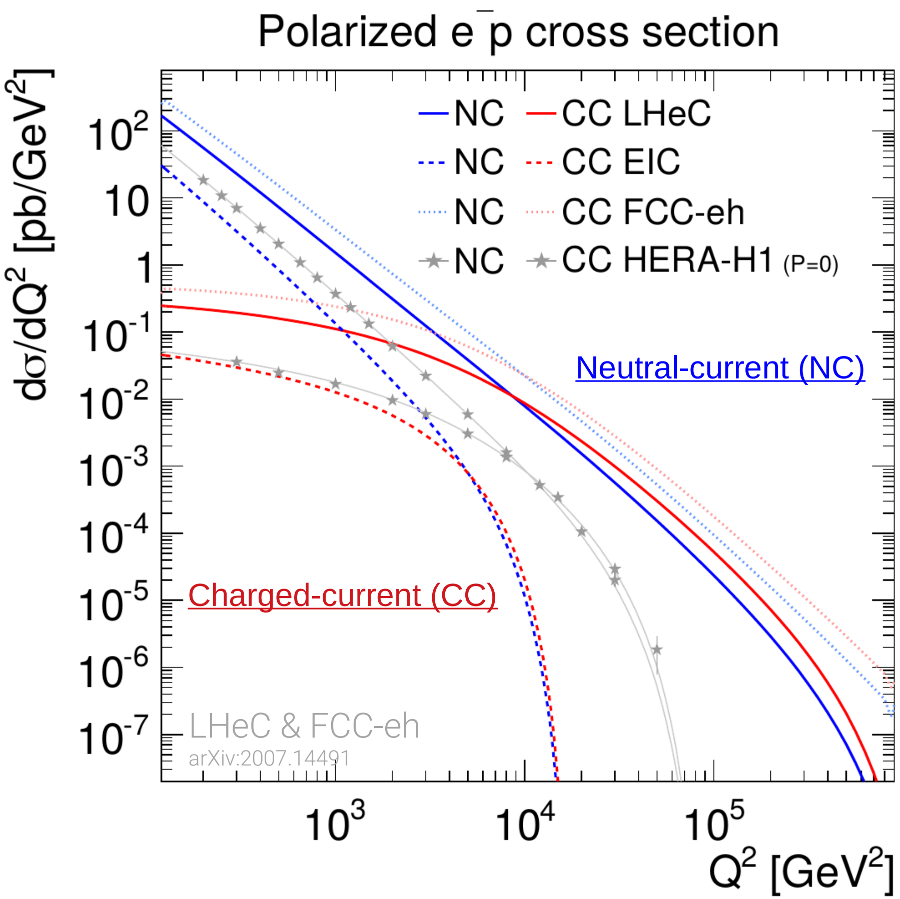
- Dedicated electron-ring attached to FCC-hh
- Energy recovery linac: E_e = 60 GeV
- $\sqrt{s}$ ~ 3.5 TeV
- More than 1 ab^{-1} integrated luminosity

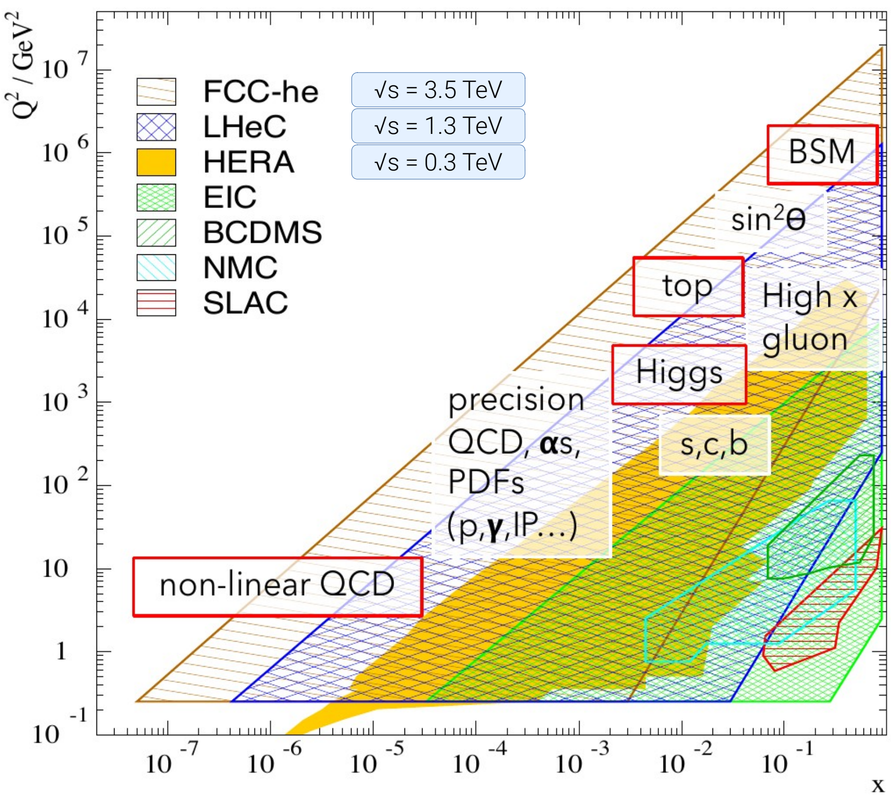


LHeC – ep data in 2030s

- ERL attached to HL-LHC
- E_e = 50 GeV → $\sqrt{s}$ ~ 1.3 TeV

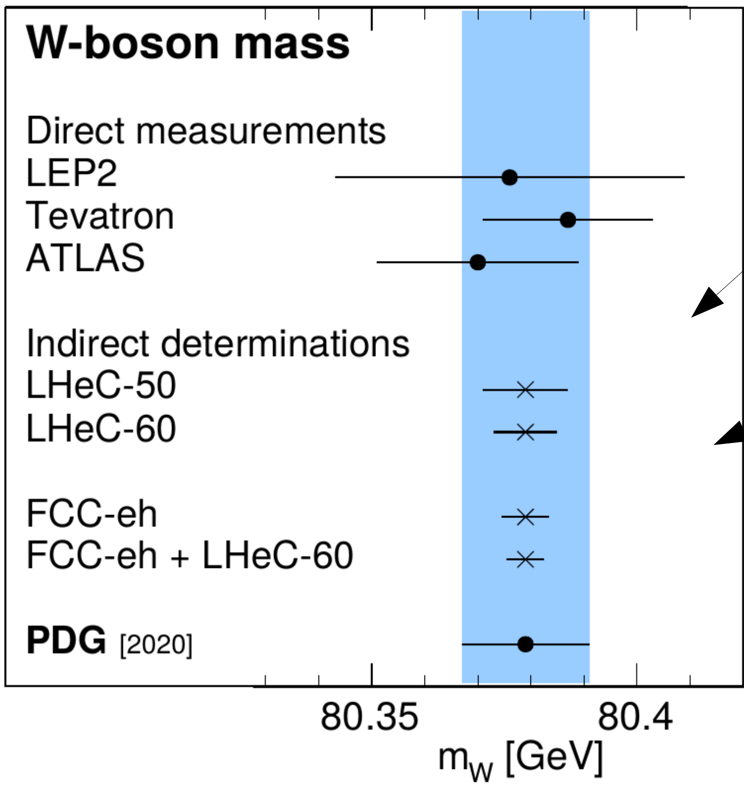
Electroweak physics in inclusive DIS





Expectations: m_W + PDF

Determine W-boson mass together with proton-PDFs



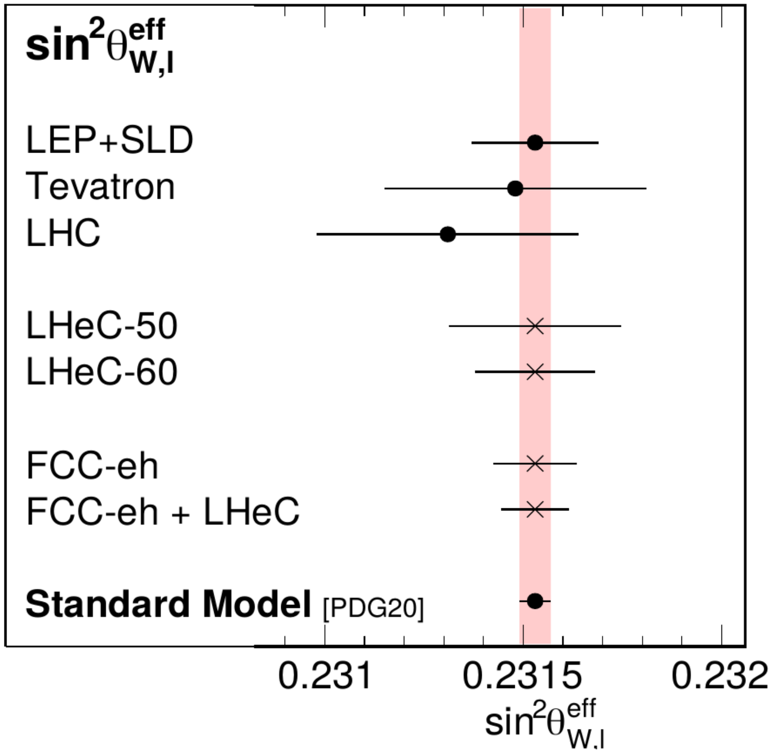
- LHeC with L ~ $1ab^{-1}$
  - LHeC (E_e=50GeV): $\Delta m_W = \pm 8$ MeV
  - LHeC (E_e=60GeV): $\Delta m_W = \pm 6$ MeV
- FCC-eh with L ~ $1ab^{-1}$ **$\Delta m_W = \pm 4.5$ MeV**

  (includes PDF uncertainty of about ±3.6 MeV)
  - FCC-eh + LHeC: $\Delta m_W = \pm 3.6$ MeV

- Indirect determination of m_W
- Complementary to 'direct' measurements

  → Consistency test of EW Standard Model
- Smallest uncertainties from a single experiment

The weak mixing angle



$\Delta\sin^2\theta_W$ (FCC-eh) = ±0.00011
= $\pm 0.00010_{(exp)}$ $\pm 0.00004_{(PDF)}$

Weak mixing angle

- $\sin^2\theta_W$ in neutral-current vector couplings (only)

$$g_V^f = \sqrt{\rho_{NC,f}}\left(I^3_{L,f} - 2Q_f\,\kappa_f\,\sin^2\theta_W\right)$$

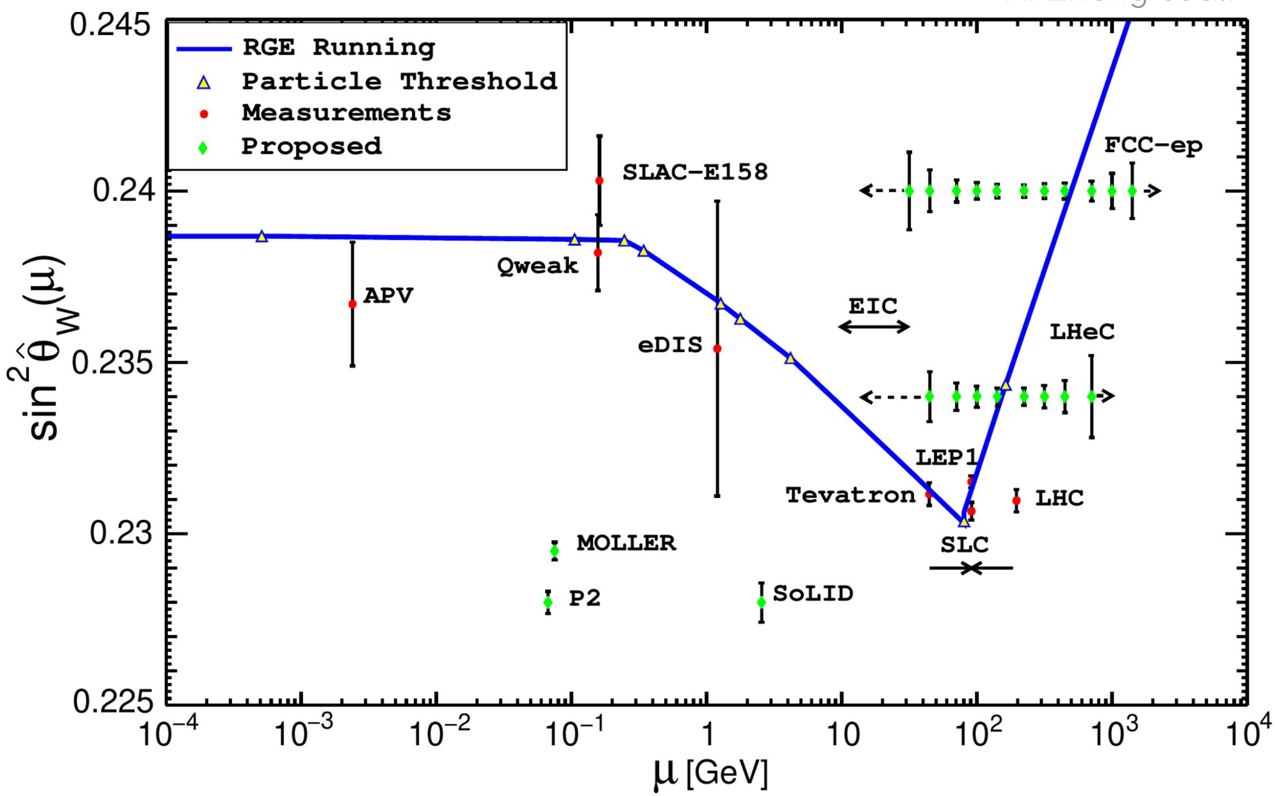
$\sin^2\theta_W$ + PDF fit

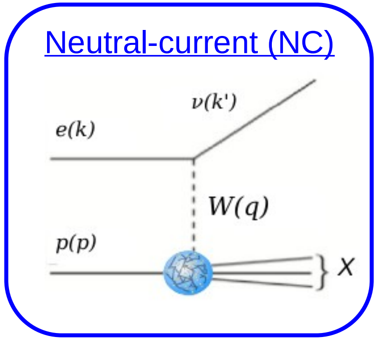
- Comparison to Z-pole data
- At future DIS facilities:
  Most precise single measurement possible
- Note: need theory to map $\sin^2\theta_W$ to effective leptonic weak mixing angle

$\Delta\sin^2\theta_W$ (LHeC-50) = ±0.00021
$\Delta\sin^2\theta_W$ (LHeC-60) = ±0.00015
$\Delta\sin^2\theta_W$ (FCC-eh+LHeC) = ±0.000086

Running of the weak mixing angle

X. Zheng et al.

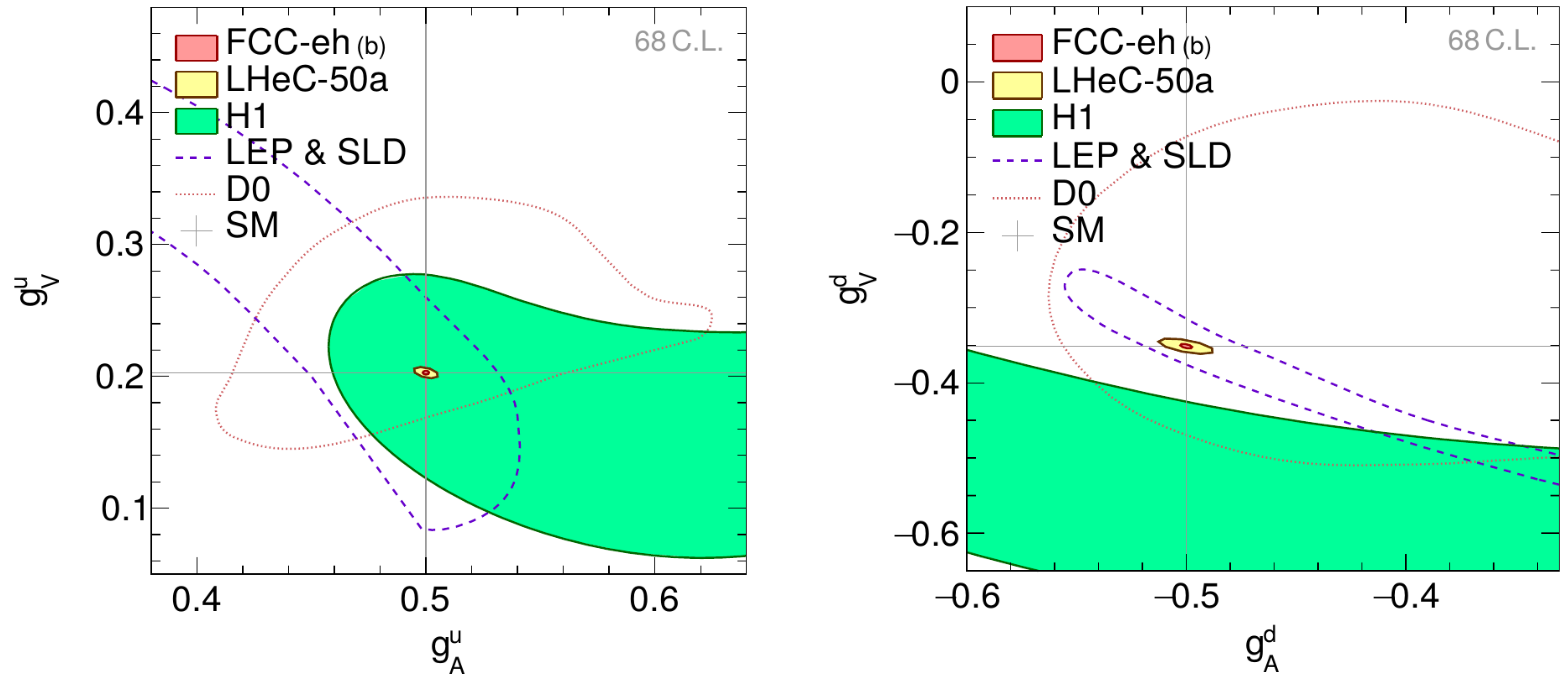




- Simultaneous determination of multiple values of $\sin^2\theta_W$ together with PDFs at different Q^2
- Per mille uncertainties in about 20 < Q < 2000 (700) GeV in spacelike regime
- Unique measurement of 'running' at high scales

Light quark NC couplings

Light quark (*u*- & *d*-type quarks) neutral-current couplings to the *Z*-boson



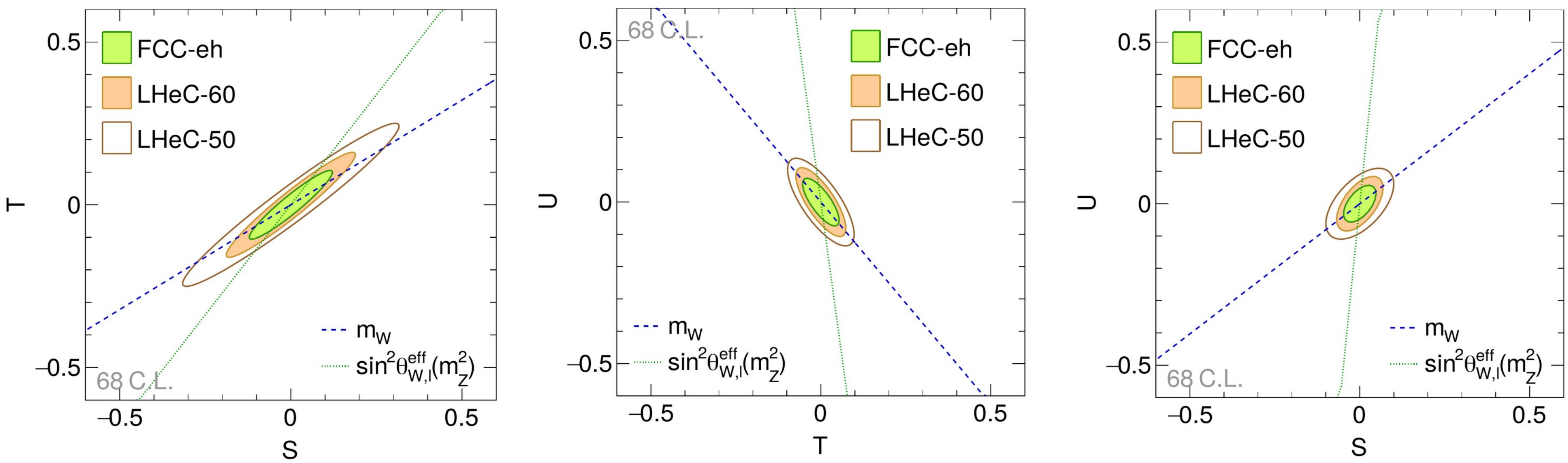
- LHeC already improves by more than an order of magnitude
- FCC-eh with per-mille precision
- *u*-type and *d*-type can be separated – no sign ambiguity as in *Z*-pole data due to *γZ* terms

STU parameters from inclusive DIS

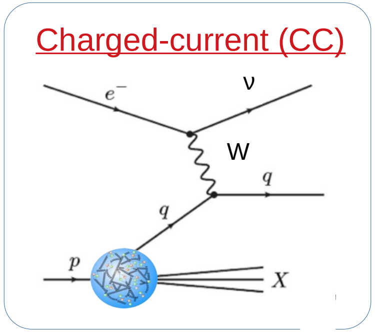
S, T, U parameters are non-SM contributions to Z & W-boson self-energies

- 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

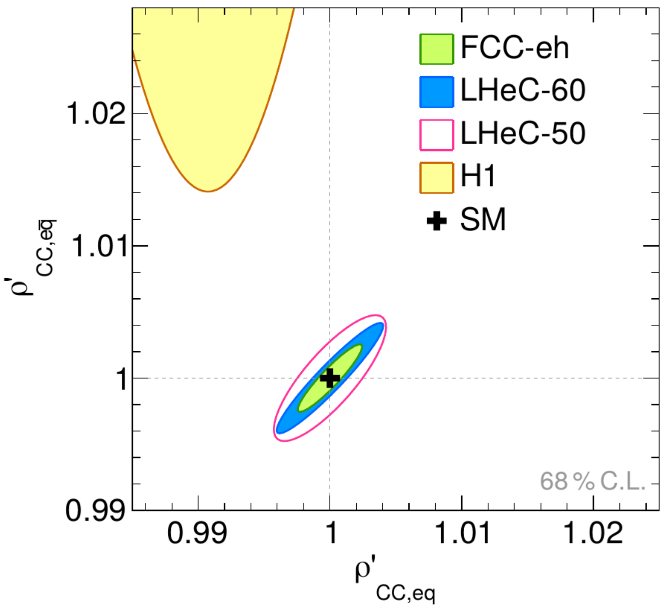


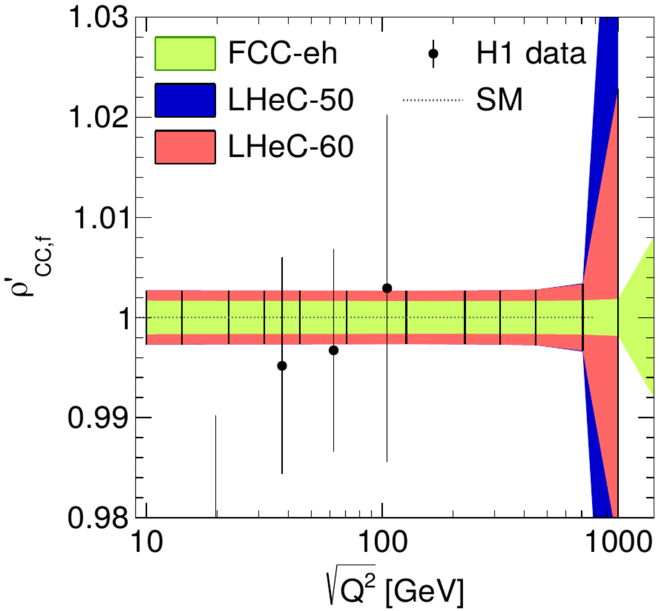
Charged current



Study charged current cross sections in DIS

$$W_2^- = x\left((\rho_{CC,eq}\rho'_{CC,eq})^2U + (\rho_{CC,e\bar{q}}\rho'_{CC,e\bar{q}})^2\overline{D}\right)$$
$$xW_3^- = x\left((\rho_{CC,eq}\rho'_{CC,eq})^2U - (\rho_{CC,e\bar{q}}\rho'_{CC,e\bar{q}})^2\overline{D}\right)$$



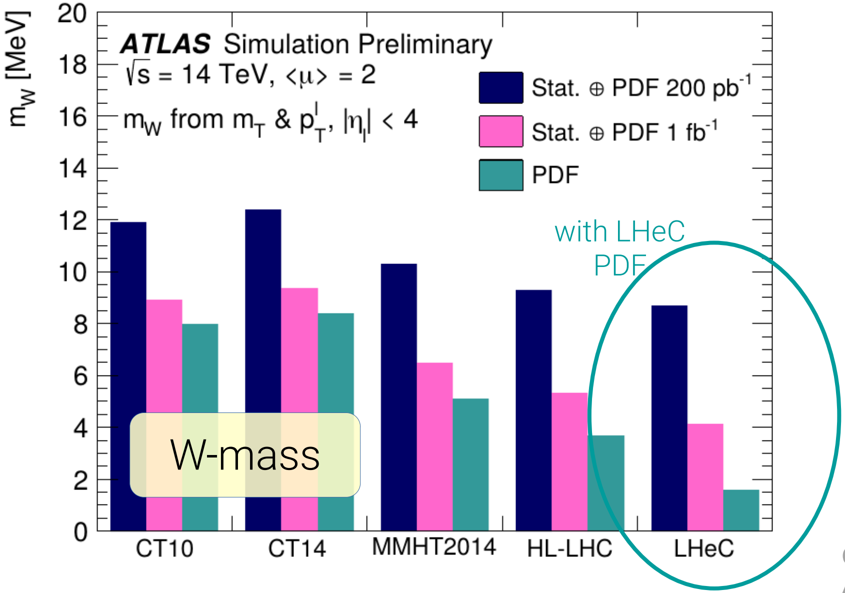


Charged current couplings not well studied experimentally – unique to DIS

The impact of LHeC on HL-LHC (through PDFs)

W-mass measurements in pp

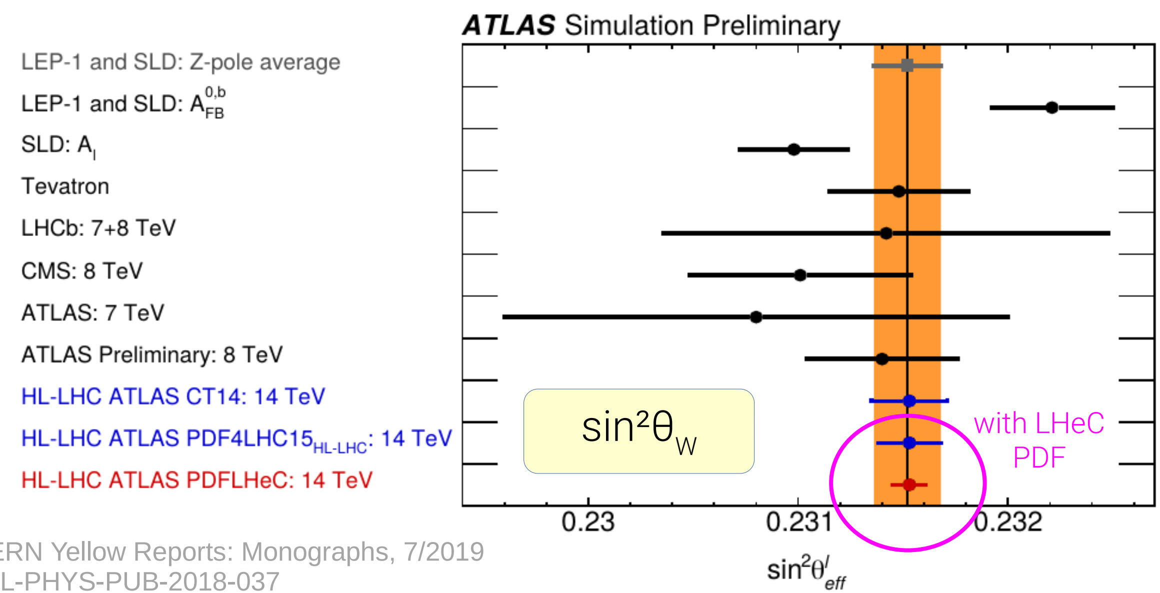
- Major uncertainty from PDFs



- Reduction of PDF uncertainty only feasible with LHeC PDFs ($\Delta m_W^{PDF} \sim 2$MeV)

Effective weak mixing angle in pp

- Large uncertainty from PDFs



CERN Yellow Reports: Monographs, 7/2019
ATL-PHYS-PUB-2018-037

- HL-LHC−PDF reduces uncertainty by 10-25%
- → LHeC *ep* data would provide needed factor of 5−10 in PDF improvement to exceed LEP precision

Summary

The LHeC and FCC-eh projects

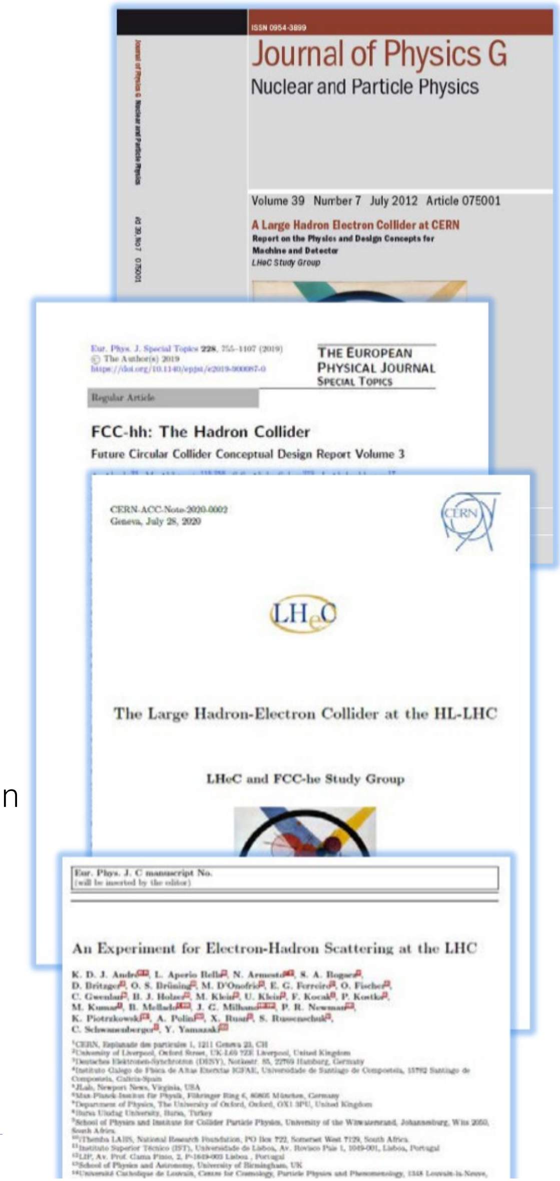
- 50 GeV electron from ERL on 7TeV or 50 TeV protons synchronous with LHC or FCC-hh collisions
- Very rich & diverse physics programme

Electroweak physics (Eur.Phys.J.C 80 (2020) 831 & CDR-2020 [arXiv:2007.14491])

- Fundamental EW parameters: competitive with other measurements
- Complementary to Z-pole data – different aspects of GSW theory are measured
- Several unique measurements possible (Q^2-dependence, charged current, light-quarks couplings,...)

Support of HL-LHC and FCC-hh proton-proton programme

- Complementary measurements (s-channel vs. t-channel, clean low-p_T measurements, clean QCD final-state [H→bb] , etc...)
- Supportive measurements (PDFs, parton shower, hadronisation, fragm. functions, etc...)
- Competeing measurements (Higgs, EW, etc...)
- PDFs for phenomenology
- clarification of initial versus final state effects in hadronic collisions (the small system problem)



Top-quark mass through EW correction

Higher order EW corrections

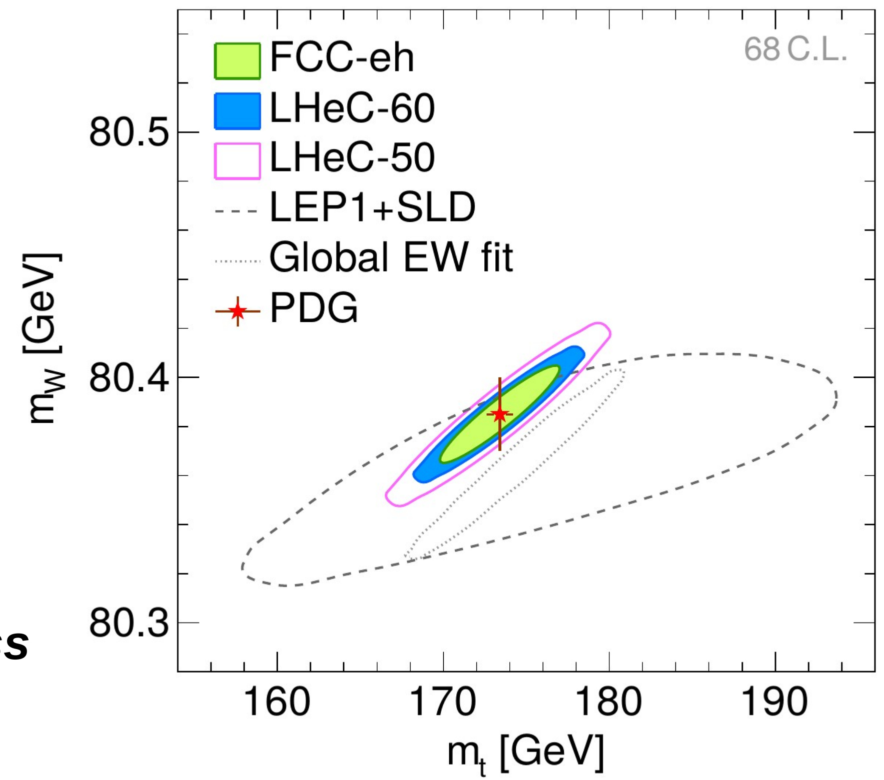
- Dominant term ρ_t in EW-HO corrections proportional to m^2_t/m^2_W
- Same relation as in Z-pole physics

FCC-eh

- Significantly better than LEP+SLD combination
- Higher sensitivity than 'global EW fit'
  (GFitter, EPJ C78 (2018) 675, fit w/o direct m_t & m_W measurements)

Top-mass determination with external W-mass

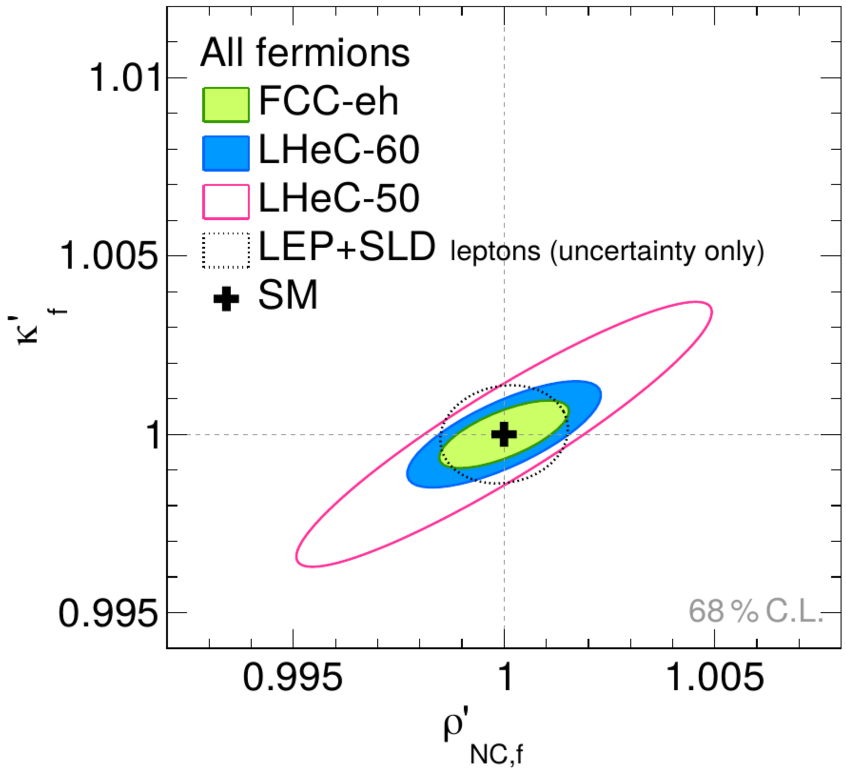
Δm_t (FCC-eh) ~ ±810 MeV (incl. PDF uncert., not incl. Δm_W)



Higgs mass from m_H+PDF fit: Δm_H (FCC-eh) ~ $^{+10.5}_{-9.6}$ GeV

Anomalous form factors

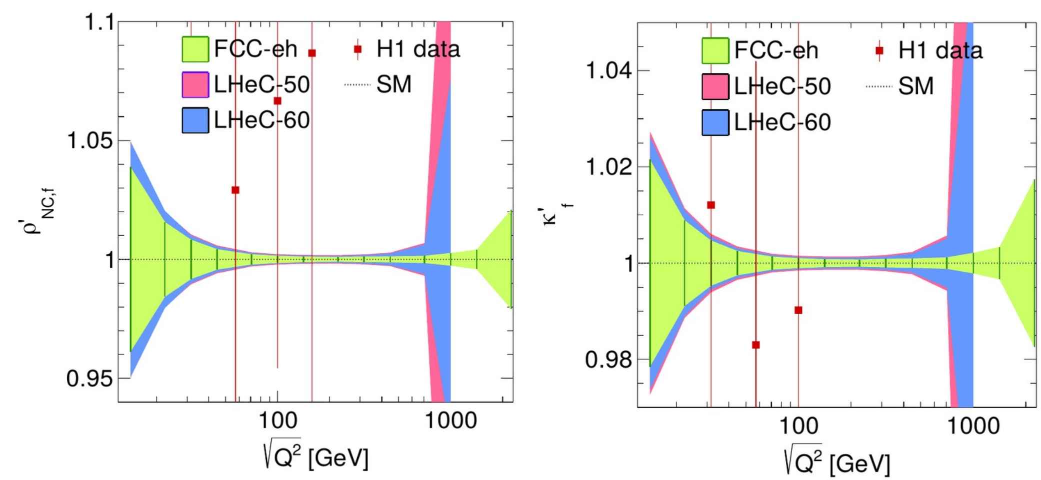
Generically parameterise new physics by modified EW-couplings



- Introduce anomalous form factors ρ' and κ'
  In SM: ρ' and κ' = 1

$$g_A^f = \sqrt{\rho'_{\mathrm{NC},f}\rho_{\mathrm{NC},f}}\, I^3_{\mathrm{L},f}\,,$$
$$g_V^f = \sqrt{\rho'_{\mathrm{NC},f}\rho_{\mathrm{NC},f}}\, \left(I^3_{\mathrm{L},f} - 2Q_f\kappa'_f\kappa_f\sin^2\theta_W\right)$$

- Parameters may be Q² dependent
  (similar to running weak mixing angle)



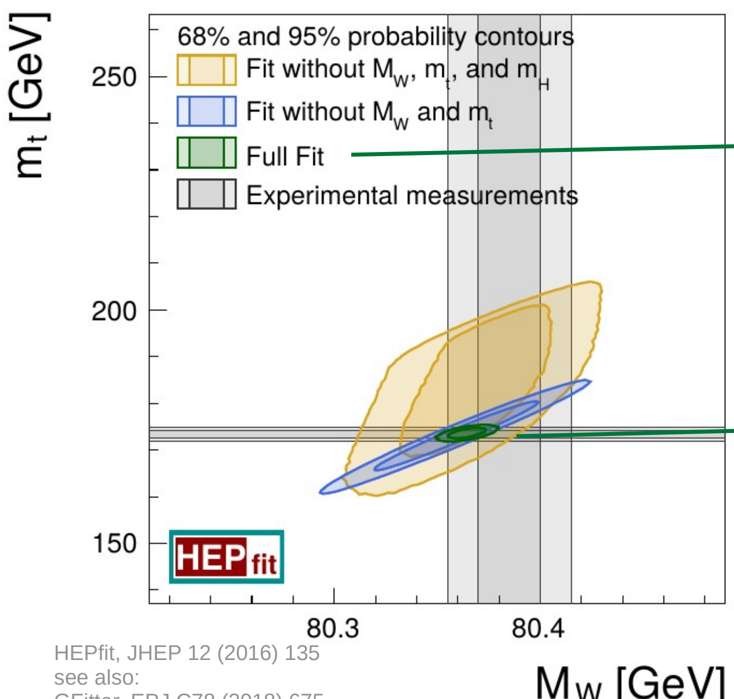
(The) global electroweak fit – with FCC-eh

Global electroweak fit

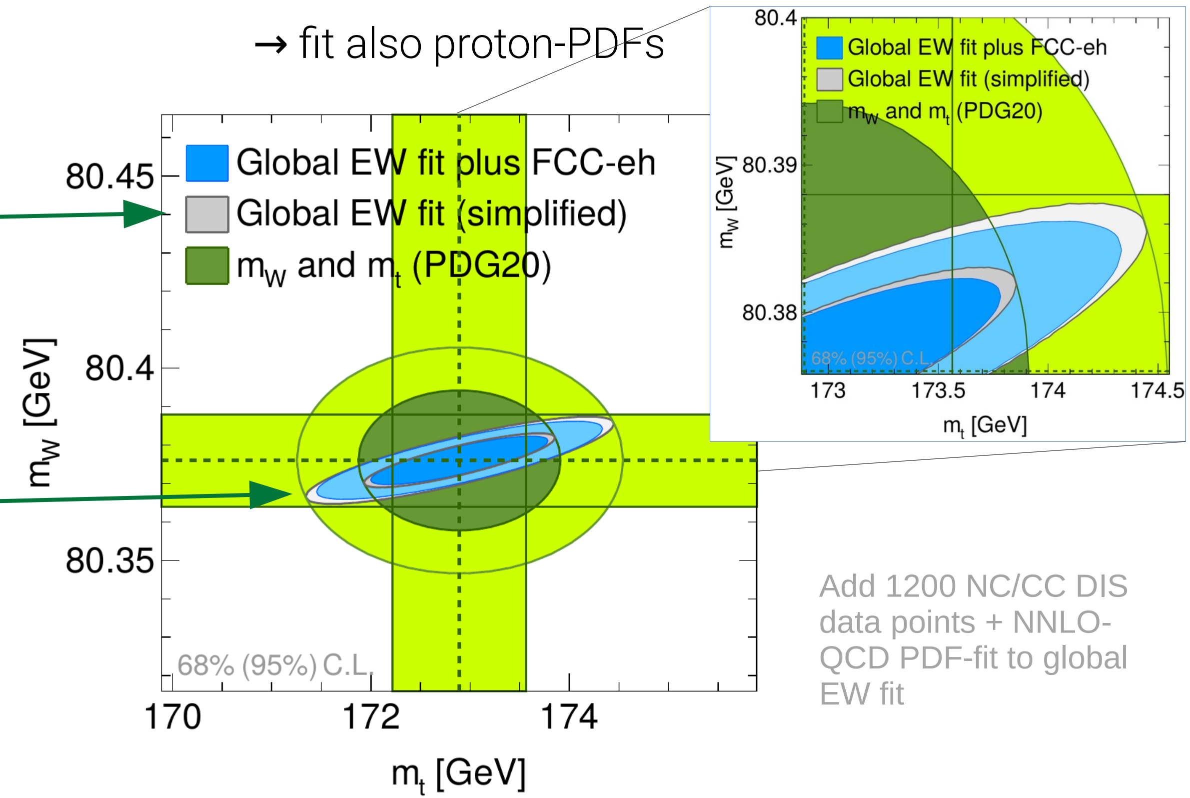
- Many precision observables fitted together
- Fit w/o m_W & m_t compared on slide 16
- Full fit with m_w & m_t, where ρ_t defines correlation

Global electroweak fit with FCC-eh

- simplified setup: drop all observables that do not contribute significantly to m_W−m_t result
- Add FCC-eh inclusive DIS data;
  → fit also proton-PDFs



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



Add 1200 NC/CC DIS data points + NNLO-QCD PDF-fit to global EW fit

Electroweak physics in inclusive DIS

Inclusive DIS (neutral-current)

$$\frac{d^2\sigma^{\rm NC}(e^\pm p)}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+\tilde{F}_2^\pm(x,Q^2) \mp Y_- x\tilde{F}_3^\pm(x,Q^2) - y^2\tilde{F}_{\rm L}^\pm(x,Q^2)\right]$$

$$\tilde{F}_2^\pm = F_2 - (g_V^e \pm P_e g_A^e)\varkappa_Z F_2^{\gamma Z} + \left[(g_V^e g_V^e + g_A^e g_A^e) \pm 2P_e g_V^e g_A^e\right]\varkappa_Z^2 F_2^Z$$

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

On-shell scheme

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

Z-exchange normalisation

$$\varkappa_Z(Q^2) = \frac{Q^2}{Q^2+m_Z^2}\frac{1}{4\sin^2\theta_W\cos^2\theta_W}$$

NC couplings

$$g_A^f = \sqrt{\rho_{{\rm NC},f}}\, I_{{\rm L},f}^3\,,$$
$$g_V^f = \sqrt{\rho_{{\rm NC},f}}\left(I_{{\rm L},f}^3 - 2Q_f\,\kappa_f\,\sin^2\theta_W\right)$$

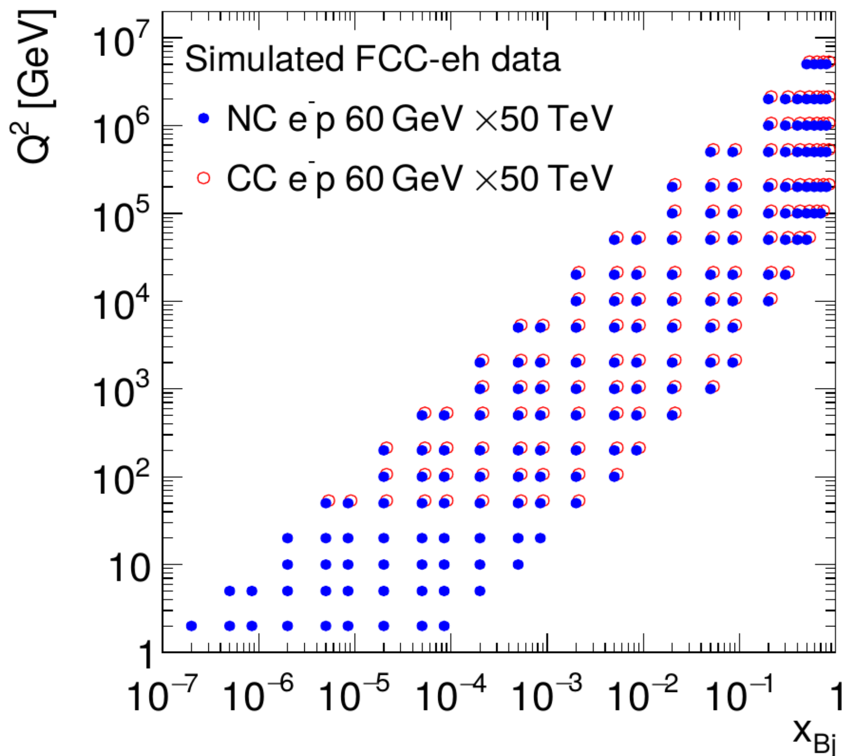
Independent SM paramters: α, m_Z, m_W + PDFs

Methodology I – simulated FCC-eh data

Simulated NC and CC DIS data

- About 1200 cross section data points dσ/dQ²dx
- Luminosity of 1 ab^{-1}
- Full set of systematic uncertainties

Source of uncertainty	Size of uncertainty	Uncertainty on cross section $\Delta\sigma_{NC}$	Uncertainty on cross section $\Delta\sigma_{CC}$
Scattered electron energy scale $\Delta E'_e/E'_e$	0.1 %	0.1 – 1.7 %	–
Scattered electron polar angle	0.1 mrad	0.1 – 0.7 %	–
Hadronic energy scale $\Delta E_h/E_h$	0.5 %	0.1 – 4 %	1.0 – 8.6 %
Calorimeter noise (only $y < 0.01$)		0.0 – 1.1 %	included above
Radiative corrections		0.3 %	–
Photoproduction background ($y > 0.5$)	1 %	0.0 or 1.0 %	–
Uncorrelated uncertainty (efficiency)		0.5 %	0.5 %
Luminosity uncertainty (normalization)		1.0 %	1.0 %



- Simulated datasets for
  - NC and CC DIS
  - electron and proton runs
  - different electron beam polarisations
  - low-E_p run

Methodology II – simulated FCC-eh data

Fitting methodology

- QCD (PDF-) fit in NNLO precision using ZM-VFNS from QCDNUM
  → 13 free PDF parameters
  → Uncertainties on EW parameters include PDF uncertainties
- Plus: fit EW parameter of interest

EW calculations

- Calculations are performed in on-mass shell scheme:
  (α_{em}, m_Z, m_W, Δr) with $\Delta r=\Delta r(\alpha_{em},m_W,m_Z,m_t,m_H,...)$
- Dependence on m_t and m_H through loop-corrections (Δr)
- $\sin^2\theta_W$ and g_f are calculated quantities and thus no free parameters
- More general, also vector and axial-vector couplings are 'free' parameters