Electroweak Physics with the LHeC+FCCeh

Definitions

Measurements

+ Simulations

Couplings

EFT + h.o. Studies

Daniel Britzger, Max Klein, Hubert Spiesberger

For the LHeC Study Group

http://lhec.web.cern.ch

DIS2018, Kobe, 19.4.2018

Electroweak Physics Probing Nuclear Structure *)
Deep Inelastic Scattering Testing the Electroweak Theory

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

$$\mathbf{xF}_3^{\pm} = \kappa_Z(\pm a_e + P\cancel{v_e}) \cdot xF_3^{\gamma Z} + \kappa_Z^2(\mp 2\cancel{v_e} a_e - P(\cancel{v_e^2} + a_e^2)) \cdot xF_3^Z.$$

$$\kappa_Z(Q^2) = \frac{Q^2}{Q^2 + M_Z^2} \cdot \frac{1}{4\sin^2\Theta\cos^2\Theta} \qquad v_f = i_f - e_f 2\sin^2\Theta \qquad a_f = i_f$$

$$(F_2, F_2^{\gamma Z}, F_2^Z) = x\sum(e_q^2, 2e_q v_q, v_q^2 + a_q^2)(q + \bar{q})$$

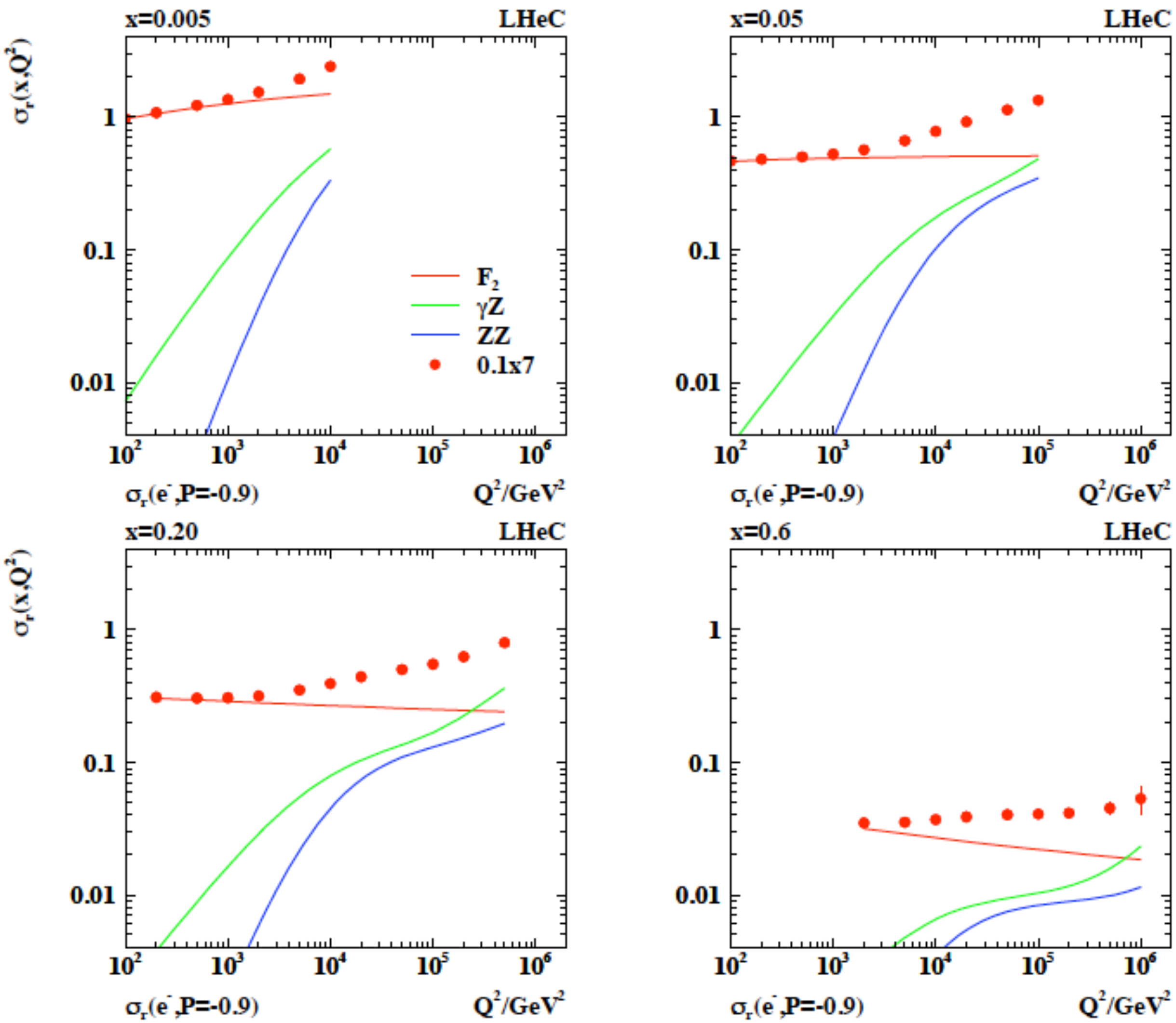
$$(xF_3^{\gamma Z}, xF_3^Z) = 2x\sum(e_q a_q, v_q a_q)(q - \bar{q}),$$

	e^2	2ev
u	4/9	2/9
d	1/9	2/9

NC: γγ, γZ, ZZ. Lepton beam helicity P, M_Z, v and a couplings, PV through va
CC: pure weak cross section (G_F, M_W) → 3 independent variables, DIS: OMS

*) M. Klein and T. Riemann[1]
Institut für Hochenergiephysik der AdW der DDR, DDR-1615 Berlin-Zeuthen
Received 19 October 1983 Z. Phys. C – Particles and Fields 24, 151–155 (1984)

Reduced NC e^-p Scattering Cross Section [P=-0.9, 10fb^{-1}]



Huge Z exchange effects at LHeC

At small Q^2 , σ_r=F_2

Both at x=0.2 (the point of Bj scaling) and at larger x (the region of gluon bremsstrahlung which makes F_2 decrease with Q^2), the reduced NC cross section rises

Polarisation Asymmetry and R=NC/CC

$$\frac{2}{P_L - P_R} \cdot A^{\pm} \simeq \mp\kappa_Z a_e \frac{F_2^{\gamma Z}}{(F_2 + \kappa_Z a_e Y_- x F_3^{\gamma Z}/Y_+)} \simeq \mp\kappa_Z a_e \frac{F_2^{\gamma Z}}{F_2}$$

$$\frac{2}{P_L - P_R} \cdot A^{\pm} \simeq \pm\kappa \frac{1 + d_v/u_v}{4 + d_v/u_v}.$$

Classic asymmetry (Prescott et al, 1978) accesses weak interaction, $F_2^{\gamma Z}$ is a new, direct measure of valence quarks at high x

$$R^{\pm} = \frac{\sigma_{NC}^{\pm}}{\sigma_{CC}^{\pm}} = \frac{2}{(1 \pm P)\kappa_W^2} \cdot \frac{\sigma_{r,NC}^{\pm}}{\sigma_{r,CC}^{\pm}}$$

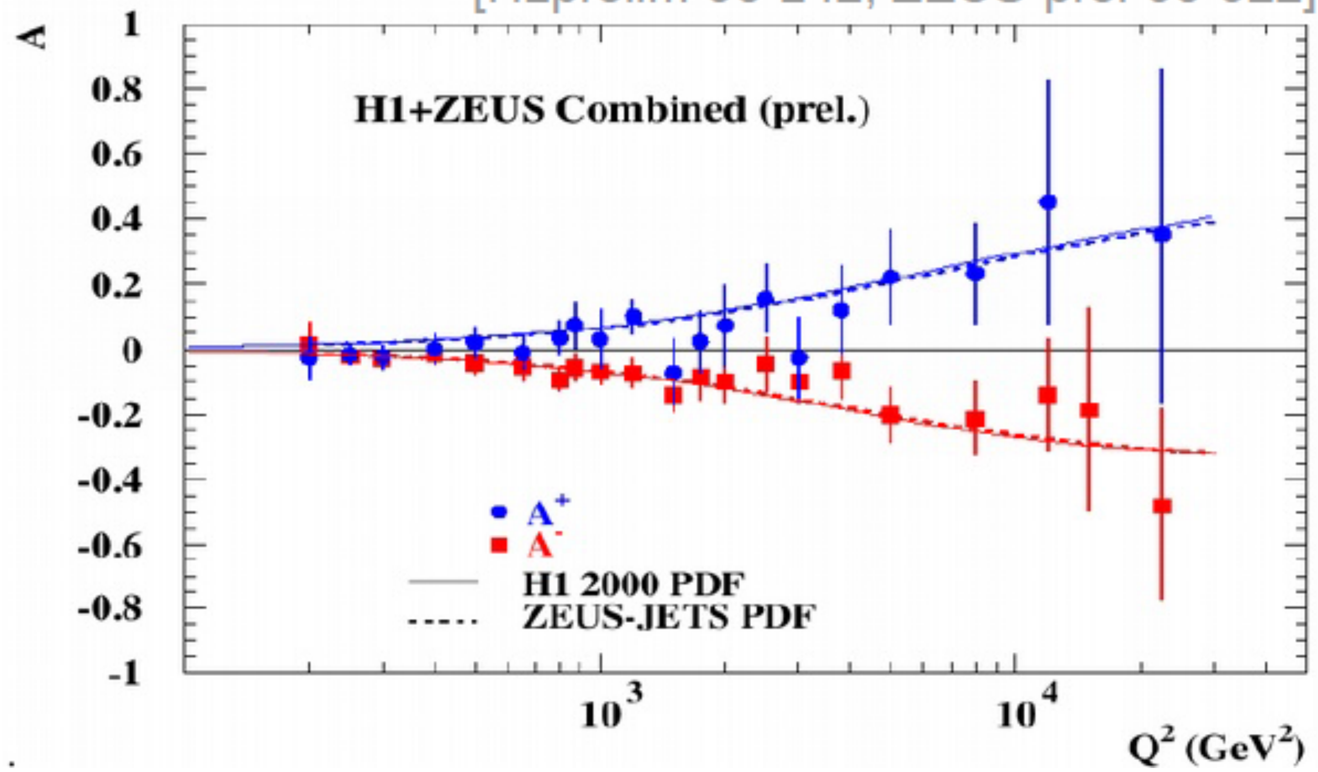
$$R^{\pm} \simeq \frac{2a_e^2}{(1 \pm P)\cos^2\Theta} \cdot \frac{Y_+ F_2^Z - Y_- P x F_3^Z}{Y_+ W_2^{\pm} + Y_- x W_3^{\pm}}$$

R accesses weak interaction and the pure weak structure functions which are best measured at the LHeC/FCC-eh

Note that in experiment you would measure the cross sections and determine all correlations which is still more informative than A or R but contains their physics.

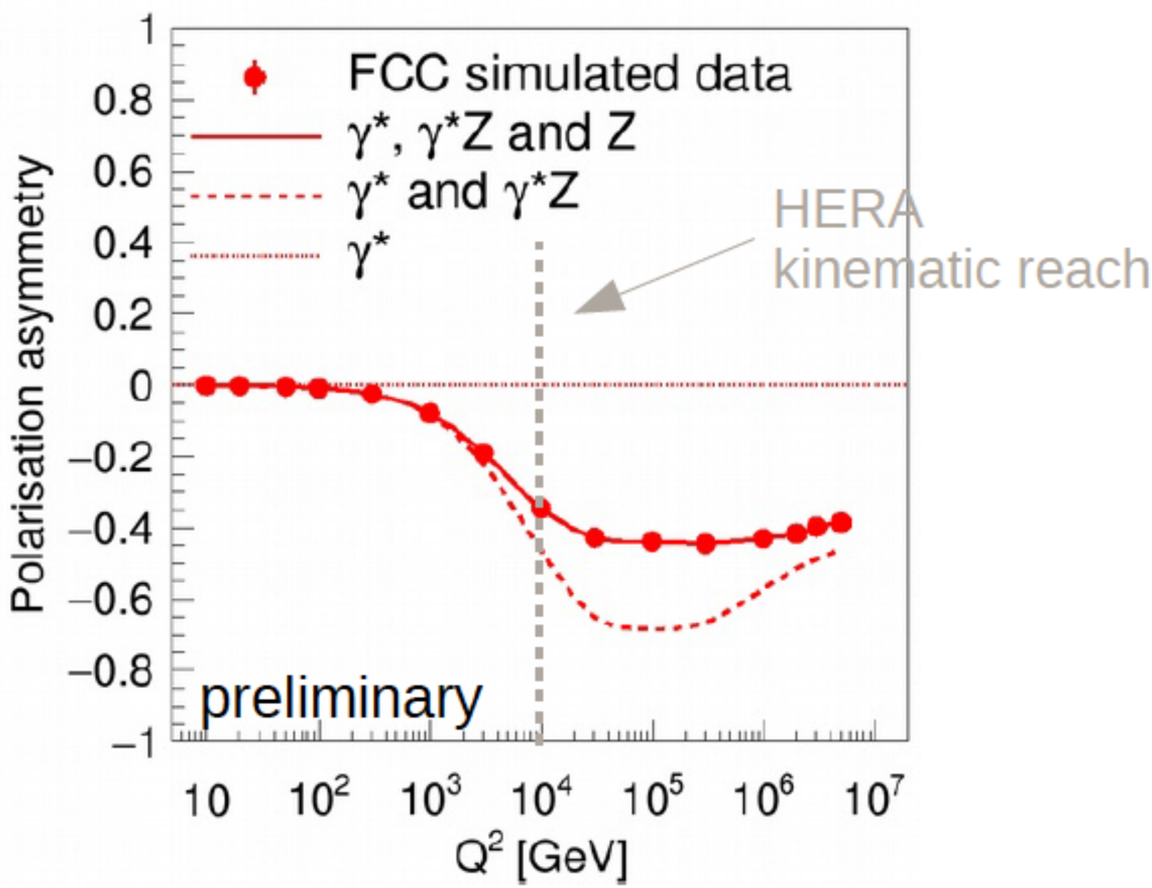
PV Asymmetry in NC

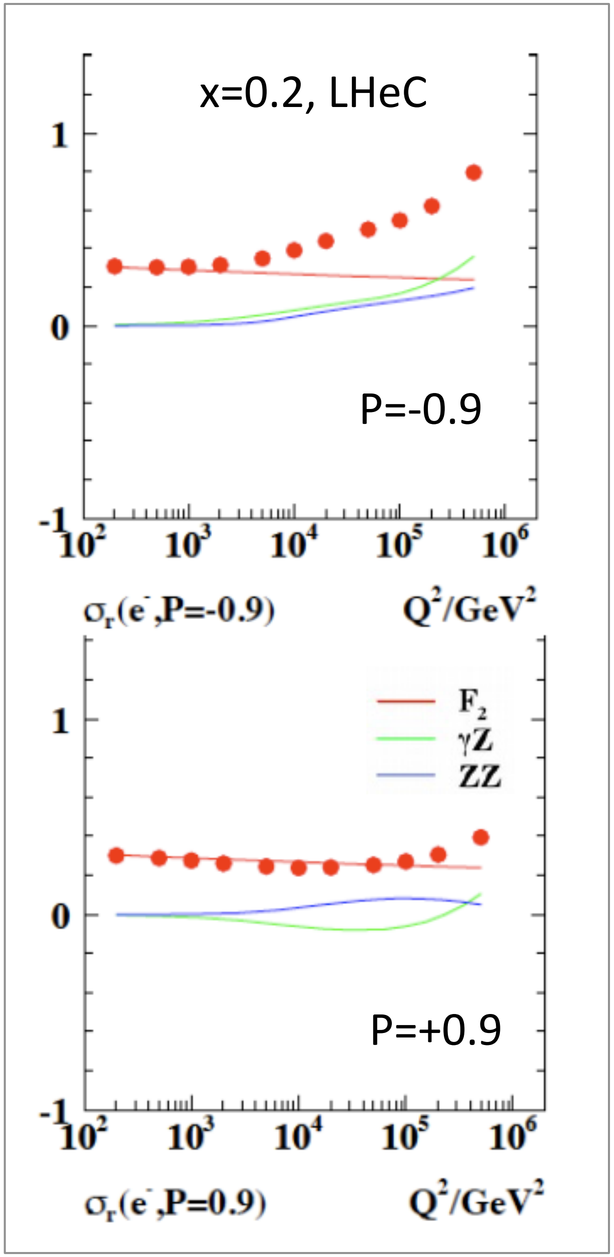
H1+ZEUS
[H1prelim-06-142, ZEUS-prel-06-022]



HERA: 20% asymmetry at $Q^2 = 10^4$ GeV^2 $A^+ = - A^-$

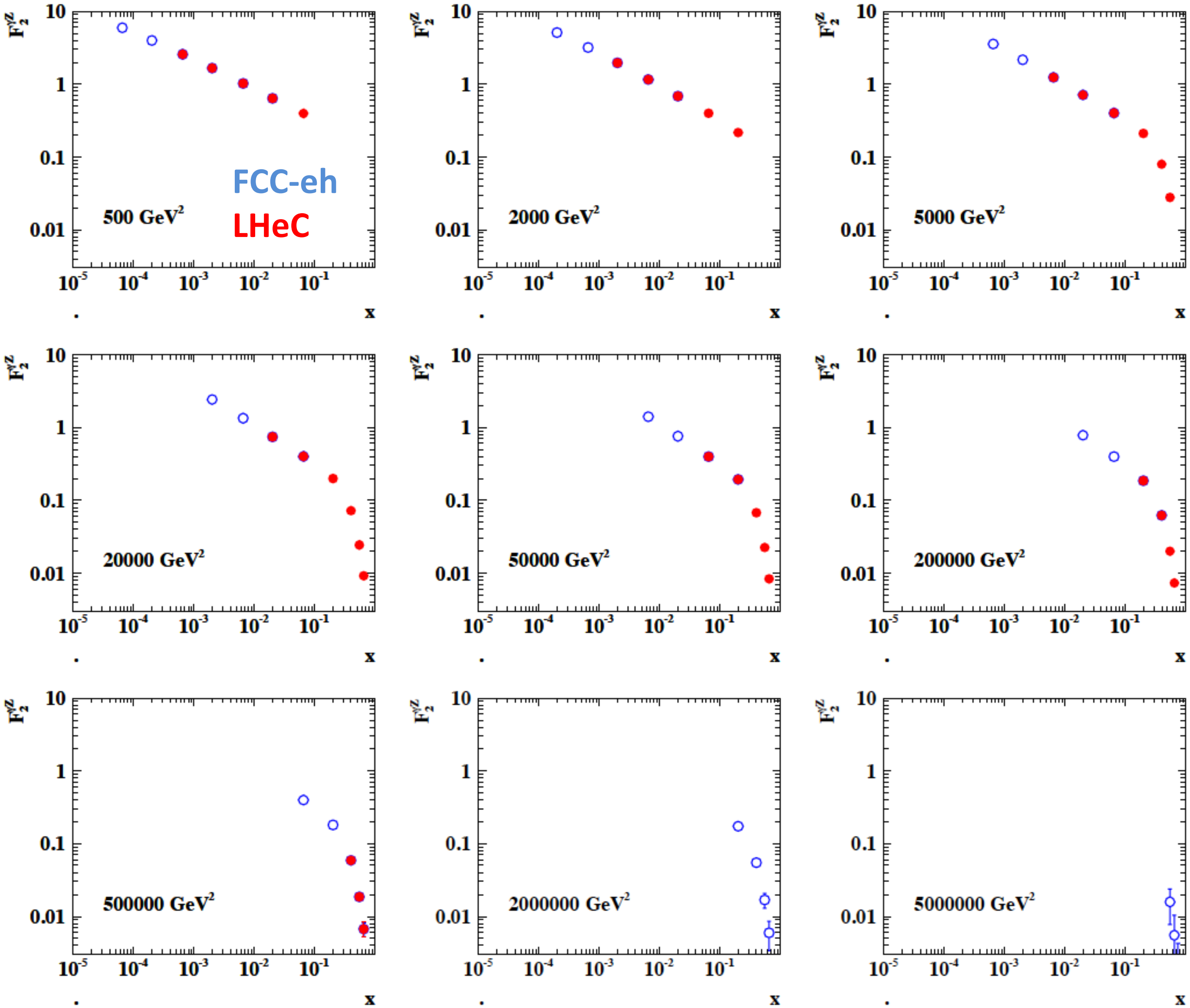
PV Asymmetry in NC



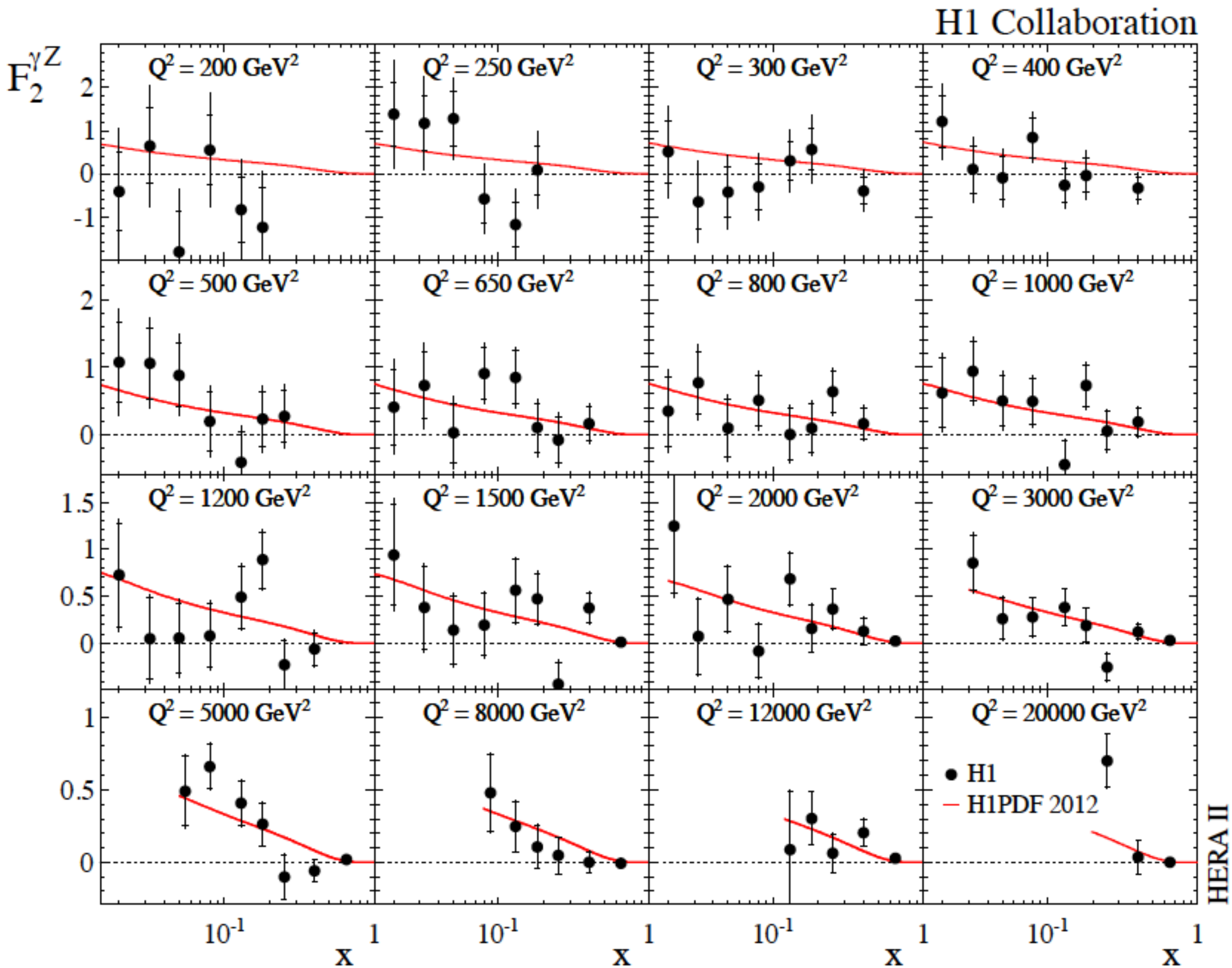


FCCeh: 40% integrated asymmetry for $Q^2 > 10^4$ GeV^2 , locally (x) much larger

Parity Violation Structure Function $F_2^{\gamma Z} = x \sum 2 e_q v_q (q + \bar{q})$



LHeC: 7 TeV, FCC-eh: 50 TeV, E_e=60 GeV, integrated L of 100 fb^{-1} for P= +- 0.8



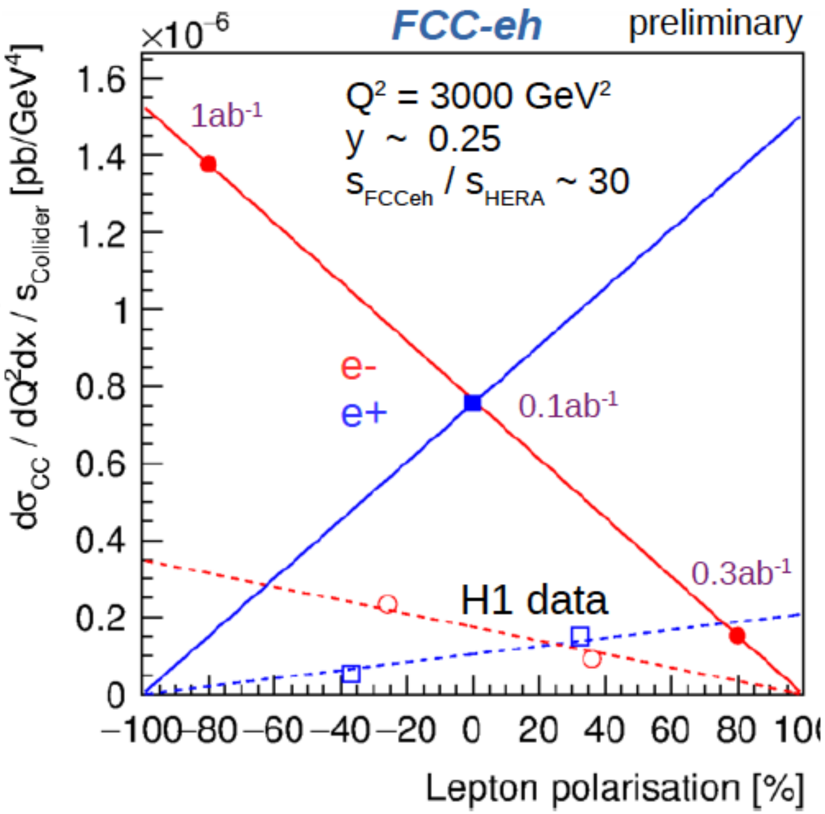
H1: arXiv:1207.7007: much smaller x and Q^2 range, imprecise, but first measurement ever

Charged Currents

$$\frac{d^2\sigma^{CC}(e^\pm p)}{dx dQ^2} = (1 \pm P_e)\frac{G_F^2}{4\pi x}\left[\frac{m_W^2}{m_W^2+Q^2}\right]^2\left(Y_+ W_2^\pm(x,Q^2) \mp Y_- x W_3^\pm(x,Q^2)\right)$$

$$W_2^- = x\left(U+\overline{D}\right), \quad xW_3^- = x\left(U-\overline{D}\right)$$

$$W_2^+ = x\left(\overline{U}+D\right), \quad xW_3^+ = x\left(D-\overline{U}\right)$$



Data sets:

1ab^{-1} P=-0.8 to enlarge rate for WW→ H

0.3ab^{-1} P=+0.8 for eweak physics

0.1ab^{-1} unpolarised with positrons

Data (NC,CC) Simulation for QCD + el.weak Evaluation

Numerical treatment of correlated and uncorrelated systematic and statistical errors
[based on PHE-1990-02 (J.Blümlein, M.Klein), cross checked with H1 Monte Carlo]

source of uncertainty	error on the source or cross section
scattered electron energy scale $\Delta E'_e/E'_e$	0.1 %
scattered electron polar angle	0.1 mrad
hadronic energy scale $\Delta E_h/E_h$	0.5 %
calorimeter noise (only $y < 0.01$)	1-3 %
radiative corrections	0.5%
photoproduction background (only $y > 0.5$)	1 %
global efficiency error	0.7 %

- Assumptions gauged with H1, probably conservative.
- This approach determines full set of uncorrelated and correlated uncertainties
- ALL PDFs and electroweak fit results presented to this workshop have full systematic error
- This also holds for the LHeC CDR alphas analysis leading to 0.1-0.2% total uncertainty

NC Cross Section Correlated Uncertainties (Q^2=20000 GeV^2)

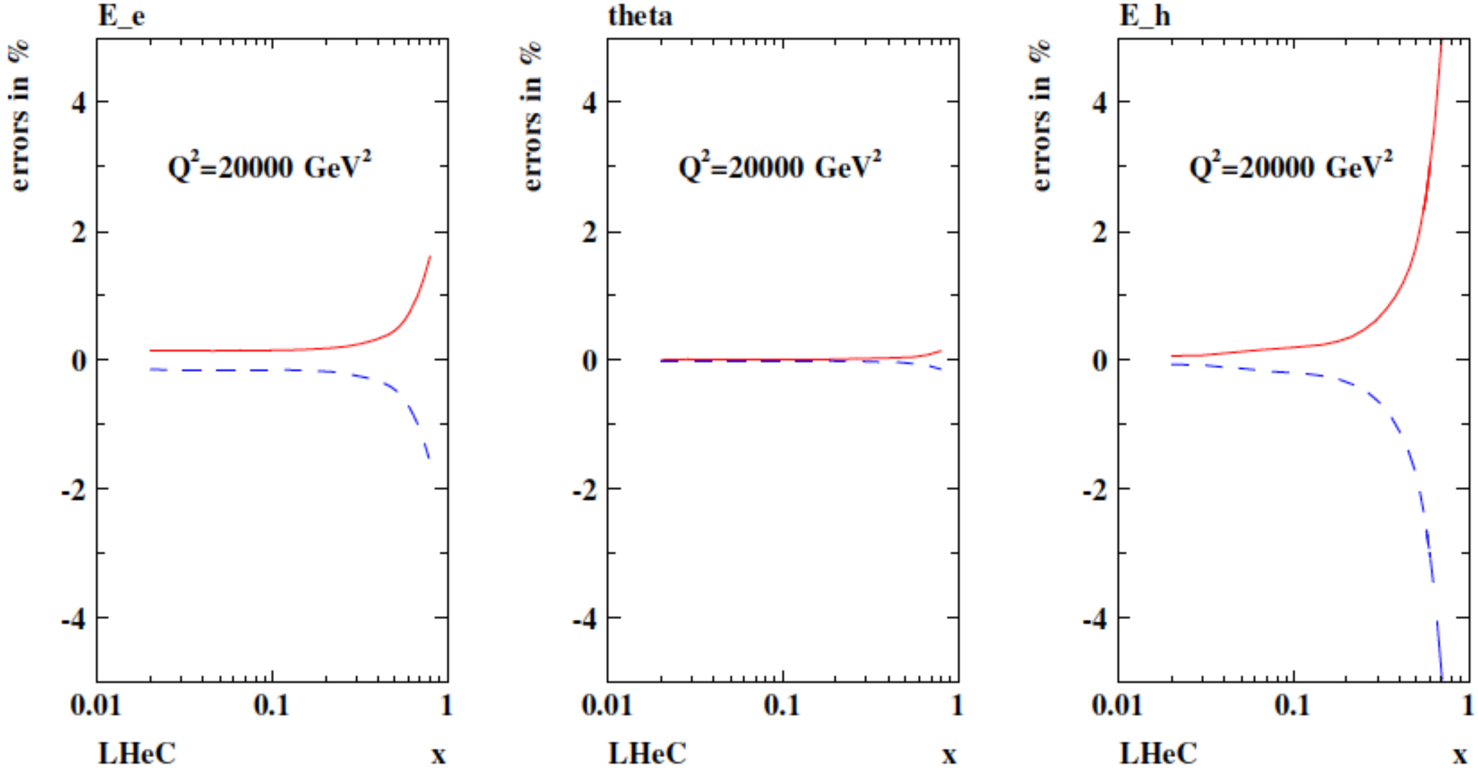


Figure 3.3: Neutral current cross section errors, calculated for $60 \times 7000\,\mathrm{GeV}^2$ unpolarised $e^- p$ scattering, resulting from scale uncertainties of the scattered electron energy $\delta E'_e/E'_e = 0.1\,\%$, of its polar angle $\delta\theta_e = 0.1\,\mathrm{mrad}$ and the hadronic final state energy $\delta E_h/E_h = 0.5\,\%$, at large $Q^2 = 20000\,\mathrm{GeV}^2$ and correspondingly large x. Note that the characteristic behaviour of the relative uncertainty at large x, i.e. to diverge $\propto 1/(1-x)$, is independent of Q^2, i.e. persistently observed at $Q^2 = 200000\,\mathrm{GeV}^2$ for example too.

From LHeC CDR

NC Cross Section Correlated Uncertainties (Q^2=2 GeV^2)

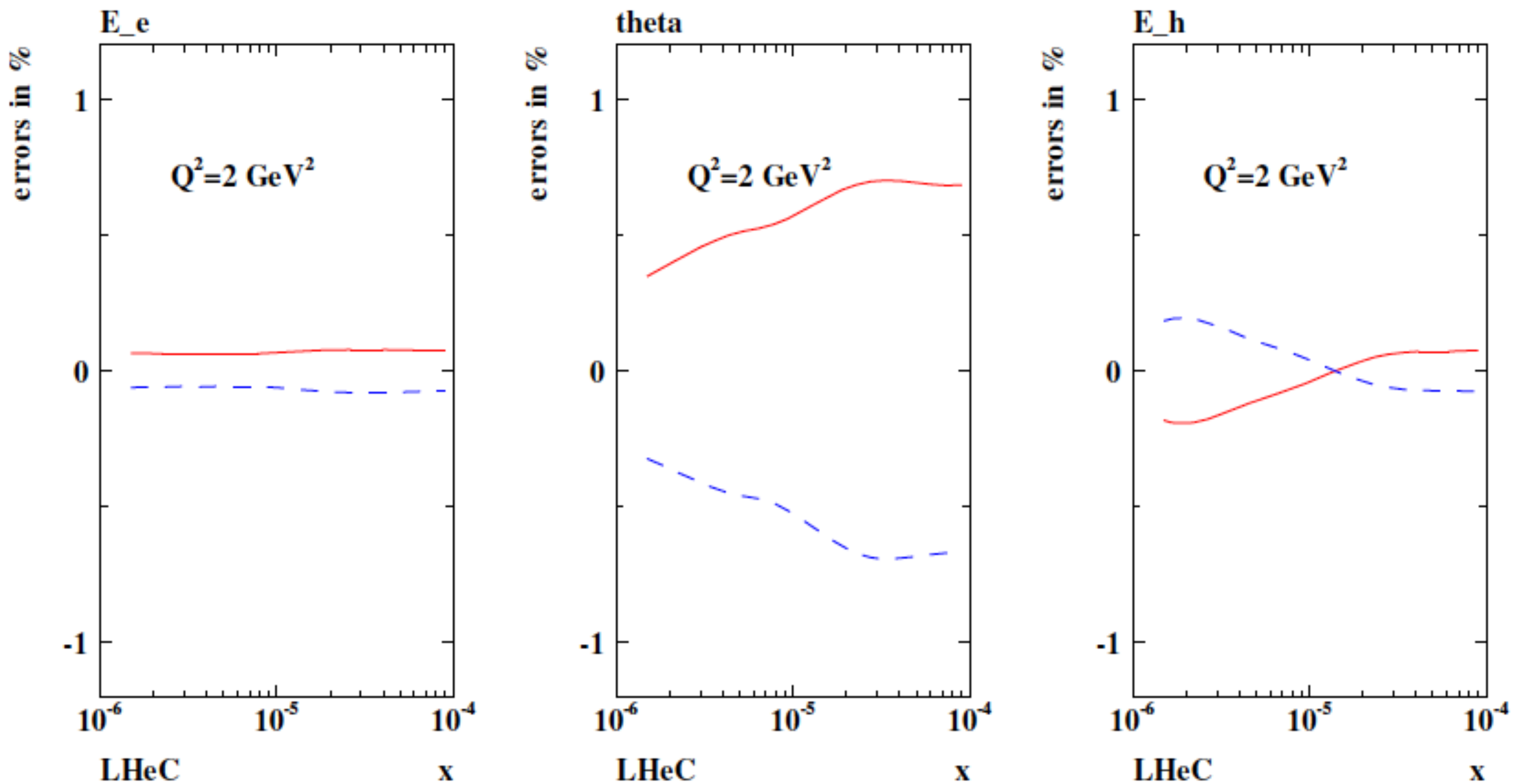


Figure 3.2: Neutral current cross section errors, calculated for $60 \times 7000\,\mathrm{GeV}^2$, resulting from scale uncertainties of the scattered electron energy $\delta E'_e/E'_e = 0.1\,\%$, of its polar angle $\delta\theta_e = 0.1\,\mathrm{mrad}$ and the hadronic final state energy $\delta E_h/E_h = 0.5\,\%$, at low $Q^2 = 2\,\mathrm{GeV}^2$ and correspondingly low x.

From LHeC CDR

Framework and Definitions

PDF+EW-fit

- PDF fit in NNLO precision
  - ZM-VFNS using QCDNUM
  - 13 free PDF parameters

EW calculations

- 1-loop EW corrections
- On-shell parameters are:
  (α_{em}, m_Z, m_W, Δr) with
  $\Delta r = \Delta r(\alpha_{em}, m_W, m_Z, m_t, m_H, \ldots)$

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

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

cf H1 to be published, Z Zhang this conference

MSbar: Spiesberger/Dittmaier, in preparation

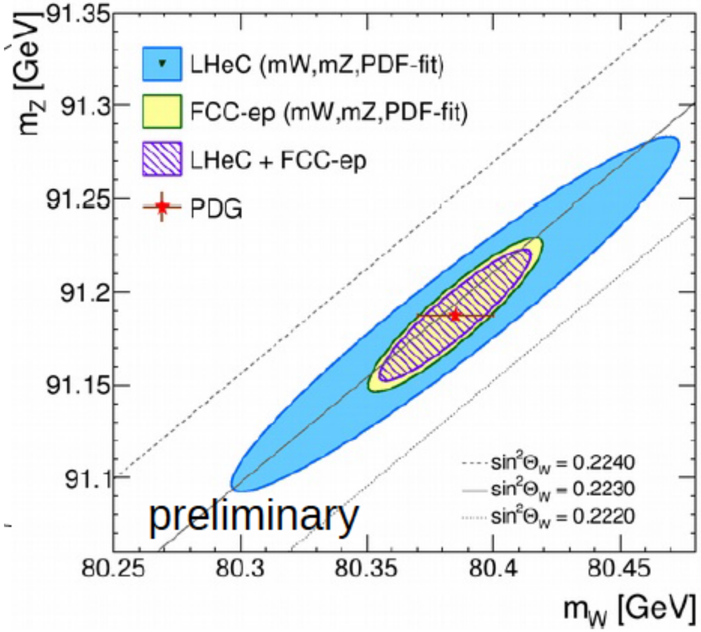
- m_t and m_H enter through loop-corrections (Δr)
- $\sin^2\theta_w$ and g_f are calculated quantities
- More general, also vector and axial-vector couplings are 'free' parameters

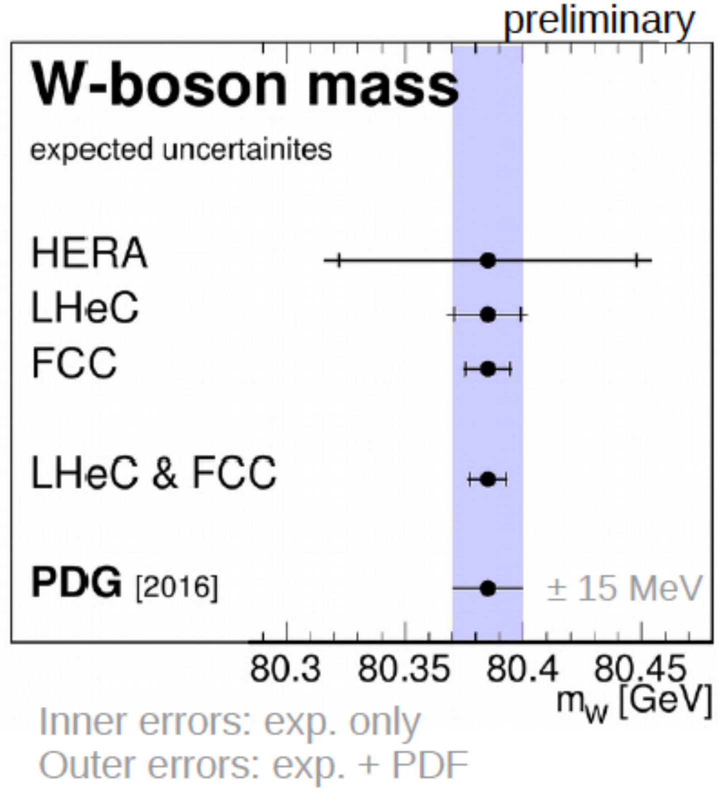
New: parameterise effective h.o. corrections as deviations ρ' and κ'

$$\rho'_{\mathrm{NC}} \to \rho'_{\mathrm{NC}}\rho_{\mathrm{NC}}$$
$$\kappa'_{\mathrm{NC}} \to \kappa'_{\mathrm{NC}}\kappa_{\mathrm{NC}}$$
$$\rho'_{\mathrm{CC}} \to \rho'_{\mathrm{CC}}\rho_{\mathrm{CC}}$$

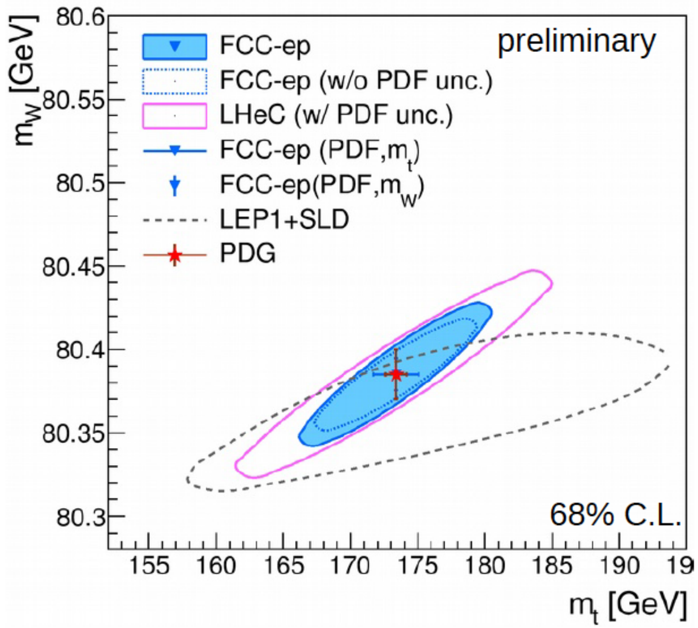
W.Hollik, CERN-TH.5547/1989

W,Z, top [loop] Masses [from inclusive data only] at LHeC/FCCeh





- LHeC $\pm 14_{(exp)} 10_{(PDF)}$ MeV
- FCC $\pm 9_{(exp)} 4_{(PDF)}$ MeV



In ep PDFs not limiting factor
For pp, LHC predict M_W to 2.8 MeV with LHeC PDFs (S Camarda)

MZ similar. H and t from loops for consistency measurable directly with much better accuracy.

Masses from inclusive NC+CC Cross Sections

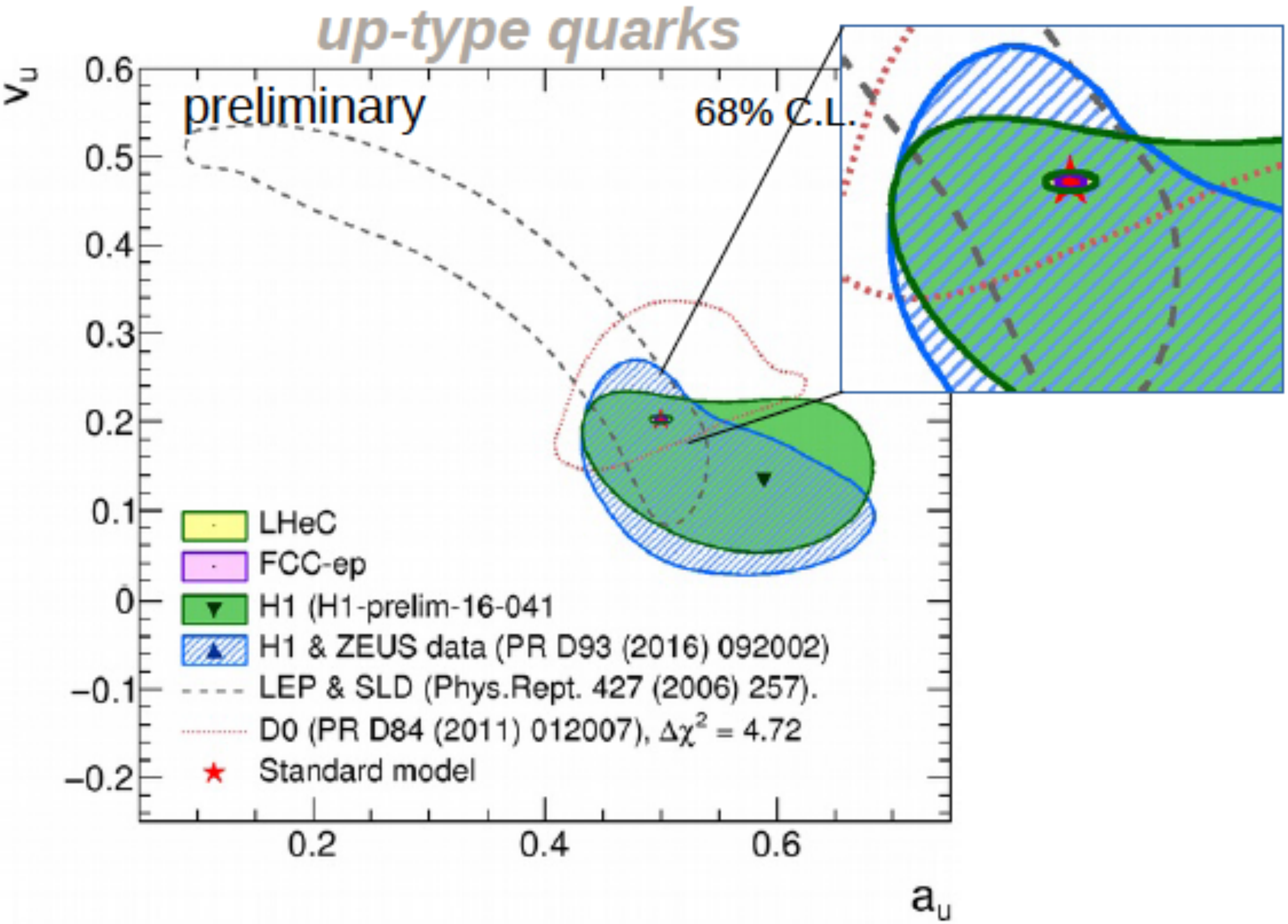
Parameter	HERA	LHeC	FCC-eh
Δm_W [MeV]	$\pm 63_{(exp)} 29_{(pdf)}$	$\pm 14_{(exp)} 10_{(pdf)}$	$\pm 9_{(exp)} 4_{(pdf)}$
Δm_Z [MeV]	$\pm 56_{(exp)} 25_{(pdf)}$	$\pm 16_{(exp)} 10_{(pdf)}$	$\pm 16_{(exp)} 10_{(pdf)}$
Δm_t [GeV]	$\pm 10_{(exp)} 5_{(pdf)}$	$\pm 2.6_{(exp)} 1.7_{(pdf)}$	$\pm 1.7_{(exp)} 0.5_{(pdf)}$
Δm_H [GeV]	$> \mathcal{O}(100\,\mathrm{GeV})$	$\pm 31_{(exp)} 22_{(pdf)}$	$\pm 20_{(exp)} 4_{(pdf)}$

Table 4: Summary of electroweak parameters from HERA-II data and LHeC and FCC-ep simulated data.

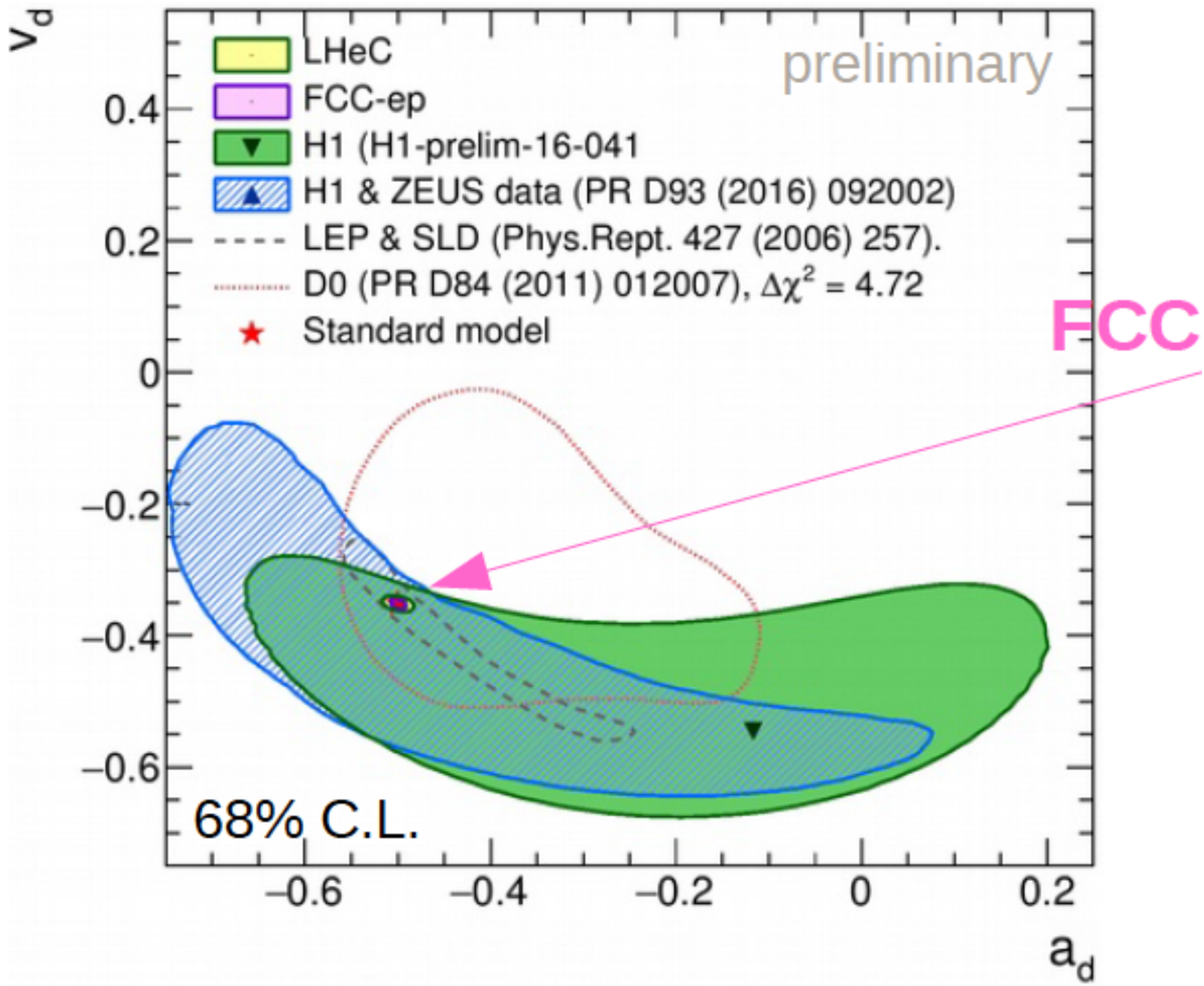
OMS: W,Z direct. top. Higgs through loops

1987 expected 100 MeV for MW [JB, MK, TR] at HERA

Light up Quark NC Couplings



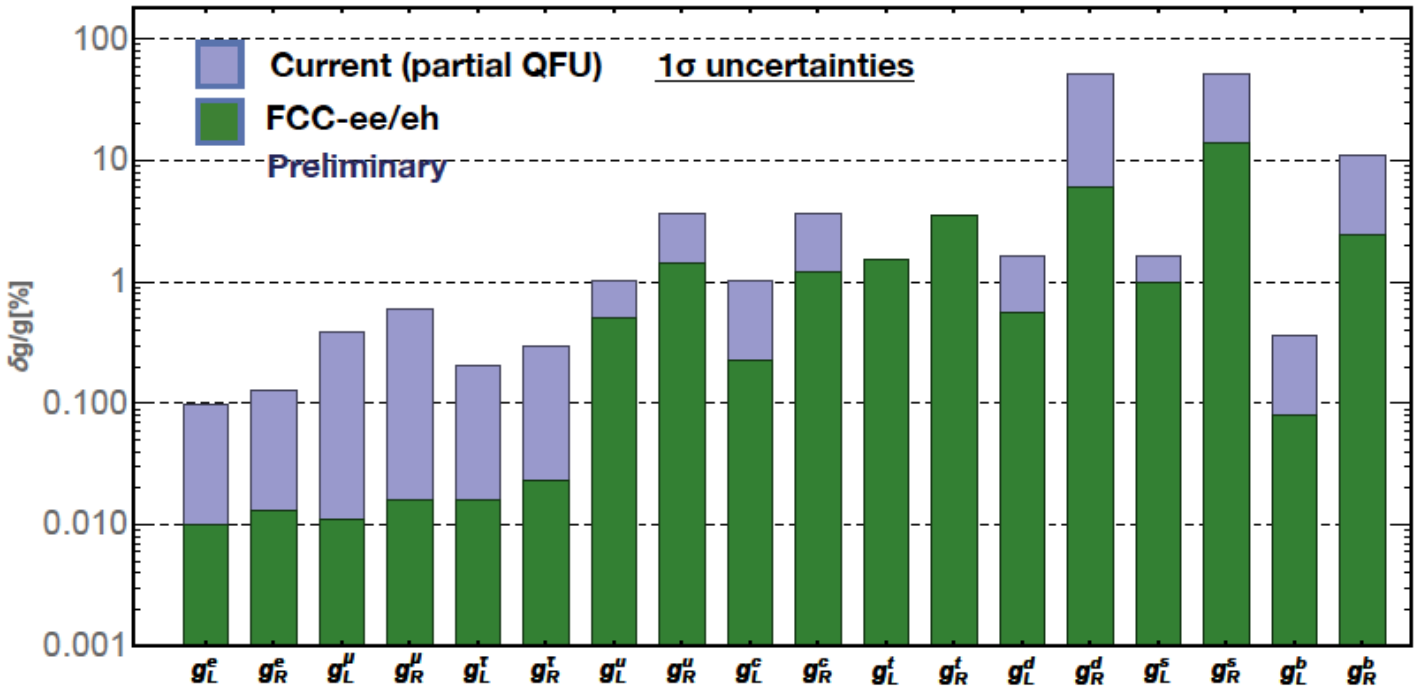
Light down Quark NC Couplings



First preliminary Global Electroweak Analysis FCC ee+eh

J de Blas (Amsterdam FCC week)

- **Global fit to electroweak precision measurements at FCC-ee + FCC-eh**



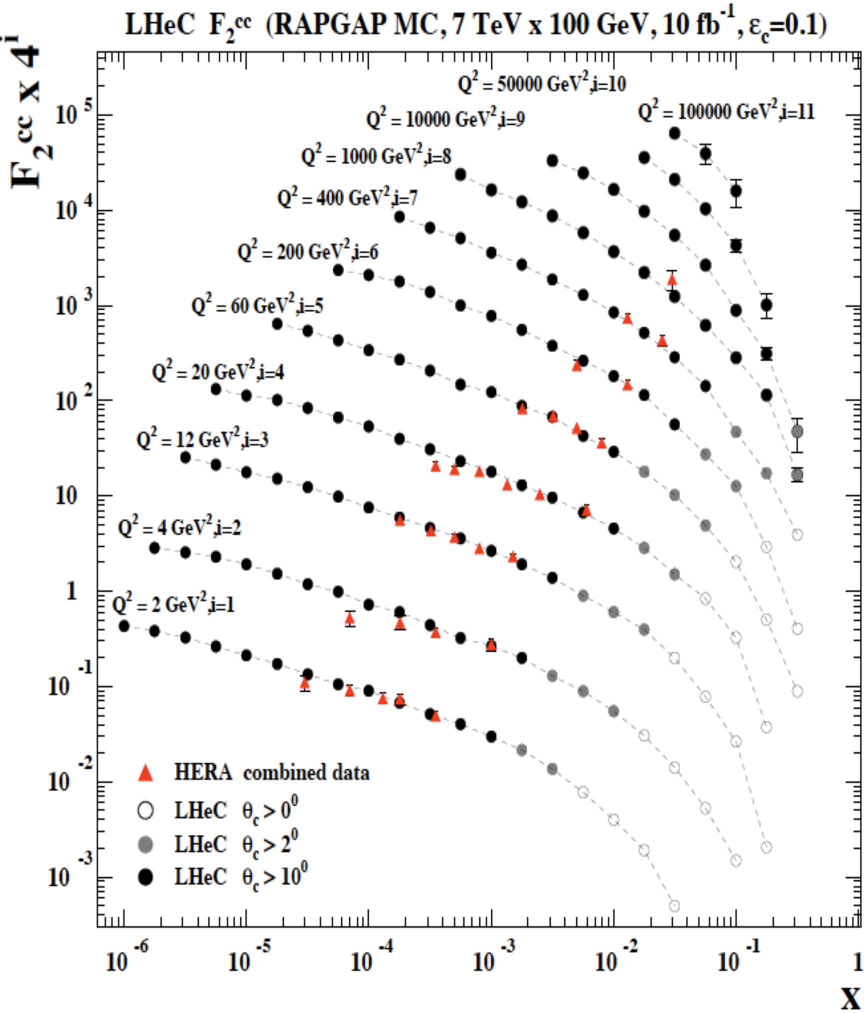
No Fermion flavour universality assumed

Independent info about all 3 SM fermion families

FCC-eh (and LHeC) has much more information to provide than up + down NC couplings.
-We can measure the interference parts of F_2^{cc} and F_2^{bb} → get v and a couplings for c,b
-Scale dependence of $\sin^2\Theta_W(Q)$ for Q ~ 300 MeV (PERLE) to 1 TeV (LHeC), 3 TeV (FCCeh)
[low scales: elastic lepton-nucleon scattering MK T Riemann, Z Phys C8 (81) 239: Jlab, MESA]

Charm F_2^{cc} and Mass

LHeC CDR arXiv:1206.2913



HERA 0.0005/2.5 .. 0.05/2000 GeV²
LHeC 0.00001/1 .. 0.2/200000 GeV²

ε(c) assumed 10%, 1% light background, ~3% δ(syst)

Heavy Flavour with LHeC
Beam spot (in xy): 7μm
Impact parameter: better than 10μm
Modern Silicon detectors, no pile-up
Higher E, L, Acceptance, ε, than at HERA
→ Huge improvements predicted

	HERA	LHeC
$m_c(m_c)$/GeV	1.26	?
δ(exp)	0.05	0.003
δ(mod)	0.03	~0.002
δ(par)	0.02	~0.002
$\delta(\alpha_s)$	0.02	0.001

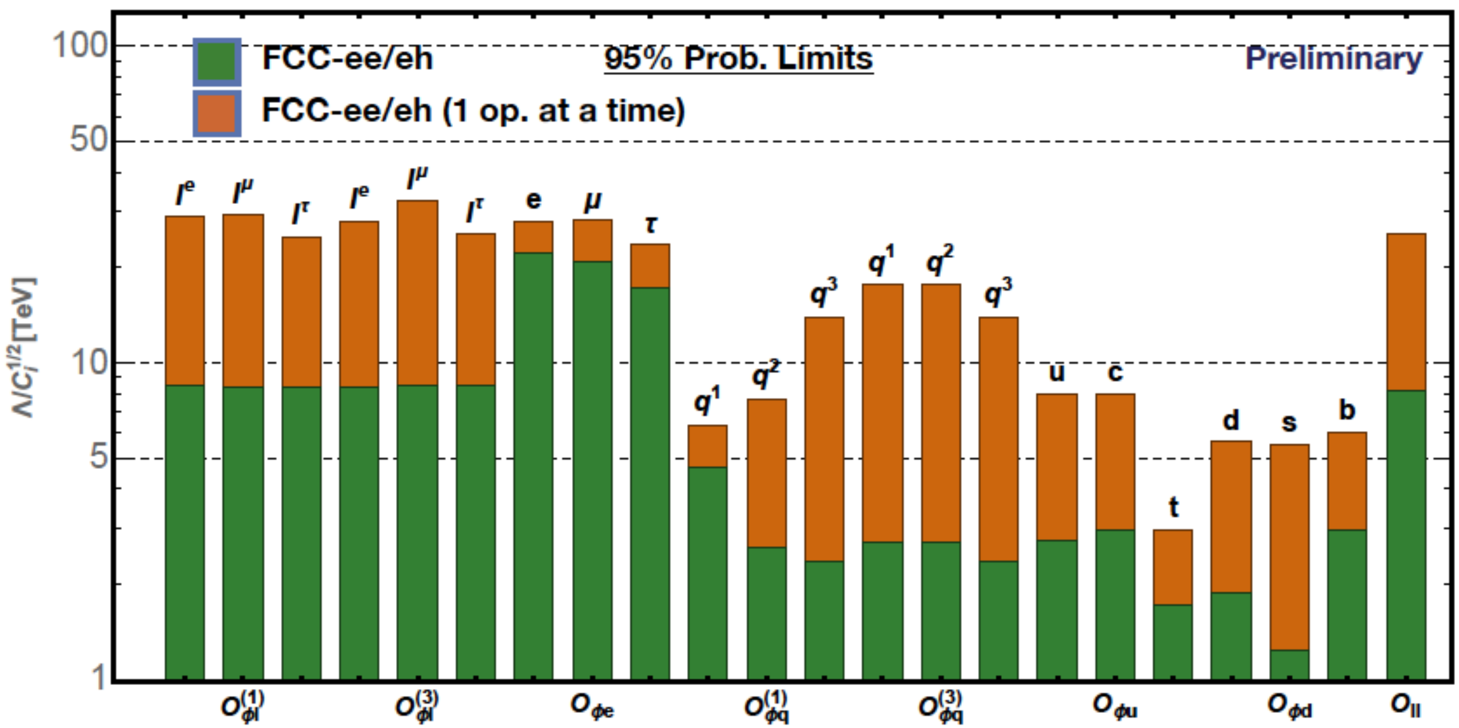
LHeC determines strong coupling to 0.1%
High precision PDF data will reduce the mod and par errors by a very large amount.

Determination of charm mass to 3 MeV: crucial for M_W in pp or H→ cc in ep
cf also NNPDF3.1 (arXiv:1706.00428) and refs

First preliminary Global Electroweak Analysis FCC ee+eh

Combination of ee and ep; Test of SM to O(20) TeV; a Model also for LHeC + e^+e^- wherever

- **Global fit to electroweak precision measurements at FCC-ee + FCC-eh**



No Fermion flavour universality assumed **Independent info about all 3 SM fermion families**

$$\mathcal{L}_{\rm NC} = -\frac{e}{sc}(1+\delta^U g_{\rm NC}) Z_\mu \sum_\psi \overline{\psi^i}\gamma^\mu\Big[\Big(g_L^\psi\delta_{ij} + (\delta^D g_L^\psi)_{ij}\Big)P_L + \Big(g_R^\psi\delta_{ij} + (\delta^D g_R^\psi)_{ij}\Big)P_R + \delta^Q g_{\rm NC}\delta_{ij}\Big]\psi^j$$

$$\mathcal{O}_{\phi f}^{(1)} = (\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\overline{f}\gamma^\mu f) \qquad \mathcal{O}_{\phi f}^{(3)} = (\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi)(\overline{f}\gamma^\mu\sigma_a f) \qquad \ldots$$

J De Blas

Definitions of ρ' and κ's

Neutral current

Universal higher-order corrections are be taken into account by Q^2-dependent form factors $\rho_{\rm NC}$ and $\kappa_{\rm NC}$. Many extensions of the Standard Model predict modifications of the weak neutral-current couplings. These can be described conveniently by introducing additional parameters $\rho'_{\rm NC}$ and $\kappa'_{\rm NC}$, which can be also considerd to be Q^2 dependent:

$$g_A^f = \sqrt{\rho_{{\rm NC},f}\rho'_{{\rm NC},f}}\, I^3_{{\rm L},f}\,, \tag{1}$$

$$g_V^f = \sqrt{\rho_{{\rm NC},f}\rho'_{{\rm NC},f}}\left(I^3_{{\rm L},f} - 2Q_f\kappa_{{\rm NC},f}\kappa'_{{\rm NC},f}\sin^2\theta_W\right). \tag{2}$$

The estimated relative uncertainties of the $\rho'_{\rm NC}$ or $\kappa'_{\rm NC}$ achieved with the LHeC or FCC-eh data, can also be interpreted as the relative uncertainty of a direct determination of the $\rho_{\rm NC}$ parameters or $\sin^2\theta_w^{\rm eff}$.

Charged current

Higher-order EW corrections to the CC cross sections are collected in form factors $\rho_{{\rm CC},eq/e\bar{q}}$. Similarly as for NC, modifications of the SM formalism can be expressed by introducing the additional $\rho'_{\rm CC}$ parameters:

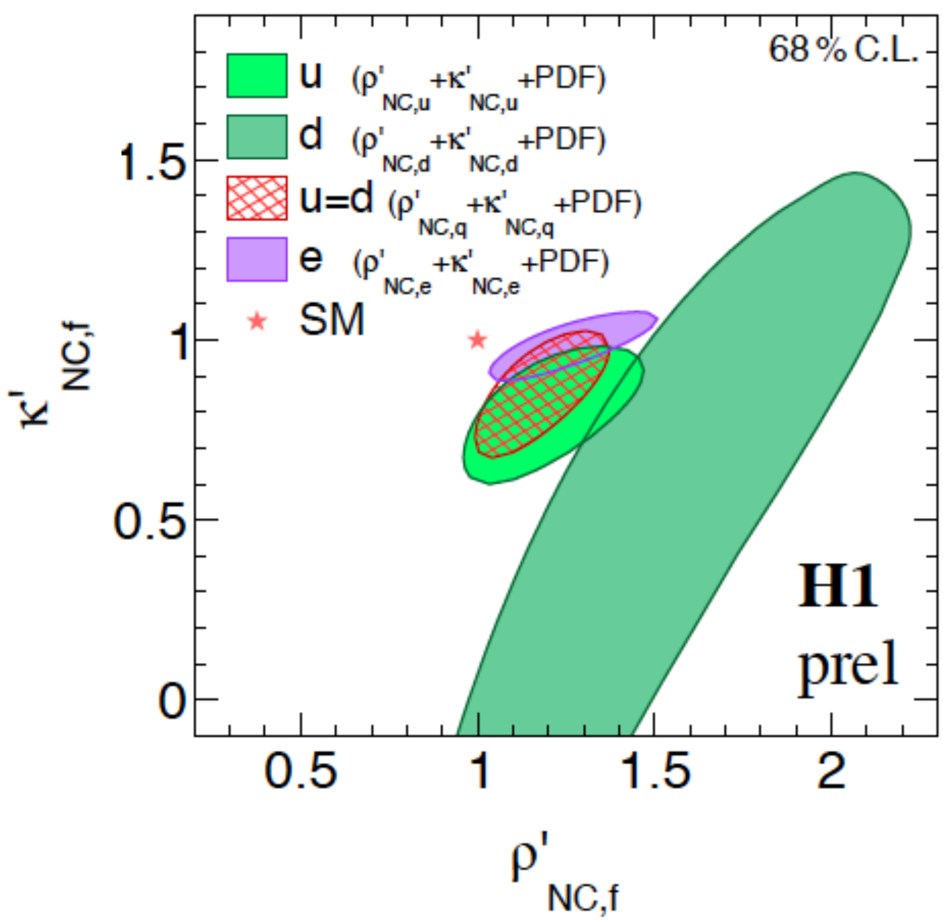
$$W_2^- = x\left((\rho_{{\rm CC},eq}\rho'_{{\rm CC},eq})^2 U + (\rho_{{\rm CC},e\bar{q}}\rho'_{{\rm CC},e\bar{q}})^2\overline{D}\right), \tag{3}$$

$$xW_3^- = x\left((\rho_{{\rm CC},eq}\rho'_{{\rm CC},eq})^2 U - (\rho_{{\rm CC},e\bar{q}}\rho'_{{\rm CC},e\bar{q}})^2\overline{D}\right), \tag{4}$$

$$W_2^+ = x\left((\rho_{{\rm CC},eq}\rho'_{{\rm CC},eq})^2\overline{U} + \rho_{{\rm CC},e\bar{q}}\rho'_{{\rm CC},e\bar{q}})^2 D\right), \tag{5}$$

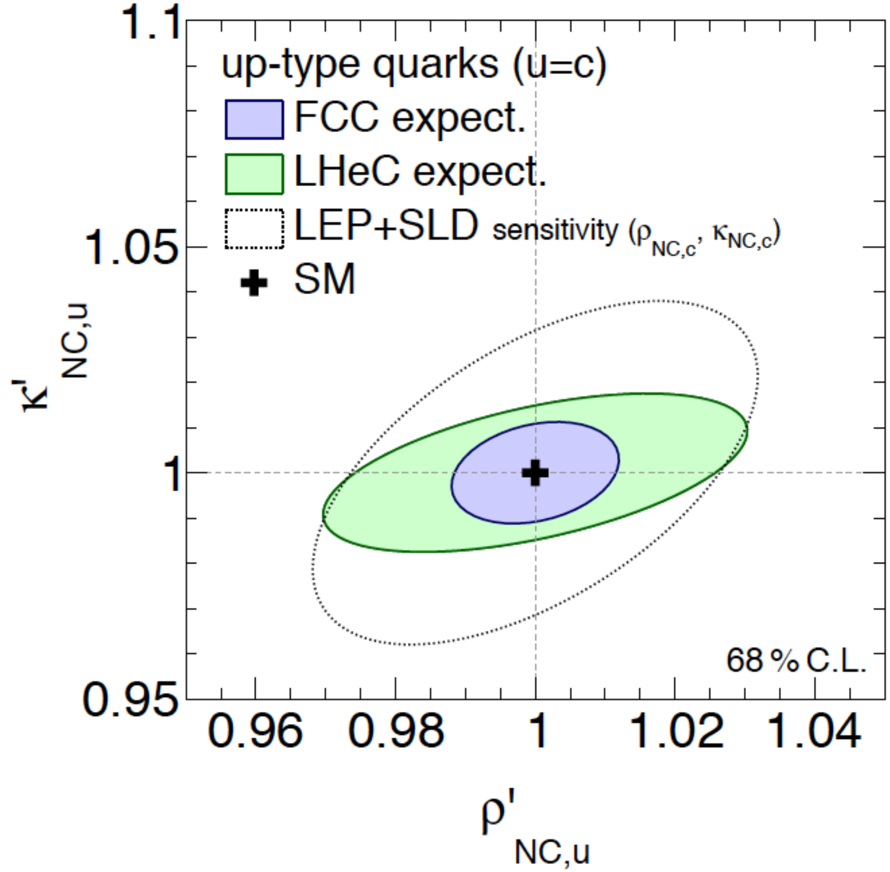
$$xW_3^+ = x\left((\rho_{{\rm CC},e\bar{q}}\rho'_{{\rm CC},e\bar{q}})^2 D - \rho_{{\rm CC},eq}\rho'_{{\rm CC},eq})^2\overline{U}\right). \tag{6}$$

LHeC/FCCeh h.o. Tests of Electroweak SM

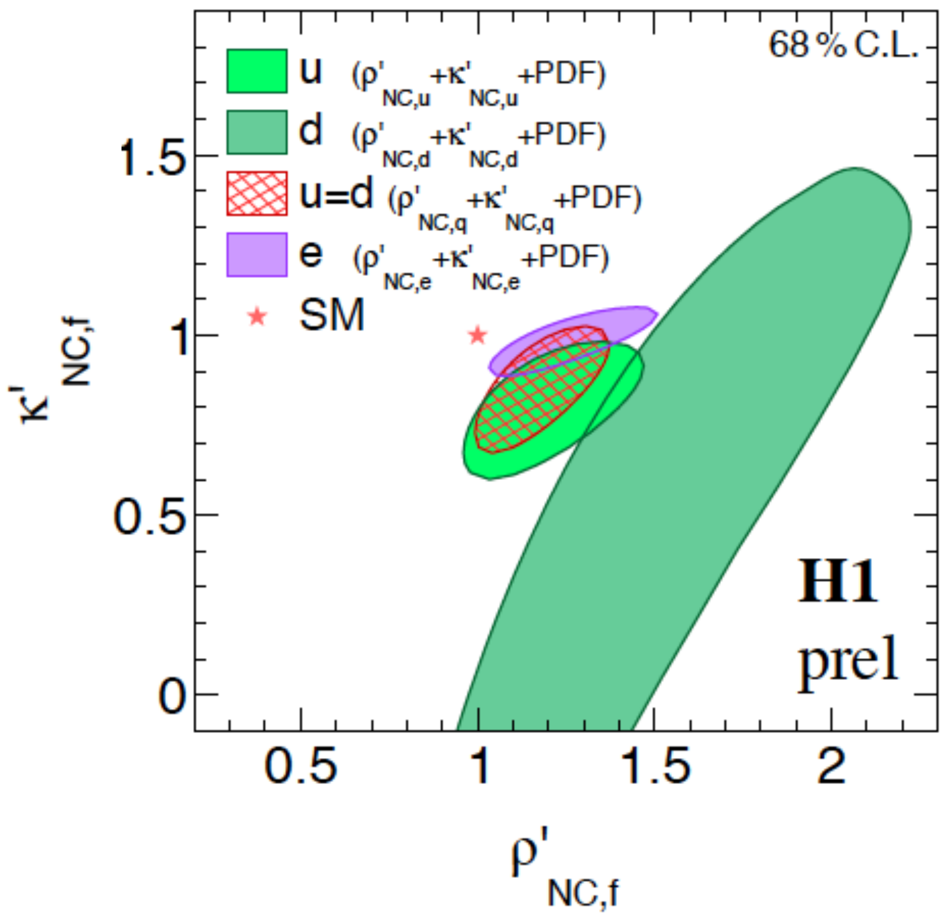


Z Zhang, H1, This Conference.

Up Quarks

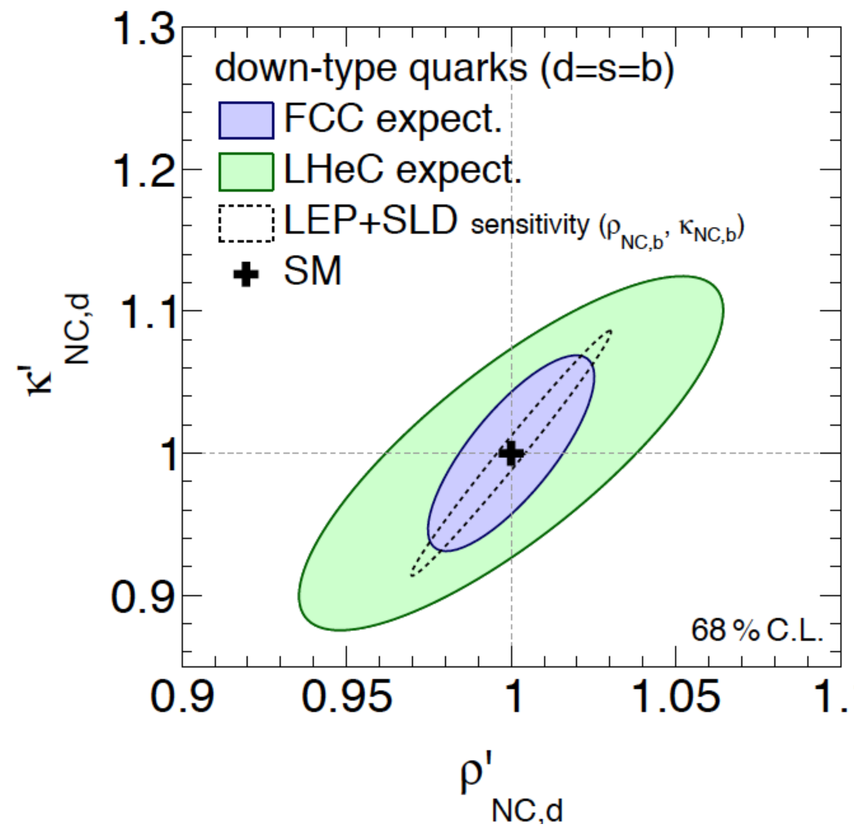


LHeC/FCCeh h.o. Tests of Electroweak SM



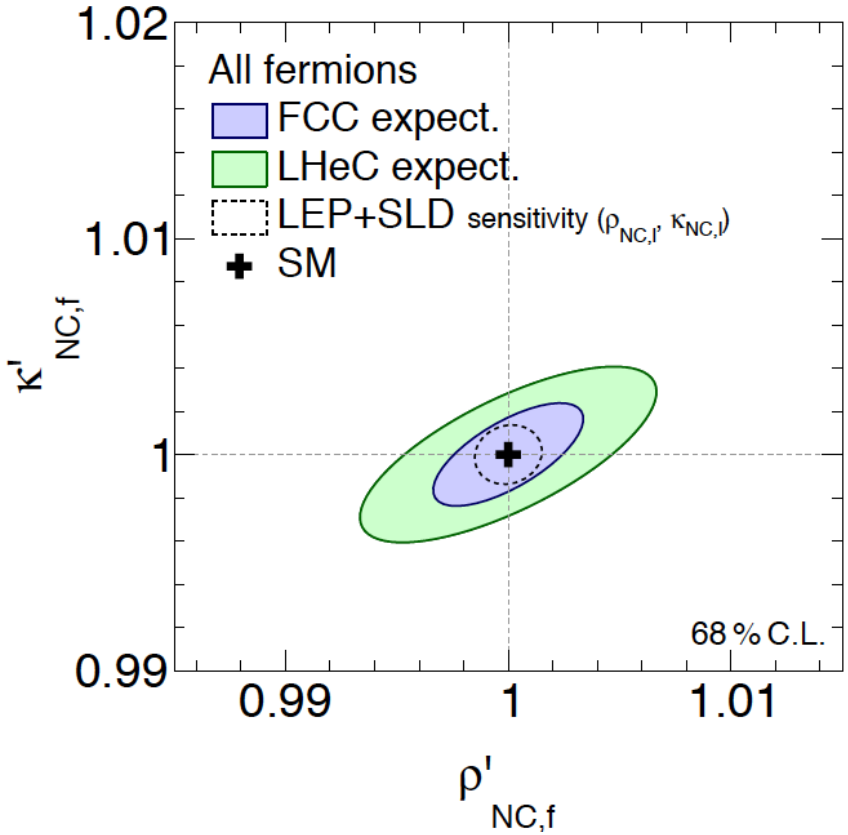
Z Zhang, H1, This Conference.

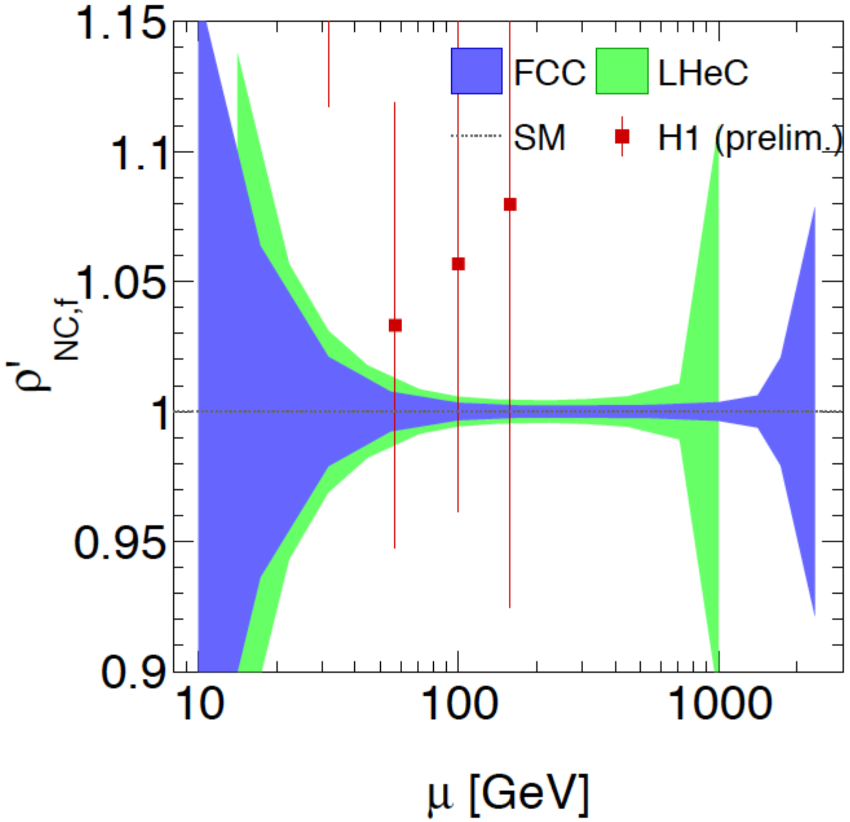
Down Quarks



LHeC/FCCeh h.o. Tests of Electroweak SM

Neutral Currents



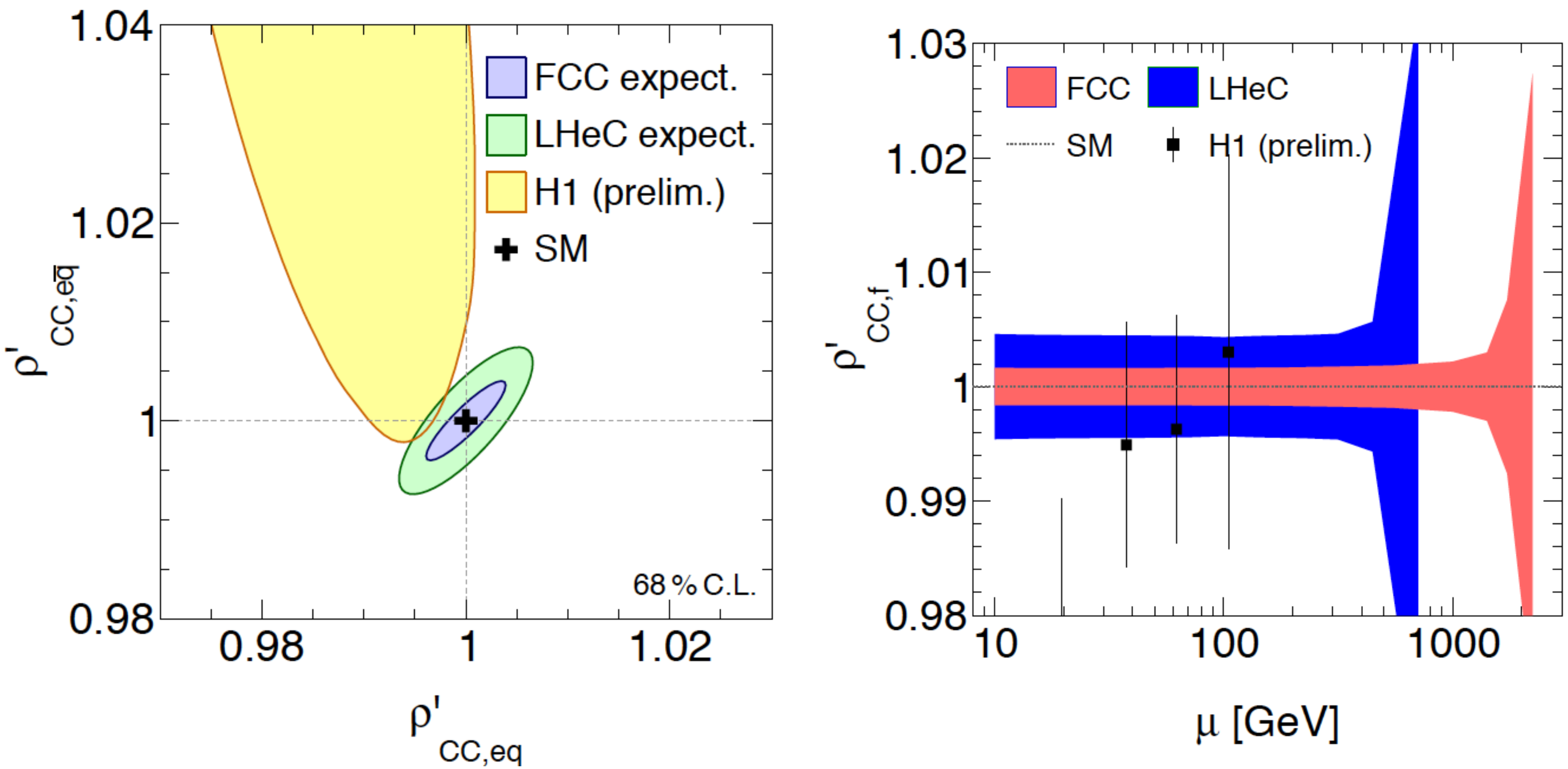


Test of eweak SM in NC to permille level. κ uncertainty describes $\sin^2\theta$ sensitivity.

Test of eweak theory in space like configuration. Precision vs scale $\mu=\sqrt{Q^2}$

LHeC/FCCeh h.o. Tests of Electroweak SM

Charged Currents



Test of eweak SM in CC to few permille level. Quark-Antiquark distinction.

Note that CC at H1 is large x dominated → reduced sensitivity to eqbar

Test of eweak theory in space like configuration. Precision vs scale $\mu=\sqrt{Q^2}$

Summary

Study of electroweak effects in NC and CC inclusive cross sections performed.

Full consideration of experimental, syst+stat uncertainties [as in α_s analysis].

Joint QCD (PDF) and electroweak analysis. PDFs do not dominate eweak tests.

$s=Q^2_{max} = 4E_eE_p$ = 1.7 TeV^2 (LHeC) and 12 TeV^2 >> $M_{W,Z}{}^2$. Very large luminosity →

High precision measurements → New laboratory for testing EW SM at new scales.

Initial determination of light quark couplings done, to 1% precision.

Novel parameterisation of h.o. effects in NC and CC couplings, including $\sin^2\theta$.

Measurement of scale dependence with unique and unprecedented precision.

First joint EFT and coupling fit analysis done for future ee and ep colliders (FCC).

Next: Formulation of DIS in MSbar, Tests for c,b (e) couplings. LHeC & e^+e^- , …

backup

PDFs and their effect on electroweak physics

FCC-eh and LHeC:Input: high precision (stat+syst) data on

Neutral Current (x: 10^{-6}-1; Q^2:1-10^6) Charged Current (10^{-4}-1; 100-10^6)

Tagging of Charm and Beauty with high precision and coverage. ep (eD)

Completely new PDF Programme

Determine ALL pdfs in a coherent way + the strong coupling to 0.1% accuracy

No higher twists, no nuclear corrections, no symmetry assumptions, N^3LO

→ ubar, uv, dbar, dv, s, c, b, t, xg and $alpha_s$

This essentially removes the PDF uncertainties on the electroweak variables, in ep but as well for pp.

For the Higgs this means that ep can turn pp into a precision Higgs facility

Definitions (J De Blas, Amsterdam FCC week)

- **EWPO sensitive to modifications of NC couplings**

$$\mathcal{L}_{\rm NC} = -\frac{e}{sc}(1+\delta^U g_{\rm NC}) Z_\mu \sum_\psi \overline{\psi^i}\gamma^\mu\Big[\Big(g_L^\psi \delta_{ij} + (\delta^D g_L^\psi)_{ij}\Big)P_L + \Big(g_R^\psi \delta_{ij} + (\delta^D g_R^\psi)_{ij}\Big)P_R + \delta^Q g_{\rm NC}\delta_{ij}\Big]\psi^j$$

Flavor non-universal contributions

$$\delta^D g_L^{\nu, e} = -\frac{1}{2}\left(C_{\phi l}^{(1)} \mp C_{\phi l}^{(3)}\right)\frac{v^2}{\Lambda^2}, \qquad \delta^D g_R^e = -\frac{1}{2} C_{\phi e}^{(1)} \frac{v^2}{\Lambda^2}$$

$$\delta^D g_L^{u, d} = -\frac{1}{2}\left(C_{\phi q}^{(1)} \mp C_{\phi q}^{(3)}\right)\frac{v^2}{\Lambda^2}, \qquad \delta^D g_R^{u, d} = -\frac{1}{4} C_{\phi u, d}^{(1)} \frac{v^2}{\Lambda^2}$$

Flavor-universal contributions

$$\delta^U g_{\rm NC} = -\frac{1}{2}\left[\Delta_{G_F} + \frac{C_{\phi D}}{2}\right]\frac{v^2}{\Lambda^2}$$

$$\delta^Q g_{\rm NC} = -Q\left(\frac{sc}{c^2-s^2}C_{\phi WB} + \frac{s^2c^2}{c^2-s^2}\left[\Delta_{G_F} + \frac{C_{\phi D}}{2}\right]\right)\frac{v^2}{\Lambda^2}$$

Indirect effect associated to modifications in μ decay (G_F)

$$\Delta_{G_F} = \left(C_{\phi l}^{(3)}\right)_{22} + \left(C_{\phi l}^{(3)}\right)_{11} - (C_{ll})_{1221}$$

10 Operators

$$\mathcal{O}_{\phi f}^{(1)} = (\phi^\dagger i \overleftrightarrow{D}_\mu \phi)(\overline{f}\gamma^\mu f)$$

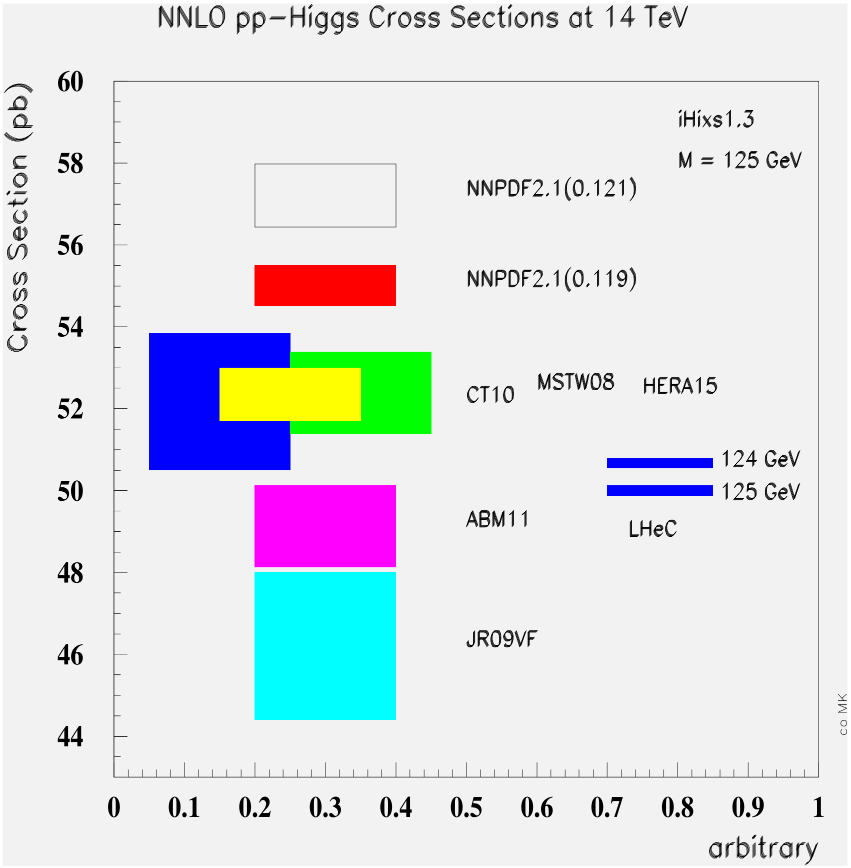
$$\mathcal{O}_{\phi f}^{(3)} = (\phi^\dagger i \overleftrightarrow{D}_\mu^a \phi)(\overline{f}\gamma^\mu \sigma_a f)$$

$$\mathcal{O}_{\phi D} = \left|\phi^\dagger i D_\mu \phi\right|^2$$

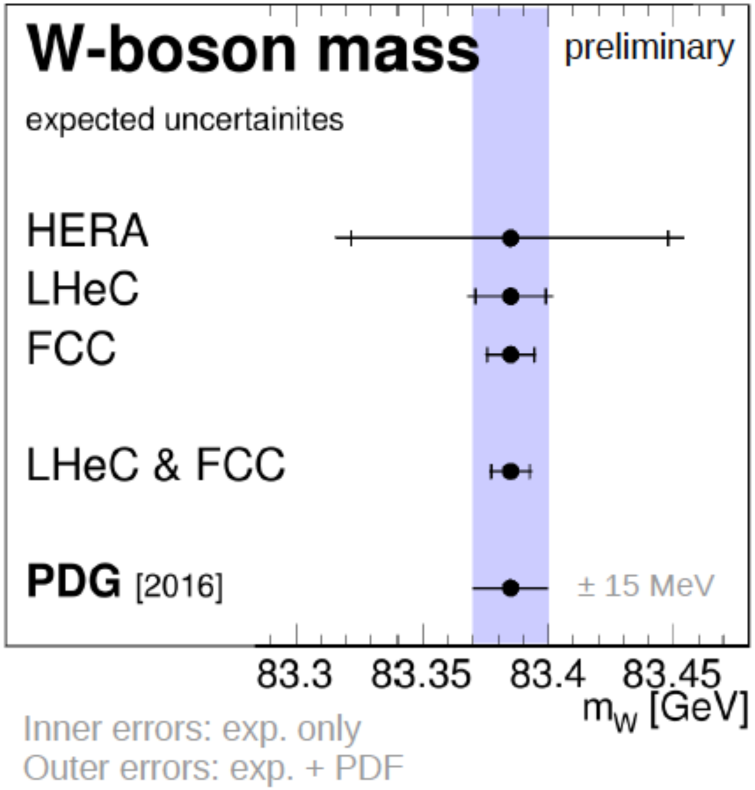
$$\mathcal{O}_{\phi WB} = (\phi^\dagger \sigma_a \phi) W_{\mu\nu}^a B^{\mu\nu}$$

$$\mathcal{O}_{ll} = (\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$$

High Precision for the LHC



Predict the Higgs cross section in pp to 0.2% precision which matches the M_H measurement and removes the PDF error



Spacelike M_W to 10 MeV from ep
→ Electroweak thy test at 0.01% !

Predict M_W in pp to 2.8 MeV →
Remove PDF uncertainty on M_W LHC