Electroweak physics with inclusive DIS at the LHeC and FCC-eh

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for the LHeC study group

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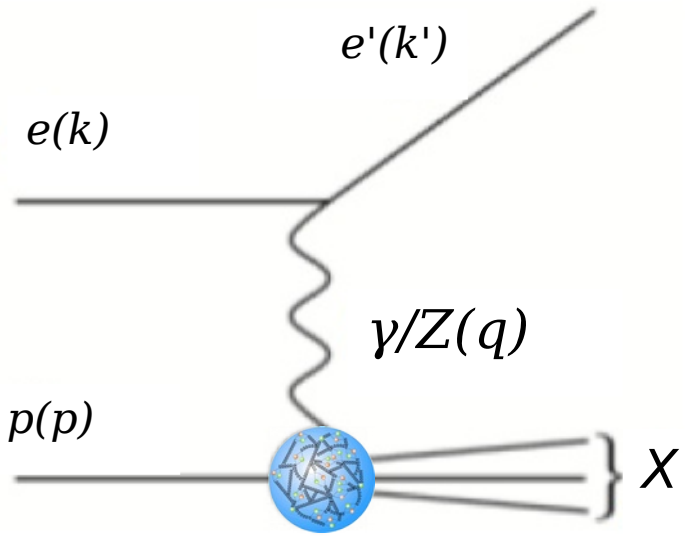
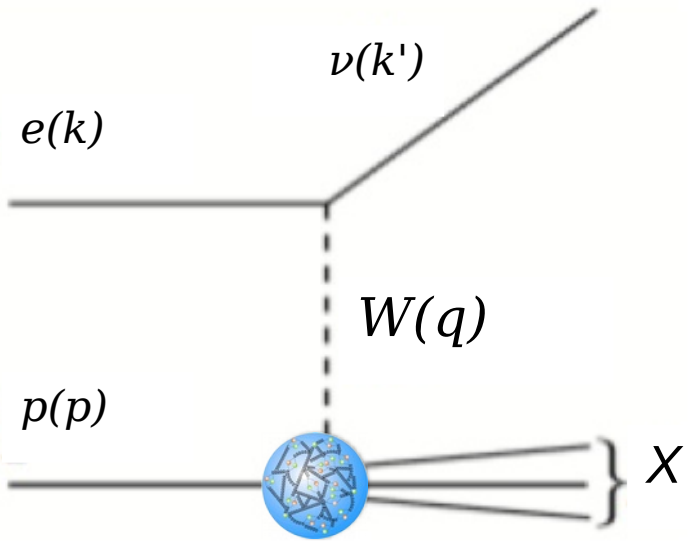
Deep-inelastic electron-proton scattering

Neutral current scattering
$ep \to e'X$



Charged current scattering
$ep \to \nu_e X$



R-D. Heuer

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

-> Both: Electroweak (EW) and QCD physics are equally important at LHeC (?)

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

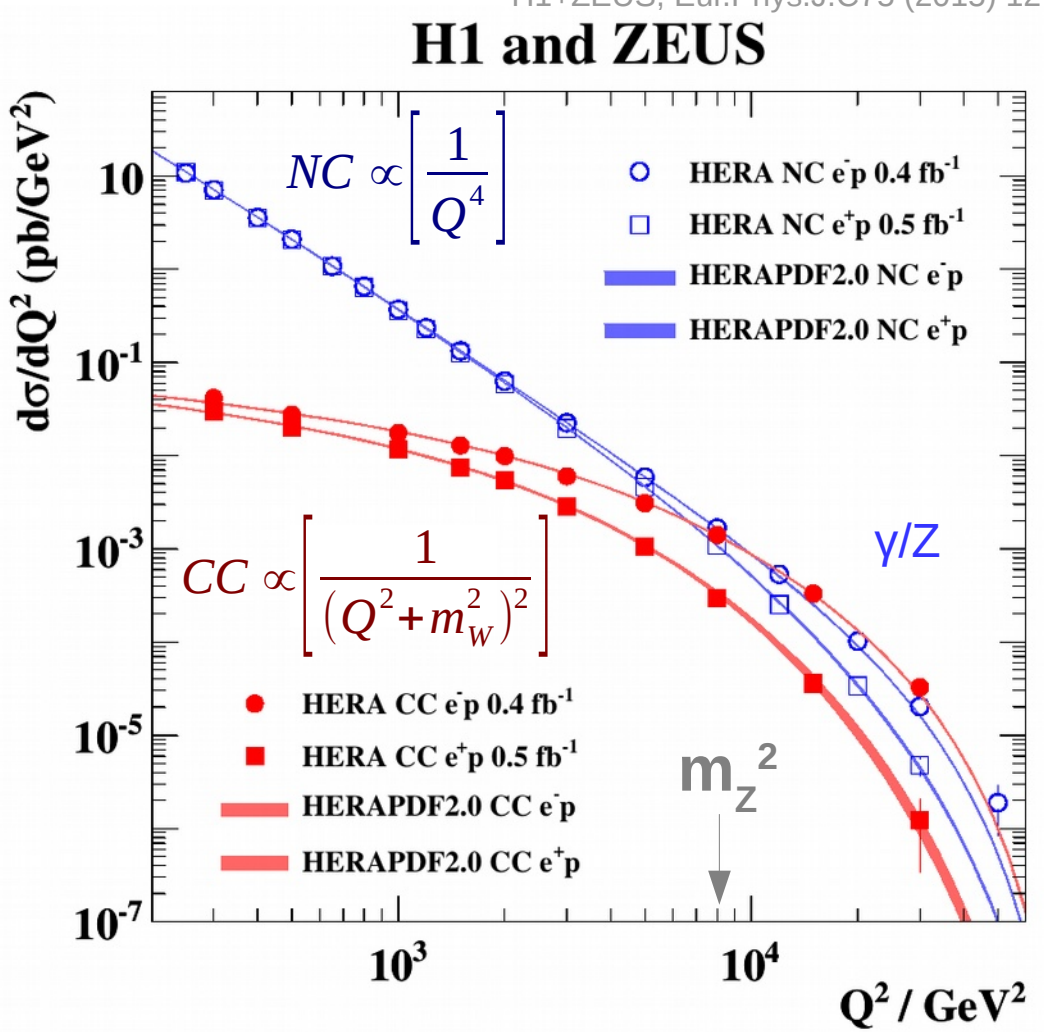
Around EW unification scale

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

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 in NC DIS

Cross section expressed by generalised structure functions

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

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

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

Quark-parton model

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

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

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

EW scheme

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

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

$$(1 + \Delta r)$$

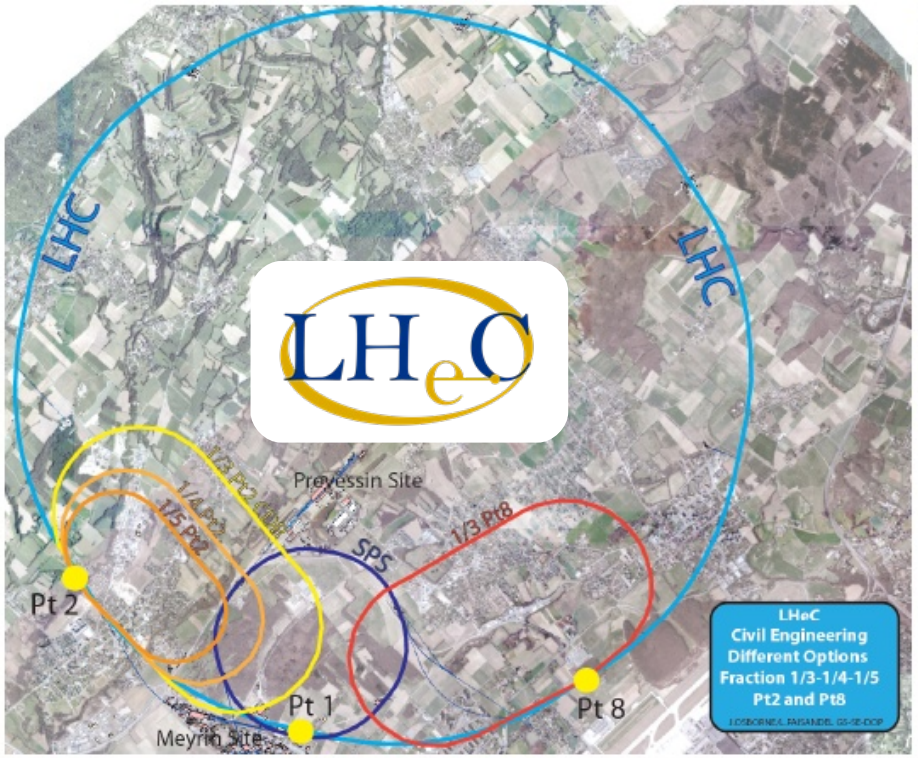
NC DIS cross sections: *γγ, γZ, ZZ exchange*

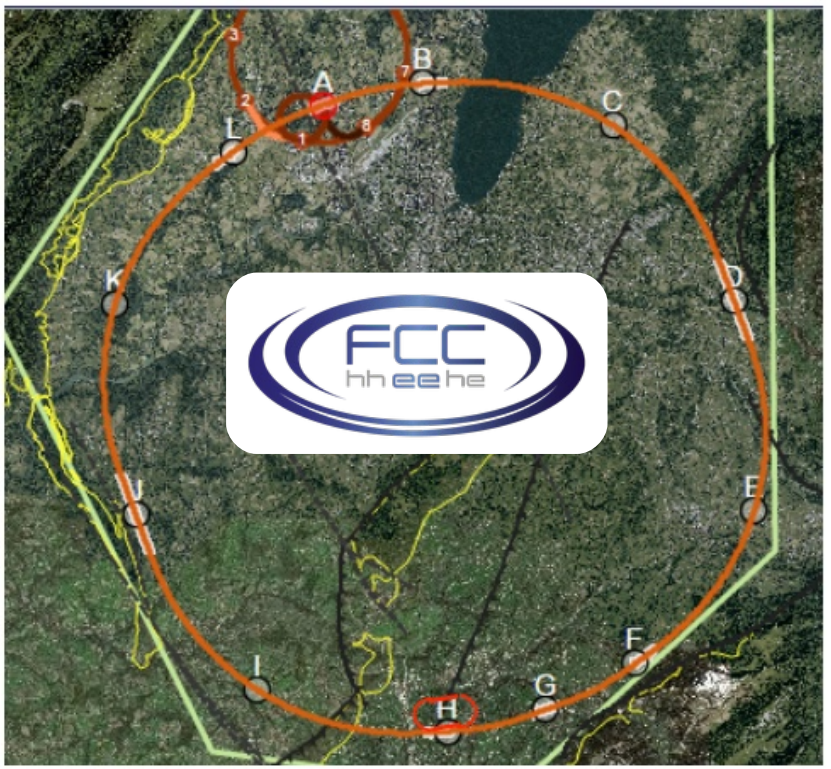
- *axial-vector & vector couplings (a,v): parity violation if both are present*

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)

Future proposed ep-colliders: LHeC & FCC-eh





Electron ring

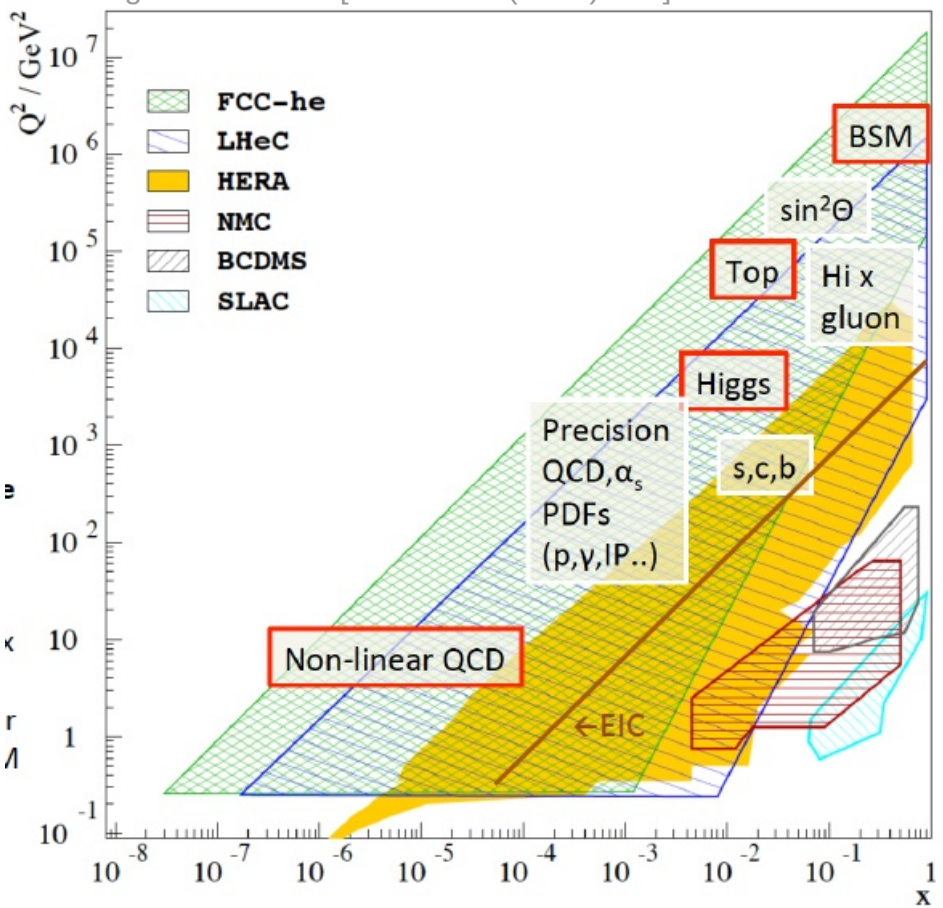
- Energy recovery linac: E_e = 60 GeV
- Polarisation up to P_e ~ 80%
- Similar concept for LHeC & FCC-eh

Center-of-mass energies

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

LHeC & FCC-eh: Large kinematic range

e.g.: P. Newman [NPPS 191 (2009) 307]



Comprehensive physics programme

- Higgs physics
- Top-Quark (properties, top-PDFs)
- Heavy-quarks (s,c,b-quarks)
- low-x physics (non-linear QCD?), also e-Ion
- Precision QCD physics (strong coupling, PDFs)
- Electroweak physics...

Huge increase of kinematical reach over previous DIS experiments

Simulated data sets

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

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

see also talks by C. Gwenlan, A. Cooper-Sarkar

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

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

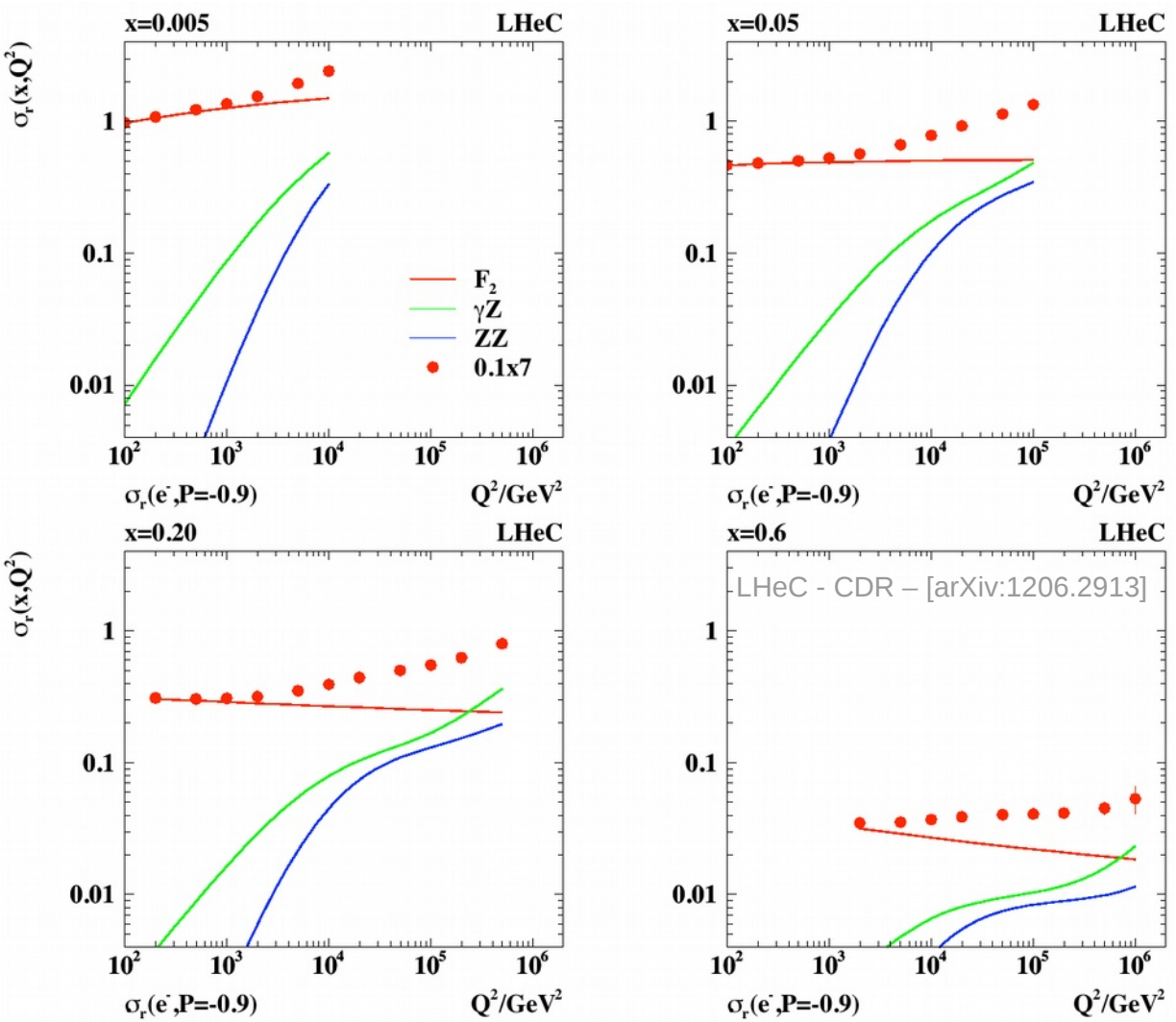
Huge Z exchange effects

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

- 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



NC DIS Polarisation asymmetry

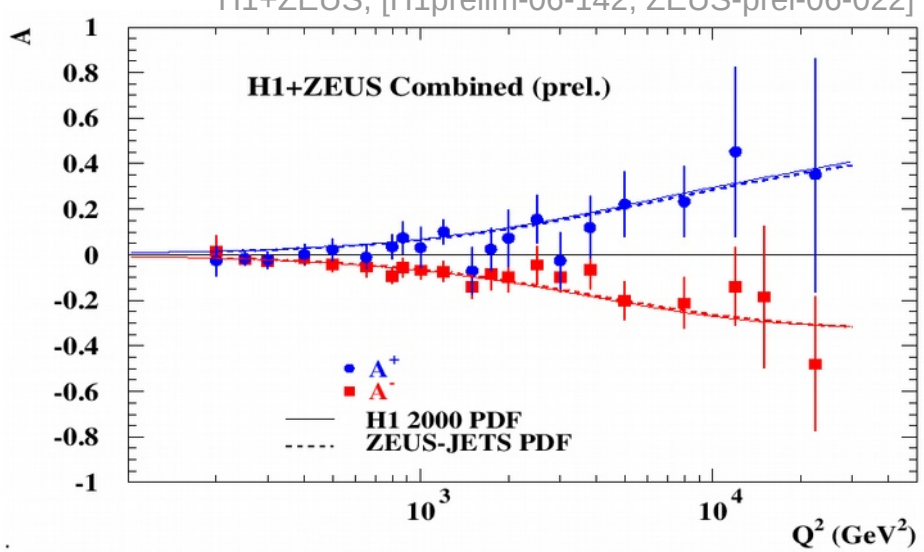
Polarisation asymmetry

- 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

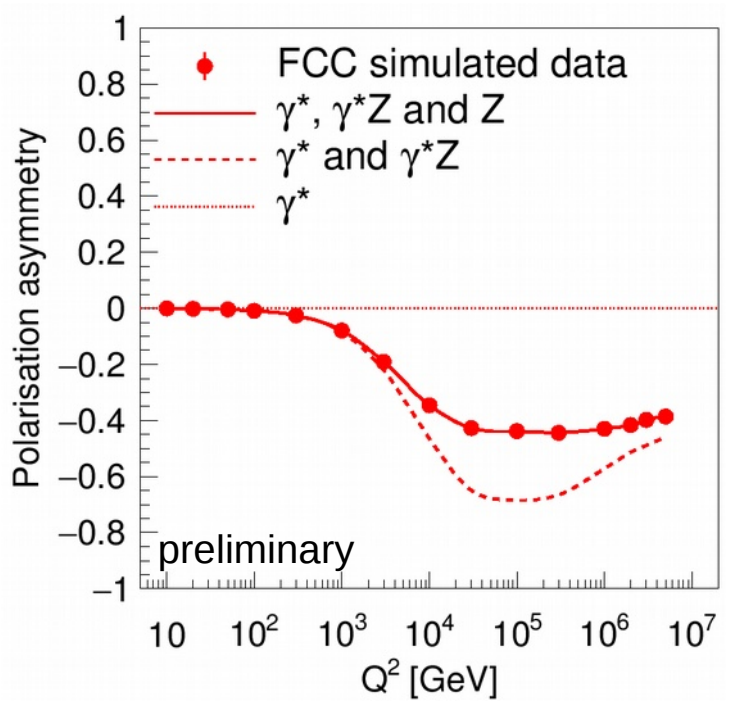
H1+ZEUS, [H1prelim-06-142, ZEUS-prel-06-022]



Cross section asymmetry as a function of Q^2

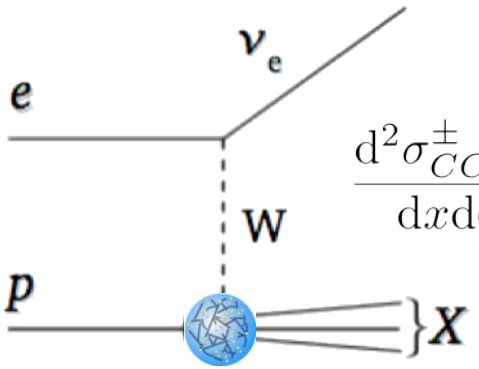
Polarisation asymmetry at LHeC & FCC

- 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



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

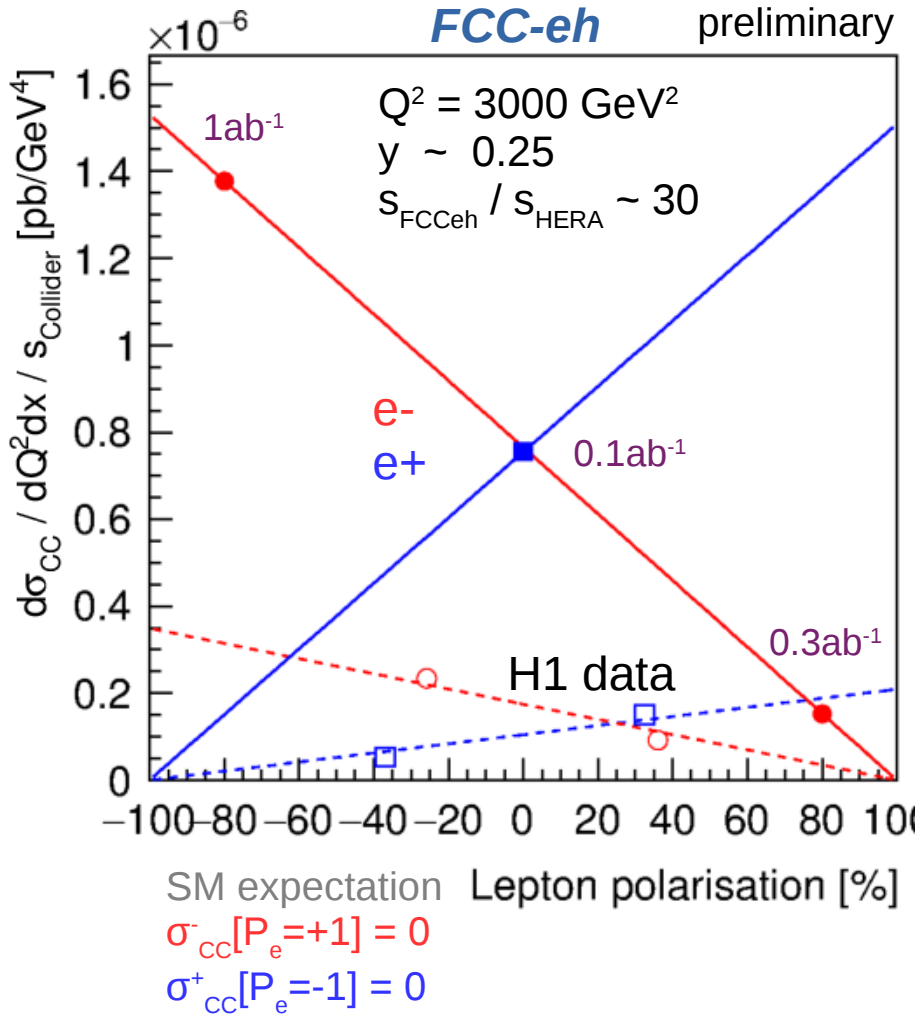
CC depends on longitudinal polarisation

- W-boson couples only to left-handed particles

LHeC and FCC

- Huge cross section due to √s
- For fixed (Q2,y), increase due lower x values
  -> Gluon induced processes
  -> Helicity effects important at high-x (only)

Most data: electrons with P~-80%



Study of EW parameters - methodology

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

- account for correlations to PDF uncertainties,
  since these are also determined from DIS data

For this study

- Employ only <u>inclusive NC and CC DIS</u> data
- <u>No direct measurements</u> of real Z/W-bosons (or t, H)

-> significant improvements expected if direct measurements are further considered

HERA or published results as reference

- H1+ZEUS combined data (unpolarized) (EPJ C75 (2015) 2)

LHeC and FCC-eh: Simulated NC&CC DIS data

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

Electroweak parameters in inclusive DIS

Fitting methodology

- QCD (PDF) fit in NLO precision using ZM-VFNS using QCDNUM
  - 13 free PDF parameters
  - details of PDF fit are only of minor importance,
    because PDF fit is used only used to determine PDF uncertainties on EW parameters

EW calculations

- Calculations are performed in on-mass shell scheme:
  (α_{em}, m_Z, m_W, Δr) with $\Delta r = \Delta r(\alpha_{em}, m_W, m_Z, m_t, m_H, \ldots)$
- More general, also <u>vector</u> and <u>axial-vector couplings</u> are 'free' parameters
- 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

Weak-boson masses

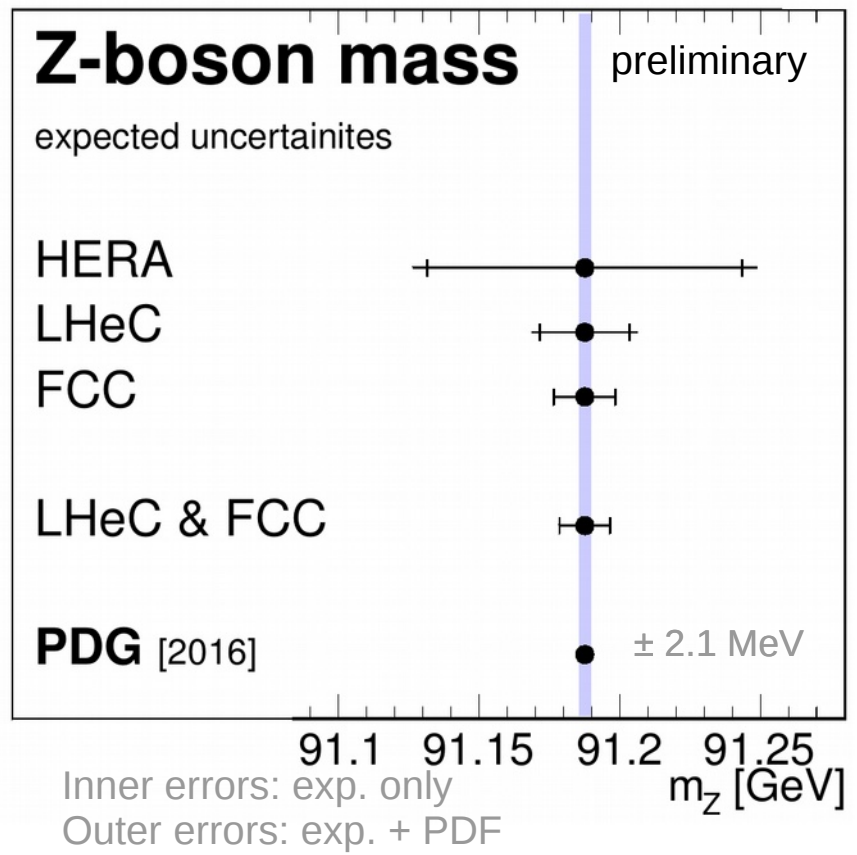
Z-boson mass from EW+PDF fit to inclusive NC&CC DIS data

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

Z-boson mass

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

-> Measurement of Z-boson mass not limited by PDFs



Weak-boson masses

W-boson mass from NC&CC DIS data

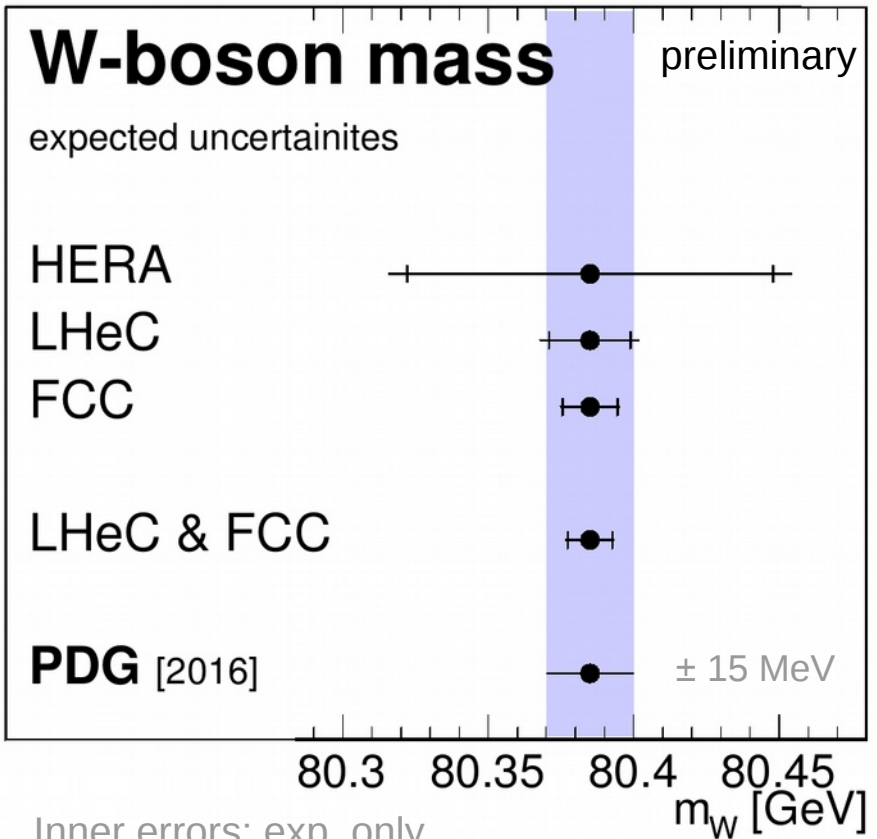
- All other masses expected to be known
- HERA $\pm 63_{(exp)}29_{(PDF)}$
- LHeC $\pm 14_{(exp)}10_{(PDF)}$
- FCC $\pm 9_{(exp)}4_{(PDF)}$

HERA prospects (1987)
m_W ~ ± 80-100 MeV
Our HERA value
m_W ~ $\pm 63_{(exp)}29_{(PDF)}$

Competitive W-boson mass

- CC kinematics constraint by IS + FS measurements
  -> no missing E_T needed !!
- PDF uncertainties are small

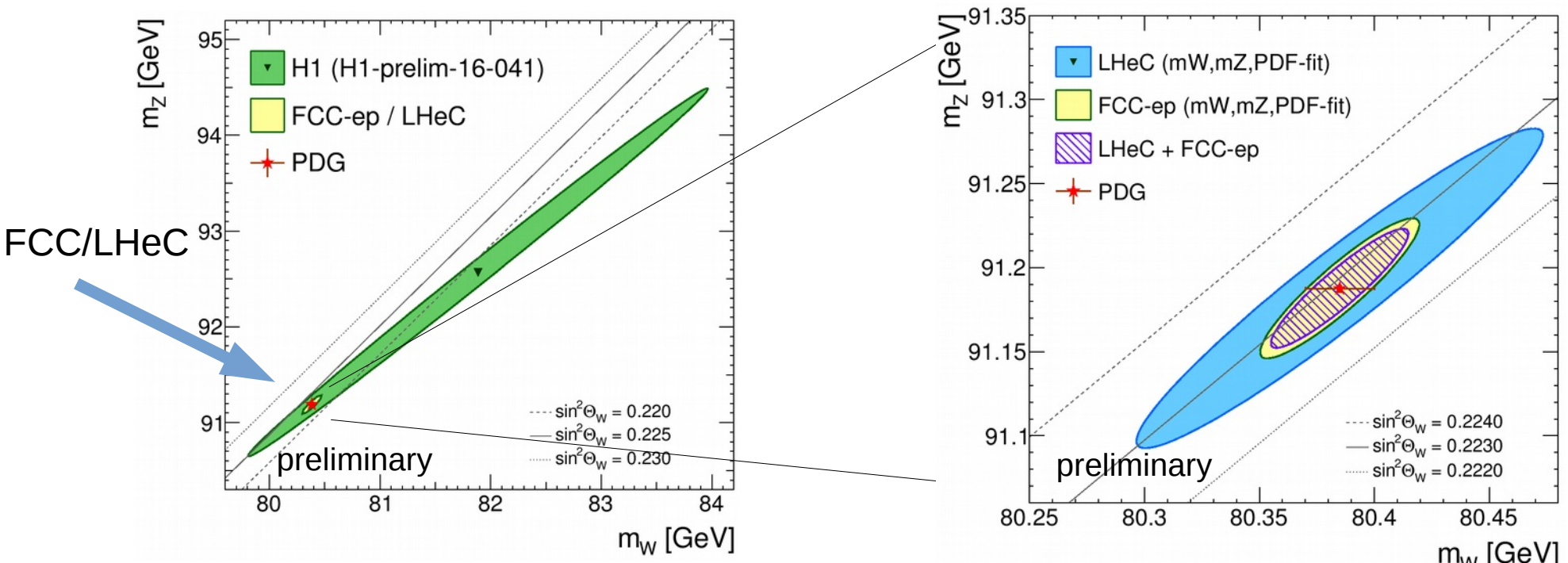
W-boson masss at high precision



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

(Indirect) determination of boson masses

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



- LHeC & FCC: Greatly improved precision as compared to HERA
  - Benefit from increadibly higher cross sections than HERA
  - Correlation between m_W and m_Z will be reduced with increasing scale (FCC) -> higher precision
- HERA with large uncertainty due to m_W-m_Z correlation (H1-prelim-16-041)
- PDFs will not be the limiting factor for EW physics !

W-boson and top-mass

Top mass and W-boson mass

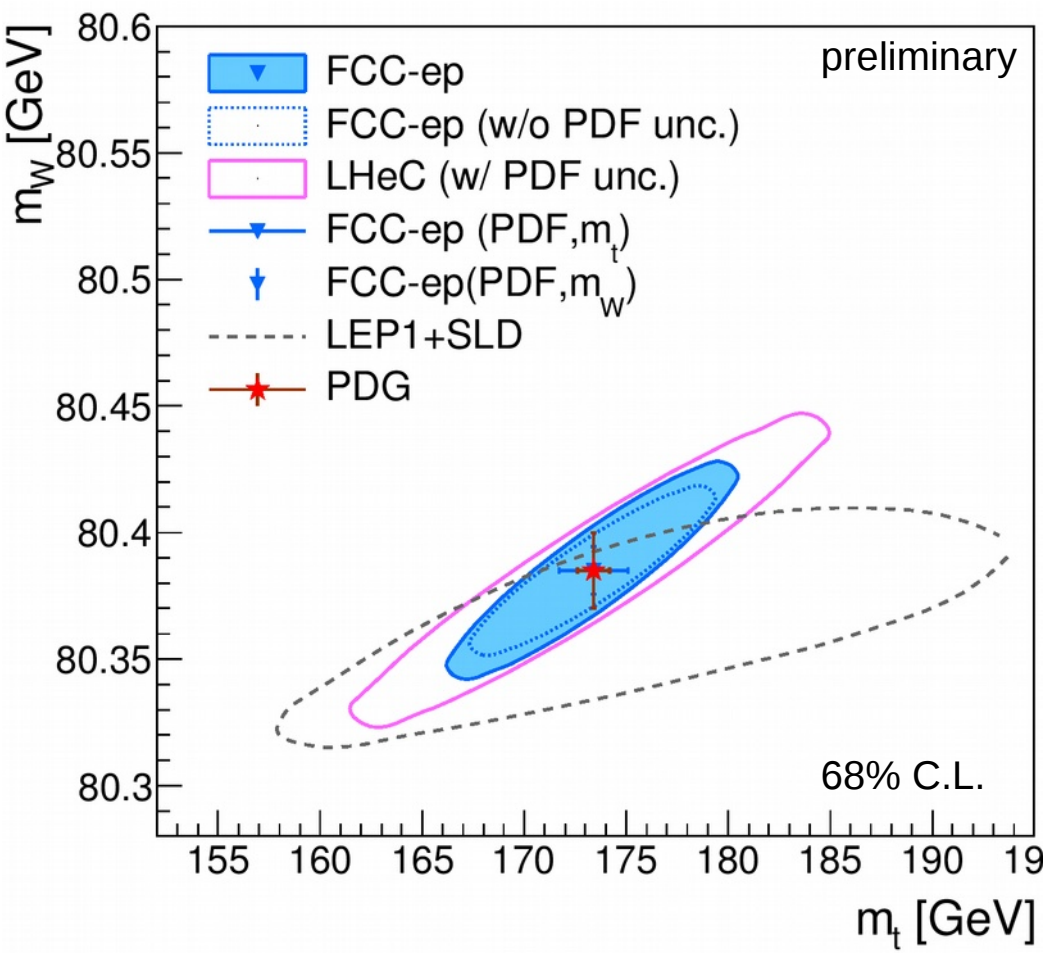
- Highly correlated
- Very sensitive to BSM physics
  'holy grail' of EW physics

m_W-m_t determinations

- large correlation (as expected)
- significant improvement over LEP+SLD results expected
- PDF uncertainties will not be limiting factors

This is only from inclusive DIS !

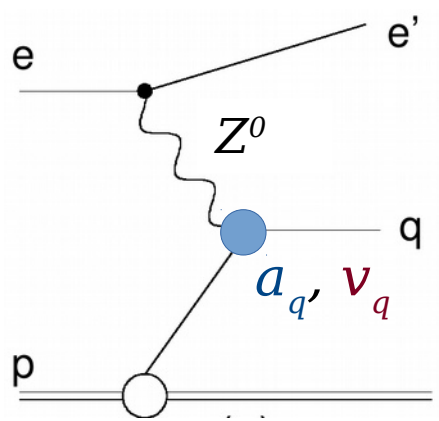
- -> additional measurements of top or W-boson production will be allow for significant improvements



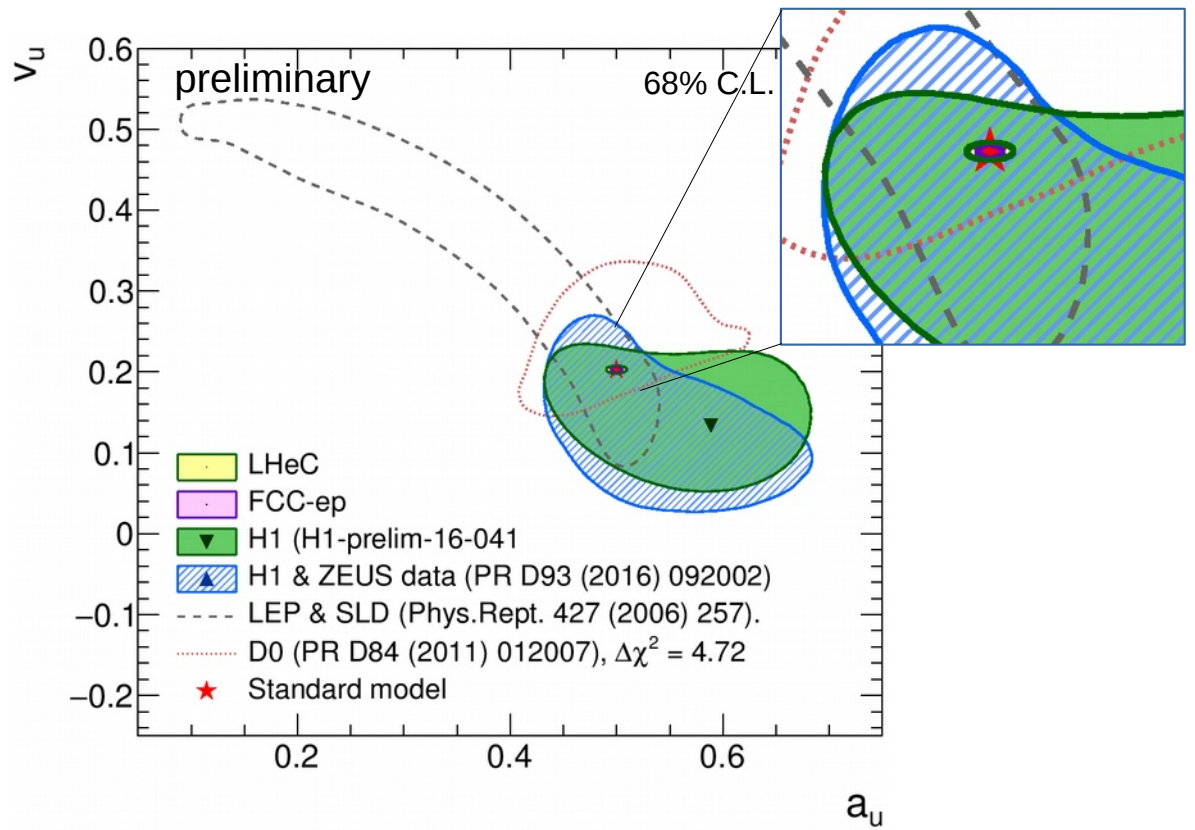
Light quark couplings at LHeC and FCC-eh

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

- Couplings of quarks to Z-boson



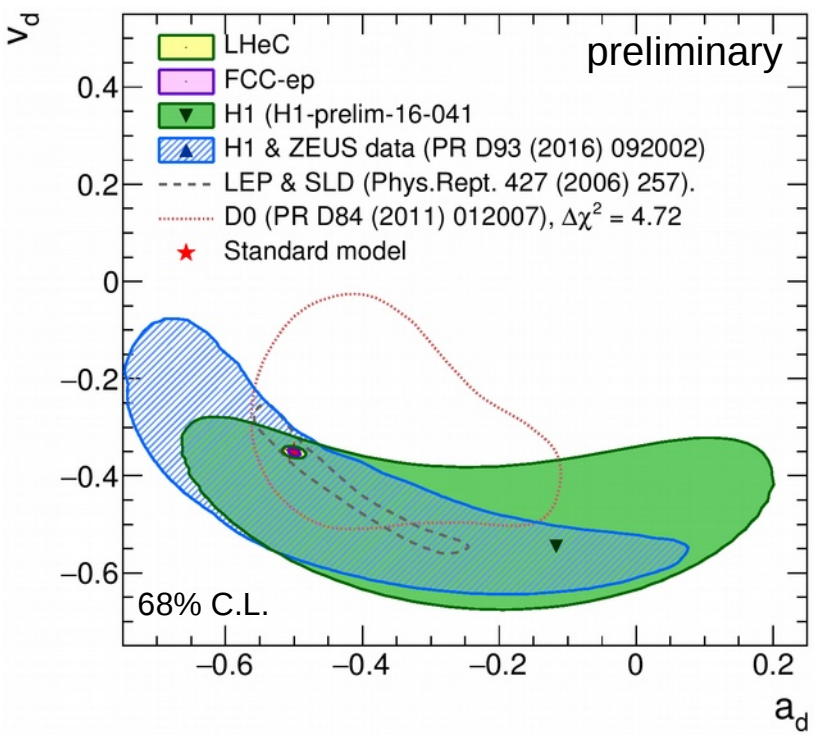
$$a_q = I^{(3)}_{q,L} \qquad v_q = I^{(3)}_{q,L} - 2\,Q_q \sin^2\theta_W$$

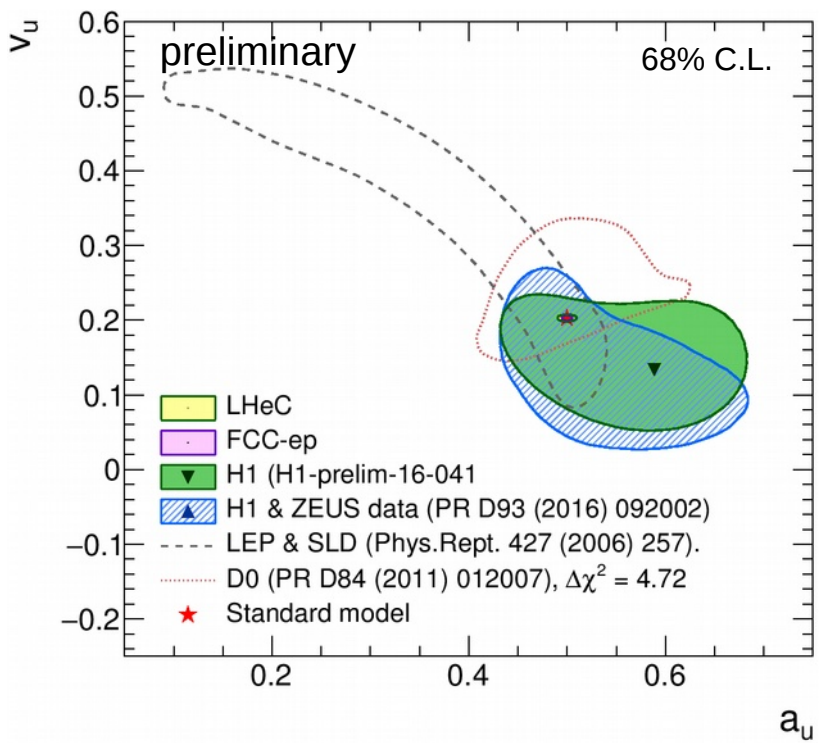


LHeC and FCC-ep

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

Light quark couplings at LHeC and FCC-eh





LHeC and FCC-ep

- Up-quark and down-quark couplings determined simultaneously
- Very precise measurements of weak light-quark couplings 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

High precision test of electroweak sector of Standard Model

Weak mixing angle

Weak mixing angle

- on-shell scheme:
  No scale dependence

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

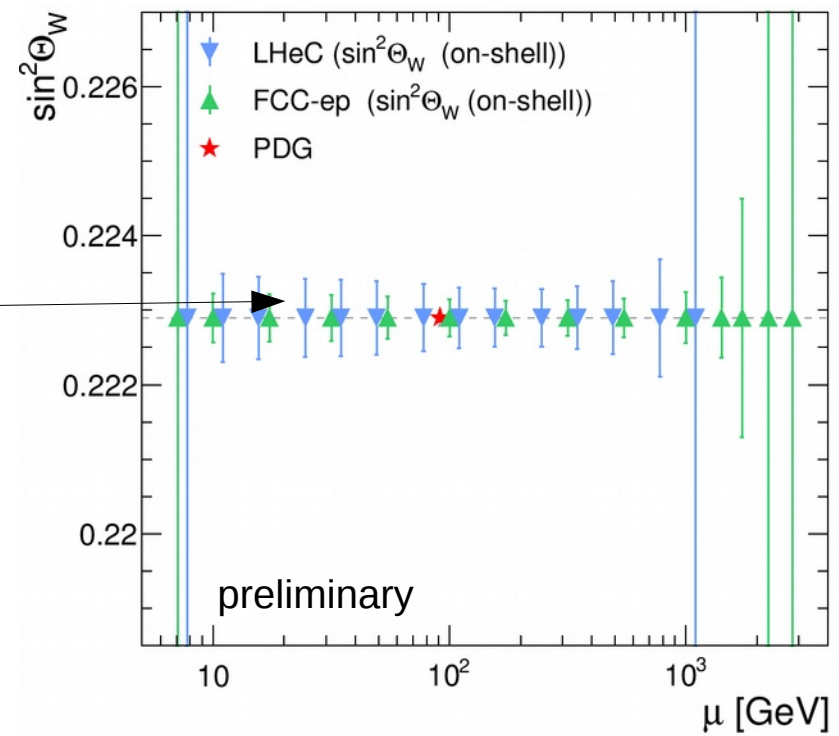
Weak mixing angle

- Expected precision:

LHeC	±0.0003(exp)	0.0002(PDF)
FCC	±0.0002(exp)	0.00008(PDF)
PDG	±0.00010	

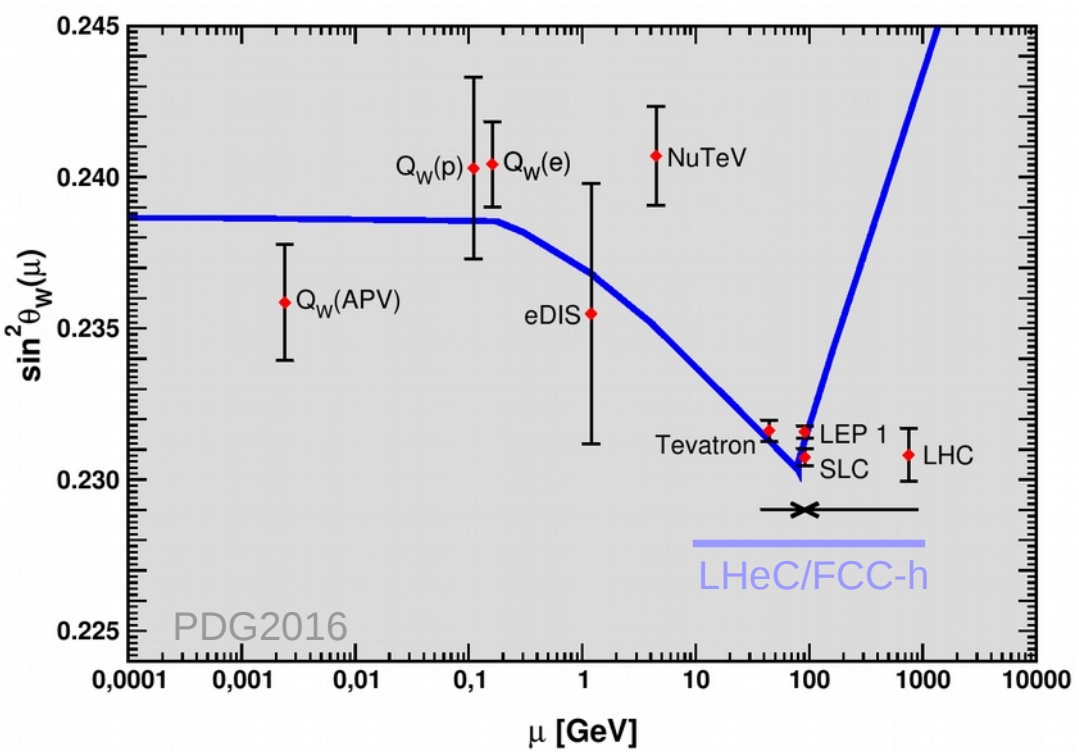
- Inclusive data will be competitive to direct measurements at the Z-pole

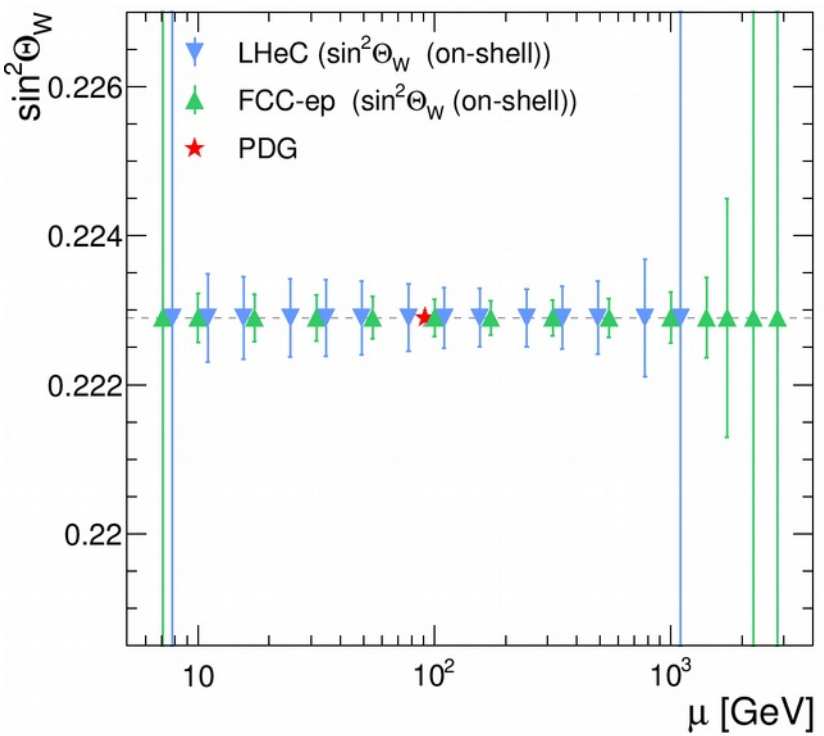
Δm_W ~10-15 MeV over a wide range



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

Weak mixing angle



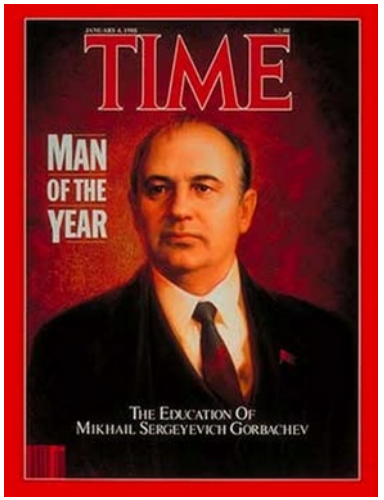


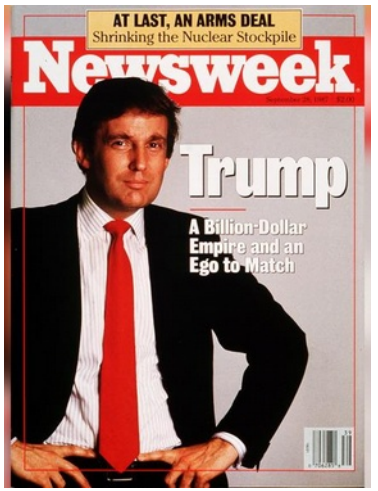
on-shell translated to

- MS-bar definition or 'effective' weak mixing angle

Precise tests of weak mixing angle over a large scale range
At EW-scale: complementary to s-channel extractions

30 years ago: 1987





LHeC and FCC

Summarizing, ~~HERA~~ ~~should~~ allow for meaningful tests of the electroweak theory, complementary to e^+e^--colliders and more accurate than presently operating fixed target or $\bar{p}p$-experiments.

J. Blümlein, M. Klein, T. Riemann, Conference: C87-05-25 (Warsaw Sympos (1987) 39 & DESY HERA Workshop (1987) 687

Conclusions

Studies of EW parameters using simulated LHeC and FCC-eh data

- *Complementary regime to LEP and LHC (space-like momentum transfer)*

LHeC and FCC-eh inclusive DIS data

- *Precision of EW parameters will greatly improve HERA results*
- *Competitive with LEP+SLD results in case of indirect determinations*
- *'ultimate' measurement of weak couplings of light-quarks*
- *Competitive measurements of the W-boson mass*

DESY	*-> CERN*
EUR	*-> CHF*
PETRA	*-> LEP*
HERA	*-> LHeC*

EW physics

- *High accuracy over impressive range from 10 GeV up to the TeV regime*

Expected precision

- *PDFs will not be the limiting factor for EW studies*
- *Additional direct measurements (e.g. Z, W, top, H production) will support the indirect determinations (not studied here)*

New physics beyond the SM may show up at large momentum transfers or in precision Standard Model measurements