Electroweak physics at LHeC/FCCeh

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Deep-inelastic electron-proton scattering

Neutral current scattering
\[ e p \rightarrow e' X \]

Charged current scattering
\[ e p \rightarrow \nu_e X \]

- Study the structure of the proton -> bound together by QCD dynamics
- Probe electroweak structure of the Standard Model
  -> Unification of electromagnetic and weak force, chiral structure of EW interactions

-> Extract fundamental QCD and EW parameters
Reduced NC e⁺p scattering cross sections

Cross section expressed by generalised structure functions

\[ \frac{d \sigma_{NC}^Z}{dQ^2 dx} = \frac{2 \pi \alpha^2}{x} \left[ \frac{1}{Q^2} \right]^2 (Y_1 F_2 + Y_2 x F_3 + y^2 F_L) \]

Z exchange effects

\[ F_2 = F_2^{\gamma} + \kappa_Z (-v_e + P a_e) F_2^{\gamma Z} + \kappa_Z^2 (v_e + a_e^{\pm} + P v_e a_e) F_2^{Z} \]
\[ x F_3 = + \kappa_Z (\pm a_e + P v_e) F_3^{\gamma Z} + \kappa_Z^2 \left( \mp 2 v_e a_e - P (v_e^2 + a_e^2) \right) x F_3^{Z} \]

• Interference and Z-exchange (Q^2>m_Z^2)
• Cross section raises for high-x due to EW effects. Contrary to HERA:
  • x ~ 0.05 'scaling'
  • x > 0.05 gluon bremsstrahlung

Quark-parton model

\[ [F_2, F_2^{\gamma Z}, F_2^Z] = x \sum_q [e_q^2, 2 e_q v_q, v_q^2 + a_q^2] \{ q + \bar{q} \} \]
\[ [xF_3^{\gamma Z}, xF_3^Z] = x \sum_q [2 e_q a_q, 2 v_q a_q] \{ q - \bar{q} \} \]
Inclusive cross section at HERA and LHeC

Inclusive cross section at HERA
- CC mediated by massive gauge boson
- NC γ/Z-interference and ZZ effects will become important (higher $Q^2$)

H1 and ZEUS at HERA
- precise measurement of NC and CC up to: kinematic limit: $Q^2 \sim 10^5$ GeV$^2$
- Longitudinal polarized beams (O(±35%))
- Lumi: two times 0.5 fb$^{-1}$
- At highest $Q^2$: precision fully limited by statistics
**LHeC – ep single differential cross section**

**LHeC/FCCeh increased kinematic range**
- Lower $Q^2$: considerably increased cross section
- Higher $Q^2$: Greatly improved kinematic limit
  - LHeC: $Q^2 \sim 1.7 \times 10^6 \text{ GeV}^2$
  - FCCeh: $Q^2 \sim 12 \times 10^6 \text{ GeV}^2$

- Huge luminosity further increase kinematic range

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Unpolarized $e^+p$ cross section

- LHeC $e^+p$ NC
- LHeC $e^+p$ CC
- FCC $e^+p$ NC
- FCC $e^+p$ CC

*H1 data*
Polarized lepton beams at LHeC

LHeC/FCCeh running scenario
- \( e^- \) +80\%, -80\% \((1 \text{ab}^{-1})\)
- \( e^+ \) unpolarised lepton beam \((0.3 \text{ab}^{-1})\)

CC: No right-handed weak currents

\[ Q^2 = 3000 \text{ GeV}^2 \]
\[ y \sim 0.25 \]
\[ s_{\text{FCCeh}} / s_{\text{HERA}} \sim 30 \]
**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

**Polarisation asymmetry at LHeC & FCC-eh**
- At large $x$:
  $A^\pm$ measures $d_v/u_v$ ratio of valence quarks

**Cross section asymmetry as a function of $Q^2$**

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

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HERA reach

LHeC reach

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preliminary
Methodology – Study of EW parameters

EW parameters are determined in combined fit: PDF+EW

- account for correlations with PDF uncertainties
- NNLO QCD + 1-loop EW calculations
  - EW: On-shell calculation ($\alpha_{em}, m_Z, m_W, \Delta r$)
  - $\Delta r = \Delta r(\alpha_{em}, m_W, m_Z, m_t, m_H, ...)$
- Simulated polarized NC&CC DIS data
**Z-boson mass**

**Z-boson mass from EW+PDF fit**
- all other masses expected to be known

**Z-boson mass uncertainties**
- HERA \((56)_{\text{exp}}^{25}_{\text{PDF}}\) MeV
- LHeC \((16)_{\text{exp}}^{10}_{\text{PDF}}\) MeV
- FCC \((11)_{\text{exp}}^{3}_{\text{PDF}}\) MeV
- PDF uncertainties become negligibly small (outer errors)

**Precision of Z-boson mass not limited by PDFs**

![Graph showing Z-boson mass uncertainties for HERA, LHeC, FCC, and PDG.]
**W-boson mass**

**W-boson mass from NC&CC DIS data**
- All other masses expected to be known
- H1: $\pm 89\,(\text{exp})\,73\,(\text{PDF})$ MeV (arXiv:1806.01176)
- HERA: $\pm 63\,(\text{exp})\,29\,(\text{PDF})$ MeV
- LHeC: $\pm 14\,(\text{exp})\,10\,(\text{PDF})$ MeV
- FCC: $\pm 9\,(\text{exp})\,4\,(\text{PDF})$ MeV

**High precision for W-boson mass**
- CC kinematics fully constraint by measurement
  - $\rightarrow$ no missing $E_T$ needed
  - $\rightarrow$ IS photon tagging would be crucial
- PDF (QCD) uncertainties are small

**HERA prospects ('87)**
$m_W \sim \pm 80\text{-}100$ MeV

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**W-boson mass**

**expected uncertainties**
- HERA
- LHeC
- FCC
- LHeC & FCC
- PDG [2016]

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

$p \pm 15$ MeV
Simultaneous determination of boson masses

W- and Z-boson masses: 
Most important input parameters to EW calculation (=on-shell scheme)

- Benefit from large cross sections
- CC precisely measureable
- $m_W-m_Z$ correlation aligned with $\sin^2\theta_w$
  $\rightarrow$ Predominant sensitivity through couplings, rather than propagator terms
- PDFs will not be the limiting factor for EW physics (not shown in figure)
- Multiple EW parameters can be determined simultaneously: 'global' fit becomes possible
Using only precise low-scale measurements

$G_F$ and fine structure constant $\alpha$
- Precisely measured at low scales

At EW scale
- One more fundamental parameter is needed, (commonly $m_Z$)
- Other EW parameters are then predictions (e.g. $m_W$, $\sin^2\theta$)

Using both: $G_F$ and $\alpha$
... and determine $m_W$ and $m_Z$ from inclusive DIS data
($G_F$ is a prediction, which is constraint by the MuLan measurement)

- No additional high-scale measurements needed (beyond $m_t$, $m_H$)

- Unique and unbiased test of EW theory at high scales

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

$$G_F = 1.1663787(6) \times 10^{-5} \text{GeV}^2$$
**W-boson and top-mass**

*Top mass contributes through loops*
- $\rho_t \sim m_t^2$ contributes to $\Delta r$, $\rho$ and $\kappa$

*Top mass and W-boson mass*

$m_W - m_t$ determinations
- sizeable correlation (as expected)
- significant improvement over LEP experiments
  \[
  \Delta m_t^{\text{LHeC}} = \pm 2.6 \text{ (exp)} \pm 1.7 \text{ (PDF)} \text{ GeV}
  \]
  \[
  \Delta m_t^{\text{FCC}} = \pm 1.7 \text{ (exp)} \pm 0.5 \text{ (PDF)} \text{ GeV}
  \]
- LHeC (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

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

LHeC workshop, Orsay, June 2018
Daniel Britzger – EW physics at LHeC
**Weak neutral-current couplings**

**Axial and axial-vector couplings of quarks**
- Couplings of fermions to Z-boson

\[ Z^0 \]
- \( e \) \( q \) \( l \) \( a_q, v_q \)

**Effective higher-order corrections**
- Form factors \( \rho \) & \( \kappa \)

\[ v_q = \sqrt{\rho_{NC,q}} \left( I_{q,L}^{(3)} - 2 Q_q \kappa_{NC,b} \sin^2 \theta_W \right) \]

\[ a_q = \sqrt{\rho_{NC,q}} I_{q,L}^{(3)} \]

- At tree-level: \( \rho = \kappa = 1 \)
- EW corrections yield non-zero form factors. on-shell scheme

\[ \rho_{NC,q} \sim 1 + \rho_t \]

\[ \kappa_{Z,q}^2 \sim 1 + \rho_t / \tan^2 \theta_W \]

**Born level couplings**

\[ a_q = I_{q,L}^{(3)} \]

\[ v_q = I_{q,L}^{(3)} - 2 Q_q \sin^2 \theta_W \]
Axial and axial-vector couplings of quarks
- Couplings of quarks to Z-boson

\[ a_q = I_q^{(3)} \]
\[ v_q = I_q^{(3)} - 2 Q_q \sin^2 \theta_W \]

LHeC and FCC-ep
- Polarisation of lepton beam (P_e \sim \pm 80\%) improves precision
- Very precise measurements of weak light-quark couplings feasible
Weak neutral-current couplings: quarks, electrons

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

- $a_u = 0.5 \pm 0.003$
- $a_d = -0.5 \pm 0.005$
- $\nu_u = 0.20 \pm 0.002$
- $\nu_d = -0.35 \pm 0.005$

High precision test of electroweak sector of Standard Model

**Electron couplings**
- High precision
- Though: LEP with 'ulitmate' precision

Complementary test
\( \rho' \) and \( \kappa' \) parameters

**Introduce**
- Introduce: \( \rho' \) and \( \kappa' \) parameters
- Recently also measured by H1 (arxiv:1806.01176)

\[
\nu_q = \sqrt{\rho_{NC,q} \rho'_{NC,q}} \left( I_{q,L}^{(3)} - 2 Q_q \kappa_{NC,q} \kappa'_{NC,q} \sin^2 \theta_W \right)
\]

\[
a_q = \sqrt{\rho_{NC,q} \rho'_{NC,q}} I_{q,L}^{(3)}
\]

**LEP+SLD** *Phys.Rept. 427 (2006) 257*
- Relative uncertainty on measurement of \( \rho \) and \( \kappa \) parameters
- Combined result from 5 independent experiments

**LHeC expectation**
- LHeC and FCC with very high precision: much better than 1%
- Exceed precision of a single LEP or SLD experiment
- Somewhat orthogonal to LEP: Lepton & quark couplings
**Light-quark $\rho'$ and $\kappa'$ parameters**

**Complementary test to LEP: quark parameters**
- Separate parameters for u-type and d-type quarks
- Light-quark couplings not accessible at LEP (only heavy quarks: c,b,(s))
- Fairly moderate precision at HERA

**Greatly improved precision w.r.t. HERA (H1)**
Scale dependence of $\rho'$ and $\kappa'$ parameters

Unique test of virtual EW corrections ($\rho'$ and $\kappa'$ parameters)
- 2 orders of magnitude: up to TeV range
- LEP only measured at Z-pole
- H1 provided proof-of-concept, with only moderate precision

\[ v_q = \sqrt{\rho_{\text{NC},q} \rho'_{\text{NC},q} (I_{q_L} - 2 Q_q \kappa_{\text{NC},q} \kappa'_{\text{NC},q} \sin^2 \theta_W)} \]
\[ a_q = \sqrt{\rho_{\text{NC},q} \rho'_{\text{NC},q} I_{q_L}^{(3)}} \]
Weak mixing angle $\sin^2 \theta_w$

Weak mixing angle ($\sin^2 \theta_w^{\text{lept.}}$) measureable over wide kinematic range with $\sim$0.3% precision at LHeC (FCC: $\sim$0.2%)
Charged currents

**Unique test of virtual corrections in charged current interactions**

- Precision better than 1% achievable (LHC and FCCeh)
- Wide kinematic range, and with high precision
- non-SM physics with systematic deviation

\[
\begin{align*}
W_2 &= x \left( (\rho_{CC,eq}^\prime \rho_{CC,eq}^\prime)^2 U + (\rho_{CC,eq}^\prime \rho_{CC,eq}^\prime)^2 D \right) \\
x W_3 &= x \left( (\rho_{CC,eq}^\prime \rho_{CC,eq}^\prime)^2 U - (\rho_{CC,eq}^\prime \rho_{CC,eq}^\prime)^2 D \right) \\
W_2^* &= x \left( (\rho_{CC,eq}^\prime \rho_{CC,eq}^\prime)^2 U + (\rho_{CC,eq}^\prime \rho_{CC,eq}^\prime)^2 D \right) \\
x W_3^* &= x \left( (\rho_{CC,eq}^\prime \rho_{CC,eq}^\prime)^2 D - (\rho_{CC,eq}^\prime \rho_{CC,eq}^\prime)^2 U \right)
\end{align*}
\]
**EW higher-orders in DIS for PDF fits**

**Assess impact of higher-order EW effects on PDF fits**
- Repeat 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 \(\chi^2\) by O(490 to 750 units) for 611 data points (FCCeh: >6000 units, 619pts)
- Higher-order EW effects cannot be ignored any longer (as at HERA)
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 negligible for many QCD studies (at lower scales)
- ...but have to be considered for precise PDF determinations

Highest precision for both: LHeC and FCCeh