Electroweak Physics at the LHeC

MITP Virtual Workshop
on Parity Violation and Related Topics
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Overview

- The Large Hadron electron Collider project
- Deep Inelastic Scattering, ep
  at very high energy
  - SM mass parameters
  - the weak mixing angle
  - quark neutral-current couplings
- other beyond SM parameters

➜ arXiv:2007.11799 with D. Britzger and M. Klein
see also LHeC design report update
arXiv:1206.2913 and
http://cds.cern.ch/record/2706220

Motivation

Lepton-nucleon scattering – the goal:

High-precision measurements of the 'nucleon structure'

➜ measure form factors, structure functions, (generalized) parton distribution functions, ...

- at low Q^2 elastic and quasi-elastic scattering
  ➜ form factors, response functions, polarizabilities, ...
- at high Q^2 deep inelastic scattering
  ➜ parton distribution functions, GPDs, GDAs, ...

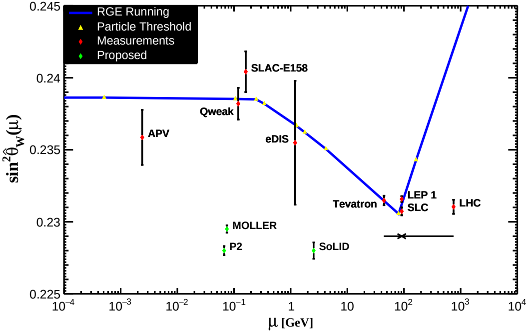
Test the dynamics of the strong interaction: QCD at high energies

Lepton scattering: only via electromagnetic and weak interaction

➜ well-controlled and separable perturbative treatment

Also: Electroweak Physics at HERA, SoLid, EIC, LHeC, ...

... the weak mixing angle at scales above the Z-resonance



The running weak mixing angle, $\sin^2 \hat{\theta}_W(\mu)$,
provides the link between low- and high-energy PV experiments

DIS at the LHeC

LHeC Study Group
arXiv:1206.2913 and CERN-ACC-Note-2020-0002
Update to appear

(see also LEP$\otimes$LHC, Aachen workshop, 1990)

Deliberation Document on the 2020 update of the European Strategy for Particle Physics (CERN-ESU-014): "realistic option"

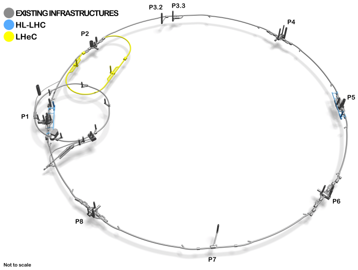
Data taking possible in the 2030s

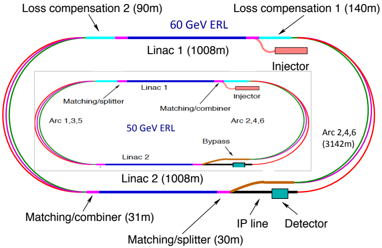
New electron linac (ERL):
$E_e = 50$ or 60 GeV, $\sqrt{s} = 1.2$ or 1.3 TeV

Integrated luminosity per year: up to 180 fb^{-1}

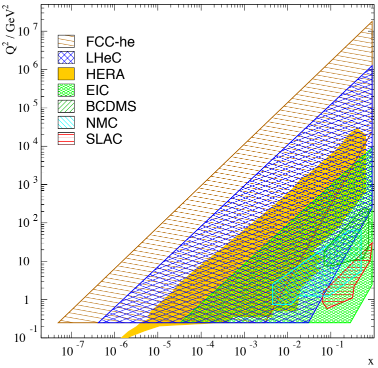
Other plans: EIC, SoLID, FCC-eh

LHeC layout





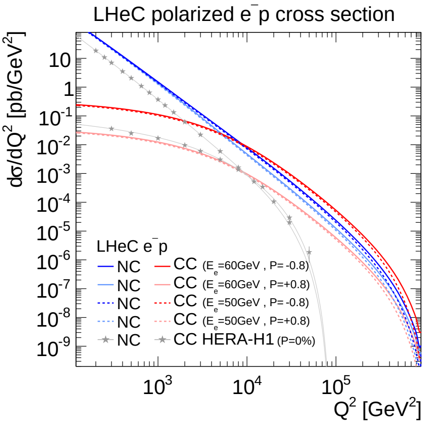
Kinematic reach



$\sqrt{s} = 1.2$ or 1.3 TeV

$x_{min} < 10^{-6}$ $Q^2_{max} \simeq 10^6$ GeV^2

Cross sections for high-energy DIS ($P_e = \pm 0.8$)



Reach to high Q^2:

Opportunity for electroweak physics

interactions strengths:
QED $\simeq$ weak
NC $\simeq$ CC

Previous studies at HERA

Final electroweak physics analysis of H1 data:
arXiv: 1806.01176, EPJC 78

The strategy:

Fits to electroweak parameters simultaneously with PDF fits:

All fits are also PDF fits

i.e. correlations of EW parameters and PDFs are under control

(4 combinations of quark PDFs plus gluon PDF, total of 13 parameters)

Summary data and uncertainties, inclusive NC and CC DIS

Processes	E_p [TeV]	Q_e	P_e	$\mathcal{L}$ [fb^{-1}]	Q^2 range [GeV^2]	No. of data points (NC, CC) LHeC-60	LHeC-50
NC, CC	7	-1	-0.8	1000	$5 - 10^6$	150, 114	150, 123
NC, CC	7	-1	$+0.8$	10	$5 - 10^6$	150, 113	146, 117
NC, CC	7	$+1$	0	10	$5 - 5 \cdot 10^5$	148, 109	145, 111
NC, CC	1	-1	0	1	$5 - 10^5$	128, 93	120, 92

several hundred data points

Source of uncertainty	Size of uncertainty	Uncertainty on cross section $\Delta\sigma_{\rm NC}$	$\Delta\sigma_{\rm CC}$
Scattered electron energy scale $\Delta E'_e/E'_e$	0.1 %	0.1 – 1.7 %	
Scattered electron polar angle	0.1 mrad	0.1 – 0.7 %	
Hadronic energy scale $\Delta E_h/E_h$	0.5 %	0.1 – 4 %	1.0 – 8.6 %
Calorimeter noise (only $y < 0.01$)	1 – 3 %	0.0 – 1.1 %	
Radiative corrections		0.3 %	
Photoproduction background ($y > 0.5$)	1 %	0.0 or 1.0 %	
Uncorrelated uncertainty (efficiency)		0.5 %	0.5 %
Luminosity uncertainty (normalization)		1.0 %	1.0 %

measurement uncertainties $O(1\%)$

Scenario	E_e	Uncorrelated uncertainty
LHeC-50a	50 GeV	0.5 %
LHeC-50b	50 GeV	0.25 %
LHeC-60a	60 GeV	0.5 %
LHeC-60b	60 GeV	0.25 %

4 scenarios
$E_e = 50$ or 60 GeV
finer binning

Many data points
Data fix normalization
Data fix PDFs (mainly from lower Q^2, 1γ-exchange)

➜ correlated normalization uncertainties strongly suppressed

➜ uncorrelated uncertainties reduced (several hundred data points)

➜ per mille uncertaintites for the measurement of cross section ratios

Equivalent to the measurement of cross section ratios, like

$$R_{CC/NC} = \frac{d\sigma_{CC}}{d\sigma_{NC}}, \quad B_c = \frac{d\sigma(e^-) - d\sigma(e^+)}{d\sigma(e^-) - d\sigma(e^+)}$$

$$A_{LR} = \frac{d\sigma_L - d\sigma_R}{d\sigma_L - d\sigma_R}$$

$$\frac{d\sigma_{NC}(\text{large}Q^2)}{d\sigma_{NC}(\text{small}Q^2)}$$

DIS at large Q^2: Neutral Current

Neutral current at tree level (LO), polarized $e^{\pm}$p scattering, inclusive

$$\frac{d^2\sigma_{NC}(e^{\pm}p)}{dxdQ^2} = \frac{2\pi\alpha^2}{Q^4 x}\left(Y_+\mathbf{F_2^{\pm}} \mp Y_- x\mathbf{F_3^{\pm}} - y^2\mathbf{F_L^{\pm}}\right)$$

$$\mathbf{F_2^{\pm}} = F_2^{\gamma} + \kappa_Z(-v_e \mp Pa_e)F_2^{\gamma Z} + \kappa_Z^2(v_e^2 + a_e^2 \pm 2Pv_e a_e)F_2^Z$$
$$x\mathbf{F_3^{\pm}} = \quad +\kappa_Z(-a_e \pm Pv_e)xF_3^{\gamma Z} + \kappa_Z^2(2v_e a_e \pm P(v_e^2 + a_e^2))xF_3^Z$$

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

$$(F_2^{\gamma},\, F_2^{\gamma Z},\, F_2^Z) = x\sum(Q_q^2,\, 2Q_q v_q,\, v_q^2 + a_q^2)(q + \bar{q})$$
$$x(F_3^{\gamma Z},\, F_3^Z) = 2x\sum(Q_q a_q,\, v_q a_q)(q - \bar{q})$$

$$v_f = I_f^{(3)} - 2Q_f\sin^2\theta_W, \quad a_f = I_f^{(3)} \quad (f = e, u, d, \ldots)$$

On-shell scheme:

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

Independent SM paramters: α, m_Z, m_W + PDFs

DIS at large Q^2: Charged Current

Charged current at tree level

$$\frac{d^2\sigma_{CC}(e^\pm)}{dxdQ^2} = \frac{1 \pm P}{2} \frac{2\pi\alpha^2}{Q^4 x} \kappa_W^2 \left(Y_+ \mathbf{W_2^\pm} \pm Y_- x\mathbf{W_3^\pm} - y^2 \mathbf{W_L^\pm} \right)$$

$$\kappa_W(Q^2) = \frac{Q^2}{Q^2 + m_w^2} \frac{1}{4\sin^2\theta_w}$$

$$\mathbf{W_2^-} = x(U + \bar{D}), \quad x\mathbf{W_3^-} = x(U - \bar{D})$$
$$\mathbf{W_2^+} = x(\bar{U} + D), \quad x\mathbf{W_3^+} = x(D - \bar{U})$$
$$U = u + c,\ \bar{U} = \bar{u} + \bar{c},\ D = d + s,\ \bar{D} = \bar{d} + \bar{s}$$

SM paramters: α, m_W, $\sin^2\theta_w$ + PDFs

Note: we include NLO EW and NNLO QCD corrections at LO:

$$d\sigma_{NC} = d\sigma_{NC}(\alpha, m_Z, m_W) \quad \text{and} \quad d\sigma_{CC} = d\sigma_{CC}(\alpha, m_Z, m_W)$$

On-shell scheme:

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

Note: $\frac{\delta m_W}{m_W} = \frac{\sin^2\theta_W}{2\cos^2\theta_W} \frac{\delta \sin^2\theta_W}{\sin^2\theta_W} \simeq 0.15 \frac{\delta \sin^2\theta_W}{\sin^2\theta_W}$

at NLO:

$$d\sigma_{NC} = d\sigma_{NC}(\alpha, m_Z, m_W, m_t, m_H, \ldots)$$

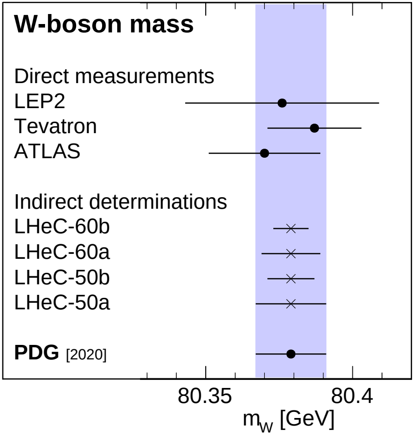
Beyond the SM:

$$d\sigma_{NC} = d\sigma_{NC}(\alpha, m_Z, m_W, \ldots, v_f, a_f)$$
$$d\sigma_{NC} = d\sigma_{NC}(\alpha, m_Z, m_W, \ldots, \rho, \kappa)$$
$$d\sigma_{NC} = d\sigma_{NC}(\alpha, m_Z, m_W, \ldots, S, T, U)$$

etc

Results: m_W+PDF fit

Fit parameter: m_W (and PDFs), all other parameters fixed

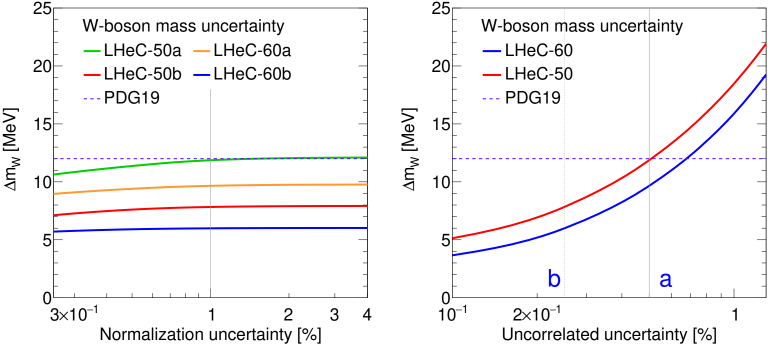


$\delta m_W = \pm 6$ MeV (LHeC-60b)
$\delta m_W = \pm 12$ MeV (LHeC-50a)
$(= \pm 9_{\text{exp}} \pm 8_{\text{PDF}}$ MeV)

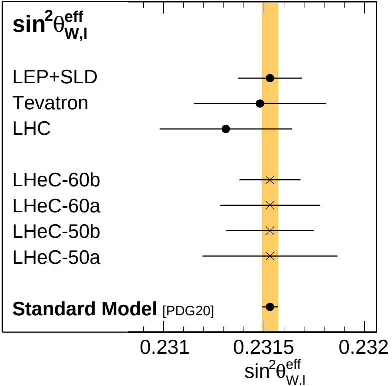
measurement errors: $O(1\%)$
expected parameter uncertainties: $O(1‰)$
for m_W, from error propagation: $O(10^{-4})$

This is an indirect determination of a SM parameter, m_W
(cf. global EW fits)

m_W: Uncertainties



$\sin^2\theta_W$+PDF fit



Fit parameter: $\sin^2\theta_W$
(in NC vector couplings only)

compared with Z-pole data

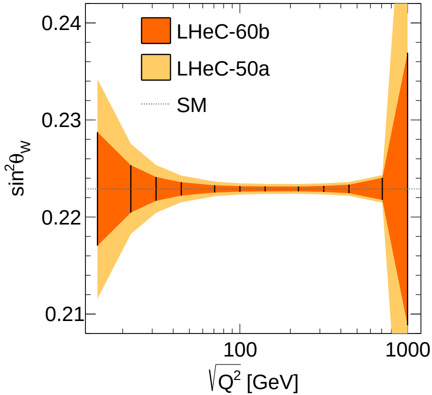
(note: need theory to map $\sin^2\theta_W$ to $\sin^2\theta^{eff}_{W,l}$)

$$\Delta\sin^2\theta_W \text{ (LHeC-50a)} = \pm 0.00028_{(exp)} \pm 0.00019_{(PDF)} = \pm 0.00034_{(tot)}$$

$$\Delta\sin^2\theta_W \text{ (LHeC-50b)} = \pm 0.00017_{(exp)} \pm 0.00014_{(PDF)} = \pm 0.00022_{(tot)} .$$

$$\Delta\sin^2\theta_W \text{ (LHeC-60a)} = \pm 0.00023_{(exp)} \pm 0.00009_{(PDF)} = \pm 0.00025_{(tot)} ,$$

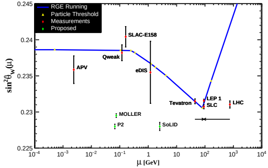
$$\Delta\sin^2\theta_W \text{ (LHeC-60b)} = \pm 0.00014_{(exp)} \pm 0.00006_{(PDF)} = \pm 0.00015_{(tot)} ,$$



Fit parameters:
12 values of $\sin^2\theta_W$
in Q^2 bins
($200 \leq Q^2 \leq 10^6$ GeV^2)

uncertainties of 1‰
in $25 < \sqrt{Q^2} < 700$ GeV

Note: on-shell scheme, $\sin^2\theta_W$ is only one parameter
In the $\overline{\text{MS}}$ scheme:
this corresponds to a measurement of the
running effective $\sin^2\theta_W$
(never measured before in one single experiment)

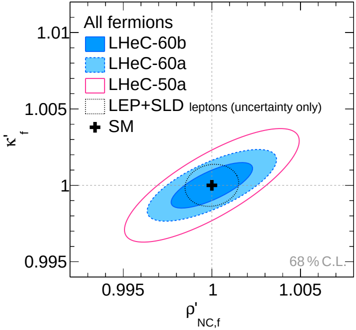


Beyond the SM: (ρ, κ)+PDF fit

- Parametrize new (heavy) physics by modified couplings

$$v_f = \sqrt{\rho'_f}\left(I_f^{(3)} - 2Q_f\,\kappa'_f\,\sin^2\theta_W\right), \quad a_f = \sqrt{\rho'_f}\,I_f^{(3)} \quad (f = e, u, d, \ldots)$$

ρ: NC/CC ratio, κ: effective weak mixing angle
can be flavor- and scale-dependent

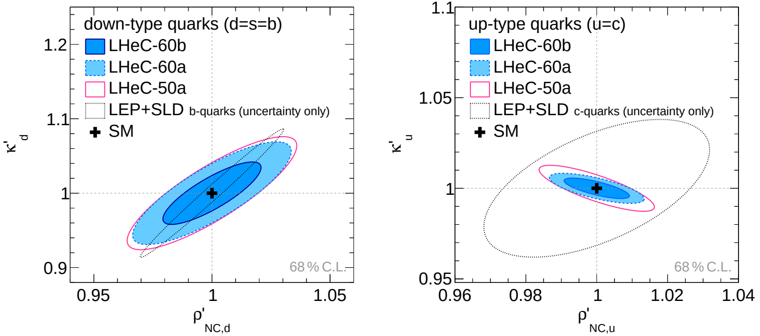


- Precision similar to LEP, SLD and D0 measurements from a single experiment

Beyond the SM: (ρ, κ)+PDF fit

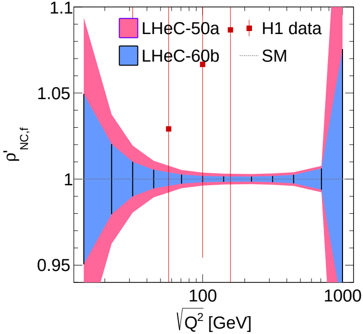
$$v_q = \sqrt{\rho'_q}\left(I_q^{(3)} - 2Q_q\,\kappa'_q \sin^2\theta_w\right), \quad a_q = \sqrt{\rho'_q}\,I_q^{(3)} \quad (q = u, d, \ldots)$$

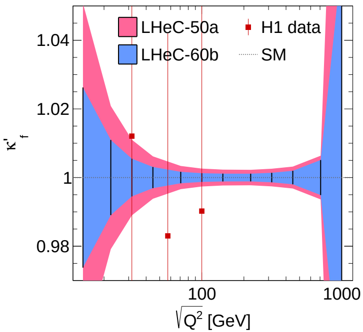
4-parameter fit of quark couplings



- Separate light-quark flavor couplings (mainly *u* and *d*)
- Similar to *c*- or *b*-tagged quark couplings from *Z*-pole

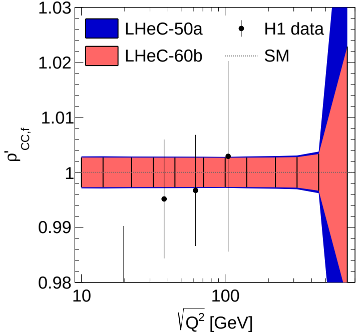
(ρ, κ)+PDF fit: scale dependence





Best sensitivity at $Q^2 \simeq 20,000$ GeV^2, 1 to 2 permille

(Note: κ'_f corresponds to effective weak mixing angle, $\sin^2 \theta^{\text{eff}}_{W,f} = \kappa'_f \sin^2\theta_W$)



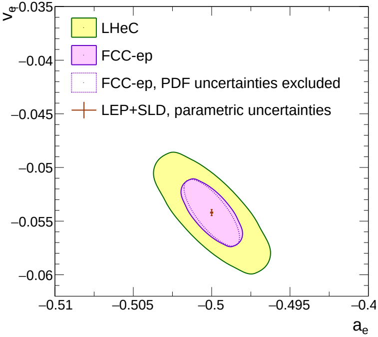
Fit parameters:
12 values of ρ'_{CC}
in Q^2 bins

0.3 % for $Q^2 < (500\ \text{GeV})^2$

ρ'_{CC}: normalization of the CC cross section

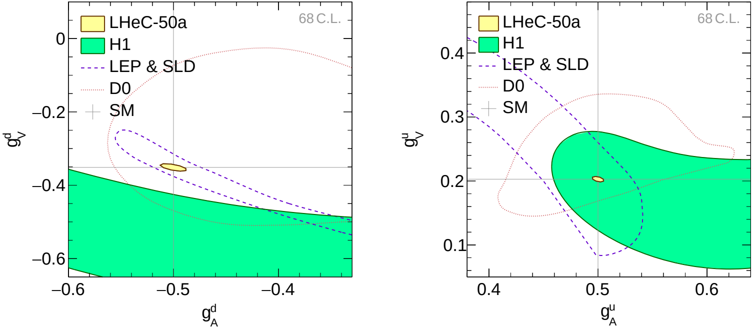
distinguished from ρ'_{NC}

Leptonic couplings: v_f, a_f+PDF fits



from PDG 2020
$v_e = 0.03817 \pm 0.00047$
$a_e = -0.50111 \pm 0.00035$

LHeC not competitive
(but only a factor 3 off)



PDG2020 average

$v_d = -0.38^{+0.04}_{-0.05}$ $\qquad$ $v_u = 0.266 \pm 0.034$

$a_d = -0.527^{+0.040}_{-0.028}$ $\qquad$ $a_u = 0.519^{+0.028}_{-0.033}$

LHeC improves by more than an order of magnitude
flavor-separated and without sign ambiguity

Theory predictions

- DIS at the LHeC
  expect high experimental precision for EW parameters

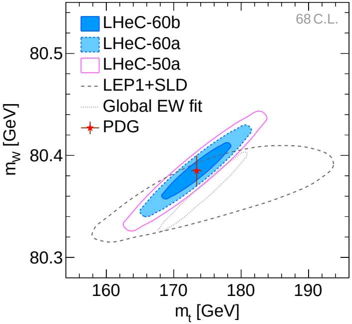
➜ Motivation for theory:
  - 2-loop calculation
  - calculation in the $\overline{\text{MS}}$ scheme
  - theory uncertainties in parameter relations:
  - on-shell $\sin^2\theta_W$ versus leptonic effective $\sin^2\theta_W$

Summary

- LHeC:
  High-precision measurements of inclusive DIS
- Precision of electroweak parameters in general similar to Z-pole observables
- ... but from space-like scattering covering a large range of Q^2
- Scale dependence of couplings
- Separated light-quark couplings
- Not only a “realistic”, but also an “interesting option”

More details, see arXiv:2007.11799

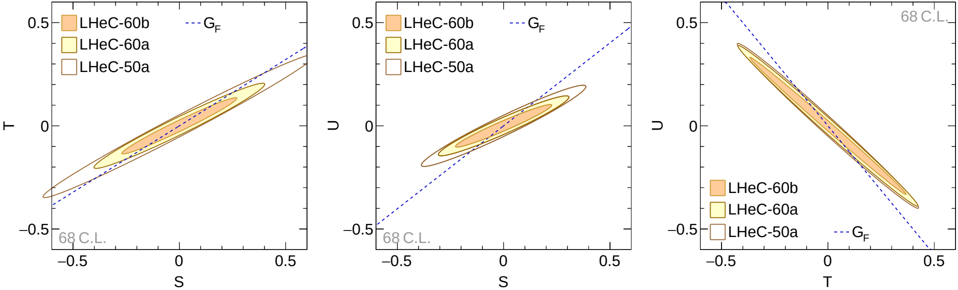
Appendix



m_W from LO (mainly, $\sin^2\theta_W$)
m_t through 1-loop

similar to indirect
m_t determinations
from Z-pole observables

STU+PDF fit



From single-parameter fits: factor 2 - 5 better than present PDG values