Electroweak physics at LHeC

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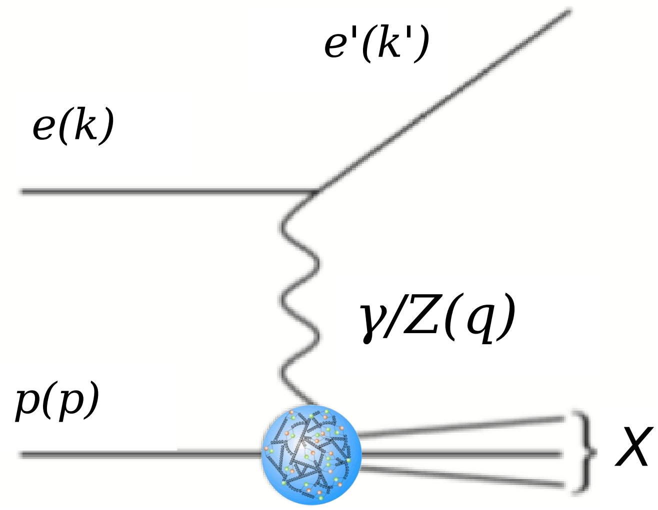
for the LHeC/FCC-eh EW+top group

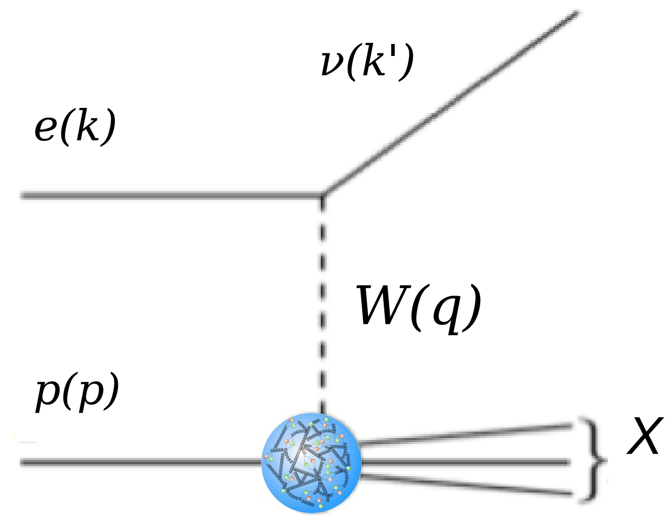
LHeC workshop 2019, Chavannes-de-Bogis, CH
25.10.2019

Deep-inelastic electron-proton scattering

Neutral current scattering
$ep \rightarrow e'X$



Charged current scattering
$ep \rightarrow \nu_e X$



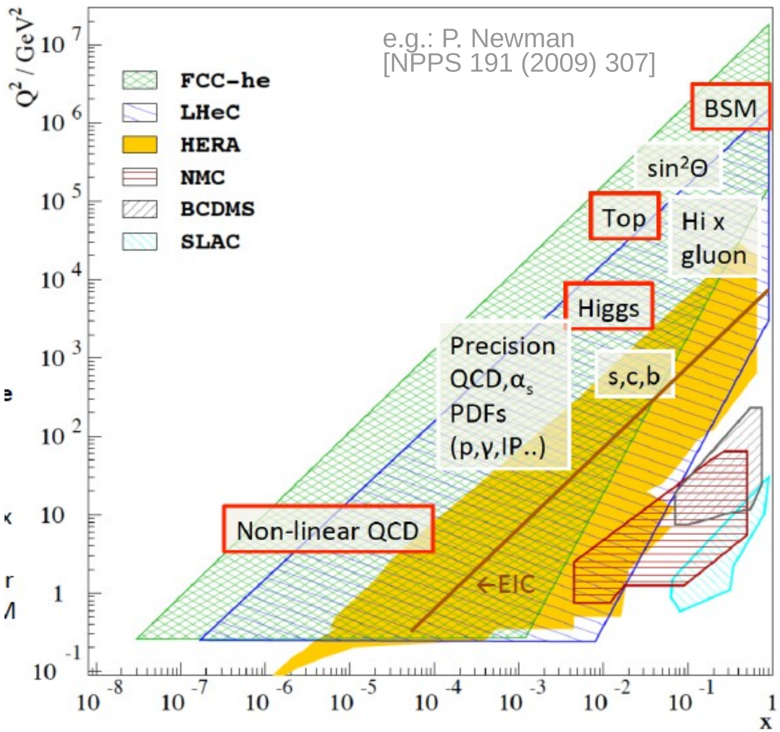
R-D. Heuer
"The point-like electron "probes" the interior of the proton via the electroweak force, while acting as a neutral observer with regard to the strong force."

→ LHeC: Electroweak (EW) and QCD physics are equally important

LHeC kinematic reach

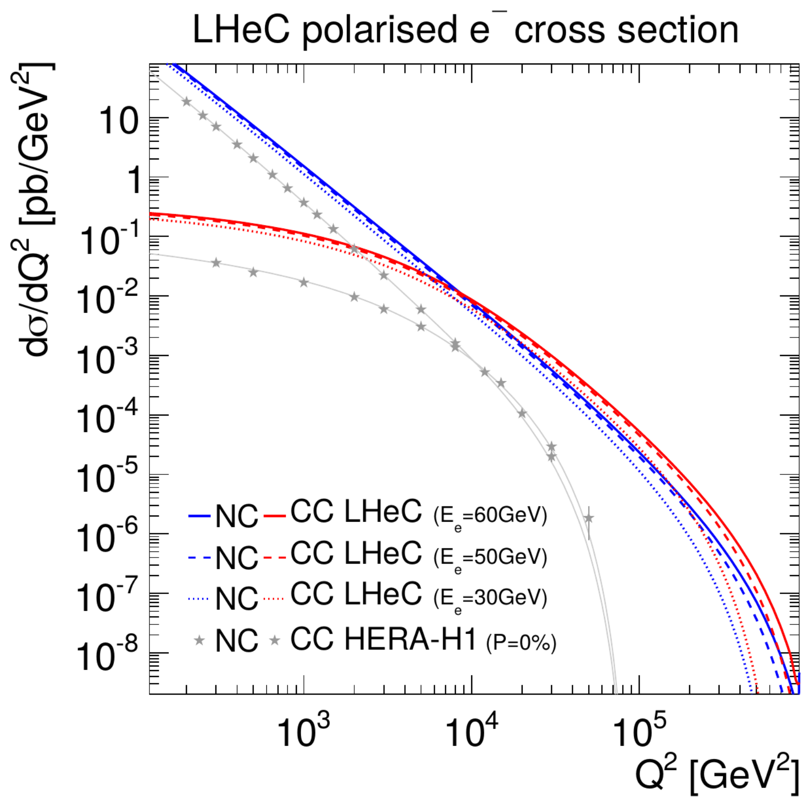
x-Q² plane

- EW physics predominantly at higher scale
- NC at HERA: $\frac{d^2\sigma^{\pm}_{NC}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}(Y_+\tilde{F}_2^{\pm} \mp Y_-x\tilde{F}_3^{\pm} - y^2\tilde{F}_L^{\pm}) \cdot (1 + \Delta^{weak}_{NC})$



polarised e-p cross section

- NC & CC DIS cross section vs. Q²



Huge luminosity further increases physics potential (up to few ab^{-1}?)

Electroweak physics

Neutral currents interactions

- γγ, γZ, ZZ exchange

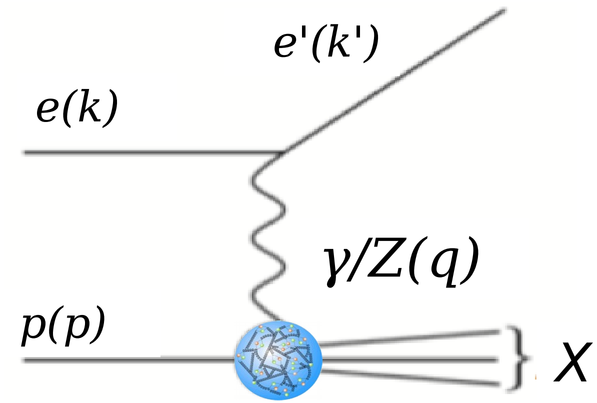
$$\tilde{F}_2^{\pm} = F_2 - (g_V^e \pm P_e g_A^e)\varkappa_Z F_2^{\gamma Z} + [(g_V^e g_V^e + g_A^e g_A^e) \pm 2P_e g_V^e g_A^e]\,\varkappa_Z^2 F_2^Z \,,$$

$$\tilde{F}_3^{\pm} = \quad - (g_A^e \pm P_e g_V^e)\varkappa_Z F_3^{\gamma Z} + [2 g_V^e g_A^e \pm P_e (g_V^e g_V^e + g_A^e g_A^e)]\,\varkappa_Z^2 F_3^Z \,,$$

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

$$x\left[F_3^{\gamma Z}, F_3^Z\right] = x \sum_q \left[2Q_q g_A^q, 2g_V^q g_A^q\right]\{q - \bar{q}\} \,.$$

Neutral current scattering

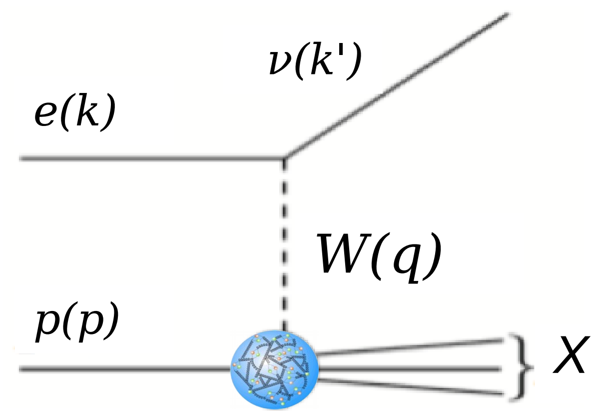


Charged currents

- purely 'weak' interactions

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

Charged current scattering



At born level

- only three independent variables:
  on-shell scheme: (α, m_W, m_Z)
  At higher EW orders: Δr (m_t, mH,…), ...

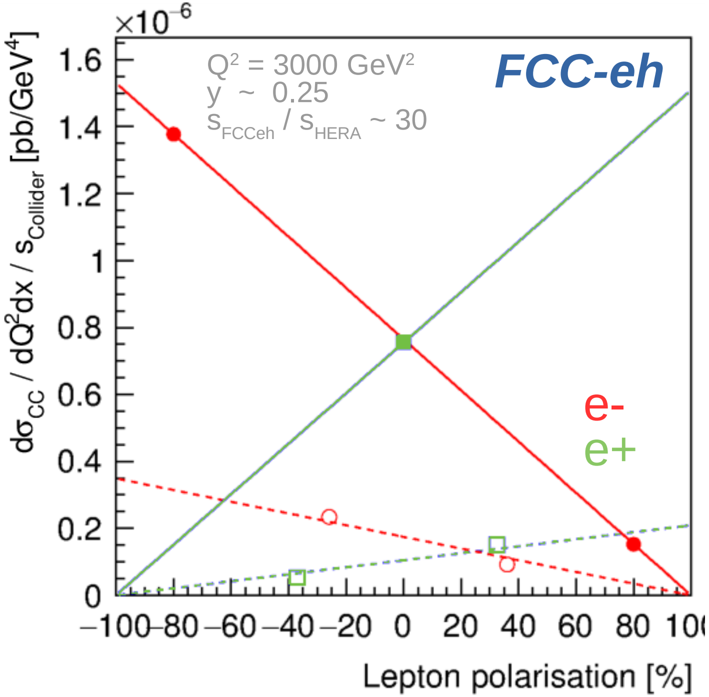
Polarized lepton beams at LHeC

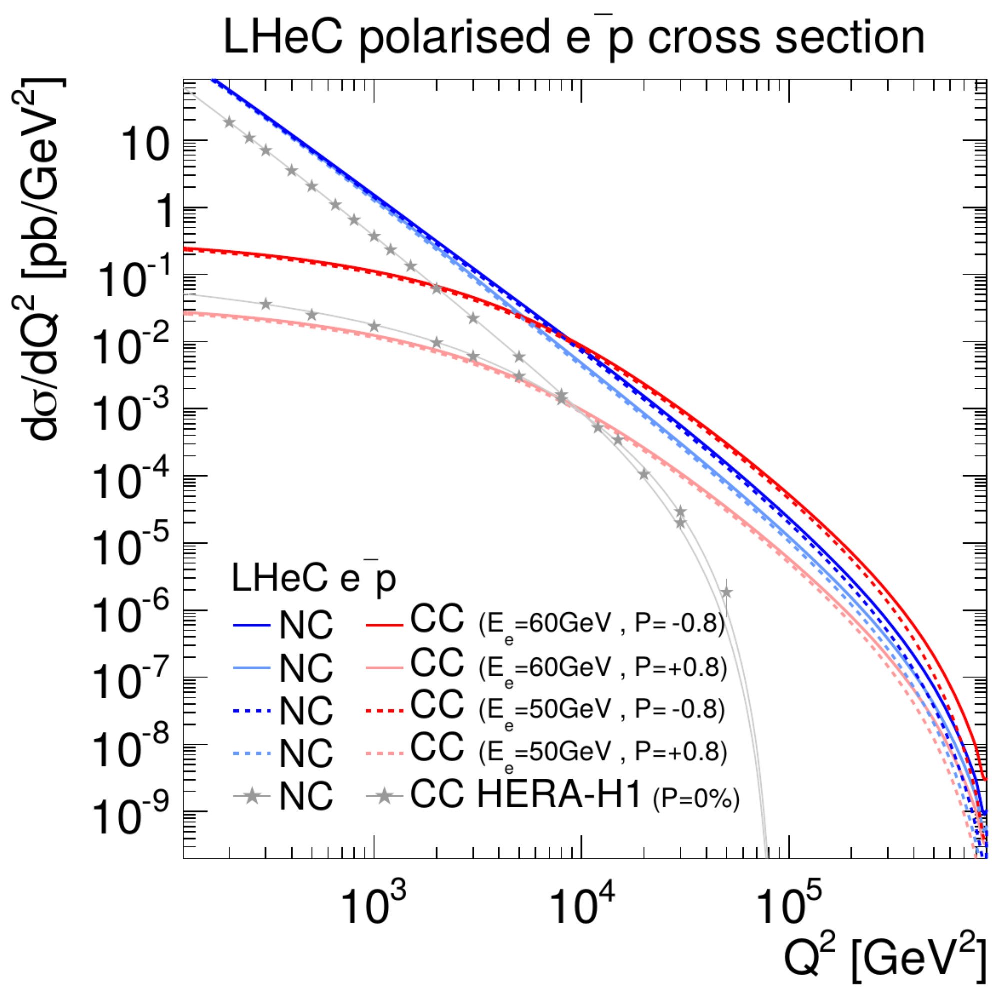
LHeC with longitud. pol. electrons

e- +80%, -80% (1ab-1)

CC proportional to P_e

$$\frac{\mathrm{d}^2\sigma^{\pm}_{CC}(P_e)}{\mathrm{d}x\mathrm{d}Q^2} = (1 \pm P_e)\frac{\mathrm{d}^2\sigma^{\pm}_{CC}}{\mathrm{d}x\mathrm{d}Q^2}$$





Polarised NC DIS: from HERA to FCC-eh

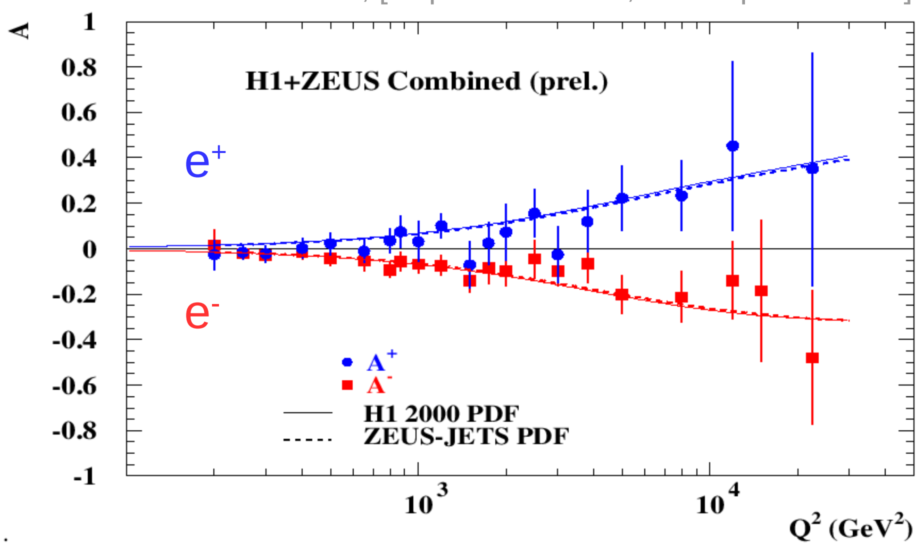
Polarisation asymmetry at HERA

- 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

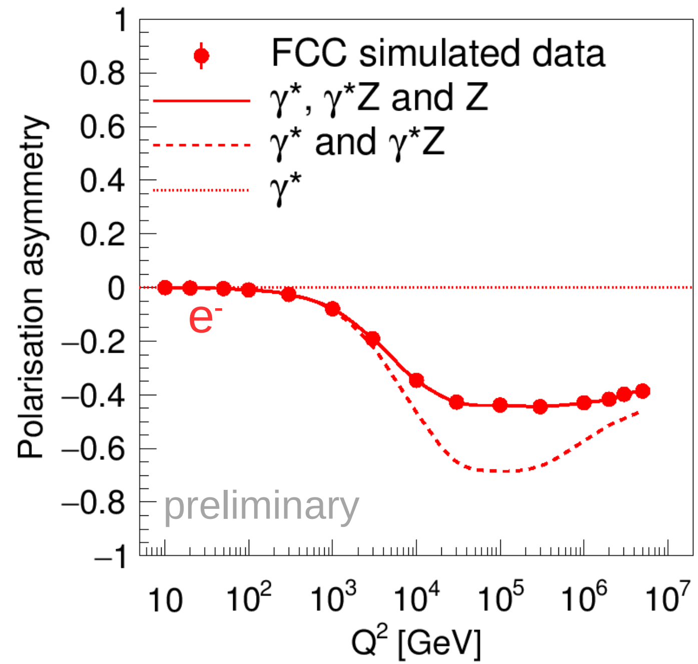
H1+ZEUS, [H1prelim-06-142, ZEUS-prel-06-022]



Cross section asymmetry as a function of Q^2

Polarisation asymmetry at FCC-eh

- Accessible range up to $Q^2 \sim 10^7$ GeV^2
- 'pure' Z-exchange becomes significant at FCC-eh



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

Study of EW parameters - methodology

EW parameters are studied in a '<u>combined fit: EW+PDF</u>'

- correlations of EW parameters with PDF are considered

Exploit inclusive NC&CC DIS data

- Equivalent to PDF studies
  see contribs by C. Gwenlan, L. Harland-Land, F. Giuli,…
- PDF fit with QCDNUM @ NNLO QCD
- 1-loop EW corrections in on-shell scheme from EPRC (H.Spiesberger)
  on-shell scheme: (α_{em}, m_Z, m_W, Δr) with $\Delta r=\Delta r(\alpha_{em},m_W,m_Z,m_t,m_H,...)$

Uncertainty estimate

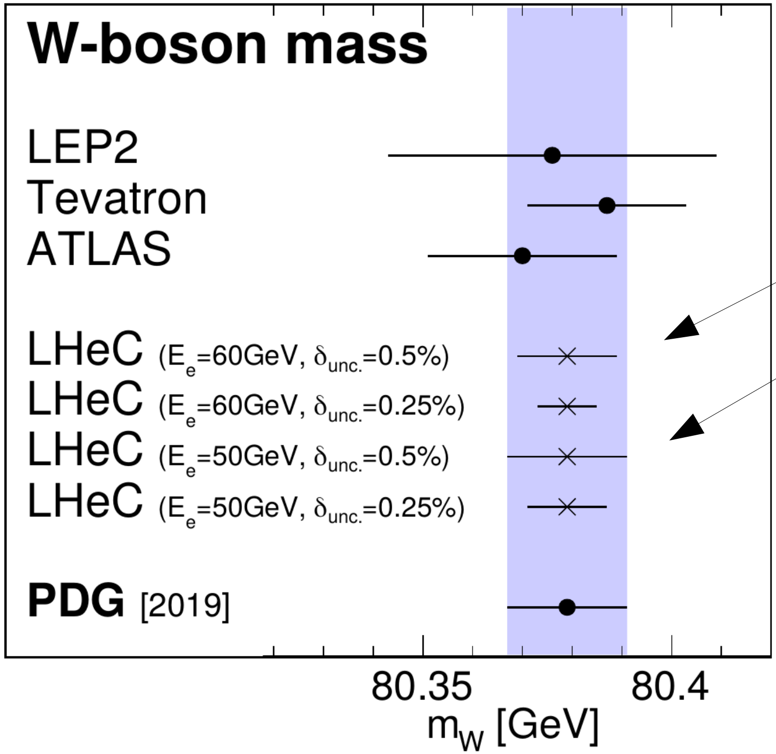
- Klein, Radescu, CERN-LHeC-Note-2013-002 PHY

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 %

W-boson mass

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

Perform fits of PDFs+m_W



W-boson mass from NC&CC DIS data

- All other mass parameters in fit are fixed
  - H1 (publ.) ± $89_{(exp)}$ $74_{(PDF)}$ MeV
  - HERA ± $63_{(exp)}$ $29_{(PDF)}$ MeV
  - LHeC-60 ± $5_{(exp)}$ $8_{(PDF)}$ MeV
  - LHeC-50 ± $8_{(exp)}$ $9_{(PDF)}$ MeV

Competitive W-boson mass

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

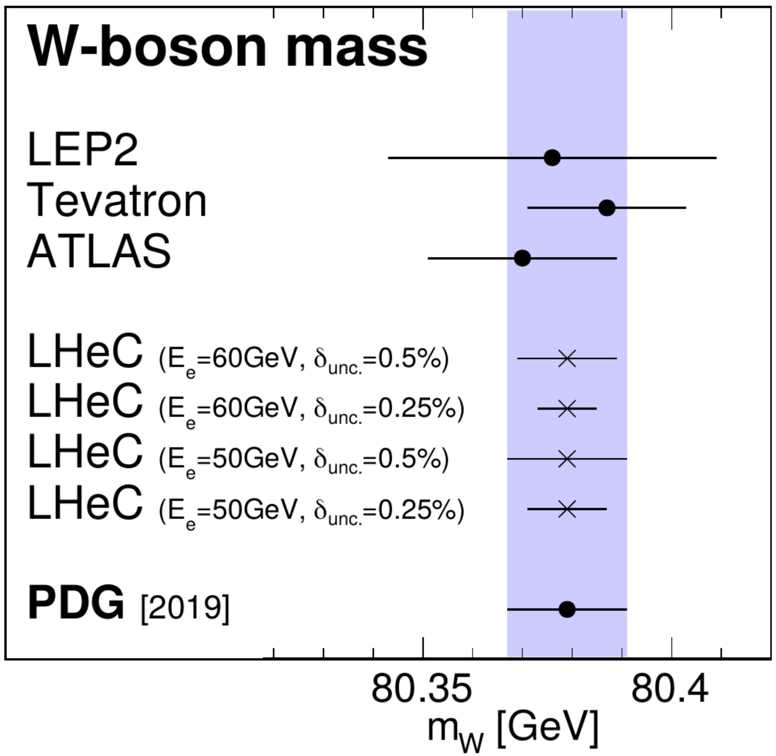
W-boson mass at high precision

- Uncorr. uncertainty of DIS data dominates

→ further reduction down to 6-8 MeV feasible

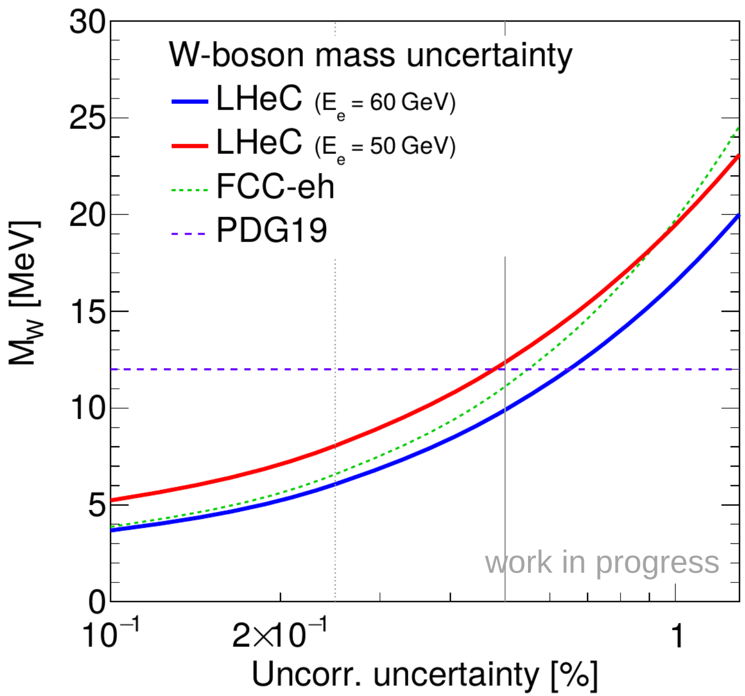
W-boson mass

Perform fits of PDFs+m_W



Global EW fit w/o W-mass measurements: δm_W~7MeV

Size of uncorrelated uncertainty



- Nominal: 0.5% (fairly conservative)
- More likely: 0.25 %
  → δm_W up to 5 MeV

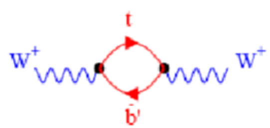
W-boson and top-quark mass

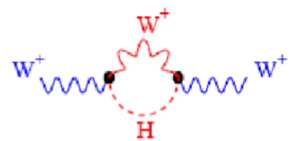
PoS DIS2017 (2018) 105

Top-quark and W-boson mass

- Top-mass dependence in DIS through (dominant) radiative corrections $\sim m_t^2$

$$\Delta r = \Delta\alpha - \frac{c_W^2}{s_W^2}\Delta\rho + \Delta r_{rem}$$





- Highly correlated with m_W

  → Highly sensitive to BSM physics

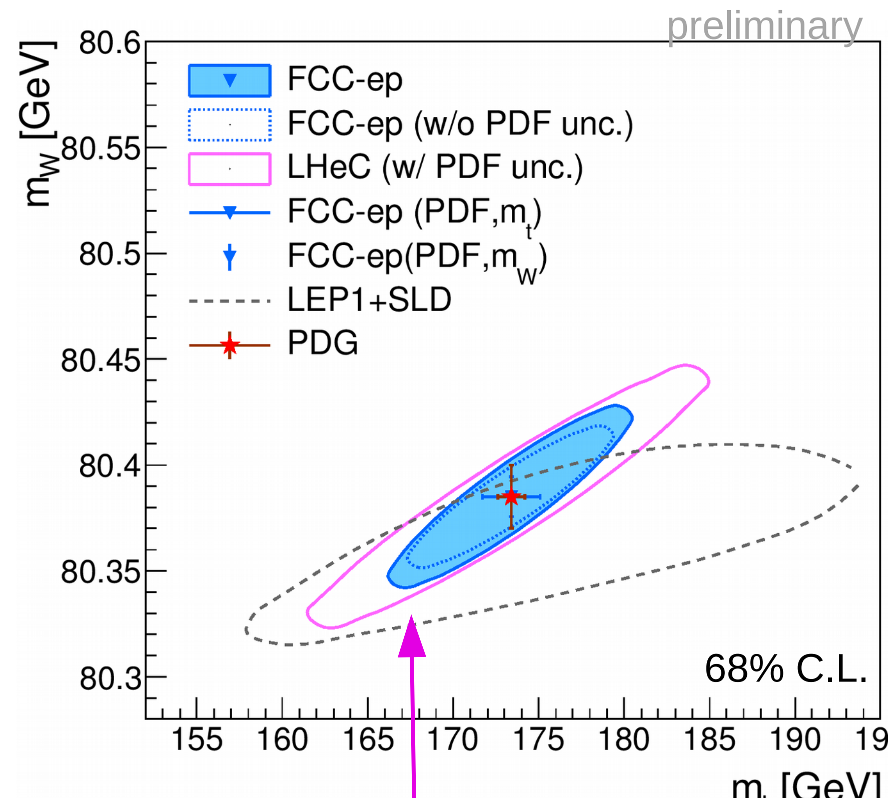
m_W-m_t determinations

- significant improvement over LEP+SLD combination
- determination from purely virtual 'EW' corrections

Top-quark mass, with m_W as external input:

- LHeC-60: $\Delta m_t \sim 1.8$GeV
- LHeC-50: $\Delta m_t \sim 2.2$GeV

  with more optimistic uncertainties ~1.2 GeV



LHeC-60

Further mass parameters

Mass parameter determination

PDF+m_Z

- δm_Z ~ 19 MeV

PDF+m_W+m_Z

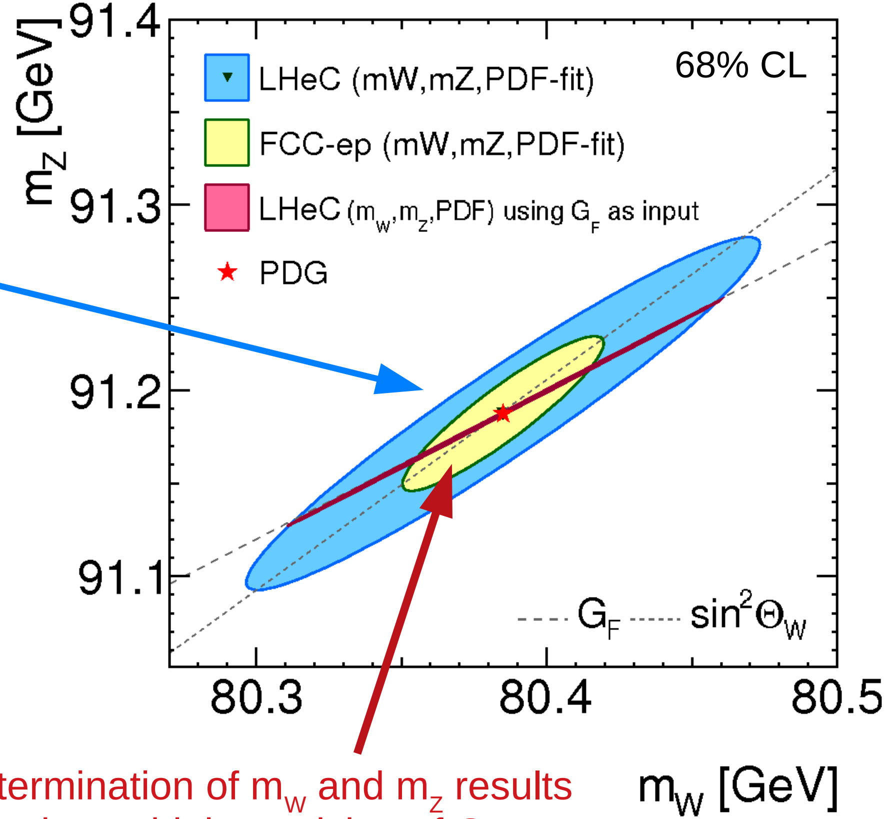
- Moderate precision when m_W and m_Z are determined simultaneously

Using low-energy inputs

- α and G_F are very well measured
  … at low energies
- With NC+CC DIS, high-energy behaviour of EW-theory can simultaneously be 'determined' and 'tested',
  … e.g. by m_W+m_Z fit

Simultaneous W and Z-boson mass

- with and w/o contraint by G_F



Simultaneous determination of m_W and m_Z results in very thin ellipse due to high precision of G_F

G_F=1.1663787(6) x 10^{-5} GeV^2

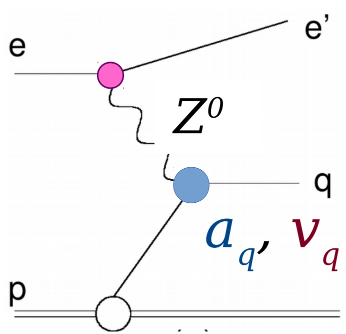
Idea goes back to: R. Beyer et al. in Future Physics at HERA 1995/96

Weak neutral current couplings: light-quarks

Weak neutral-current coupling

- Perform fit of PDFs+electroweak parameters

Couplings given by EW theory



$$g_A^q = \sqrt{\rho_{\mathrm{NC},q}} I^3_{\mathrm{L},q} \,,$$

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

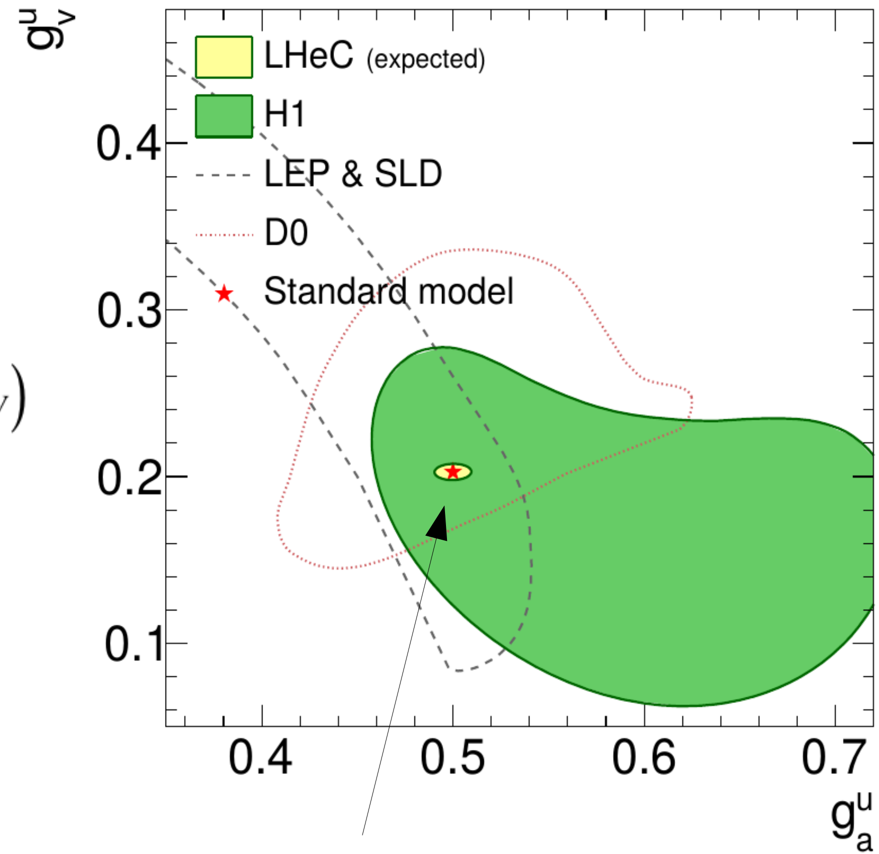
At tree level: ρ,κ=1

Couplings for 'u-type' and 'd-type' quarks

- fit: PDFs+g_A^u+g_V^u+g_A^d+g_V^d

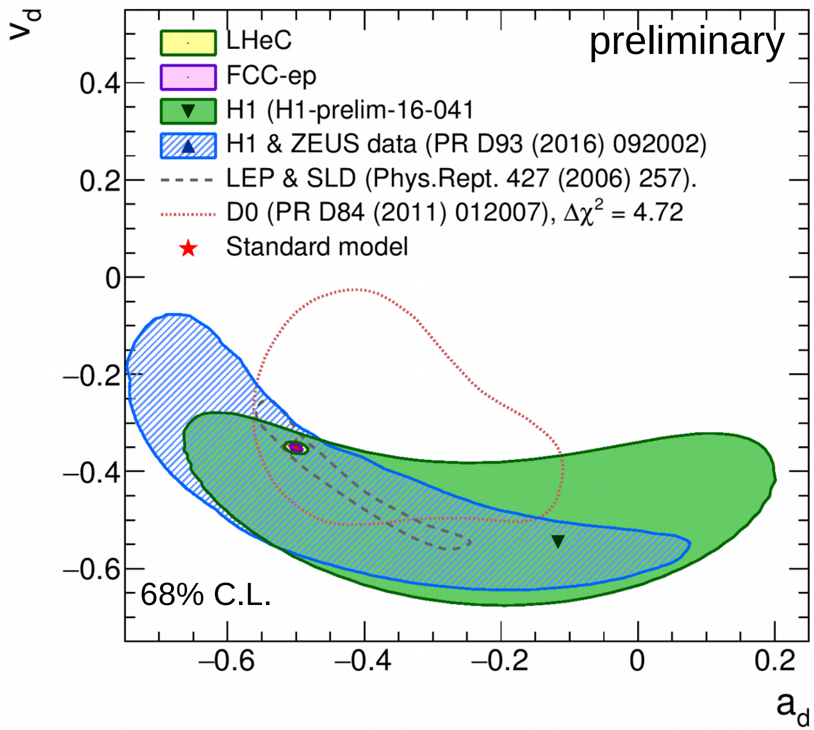
→ conservative estimate

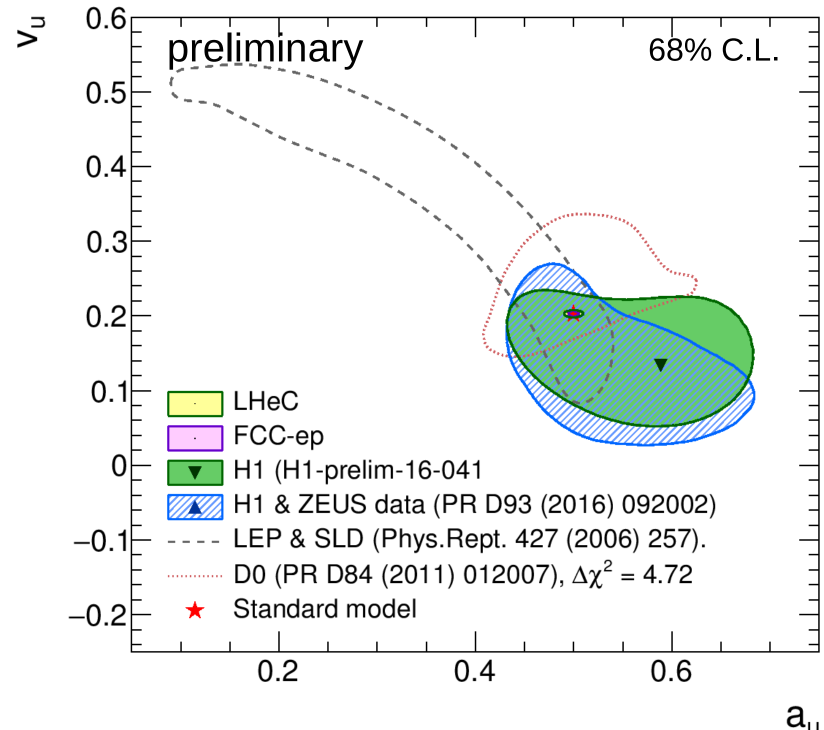
EPPSU-2020
CERN-ACC-NOTE-2018-0084



LHeC *u*-quark couplings

Light quark couplings





LHeC

- Very precise and simultaneous measurements of weak neutral current couplings of light-quark 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

ρ and κ parameters

Beyond tree-level approximation

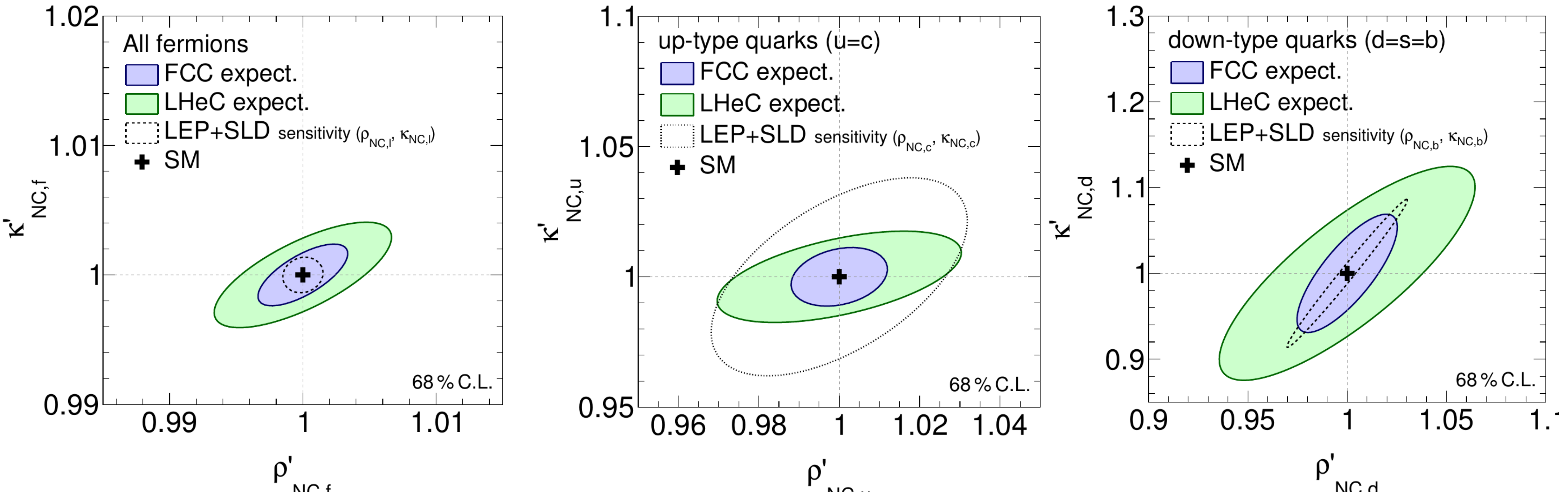
$$g_A^q = \sqrt{\rho_{\mathrm{NC},q}} I^3_{\mathrm{L},q} ,$$
$$g_V^q = \sqrt{\rho_{\mathrm{NC},q}} \left(I^3_{\mathrm{L},q} - 2Q_q \kappa_{\mathrm{NC},q} \sin^2\theta_W \right)$$

- Couplings become 'effective'

Study non-standard form factors

$$\rho_{\mathrm{NC}} \rightarrow \rho'_{\mathrm{NC}} \rho_{\mathrm{NC}} ,$$
$$\kappa_{\mathrm{NC}} \rightarrow \kappa'_{\mathrm{NC}} \kappa_{\mathrm{NC}} ,$$

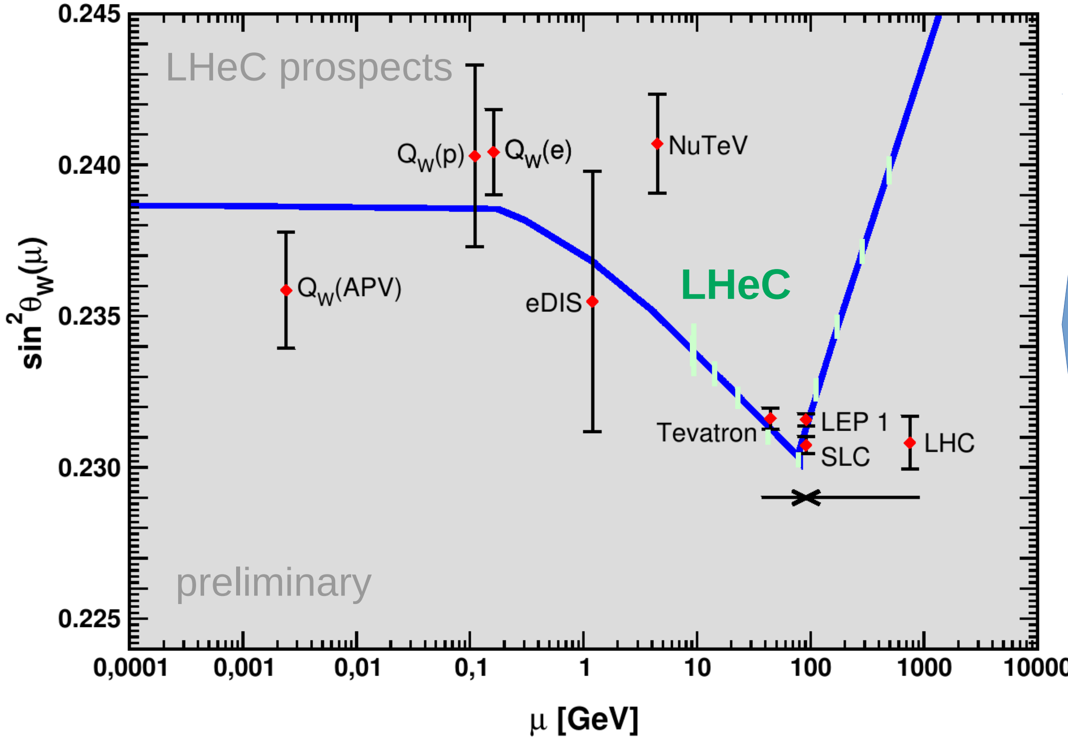
- Sensitivity similar to LEP+SLD combination, albeit comlementary sensitivity (light quarks)



Weak mixing angle $\sin^2\theta_W$

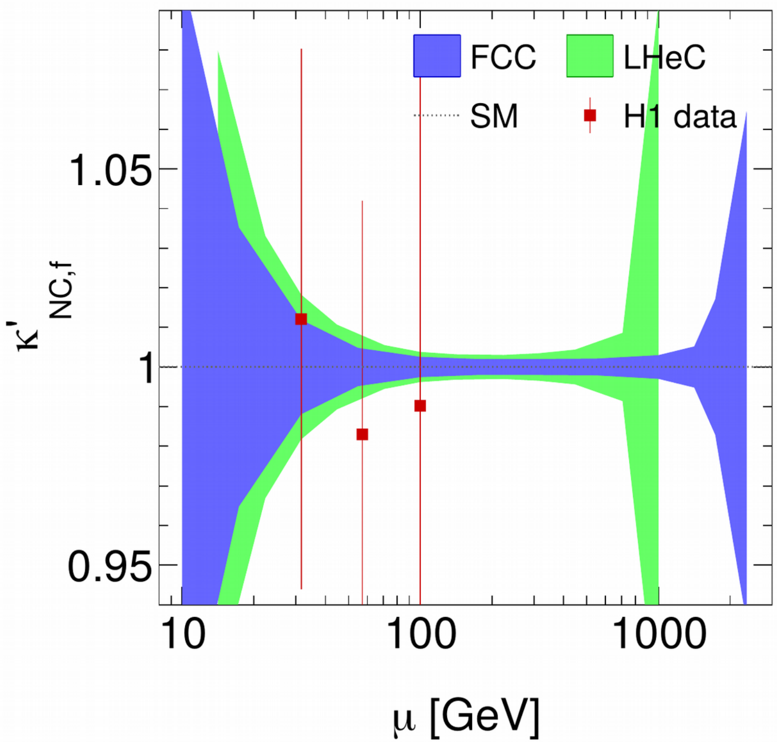
Effective weak mixing angle

- (charged leptons) in MSbar scheme



Scale dependence of κ' parameter

- Here: on-shell scheme, f = fermions



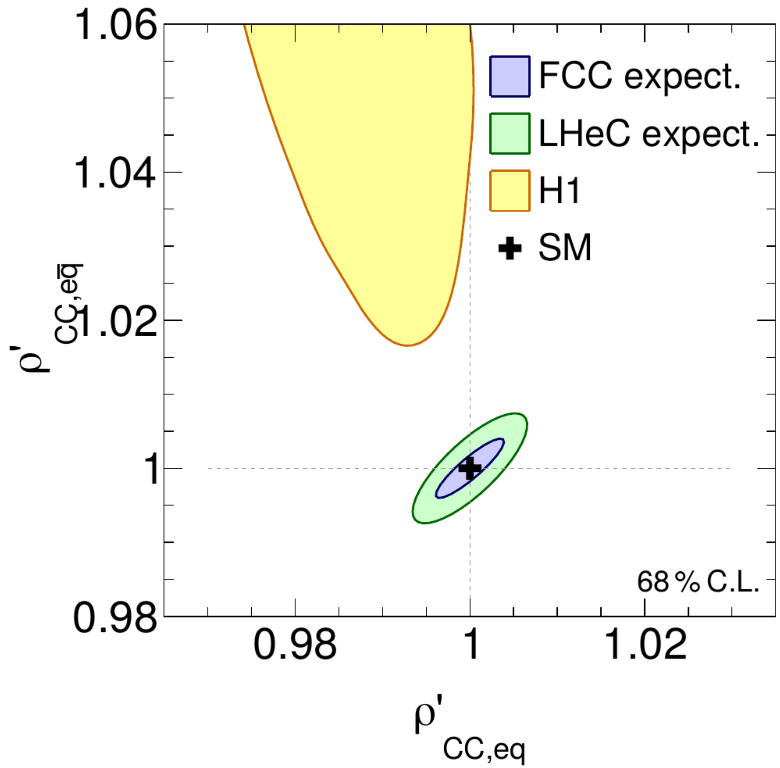
- Modification of the weak mixing angle ($\sin^2\theta_W^{l/f}$) measureable over wide kinematic range with O(0.1%) precision at LHeC
- Measurement in space-like regime $\mu^2 = -q^2$

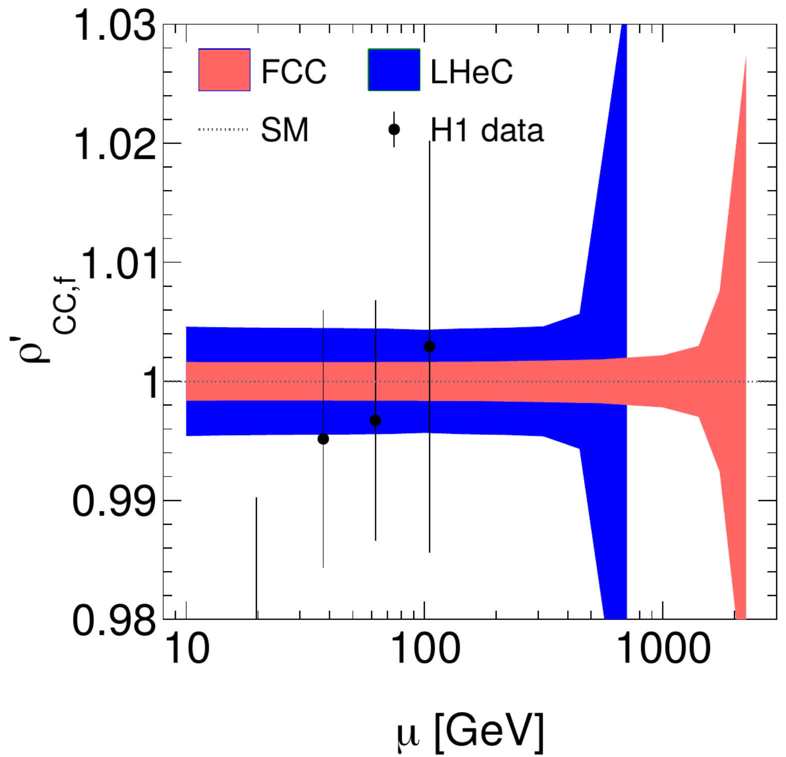
EW physics – charged currents

Unique test of virtual corrections in charged current interactions

- Precision better than 1% achievable at LHeC
- Wide kinematic range, and high precision
- non-SM physics will introduce systematic deviation ρ'_{CC}

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





EW higher-orders in DIS for PDF fits

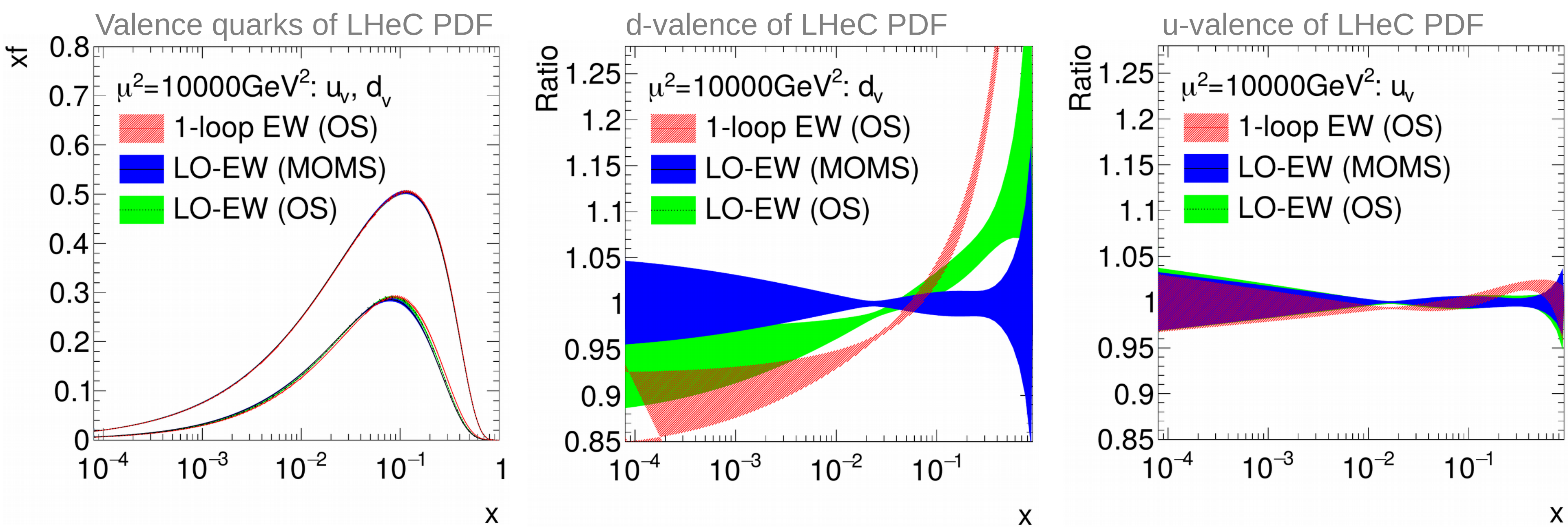
Assess impact of higher-order EW effects in LHeC-PDF fits Preliminary

- Repeat LHeC PDF determination with three EW schemes:
  on-shell (m_W,m_Z), modified-on-shell (m_Z,G_F), on-shell w/ 1-loop corrections

LHeC PDFs

- Valence quarks known up to percent precision
- LHeC: increase in χ^2 by O(490 to 750 units) for 611 data points [FCCeh: >6000 units, 619pts]

Higher-order EW effects in inclusive DIS must be accounted for in PDF fits



Single W and Z production

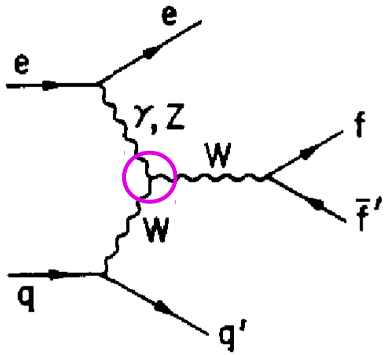
U. Baur et al., Nucl.Phys. B375 (1992) 3
U. Baur et al., Nucl.Phys. B325 (1989) 253
U. Baur et al., Conf. Proc. C90-10-04 (1990) 956 (ECFA Workshop, Aachen)

Four reactions for W and Z production

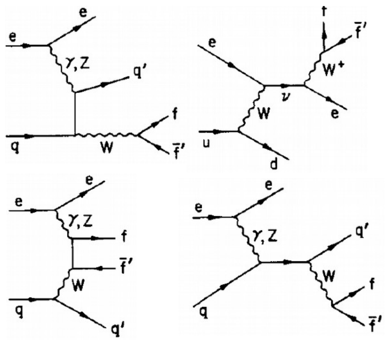
- ep → $eW^{\pm}X$
- ep → $\nu W^{-}X$
- ep → eZX
- ep → νZX

- Largest cross section for $eW^{\pm}X$ final state
  → measured already at HERA (JHEP03 (2010) 035)

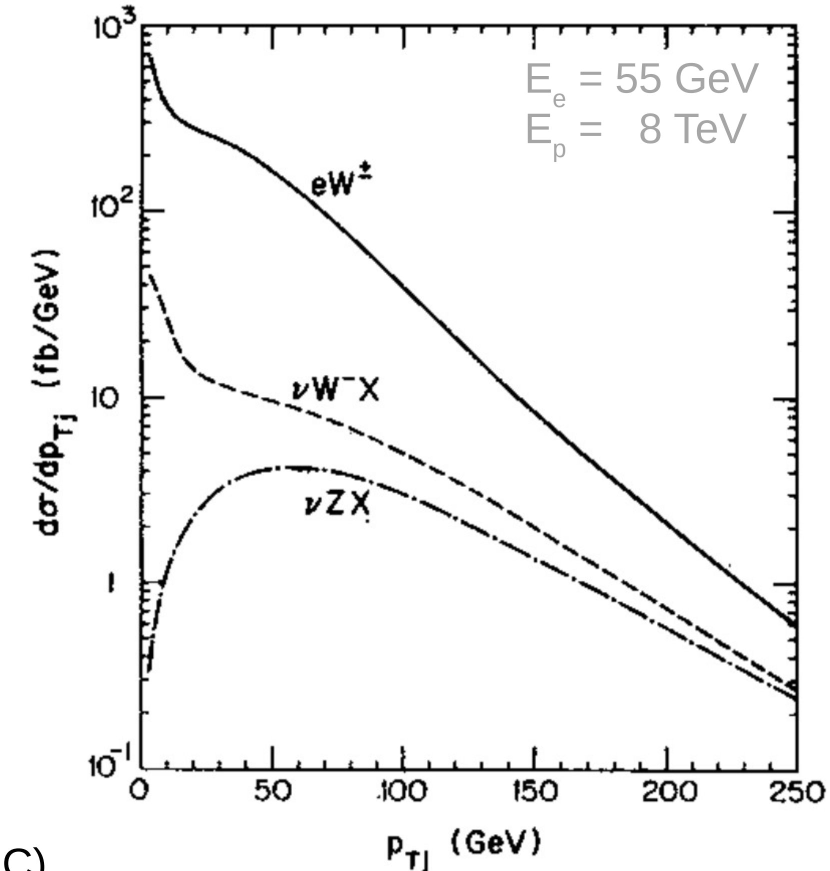
Vector boson production: ep → eWX



TGC vertex



further contributing diagrams



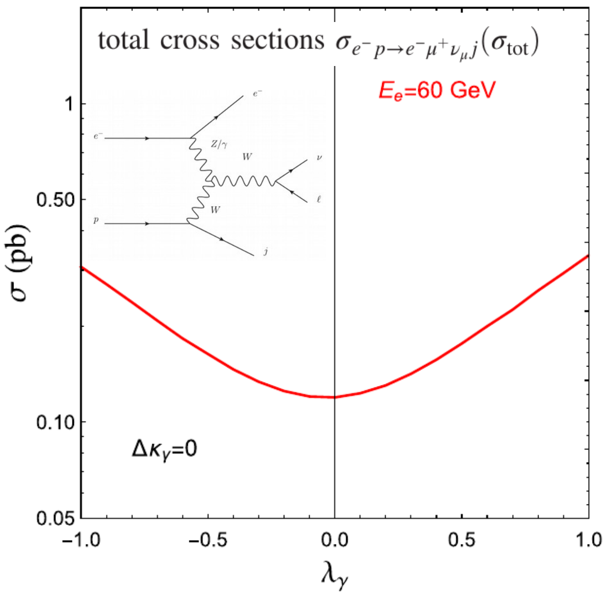
p_T of the jet from struck quark

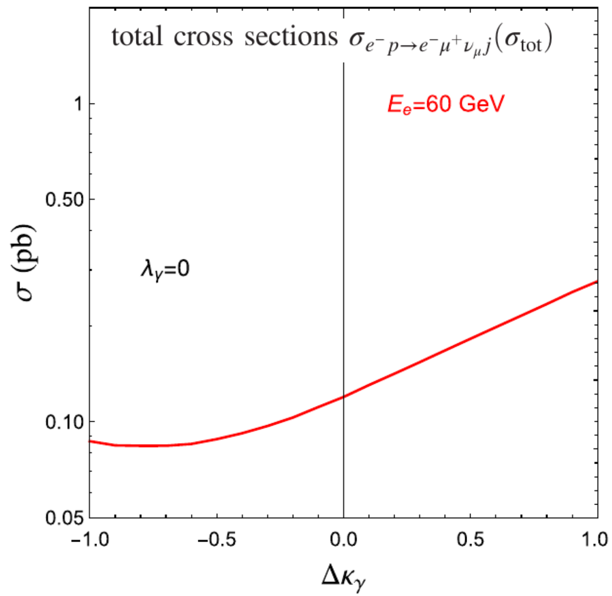
- great sensitivity to anom. triple-gauge-couplings (aTGC)
- Best channel: eWX → eνμX

anomalous TGC in eWX events $e^- p \rightarrow e^- \mu^+ \nu_\mu j$

Anomalous TGC couplings: λ_γ & $\Delta\kappa_\gamma$

- Strong cross section dependence on aTGC





- μ-channel provides information on W-polarisation
- 2 reconstruction methods explored ($\cos\Theta_{\mu W}$, $\Delta\varphi_{ej}$)

  λ_γ ~ [-0.007, 0.0056]

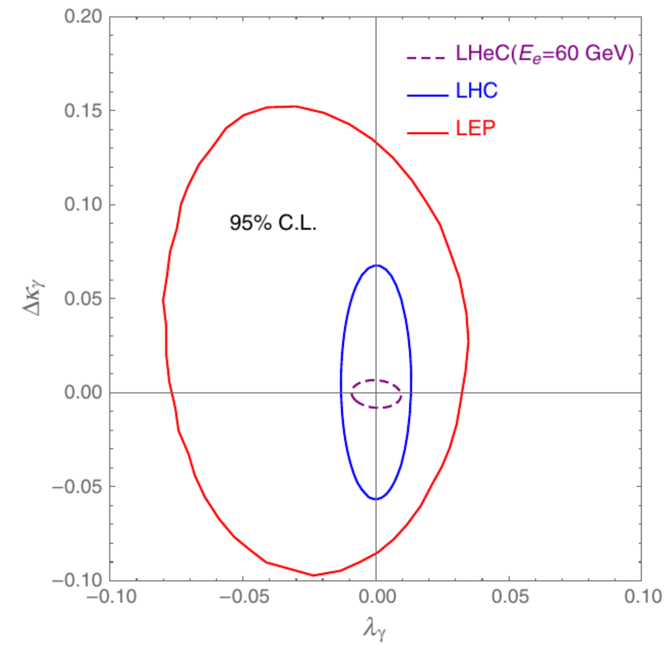
  $\Delta\kappa_\gamma$ ~ [-0.0043, 0.0054]

95% C.L., $\Delta\varphi_{e,}$ μ^+ channel alone
parton-level study: L~1ab^{-1},
detector-level study: L~2-3ab^{-1},

Bounds on aTGC

- 'realistic' analysis with Delphes
- Two parameter fit of aTGC bounds

  → significant improvment to today



Li et al., Phys. Rev. D97 (2018) 075043
Köksal et al., arXiv:1910.02307 & arXiv:1910.06747

Summary

Electroweak physics in ep

- At HERA only limited sensitivity due to luminosity and c.m. energy
- At LHeC high sensitivity to many aspects of EW theory

→ Important and fairly unexplored field in high-energy physics.

ep is in many aspects complementary to e+e- or pp

- EW couplings of light quarks
- Effective charged current couplings
- top-mass through electroweak effects
- t-channel interaction → scale dependent measurements
- (anomalous) triple-gauge-boson couplings (aTGCs)
- Electroweak effects in PDFs
- Higgs, …

Electroweak and all other SM-physics at HL-LHC

- need of LHeC-PDFs