Electroweak physics at FCC-eh

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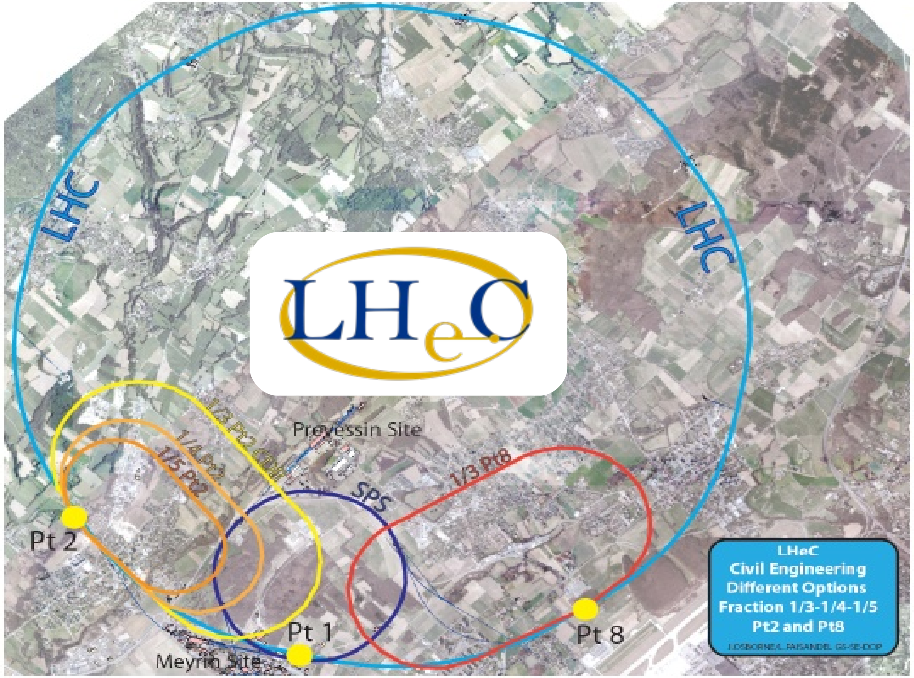
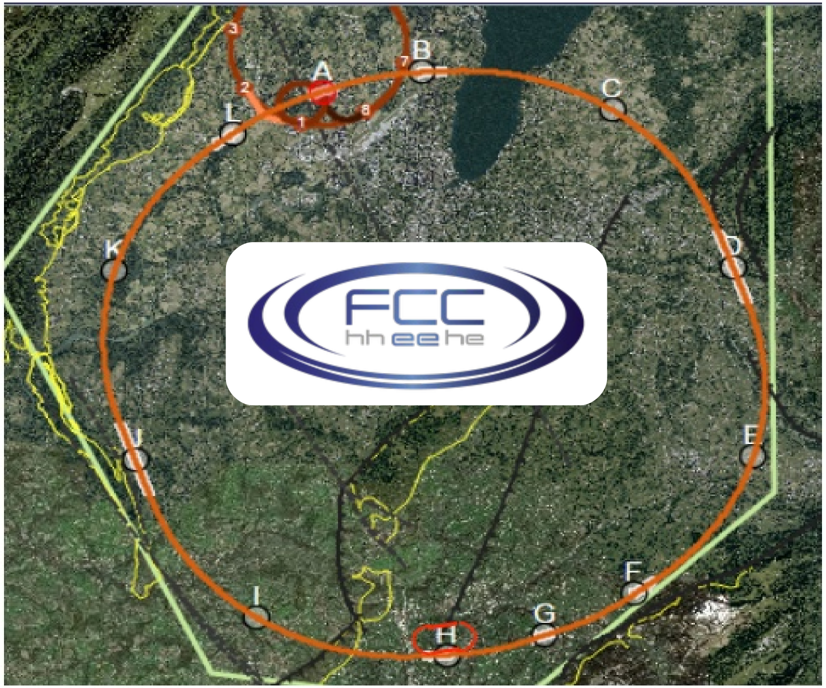
Future proposed ep-colliders: LHeC & FCC-eh





Electron ring

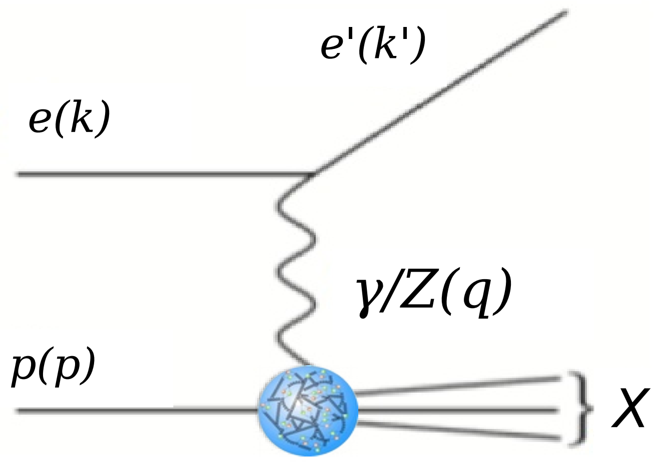
- Energy recovery linac: E_e = 60 GeV
- Polarisation up to P_e ~ 80%
- Similar concept for LHeC & FCC-eh

Center-of-mass energies

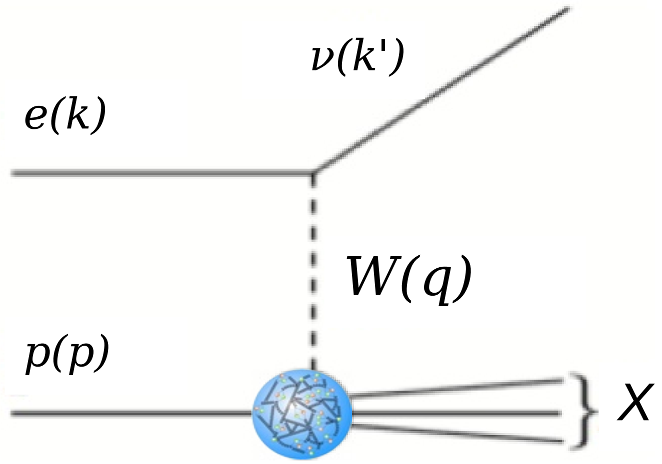
- LHeC: $\sqrt{s}$ ~ 1.3 TeV
- FCC-eh: $\sqrt{s}$ ~ 3.5 TeV
- Up to 1 ab^{-1} integrated luminosity

Deep-inelastic electron-proton scattering

Neutral current scattering
$ep \rightarrow e'X$



Charged current scattering
$ep \rightarrow \nu_e X$



R-D. Heuer

"The point-like electron "probes" the interior of the proton via the <u>electroweak force</u>, while acting as a neutral observer with regard to the <u>strong force</u>."

-> FCC-eh: Electroweak (EW) and QCD physics are equally important

Electroweak effects at HERA

Inclusive DIS as a function of Q^2

Lower values of Q^2

- NC significantly larger than CC
- CC is mediated only by massive W-boson
- NC: e^+p and e^-p are identical for photon exchange

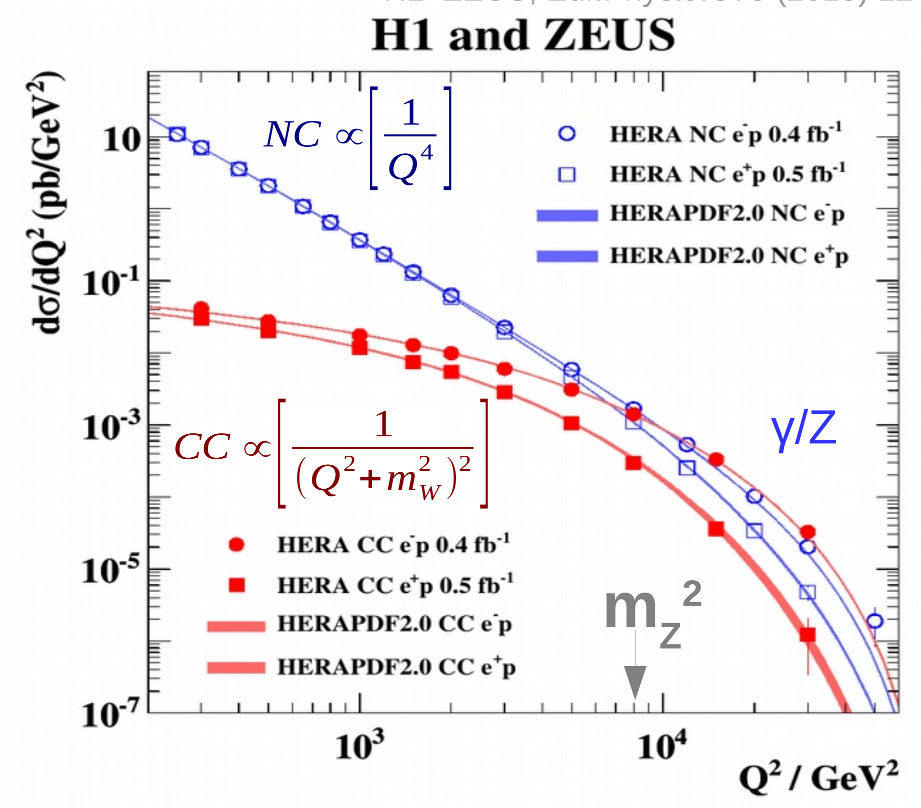
Around EW unification scale

- NC and CC of similar size
- $Q^2 \sim m_Z^2 \sim 8000$ GeV^2

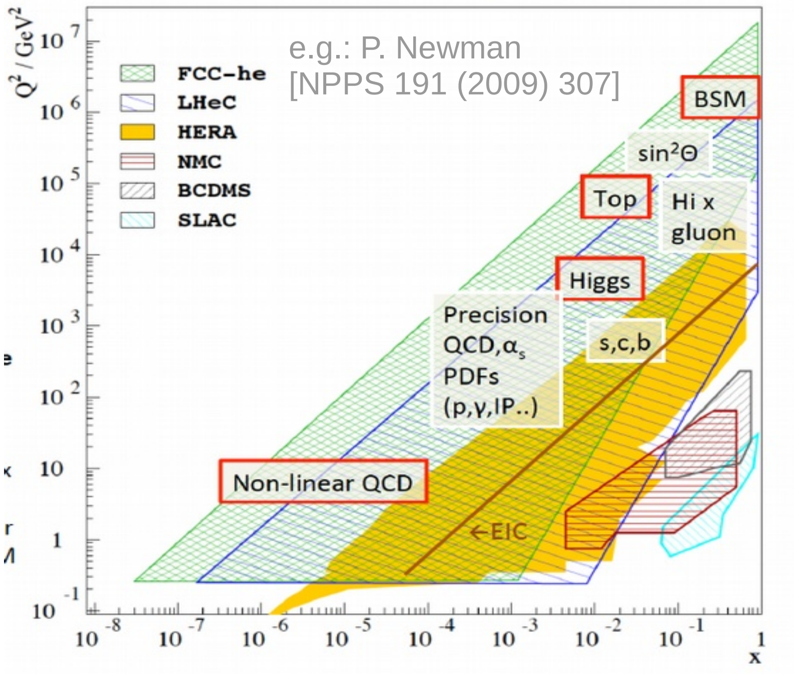
W and Z-exchange: e^+p and e^-p differ

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

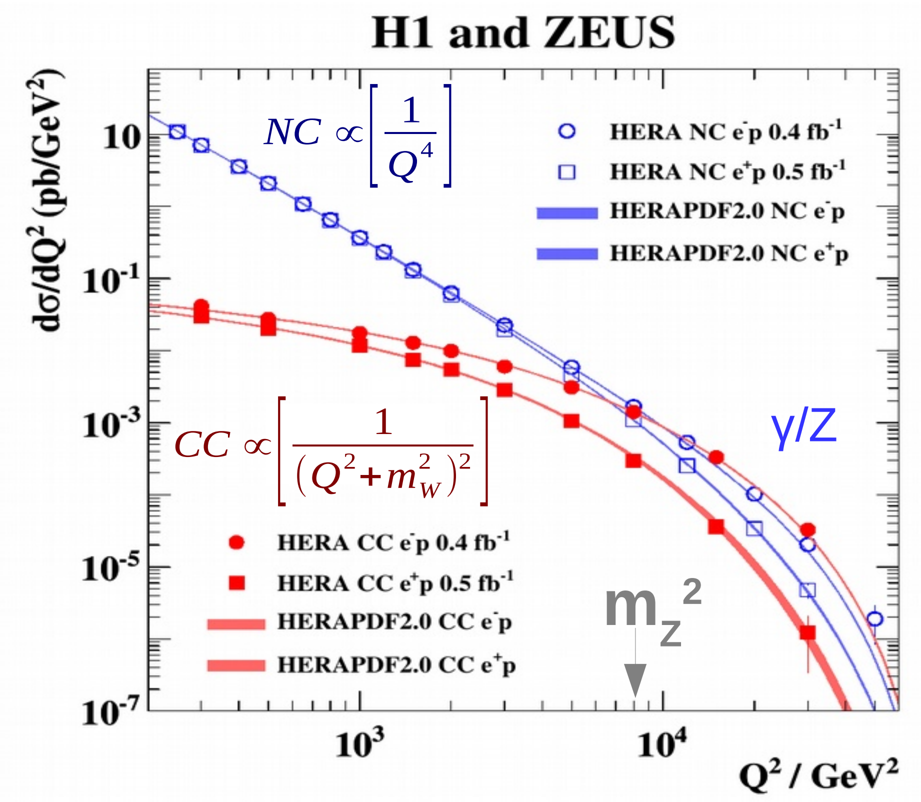
H1+ZEUS, Eur.Phys.J.C75 (2015) 12



Electroweak effects at FCC-eh



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



EW at FCC-eh in comparison to HERA

- CC Large increase of kinematic range
- CC Largely improved experimental precision
- NC γ/Z-interference and ZZ effects will become important (higher Q^2)

Electroweak effects in NC DIS

Cross section expressed by generalised structure functions

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

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

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

Quark-parton model

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

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

	e²	2ev
u	4/9	2/9
d	1/9	2/9

EW scheme

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

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

$(1+\Delta r)$

NC DIS cross sections: *γγ, γZ, ZZ exchange*

- *axial-vector & vector couplings (a,v): parity violation if both are present*

CC DIS: *purely weak cross sections (G_F,m_W)*

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

Simulated data sets

Simulated <u>neutral and charged current</u> cross sections

- Pseudo-data applicable for both: EW and QCD studies

Correlated and uncorrelated syst. and stat. errors

- Numerical treatment of errors [PHE-1990-02, J. Blümlein, M. Klein]

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 (best achieved values)
- Total cross section errors typically: 0.8% at low-x, and 2% at high-x
- Simulated data have full systematic error
- Luminosity measurement ~1% (0.5% may be reachable)

Reduced NC e⁻p scattering cross sections

Reduced cross sections

$$\frac{d^2\sigma_{NC}}{dxdQ^2} = \frac{2\pi\alpha^2 Y_+}{Q^4 x} \cdot \sigma_{r,NC}$$

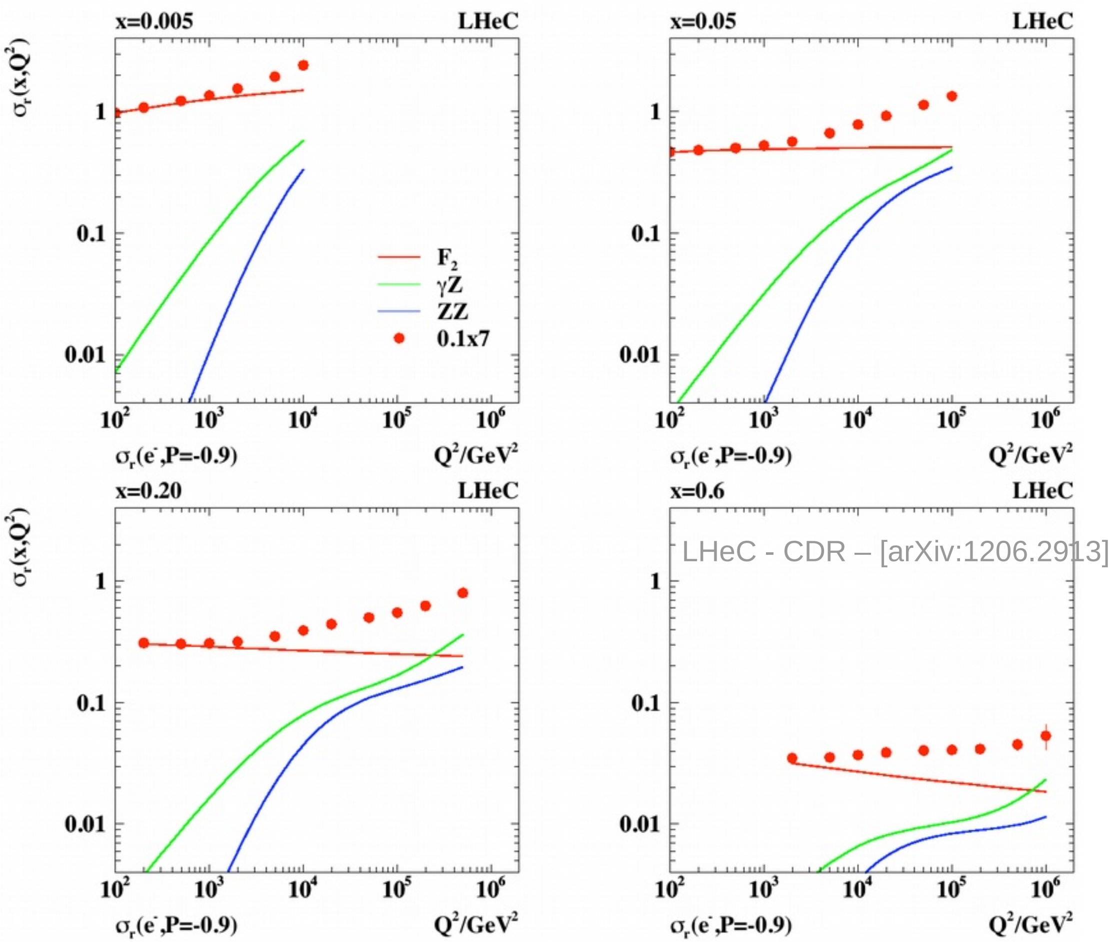
Huge Z exchange effects

- starting around EW scale
- $Q^2 > 1000\ GeV^2$

- Interference effects
- Z-exchange

Cross section raises for high-x due to EW effects

- Contrary to HERA:
  x ~ 0.2 'scaling'
  x > 0.2 gluon bremsstrahlung



LHeC - CDR – [arXiv:1206.2913]

NC DIS Polarisation asymmetry

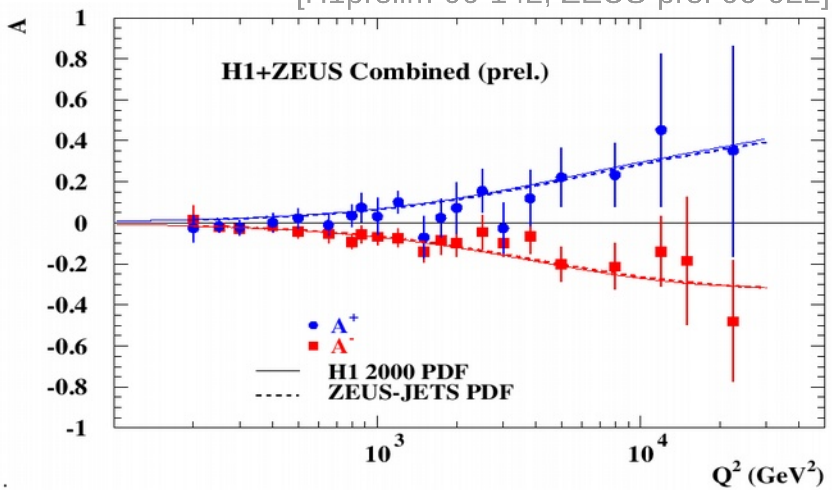
Polarisation asymmetry

- Z-exchange as a function of Q^2

$$A^{\pm} = \frac{2}{P_L^{\pm} - P_R^{\pm}} \cdot \frac{\sigma^{\pm}(P_L^{\pm}) - \sigma^{\pm}(P_R^{\pm})}{\sigma^{\pm}(P_L^{\pm}) + \sigma^{\pm}(P_R^{\pm})}$$

- Parity violation effects in NC EW interactions

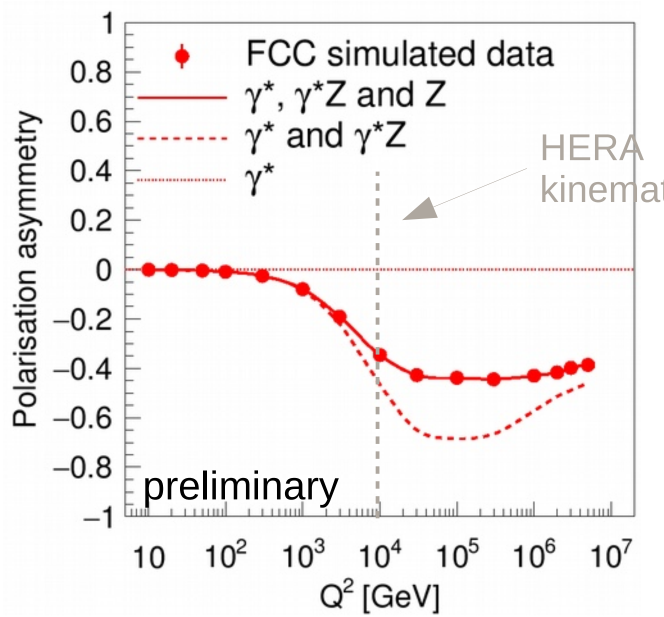
H1+ZEUS
[H1prelim-06-142, ZEUS-prel-06-022]



Cross section asymmetry as a function of Q^2

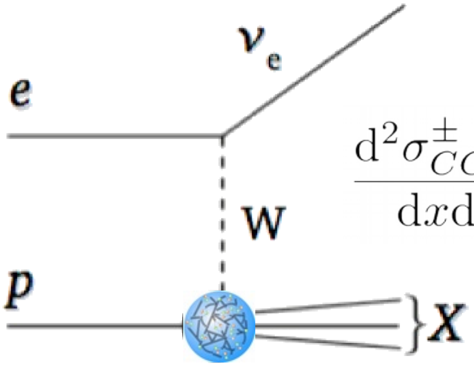
Polarisation asymmetry at FCC-eh

- At large *x*:
  $A^{\pm}$ measures d_v/u_v ratio of valence quarks



Differences btw. left- and right-handed NC DIS are expressed by $F_2^{\gamma Z}$ and $F_3^{\gamma Z}$

Polarised Charged Current DIS



$$\frac{d^2\sigma^{\pm}_{CC}(P_e)}{dx\,dQ^2} = (1 \pm P_e)\frac{d^2\sigma^{\pm}_{CC}}{dx\,dQ^2}$$

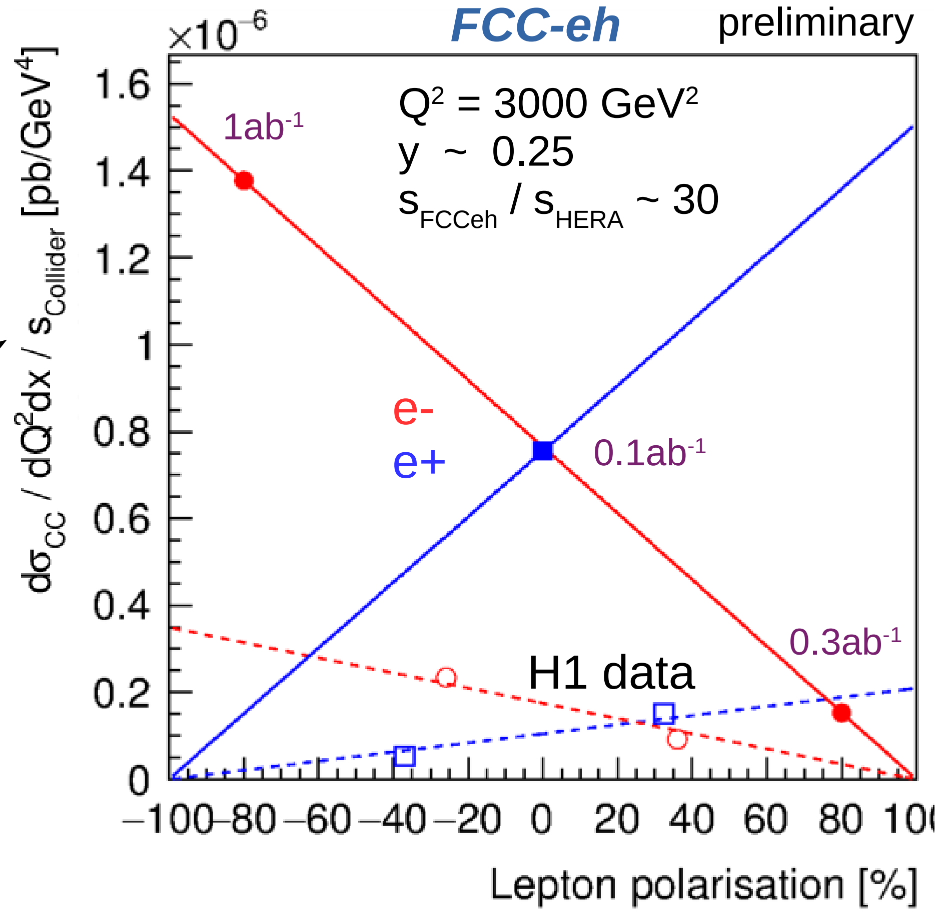
CC depends on longitudinal polarisation

- W-boson couples to left-handed particles

FCC-eh

- Huge cross section due to √s
- For fixed (Q^2,y), increase due lower x values
  -> Gluon induced processes
  -> Helicity effects important at high-x (only)

Most data: electrons with P~-80%



Methodology – Study of EW parameters

Determination of EW parameters from '<u>combined fit: PDF+EW</u>'

- account for correlations with PDF uncertainties

Simulated NC&CC DIS data

- e- +80%, -80%
- e+ unpolarised
- FCC: low-√s unpolarised electron-data

NC/CC	E_e [GeV]	E_p [TeV]	P(e)	charge	lumi. [fb^{-1}]
NC	60 (60)	50 (7)	−0.8	−1	1000
CC	60 (60)	50 (7)	−0.8	−1	1000
NC	60 (60)	50 (7)	+0.8	−1	300
CC	60 (60)	50 (7)	+0.8	−1	300
NC	60 (60)	50 (7)	0	+1	100
CC	60 (60)	50 (7)	0	+1	100
NC	20 (60)	7 (1)	0	−1	100
CC	20 (60)	7 (1)	0	−1	100

* second and third columns show FCC-eh (LHeC)

error assumptions:
elec. scale: 0.1%; hadr. scale 0.5%
radcor: 0.3%; γp at high y: 1%
uncorrelated extra eff. 0.5%

PDF+EW-fit

- PDF fit in NNLO precision
  - ZM-VFNS using QCDNUM
  - 13 free PDF parameters
  - details of PDF fit only of minor importance

See also talk by Claire Gwenlan about PDF studies

EW calculations

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

See also talk by Bryan Webber for combined QCD+EW

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

Z-boson mass

Z-boson mass from EW+PDF fit

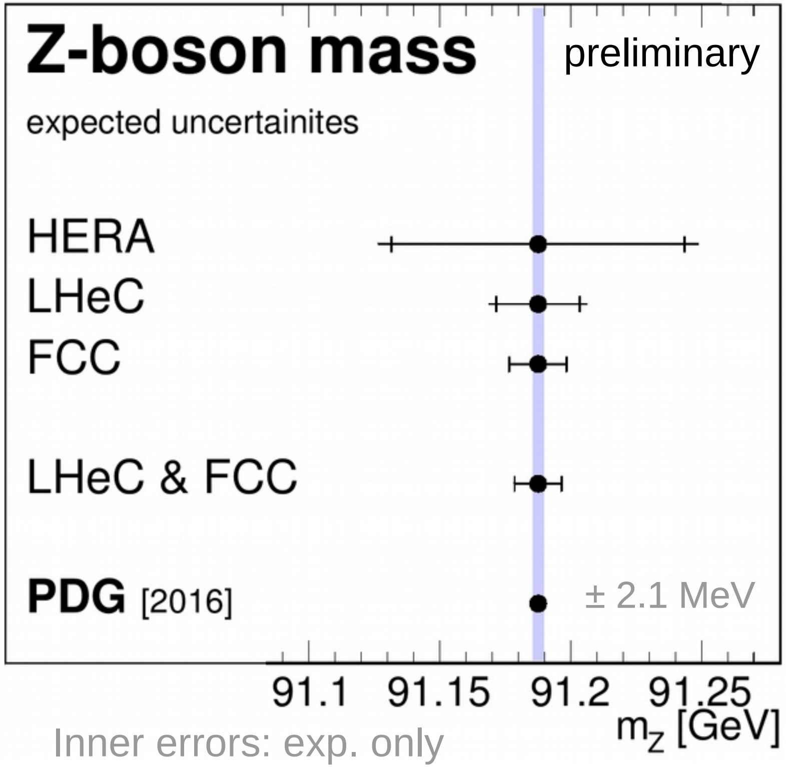
- all other masses expected to be known
- PDFs are determined as well

Z-boson mass

- HERA (56)$_{exp}$(25)$_{PDF}$ MeV
- LHeC (16)$_{exp}$(10)$_{PDF}$ MeV
- FCC (11)$_{exp}$(3)$_{PDF}$ MeV
- PDF uncertainties beome negligibly small (outer errors)

Precision of Z-boson mass not limited by PDFs

- Though: combined QCD+EW corrections may become important -> to be studied...



Inner errors: exp. only
Outer errors: exp. + PDF

HERA prospects ('87)
$m_W \sim \pm$ 80-100 MeV

W-boson mass

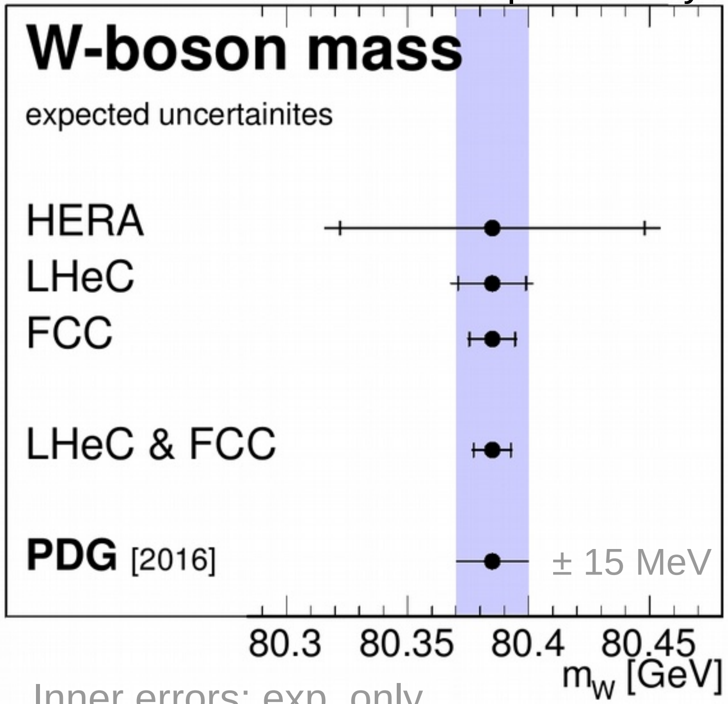
W-boson mass from NC&CC DIS data

- All other masses expected to be known
- HERA ± $63_{(exp)} 29_{(PDF)}$ MeV
- LHeC ± $14_{(exp)} 10_{(PDF)}$ MeV
- FCC ± $9_{(exp)} 4_{(PDF)}$ MeV

High precision for W-boson mass

- CC kinematics constraint by IS + FS measurements
  -> no missing E_T needed
  -> IS photon tagging would be crucial
- PDF (QCD) uncertainties are small

preliminary



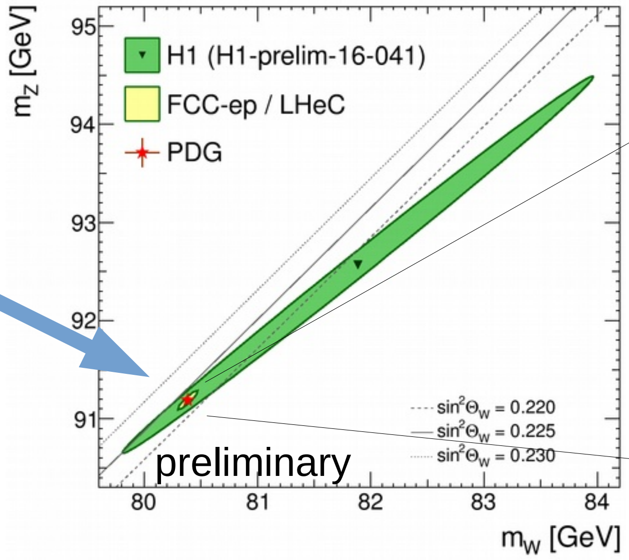
Inner errors: exp. only
Outer errors: exp. + PDF

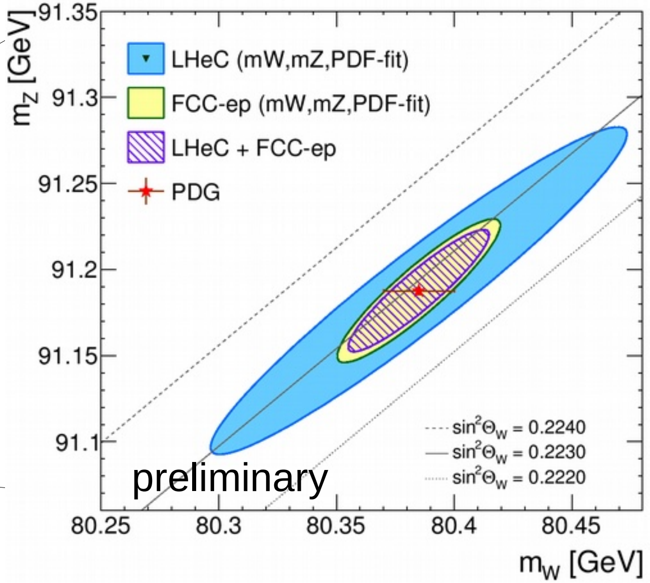
W-boson mass at high precision

Simultaneous determination of boson masses

W- and Z-boson masses: Most important input parameters to EW calculation

FCC-eh
LHeC





HERA

- Simultaneous determination not (quite) possible (H1prelim-16-041)

FCC-eh

- Greatly improved w.r.t. HERA

- Benefit from incredibly high cross sections
- m_W-m_Z correlation reduced (prop to $\sin^2\theta_W$)
- PDFs will not be the limiting factor for EW physics
- 'global' fit becomes possible

W-boson and top-mass

Top mass and W-boson mass

m_W-m_t determinations

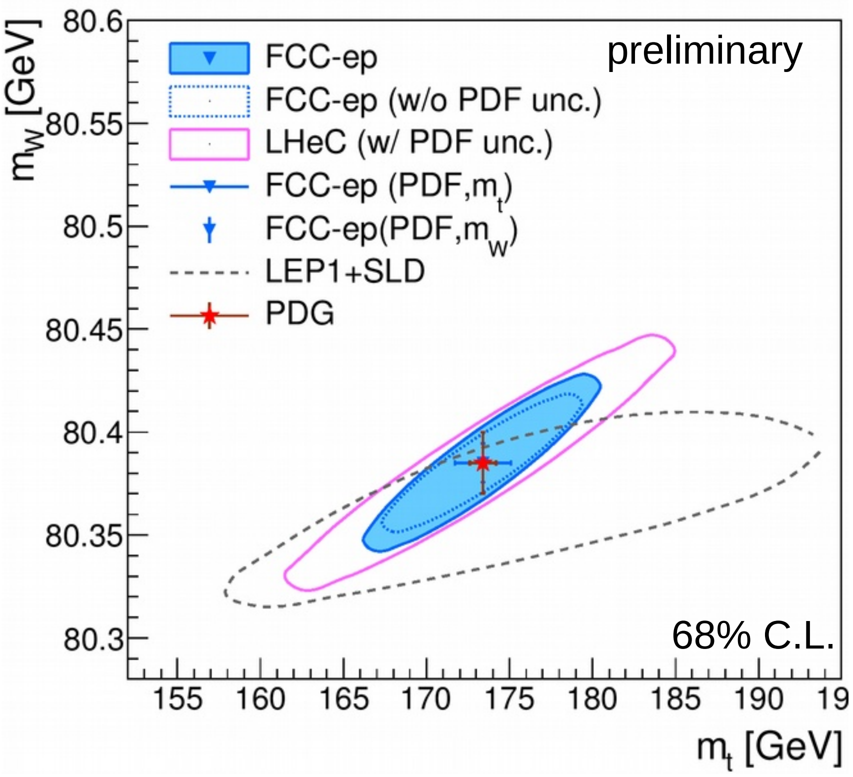
- sizeable correlation (as expected)
- significant improvement over LEP experiments

$$\Delta m_t = \pm 3.2 \text{ (exp)} \pm 2.1 \text{ (PDF) GeV}$$

- FCC-eh exceeds precision of LEP+SLD combination
- PDF uncertainties will not be limiting factors

Mind: only inclusive DIS studied here

-> additional direct measurements will provide significant improvements

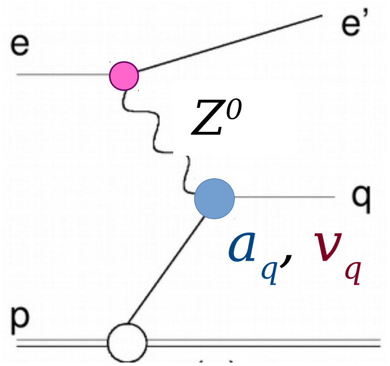


$\Delta m_H = \pm 38_{\text{(exp)}} \pm 25_{\text{ (PDF)}}$ GeV

Weak neutral couplings

Axial ***and*** *vector-axial* ***couplings of quarks***

- Couplings of ferminos to Z-boson



$$a_q = I^{(3)}_{q,L} \qquad v_q = I^{(3)}_{q,L} - 2Q_q \sin^2\theta_W$$

Mind!
conventional: ρ' ↔ √ρ

Effective higher-order corrections

- Form factors *ρ* & *κ*

$$v_q = \rho^{SM}_{Z,q} \rho'_{Z,q} \left(I^{(3)}_{q,L} - 2 Q_q \kappa^{SM}_{Z,b} \kappa'_{Z,b} \sin^2\theta_W \right)$$

$$a_q = \rho^{SM}_{Z,q} \rho'_{Z,q} I^{(3)}_{q,L}$$

- At tree-level: *ρ* = *κ* = *1*
- EW corrections yield non-zero form factors. on-shell scheme

$$\rho^2_{Z,q} \sim 1 + \rho_t \qquad \kappa^2_{Z,q} \sim 1 + \rho_t / \tan^2\theta_W$$

using $\rho_t \sim G_F m_t^2$

- Dominating effects of many SM extensions can be described by *ρ'* and *κ'*
Here:

$$\rho'_{Z,u} \quad \rho'_{Z,d} \quad \rho'_{Z,e} \qquad \kappa'_{Z,q}$$

Weak neutral couplings: form factors

Effective higher-order corrections

- SM: $\rho' = 1$
- Expected uncertainties

$\Delta\rho'_{Z,u} \sim 0.0023$ $\Delta\rho'_{Z,d} \sim 0.0034$ $\Delta\rho'_{Z,l} \sim 0.0018$

$\Delta\rho'_{Z,q} \sim 0.0017$

$\Delta\rho'_{Z,f} \sim 0.0008$

References mainly testing ρ_{lept}

$\Delta\rho^{PDG}_{Z,l} \sim 0.000115$ PDG17

$\Delta\rho^{LEP+SLD}_{Z,l} \sim 0.00037$ LEP+SLD, Z-pole fit, 'predicted'

$\Delta\rho^{LEP+SLD}_{Z,l} \sim 0.0005$ LEP+SLD, Z-pole

$\Delta\rho^{SM,theo}_{Z,l} \sim 0.00001$ EPJ C71 (2011) 1718

$\Delta\rho^{LEP+SLD}_{Z,b} \sim 0.0105$ LEP+SLD, FB-Asym

$\Delta\rho^{LEP+SLD}_{Z,c} \sim 0.0105$ LEP+SLD, FB-Asym

See also talk by Roberto Tenchini for *e, μ, τ, b, c* @FCCee

Corrections to $\sin^2\theta_W$

- SM: $\kappa' = 1$

$\Delta\kappa'_{Z,q} \sim 0.0036$

$\Delta\kappa'_{Z,l} \sim 0.0020$

LEP+SLD Z-pole (predictions)

$\Delta\kappa_l = 0.0025$

$\Delta\kappa_b = 0.0036$

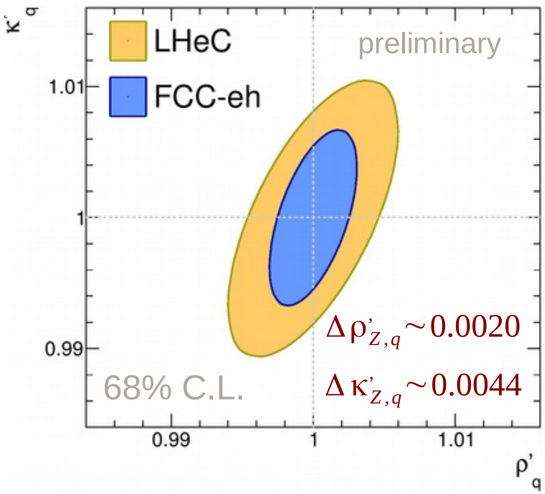
LEP+SLD (FB-Asym)

$\Delta(\sin^2\theta^{lept}_{eff}) = \pm 0.00021$

$\Delta(\sin^2\theta^{b}_{eff}) = \pm 0.016$

- Simultaneous determination: ρ' and κ'

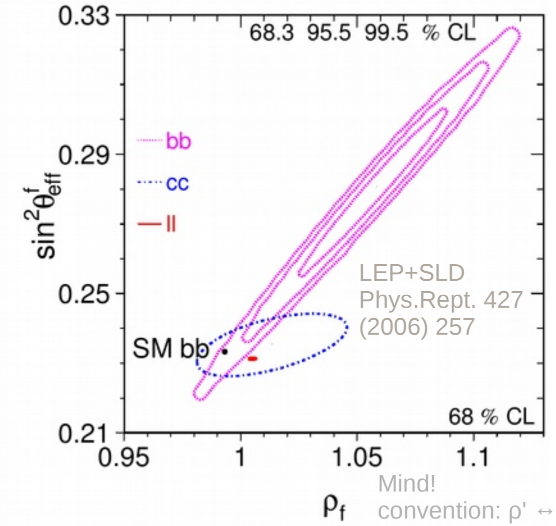
FCC-eh



$\Delta\rho'_{Z,q} \sim 0.0020$

$\Delta\kappa'_{Z,q} \sim 0.0044$

LEP+SLD

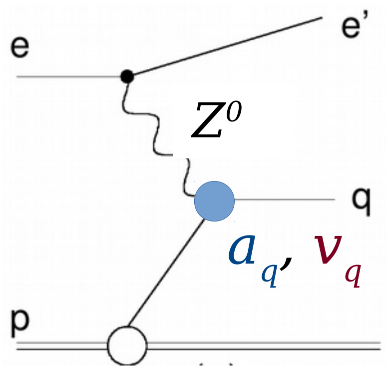


Mind! convention: ρ' ↔ √ρ

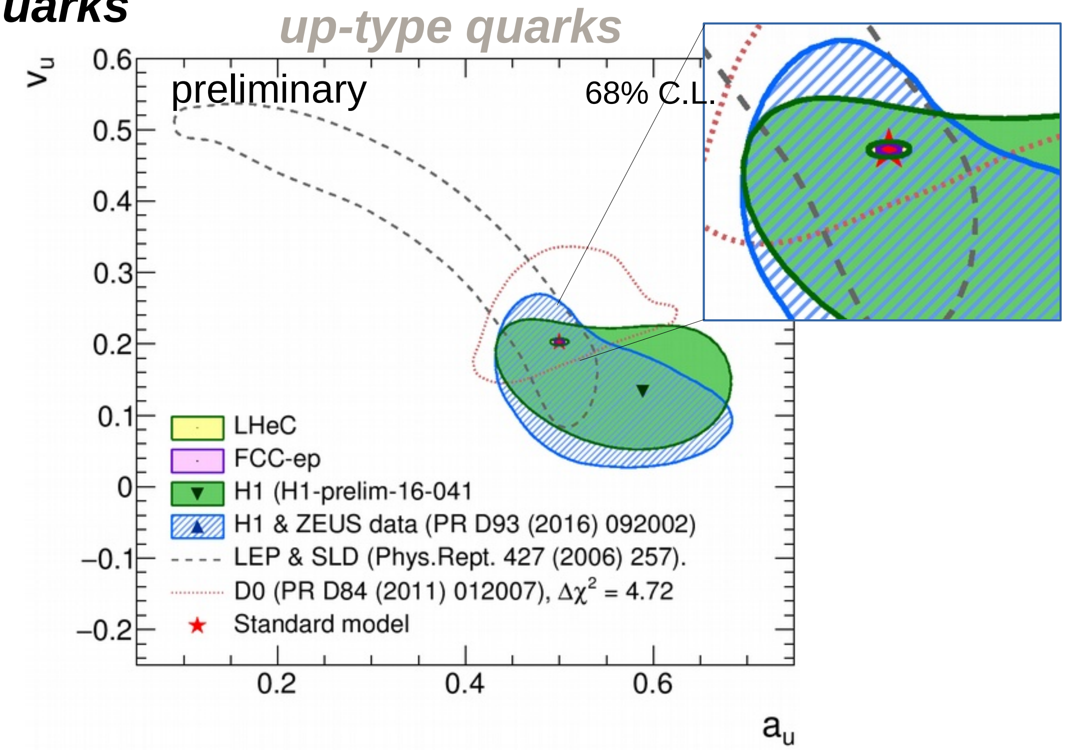
Light quark couplings at LHeC and FCC-eh

Axial and *vector-axial* couplings of quarks

- Couplings of quarks to Z-boson



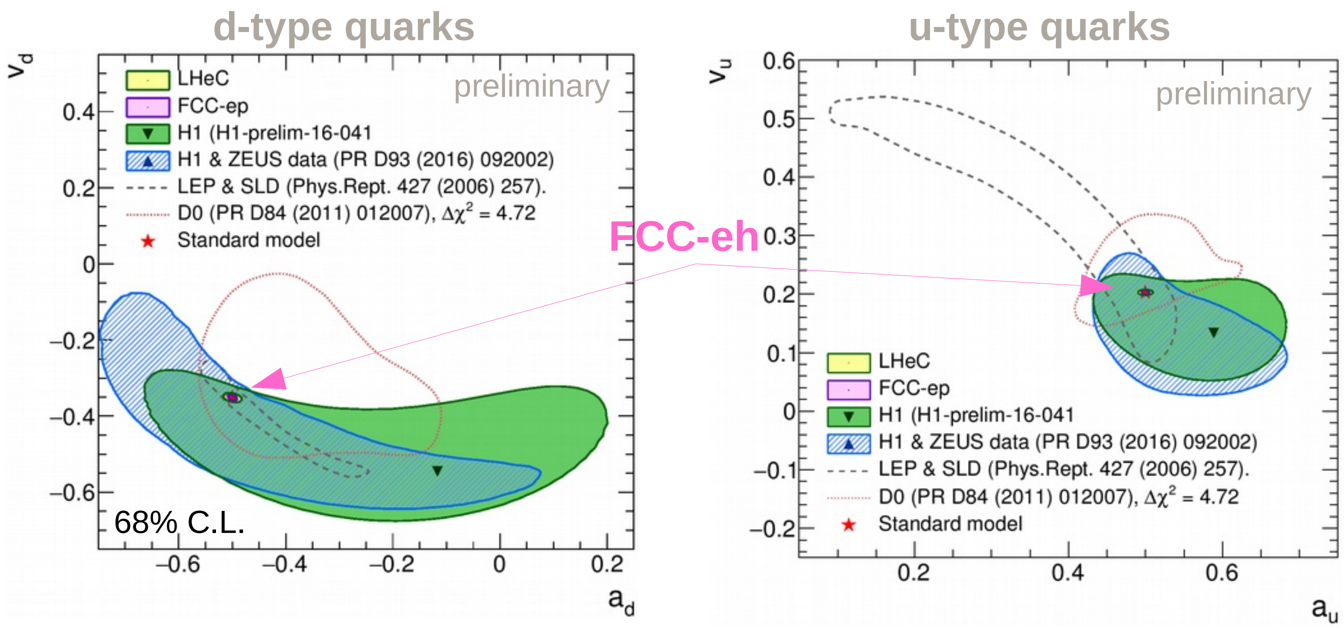
$$a_q = I^{(3)}_{q,L} \qquad v_q = I^{(3)}_{q,L} - 2 Q_q \sin^2\theta_W$$

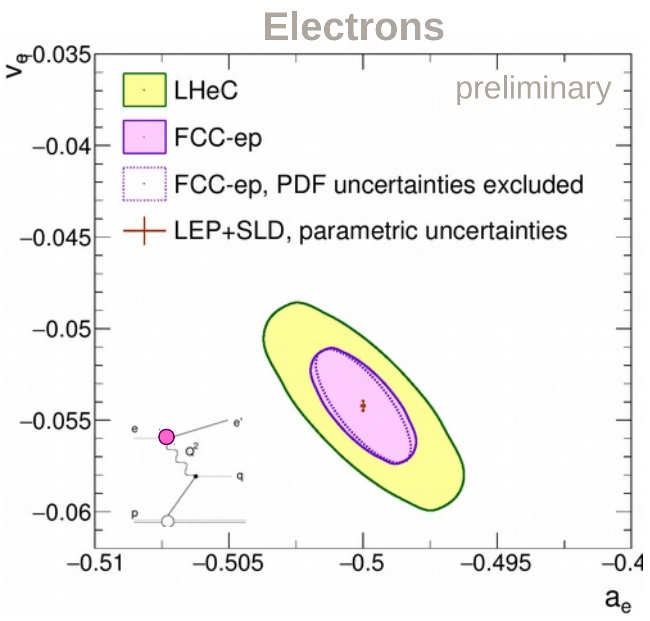


LHeC and FCC-ep

- Polarisation of lepton beam (P_e ~ ±80%) improves precision
- Very precise measurements of weak light-quark couplings feasible

Weak neutral couplings: quarks, electrons





Weak neutral quark couplings

- u- and d-quark couplings determined simultaneously
- Very precise measurements feasible

a_u = 0.5 +/- 0.003
a_d = -0.5 +/- 0.005
v_u = 0.20 +/- 0.002
v_d = -0.35 +/- 0.005

Electron couplings

- High precision
- Though:
  LEP with 'ulitmate' precision

High precision test of electroweak sector of Standard Model

Complementary test

Weak mixing angle

Weak mixing angle

- on-shell scheme:
  No scale dependence

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

Weak mixing angle

- Expected precision (very preliminary)

```
LHeC   ±0.0003(exp) 0.0002(PDF)
FCC    ±0.0002(exp) 0.00008(PDF)
PDG    ±0.00010
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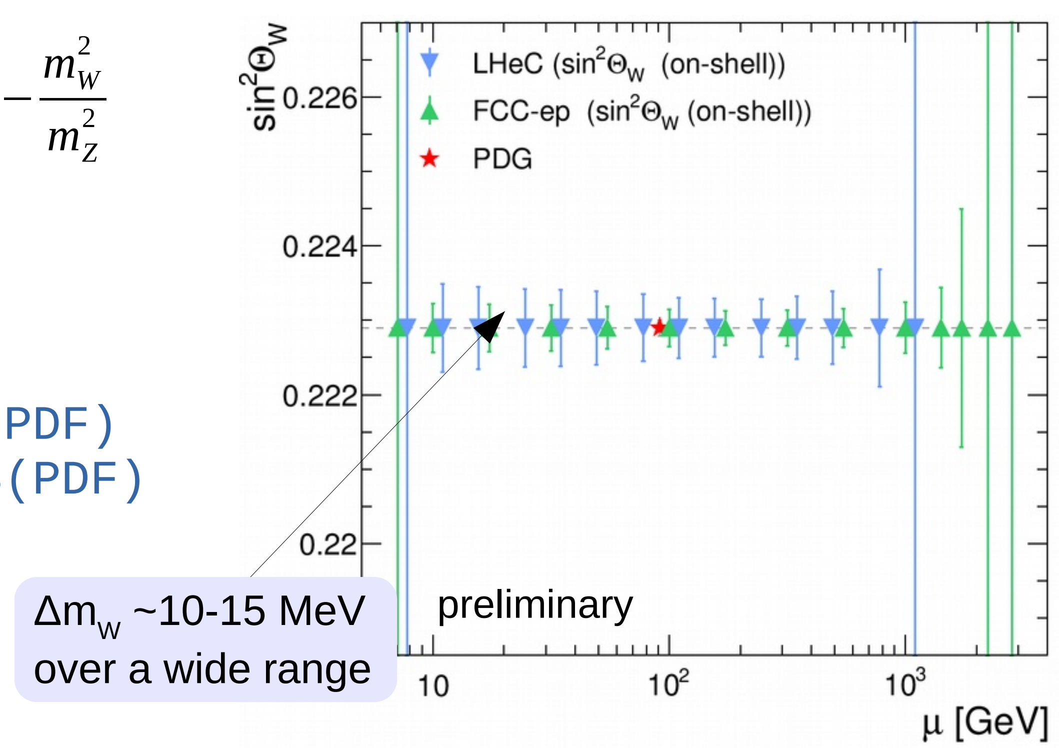
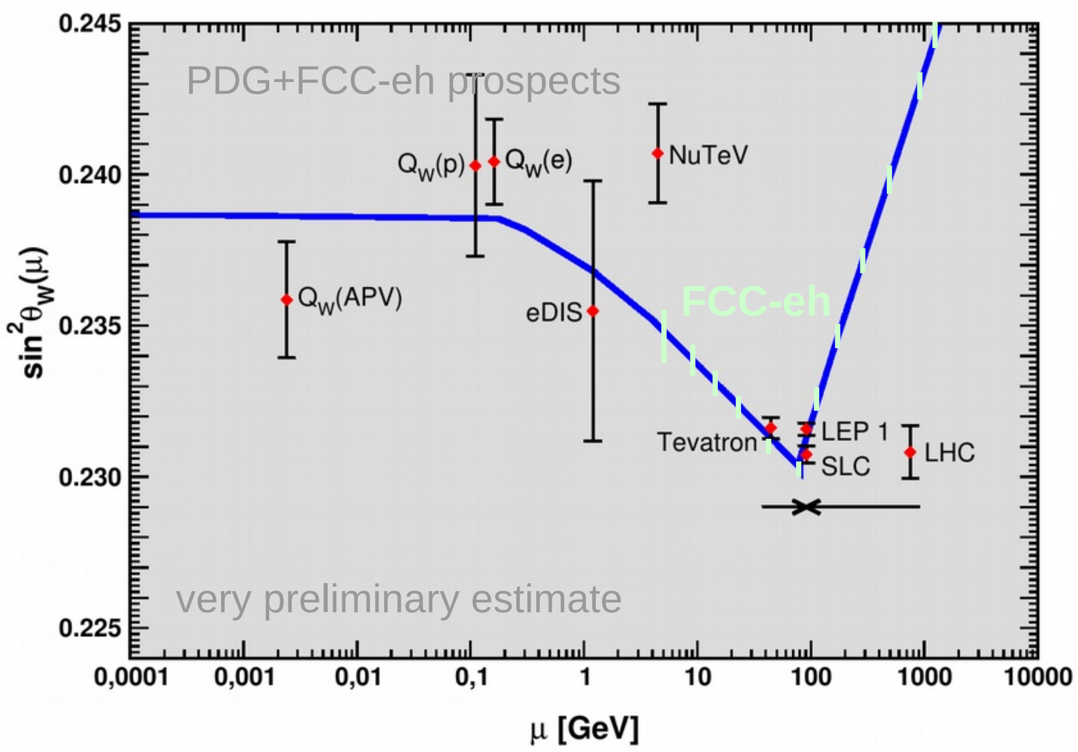
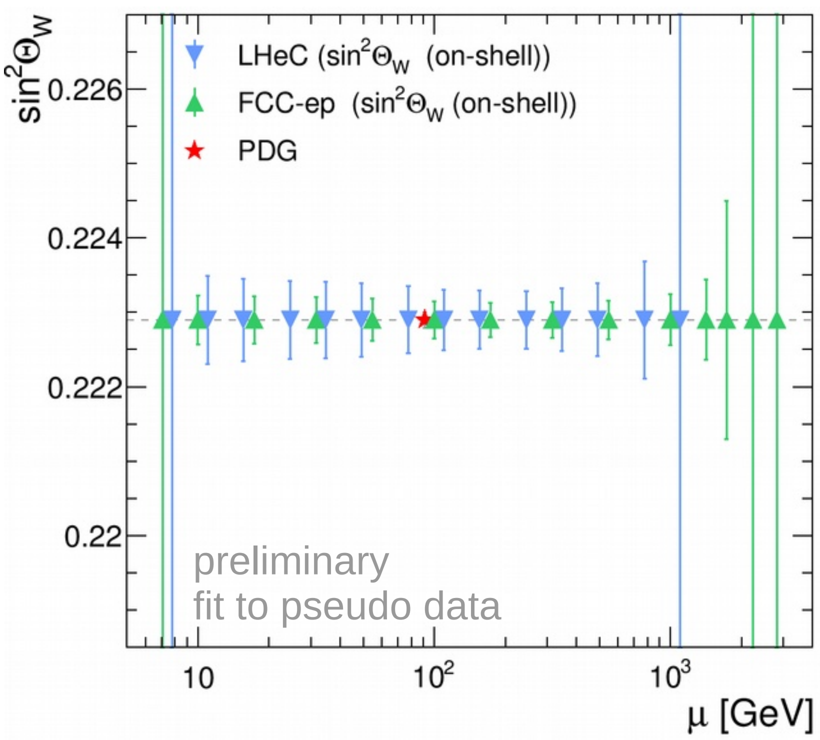
- Inclusive data will be competitive to direct measurements at the Z-pole



Inclusive DIS data from LHeC and FCC-ep probes scale dependence of EW theory in impressive range from 10 GeV up to TeV scale

Scale dependence of EW theory





Tests of scale dependence of EW theory possible
-> calculations currently missing

Summary

Studies of EW parameters using simulated inclusive DIS data

- LHeC or FCC-eh will greatly improve HERA results
- Competitive with LEP+SLD results in case of indirect determinations

Neutral currents

- Often complementary measurements to e^+e^- (with high precision): unique measurements for (light-)quark sector

Charged currents

- Highest precision with CC interactions -> W-boson mass -> because CC kinematics can be fully reconstructed

Unique test of scale dependence of EW interactions

- High accuracy in the range from 10 GeV up to the TeV regime

The two SM sectors: QCD ↔ EW

- PDFs and QCD corrections are not the limiting factor for EW physics
- EW corrections are irrelevant for many QCD studies (at lower scales)

All conclusions hold with similar precision also for the LHeC

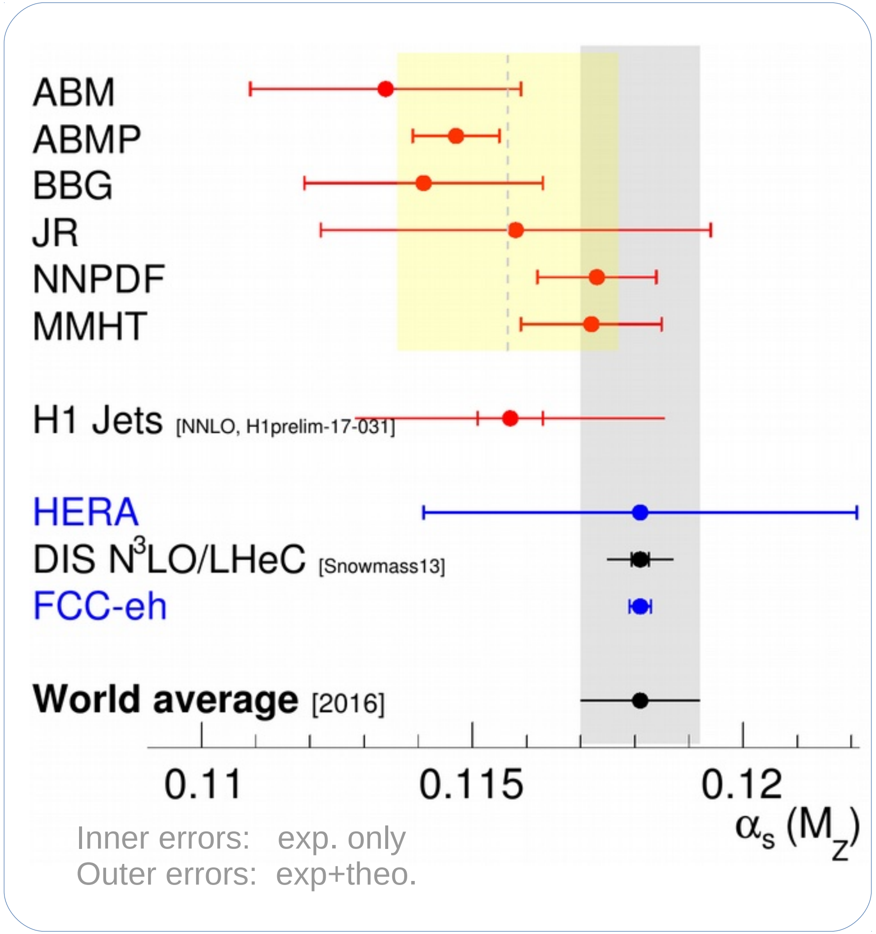
Strong coupling at FCC-eh

Strong coupling constant $\alpha_s(m_Z)$

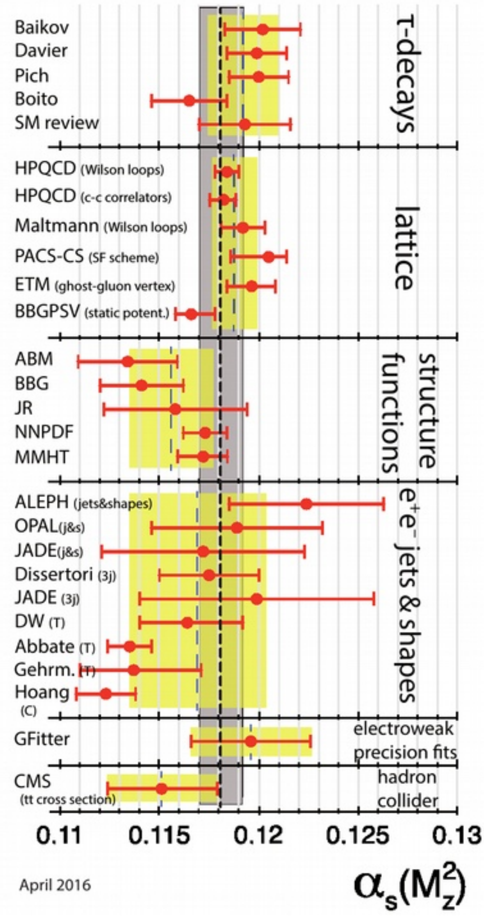
Strong coupling $\alpha_s(m_Z)$
- *Least known SM parameter*
- *Crucial for precision physics*
- *Mainly limited by theory*

DIS
- *Highest precision feasible [snowmass13]*
- *N^{3}LO almost available*

FCC-eh prospects
- *Highest precision expected incl. PDF uncert.*
- *Prospects depend on assumptions made for PDF*



PDG 2016



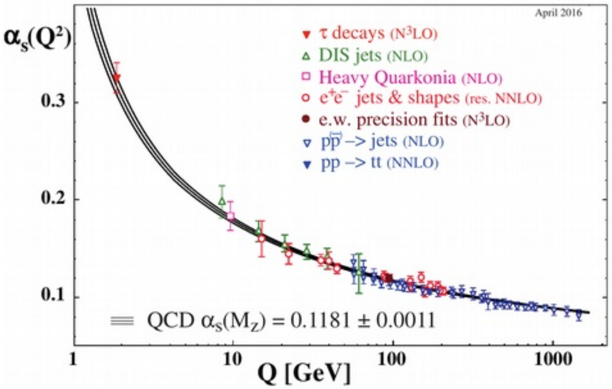
Running of strong coupling

Running of strong coupling constant

- Important test of SU(3) structure of QCD

Today's status

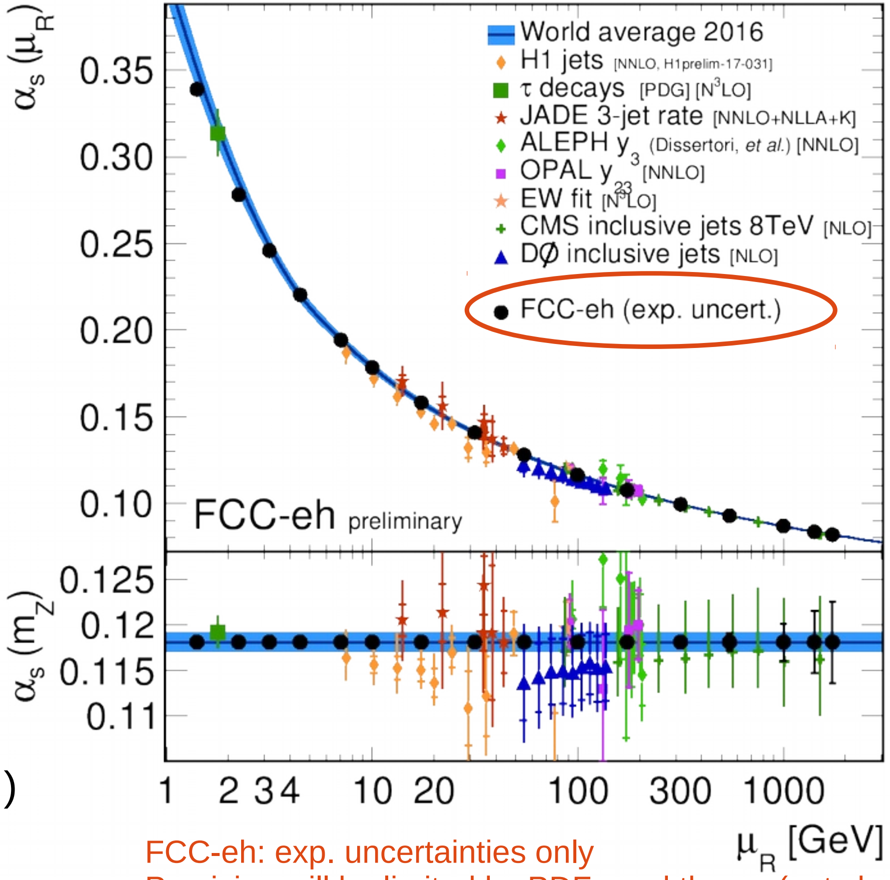
PDG 2016



FCC-eh prospects

- High <u>exerimental</u> precision
  - ~ 0.1 % for 2 < Q < 100 GeV
  - ~ 1% for Q~1TeV
- Precision clearly limited by PDFs and theory (0.5 – 1%)
- Large kinematical range accessible in a single process
- Jet measurements will further improve precision

FCC-eh prospects



FCC-eh: exp. uncertainties only
Precision will be limited by PDFs and theory (not shown)