Electroweak Physics at LHeC & FCC-eh

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with inputs from
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Outline

- Introduction
- Selected examples
- Summary

Introduction

- ❒ EW physics is an important part of the LHeC/FCC-eh physics program

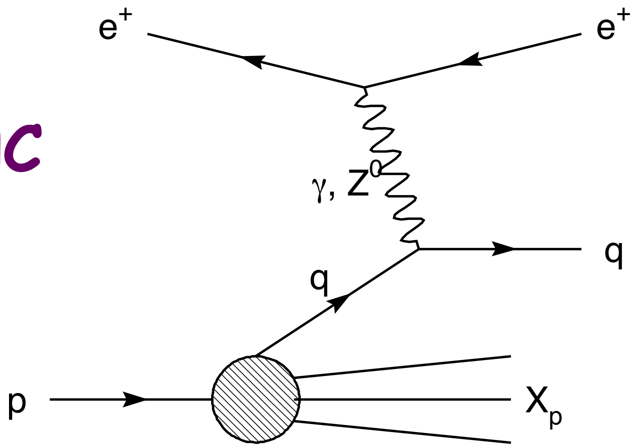
- ❒ LHeC/FCC-eh can significantly enrich the physics program of an e+e- and/or a pp collider

- ❒ HERA is a good example for some of the EW measurements

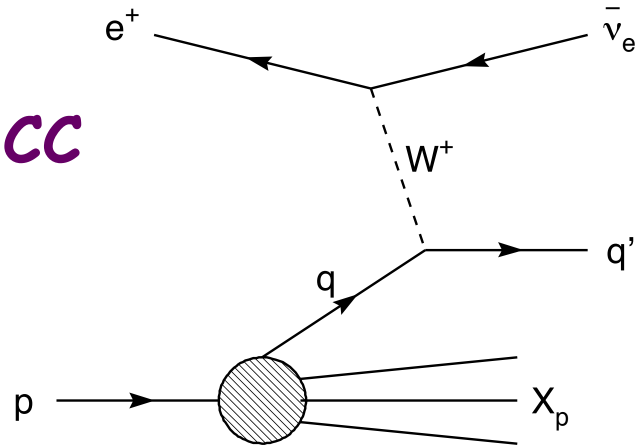
- ❒ LHeC/FCC-eh can however overcome all weak points of HERA:
  - ➤ Small EW phase space
  - ➤ Small cross section
  - ➤ Low luminosity

Neutral and Charged Current Processes

NC



CC



- **Dominant hard processes at ep colliders**
- **Event kinematics:**

  $Q^2 = -q^2$: Boson virtuality

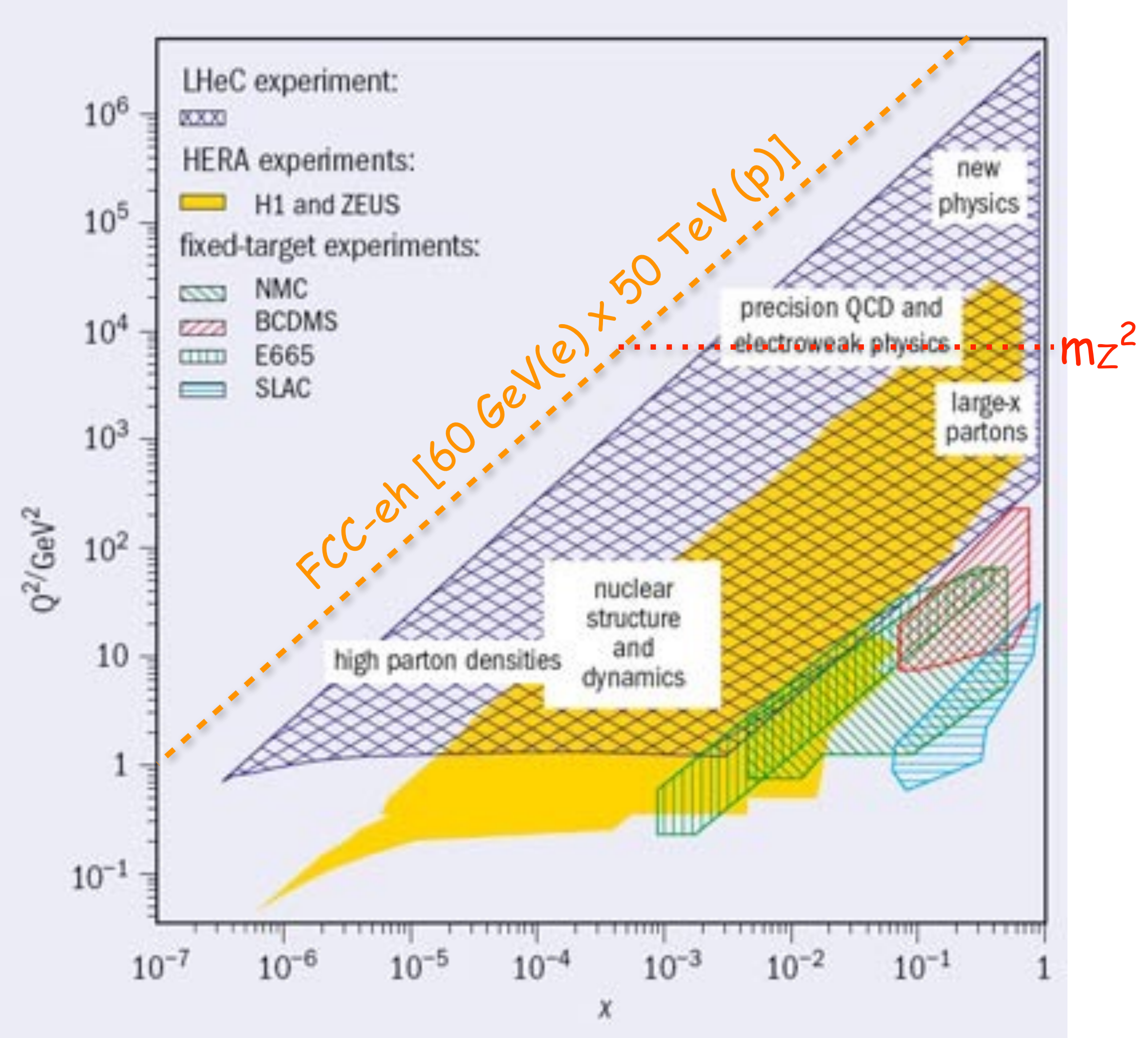
  x: momentum fraction of struck parton

  $y = Q^2/sx$: inelasticity

  can be precisely determined (for NC in particular using different methods)

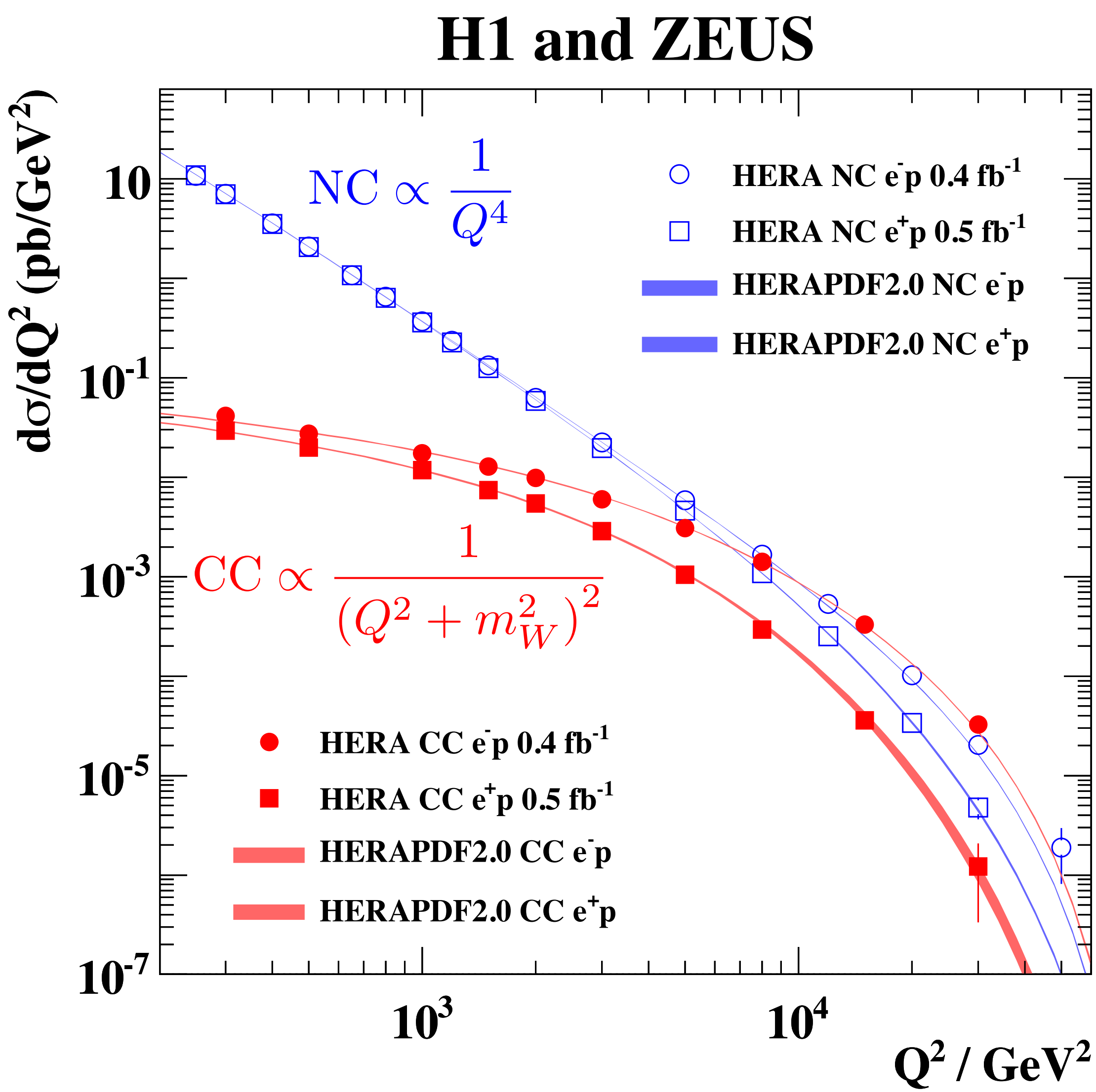
Kinematic Coverage of HERA, LHeC and FCC-eh

Modified from
Klein-Newman, CERN Cour. 49N3 (2009) 22



- HERA barely reached pure EW regime + low cross sections (next slide) & low luminosity
- LHeC has a big EW phase space + > 10^2 increase in lumi
- FCC-eh has further extension

Q^2 Dependence of NC and CC Cross Sections



EPJC75 (2015) 580, arXiv:1506.06042

One HERA legacy plot shows that NC and CC cross sections at high Q^2 are tiny

➜ HERA (EW) data were statistically limited

➜ Need much higher luminosity for precision EW measurements

Simulated Data Samples

- Simulated NC and CC 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, Blümlein-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 syst. error
- Luminosity measurement ~1% (0.5% may be reachable)

Updated MC Samples

FCC-eh (LHeC)

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

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

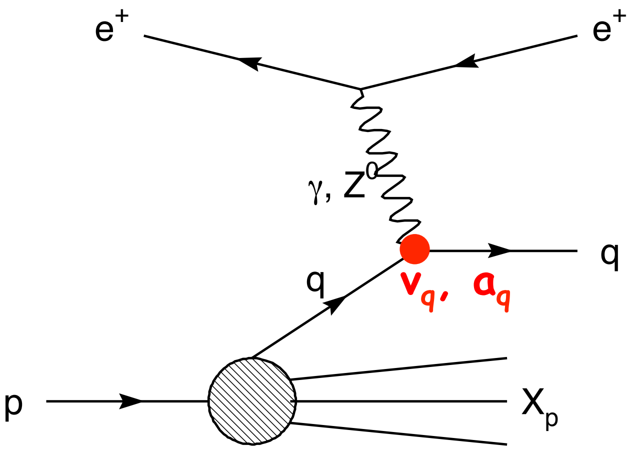
(M.Klein)

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

Light Quark Couplings v_q, a_q to Z Boson

- v_q, a_q treated as free EW parameters

- Perform combined EW + PDF fit to inclusive NC and CC cross section "data"
  - ➤ to take into account EW/PDF correlation



- PDF parameterisation a la HERAPDF

- EW calculations performed in on-mass shell scheme:
  $(\alpha_{em}, m_Z, m_W) + \Delta r$
  with
  $\Delta r = \Delta r(\alpha_{em}, m_W, m_Z, m_t, m_H, \ldots)$

Cross Sections, Structure Functions, Couplings

Klein and Riemann, Electroweak interactions probing the nucleon structure, Z. Phys.C 24 (1984) 151.

$$\frac{d^2\sigma^{\pm}_{\rm NC}}{dxdQ^2} \sim Y_+\tilde{F}_2 \mp Y_-\tilde{F}_3 - y^2\tilde{F}_L \qquad \text{with} \quad Y_\pm = 1 \pm (1-y)^2$$

γ exchange — γZ interference — Z exchange

$$\tilde{F}_2 = F_2 - (v_e - P_e a_e)\kappa_Z F_2^{\gamma Z} + (v_e^2 + a_e^2 - 2P_e v_e a_e)\kappa_Z^2 F_2^Z$$

v_e~0, ➔ some of the terms are negligible

$$x\tilde{F}_3 = -(a_e - P_e v_e)\kappa_Z xF_3^{\gamma Z} + \left[2v_e a_e - P_e(v_e^2 + a_e^2)\right]\kappa_Z^2 xF_3^Z$$

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

$$\kappa_Z^{-1} = \frac{2\sqrt{2}\pi\alpha}{G_F M_Z^2}\frac{Q^2+M_Z^2}{Q^2}$$

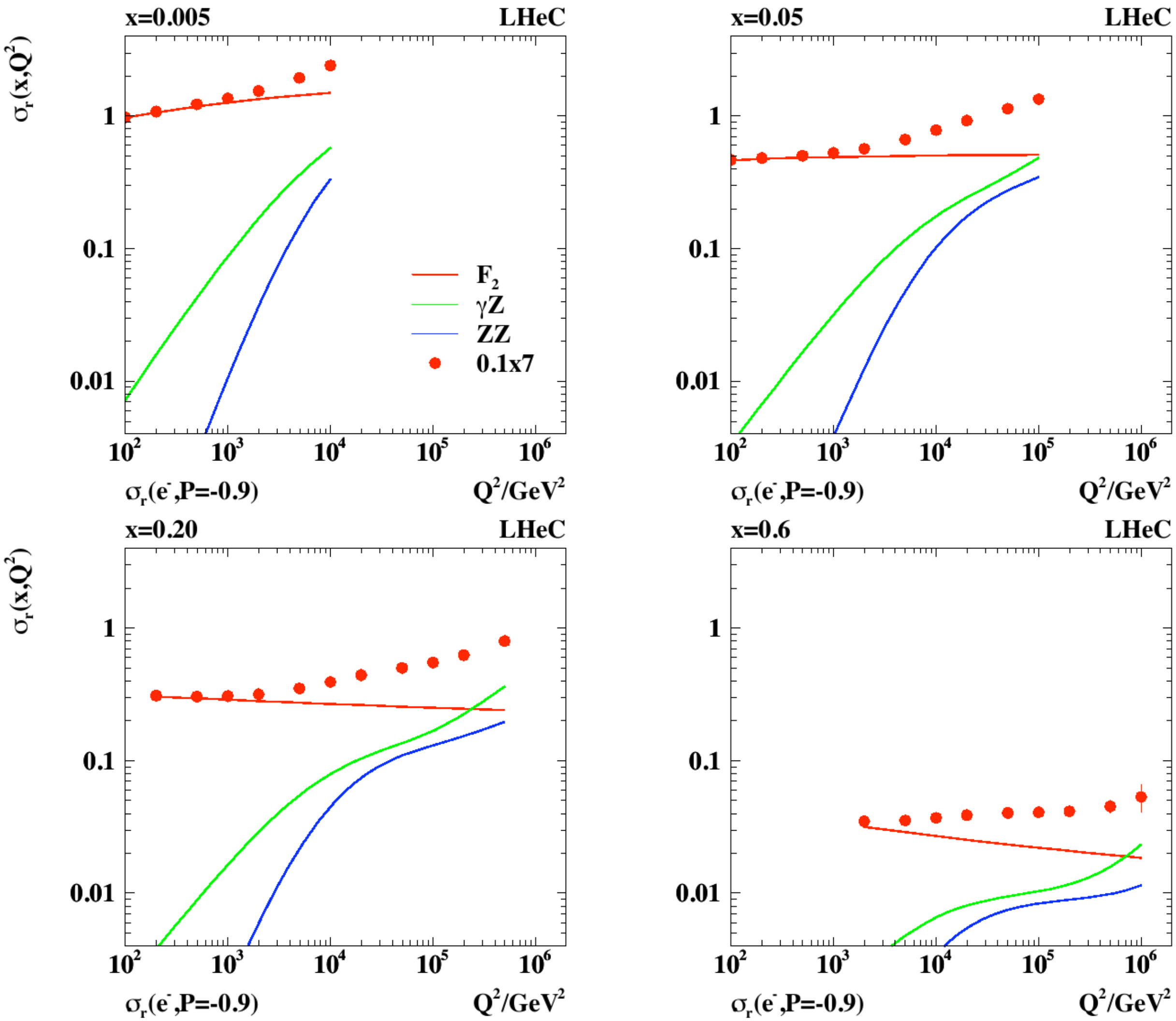
$$\left[xF_3^{\gamma Z}, xF_3^Z\right] = 2x\sum_q \left[e_q a_q, v_q a_q\right]\{q-\bar{q}\}$$

Structure function formulae given for e^-p scattering, for e^+p, $P_e \rightarrow -P_e$

CC cross sections have similar but different structure functions and PDF combinations

F_L=0 in LO parton model, F_L~g at NLO

Relative Contributions of Different Terms



Plots from CDR (old settings/samples) but features remain valid:

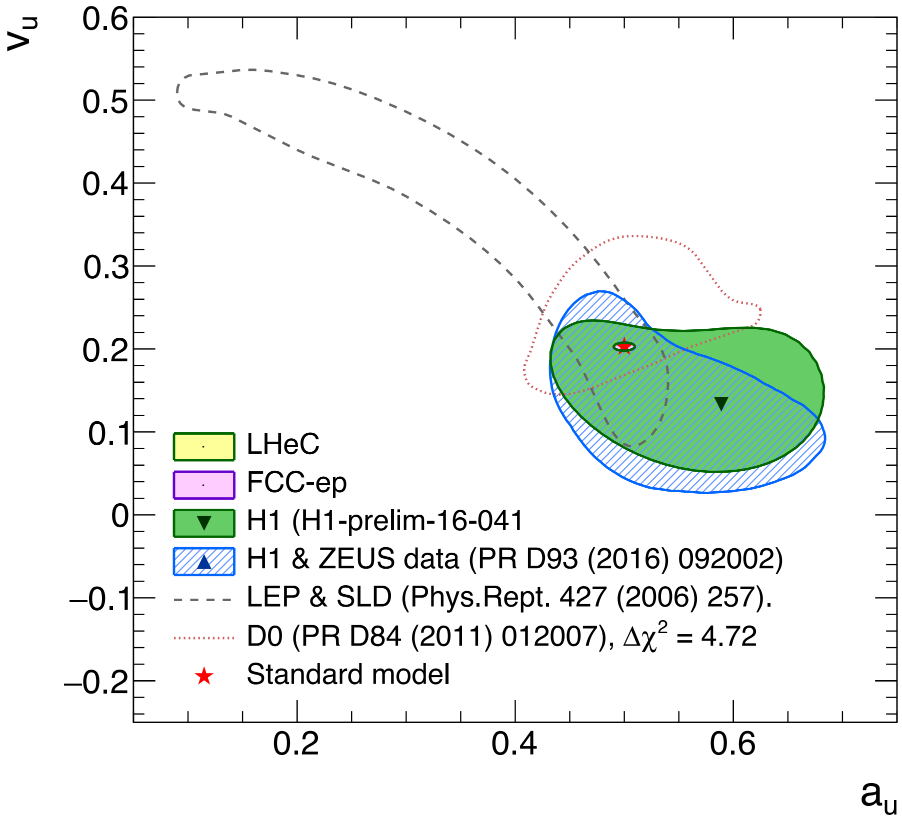
➜ increasing EW effects as Q^2 increases

➜ reach/exceed photonic contributions

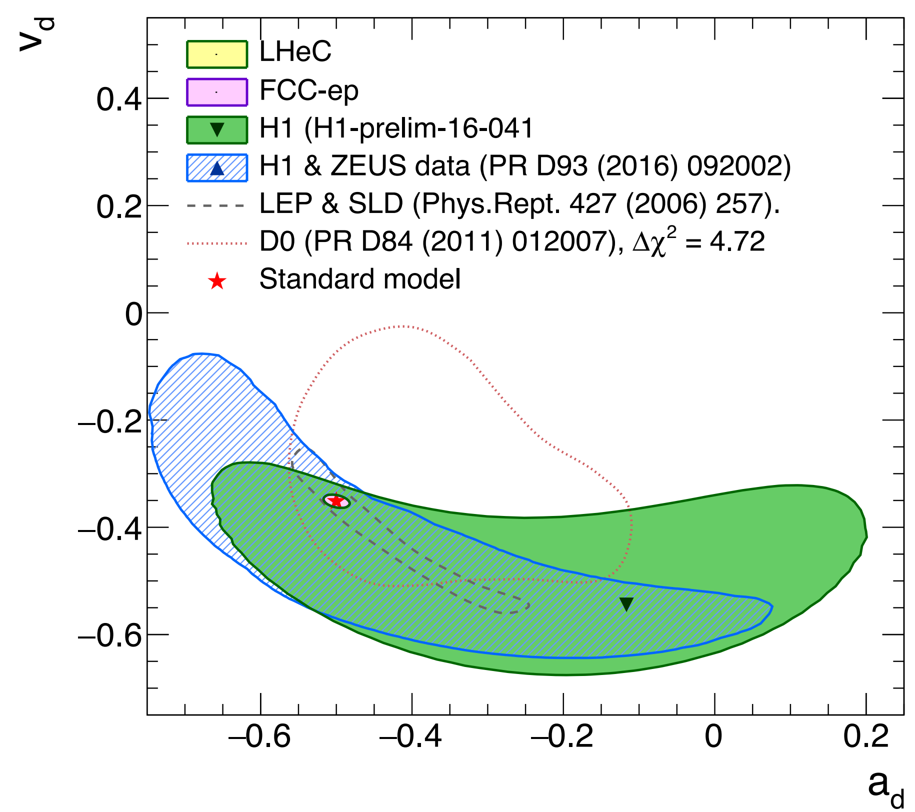
LHeC CDR: J. Phys. G39 (2012) 075001, arXiv:1206.2913

Results

u quark couplings



d quark couplings

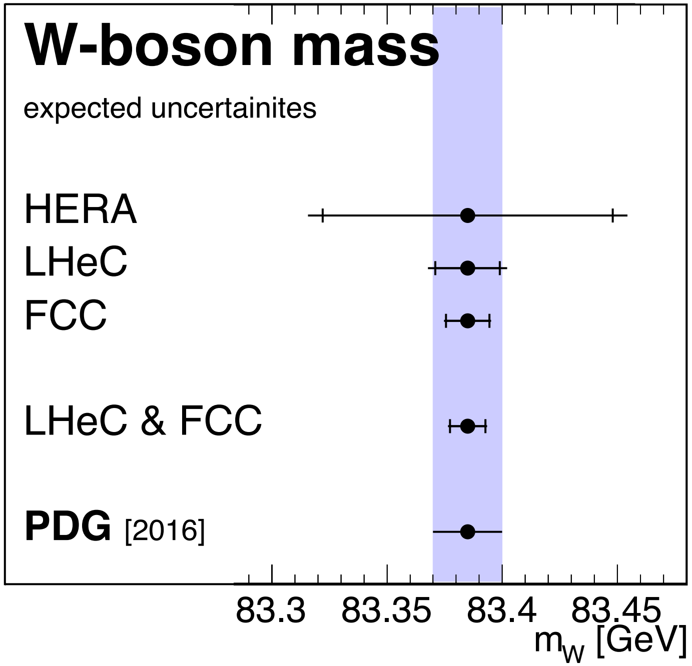


- Huge improvement in precision over LEP, Tevatron and HERA measurements
- Data with highly polarised lepton beam have a big impact
- γZ terms help to resolve the sign ambiguity presented in LEP data

W Boson Mass and Weak Mixing Angle

- In on-mass shell scheme, α_{em}, m_Z, and m_W are the main free parameters
  - α_{em} and m_Z are precisely known/measured
  - Treat m_W as free parameter

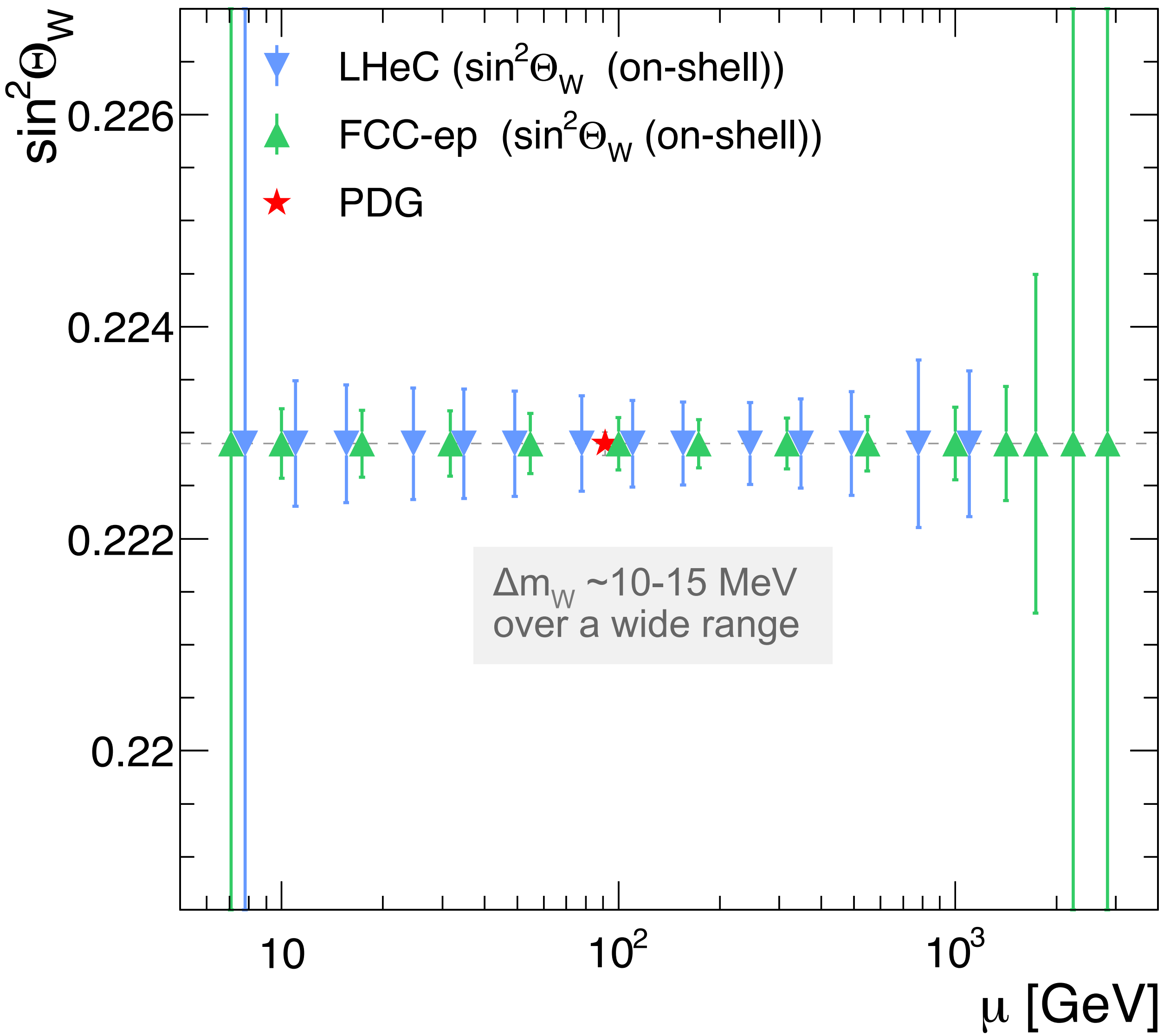
HERA	$\pm\, 63_{(exp\,)}29_{(PDF)}$
LHeC	$\pm\, 14_{(exp\,)}10_{(PDF)}$
FCC	$\pm\, 9_{(exp\,)}4_{(PDF)}$



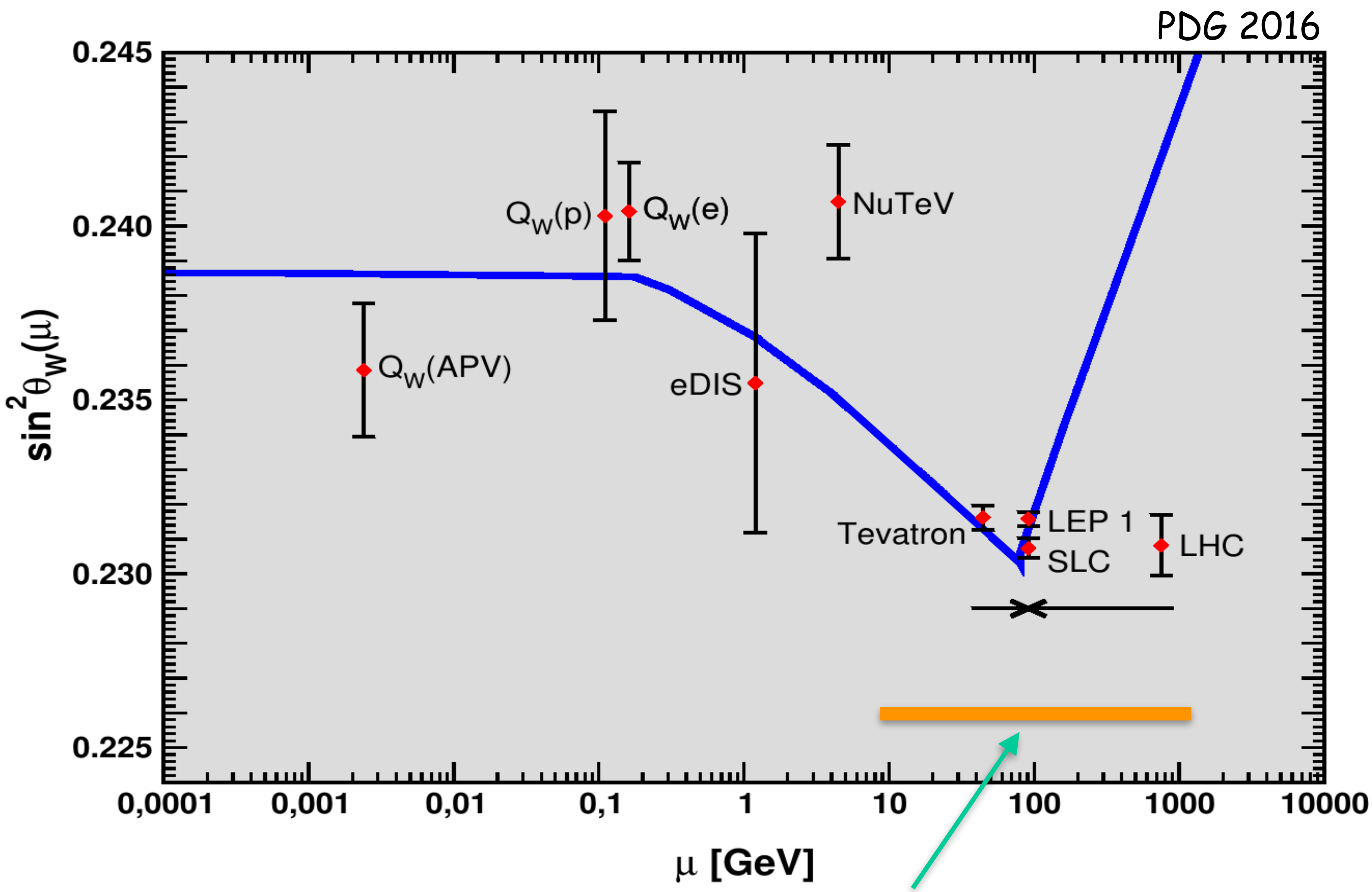
- The weak mixing angle can be derived:

$$\sin^2\theta_W(\text{on-mass-shell}) = 1 - \frac{M_W^2(\text{fit})}{M_Z^2(\text{input})}$$

Results at Different Scales ($Q^2 \rightarrow \mu$)



Convert to MS Scheme to Check Scale Dependance



LHeC/FCC-eh in a large and interesting range with large expected variations

Summary and Conclusion

- Selected EW expectations show the potential of the LHeC/FCC-eh
  - unprecedented precision on light quark couplings to Z boson
  - competitive W mass determination
  - weak mixing angle extraction over a large energy range
- Results based on simulated data samples with likely conservative uncertainties
- Only real data can
  - tell if there are deviations from the SM expectations
  - allow joint exploration of EW measurements with precision QCD and BSM physics