EW Physics at the LHeC and FCC-he

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Energy-frontier $ep$ physics in the '30s – the LHeC

$LHeC – ep$ data in 2030s

- ERL electron ring attached to HL-LHC
- Similar concept than FCC-eh but realisable much earlier
- $E_e = 50$ GeV, $L \sim 10^{34} \text{cm}^{-2} \text{s}^{-1}$

$LHeC$

- $\sqrt{s} \sim 1.2$ TeV
- Electron and positron data
- Up to 1 ab$^{-1}$ integrated luminosity
- (Symmetric) detector may be shared with ALICE3/H1
- Concurrent operation with $pp$-collisions at P1,P5,P8

$\rightarrow$ Relocatable: ERL components can be relocated from HL-LHC to FCC-hh
Dedicated electron-ring attached to the FCC-hh

Energy recovery linac
$E_e = 60$ GeV
$\sqrt{s} \sim 3.5$ TeV

High Luminosity of about $3$ ab$^{-1}$

Concurrent operation with FCC-hh
Deep-inelastic scattering

DIS: Cleanest High Resolution Microscope
→ Extraordinary QCD laboratory
→ Precision QCD and matter
→ QCD Discoveries

Empowering the HL-LHC & FCC-hh Search Programme
Transformation of HL-LHC & FCC-hh into the desired Higgs and discovery machine

Unique Facility for Nuclear Physics
Unique and complementary Higgs & Top-quark programme

Electroweak Physics

LHeC history

<table>
<thead>
<tr>
<th>LEP×LHC</th>
<th>HERA ep</th>
<th>LHC × e⁻</th>
<th>HL-LHC×ERL &amp; Higgs</th>
<th>LHeC</th>
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<tbody>
<tr>
<td>$s \sim \sqrt{1.3\text{TeV}}$</td>
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</table>
Electroweak physics in deep-inelastic scattering

Neutral current DIS
\[ ep \rightarrow e + X \]

Charged current DIS
\[ ep \rightarrow \nu + X \]

Deep-inelastic electron-proton scattering
mediated in spacelike regime, by $\gamma, \gamma Z, Z$ or $W$-boson exchange
Expectations: $m_W + \text{PDF}$

Determine $W$-boson mass together with proton-PDFs

- LHeC with $L \sim 1\text{ ab}^{-1}$
  - LHeC ($E_e=50\text{ GeV}$): $\Delta m_W = \pm 8 \text{ MeV}$
  - LHeC ($E_e=60\text{ GeV}$): $\Delta m_W = \pm 6 \text{ MeV}$
- FCC-eh with $L \sim 1\text{ ab}^{-1}$
  (includes PDF uncertainty of about $\pm 3.6 \text{ MeV}$)
  - FCC-eh + LHeC: $\Delta m_W = \pm 4.5 \text{ MeV}$
- Indirect determination of $m_W$
- Complementary to 'direct' measurements
  → Consistency test of EW Standard Model
- Smallest uncertainties from a single experiment
The weak mixing angle

Weak mixing angle
• \( \sin^2 \theta_w \) in neutral-current vector couplings (only)

\[
g_V^f = \sqrt{\rho_{NC,f}} \left( I_{L,f}^3 - 2Q_f \kappa_f \sin^2 \theta_W \right)
\]

\( \sin^2 \theta_W + \text{PDF fit} \)
• Comparison to Z-pole data
• At future DIS facilities: Most precise single measurement possible
• Note: need theory to map \( \sin^2 \theta_W \) to effective leptonic weak mixing angle

\[\Delta \sin^2 \theta_w \ (\text{FCC-eh}) = \pm 0.00011\]
\[= \pm 0.00010_{\text{exp}} \pm 0.00004_{\text{PDF}}\]

\[\Delta \sin^2 \theta_w \ (\text{LHeC-50}) = \pm 0.00021\]
\[\Delta \sin^2 \theta_w \ (\text{LHeC-60}) = \pm 0.00015\]
\[\Delta \sin^2 \theta_w \ (\text{FCC-eh+LHeC}) = \pm 0.000086\]
STU parameters from inclusive DIS

S, T, U parameters are non-SM contributions to Z & W-boson self-energies

- Studied here: 2-parameter fits incl. PDF fit
- Scheme dependence: Modified on-shell (MOMS)
- With inclusive NC&CC DIS: Possible to disentangle S, T and U
  → Complementary to Z-pole
Scale dependent measurements

Running of $\sin^2 \theta_W^{\text{eff}}$
the effective weak mixing angle is
precisely measured at the Z-pole in $e^-e^-$
and $p^-p$

New low-Q measurements will reach
higher precision in the future

Scale dependence at high-Q is only poorly
tested experimentally

With high luminosity $e^-p$ experiments
Per mille uncertainties in range of
$20 < Q < 700$ GeV in spacelike regime

$\rightarrow$ Unique measurement of the 'running' at high scales
Electroweak physics

Electroweak physics of 1st gen. quarks $g_V$ and $g_A$ of 1st gen. quarks are largely inaccessible in other processes.

\[ g_V^f = \sqrt{\rho_{NC,f}} \left( I_{L,f}^3 - 2Q_f \kappa_{NC,f} \sin^2 \theta_W \right) \]
\[ g_A^f = \sqrt{\rho_{NC,f}} I_{L,f}^3 \]

→ PDFs are not a limiting factor for EW physics
→ Also the scale dependence ('running') can be tested with high precision
Weak couplings of the $W$-boson

EW theory provides precise predictions for charged currents, but CC processes are poorly measured → neutrino escapes undetected

In DIS, the kinematics of charged currents are completely measured from final state and incoming electron

→ Weak couplings of the $W$-boson are precisely measured – even their scale dependence
The impact of LHeC on HL-LHC

**W-mass measurements in pp**
- Major uncertainty from PDFs

**Effective weak mixing angle in pp**
- Large uncertainty from PDFs

- Reduction of PDF uncertainty only feasible with LHeC PDFs ($\Delta m_W^{PDF} \approx 2\text{MeV}$)
- HL-LHC–PDF reduces uncertainty by 10-25%
- LHeC–PDFs reduces PDF uncertainties by an additional factor of 5
Direct $W$ and $Z$ production

$e^p \rightarrow v_e + V + X$

$e^-p \rightarrow e^- + V + X$

Total cross sections:
- $e^p \rightarrow W^+X \sim O(14\text{pb})$
- $e^p \rightarrow W^-X \sim O(15\text{pb})$
- $e^p \rightarrow ZX \sim O(5\text{pb})$
Direct $W$ and $Z$ production

$W$ and $Z$-boson production through 5 production channels in electron-proton scattering

Important VBF channels:

Sizeable (fiducial) cross section with leptonic decay

<table>
<thead>
<tr>
<th>Process</th>
<th>$E_e = 50$ GeV, $E_p = 7$ TeV $p_T &gt; 10$ GeV</th>
<th>$E_e = 60$ GeV, $E_p = 7$ TeV $p_T &gt; 10$ GeV</th>
<th>$E_e = 60$ GeV, $E_p = 7$ TeV $p_T &gt; 5$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^- W^+ j$</td>
<td>1.00 pb</td>
<td>1.18 pb</td>
<td>1.60 pb</td>
</tr>
<tr>
<td>$e^- W^- j$</td>
<td>0.930 pb</td>
<td>1.11 pb</td>
<td>1.41 pb</td>
</tr>
<tr>
<td>$\nu^- W^- j$</td>
<td>0.796 pb</td>
<td>0.956 pb</td>
<td>0.956 pb</td>
</tr>
<tr>
<td>$\nu^- Z j$</td>
<td>0.412 pb</td>
<td>0.502 pb</td>
<td>0.502 pb</td>
</tr>
<tr>
<td>$e^- Z j$</td>
<td>0.177 pb</td>
<td>0.204 pb</td>
<td>0.242 pb</td>
</tr>
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</table>

With 1 ab$^{-1}$ of LHeC data

$O(0.5 – 1.5$ million events$)$

→ high sensitivity to $a_TGC$

→ Sensitivity to: $\Delta \kappa_\gamma$ and $\lambda_\gamma$
**LHeC as a very unique, generic high energy γγ collider**

Wide spectrum of γγ processes will be studied at the LHeC

- \(γγ \rightarrow γγ\) : orders of magnitude higher statistics than for PbPb at the HL-LHC + γγ tagging \(⇒\) kinematic fitting

- \(γγ \rightarrow τ^+τ^-\) : orders of magnitude higher statistics than for PbPb at the HL-LHC + γγ tagging \(⇒\) new decay modes

- \(γγ \rightarrow Z\) : search for the anomalous single Z boson exclusive production

- \(γγ \rightarrow ZZ\) : possibility of first ever detection + stringent limits on anomalous quartic gauge couplings (aQGCs) using semi-leptonic decay modes, \(ZZ \rightarrow l^+l^-jj\)

- \(γγ \rightarrow W^+W^-\) : measurements of semi-leptonic decay modes, \(W^+W^- \rightarrow lνjj\), will allow for a use of Optimal Observable methods (even with single γγ tagging) for probing aQGCs; yet high statistics (\(≈\) as at the HL-LHC) is expected for fully leptonic \(W^+W^-\) decays + tagging

K. Piotrzkowski, Y. Yamazaki, in preparation
Higgs physics

Charged current

Higgs production through $WW$-fusion

Neutral current

Higgs production through $ZZ$-fusion
Higgs physics

Higgs-production cross section $\sim$200fb

Sensitivity to the decay channels $bb$, $WW$, $gg$, $\tau\tau$, $cc$, $ZZ$, $(\gamma\gamma)$

$ep \rightarrow H + \nu + X \rightarrow bb + \nu + X$

Studies with full data-analyses of simulated data

Delphes (LHeC)

Full sim using ATLAS

→ simulations show great signal over background ratio
→ symmetric detector is possible
→ Prospects validated with 'real' detector
Higgs physics – interpretation in $\kappa$ framework

Signal strength in all decay channels

High sensitivity in all six decay channels
$\rightarrow$ Significant improvement with increasing $\sqrt{s}$

$HWW$ and $HZZ$ signal strengths measured at once in DIS via selection of the final state (e or $\nu$)

Interplay between $pp$ and $ep$
(Shown here: LHeC & HL-LHC)

Complementarity between $pp$ and $ep$
- $ep$: $bb$, $WW$, $ZZ$, $cc$
- $pp$: $gg$, $\tau\tau$, $\gamma\gamma$

$LHeC$ with superior precision for $H \rightarrow ff$ and $H \rightarrow VV$
Future competition: ee, pp and/or ep

LHeC+ HL-LHC

LHeC with high(est) constraints on

- $H \rightarrow ff$ (bb, Yukawa)
- $H \rightarrow VV$ (WW, EWSB)
- $H \rightarrow 2\text{nd gen.} \ (cc)$

LHeC

- Complementary with HL-LHC
- Data in '30s
- 1/10 of the cost than FCC or ILC
Summary

**LHeC & FCC-eh projects**
- **LHeC**: 60 GeV electron times 7TeV proton (√s=1.3TeV),
- **FCC-eh**: 60 GeV electron times 50TeV proton (√s=3.5TeV),

**Electroweak physics at LHeC & FCC-eh**
- Fundamental EW parameters: Competitive with (HL-)LHC/LEP
- Complementary measurements to Z-pole data
- Unique measurements of scale dependence of EW interactions
- EW physics at HL-LHC needs LHeC-PDFs
- O(millions) directly produced W and Z-bosons → aTGC
- Outstanding γγ collider prospects → aQGC
- Extraordinary Higgs program
  - High precision to H→VV through HWW vertex
  - High precision to H→ff through Hbb vertex
  → Feasibility studies with fast and full detector simulations
Backup
LHC-Point 2 in HL-LHC era

**ALICE3**
- HI physics
  - QGP, fluid expansion
  - Color-glass condensate
  - HQ transport, Thermalisation, Hadronisation

What may happen with a ~ 4-times better calibrated energy-scale from NC DIS in-situ calibration?

**LHeC**
- Higgs
- EWK
- PDFs (for HL-LHC)
- BSM
- Top
- small-x
- eA
- ALICE3 (pp, AA)
Deep-inelastic electron-proton scattering

C. Rubbia in 1992 CERN open council meeting when LHC was approved

- Further progress needs higher energy - 1 TeV is next major goal
- Proton-proton collisions are the only open road to 1 TeV now
- LHC - most cost effective route - heavy ion and ep collisions as bonus

LHC must be the next project for CERN

LHeC history

<table>
<thead>
<tr>
<th>Year</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1984</td>
<td>LEP × LHC</td>
</tr>
<tr>
<td>1992</td>
<td>HERA ep</td>
</tr>
<tr>
<td>2012</td>
<td>LHC × e⁻</td>
</tr>
<tr>
<td>2020</td>
<td>HL-LHC × ERL &amp; Higgs</td>
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</table>

Polarized e⁻ p cross section

- NC - CC LHeC
- NC - CC EIC
- NC - CC FCC-eh
- NC - CC HERA-H1 (P=0)

E. \( s \approx \sqrt{1.3 \text{ TeV}} \)  
L ~ 1 fb⁻¹/y

F. \( s \approx \sqrt{0.3 \text{ TeV}} \)  
L ~ 0.5 fb⁻¹

G. \( s \approx \sqrt{1.5 \text{ TeV}} \)  
L ~ O(100 fb⁻¹)

H. \( s \approx \sqrt{1.3 \text{ TeV}} \)  
L ~ 1 ab⁻¹

I. '30
$\delta m_W$ with LHeC input

- $m_W$ milestone measurements for consistency of SM and BSM searches
- Study of potential of $m_W$ measurement with low pile-up runs

\[
\begin{align*}
\delta m_W & = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}} \text{ MeV} \\
\end{align*}
\]

Large theory uncertainty originates from knowledge of PDFs
Similar size than experimental uncertainties

At HL-LHC, PDFs are expected to become the largest individual uncertainty
HL-LHC PDFs will reduce that, but will remain a limiting uncertainty
With LHeC PDFs, the W-mass measurements will be exceed LEP precision

![Graph showing LHCb measurement](image1)

![Graph showing ATLAS low-$\mu$ prospects](image2)

![Graph showing ATLAS low-$\mu$ HL-LHC prospects](image3)
The Energy Recovery Linac – ERL

Energy-recovery linacs (ERL) → Well-proven accelerator concept

→ high-current & high-energy & multi-pass
→ optimised cavities & cryo-modules and a beam for collider experiments

PERLE at Orsay: ERL demonstrator facility for FCC-eh/LHeC needs 20mA, 802 MHz SRF, 3 turns → operation 2025+
Concurrent \(eh\) & \(hh\) Operation

Two HL-LHC operation modes
- \(hh\) collisions at IP1,2,5,8 – no \(e\) beam
- \(eh\) collisions at IP2 \textbf{and} \(hh\) at IP1, 5, 8
  \(\rightarrow\) non-colliding \(p\)-beam: symmetric orbit bump & vert. crossing

Three beam interaction region
- LHC proton beam optics

Schematic view of the three beams at IP2

At IP2: same vertex for all interaction types (ep, eA, pp, AA) \(\rightarrow\) optional \(hh\) running with LHeC-detector.
Update of the LHeC CDR 2020

- Update of the CDR

- 373 pages about
  - Partonic structure of the proton
  - QCD studies, $\alpha_s$, low-$x$, diffraction
  - Electroweak and top-quark physics
  - Nuclear physics
  - Higgs in DIS
  - BSM
  - Impact on the HL-LHC
  - Accelerator (Energy recovery linac)
  - PERLE facility
  - LHeC Detector

Update of LHeC-CDR