High energy photon-photon interactions at the LHeC (and FCC-eh)

50 × 7000 GeV² → 1.2 TeV ep collider delivering very high luminosity concurrently with pp collisions at LHC

XXIX International Workshop on Deep-Inelastic Scattering and Related Subjects
Santiago de Compostela, 2–6 May 2022
Large Hadron \textit{electron} Collider

\textbf{ERL}, or the on-going revolution in high energy electron acceleration techniques

\begin{itemize}
  \item \textbf{Energy Recovery Linac} technology resulted in the major breakthrough for the LHeC:
  \item $> 20$ luminosity increase
\end{itemize}
**ERL**, or the on-going revolution in high energy electron acceleration techniques

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**Machine Parameters and Operation - ep**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>CDR</th>
<th>Run 5</th>
<th>Run 6</th>
<th>Dedicated</th>
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<tbody>
<tr>
<td>$E_e$</td>
<td>GeV</td>
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<td>30</td>
<td>50</td>
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<tr>
<td>$N_p$</td>
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<td>2.2</td>
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<tr>
<td>$\epsilon_p$</td>
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<td>2.5</td>
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<td>$I_e$</td>
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<td>10</td>
<td>7</td>
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<td>Luminosity</td>
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<td>5</td>
<td>9</td>
<td>23</td>
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</tbody>
</table>

*Energy Recovery Linac technology resulted in the major breakthrough for the LHeC:*

**> 20 luminosity increase**
LHeC is NOT a super-HERA “only”!

LHeC is not just a DIS super-collider – it is much more:

New very powerful lab for electroweak & Higgs physics

+ Sensitivity to new BSM signatures

+ High energy eA collider (very complementary to EIC)
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LHeC luminosity $\approx 1000 \times$ HERA
New aspect
**HL-LHC vs. LHeC as high energy $\gamma\gamma$ colliders**

Energy reach for $\gamma\gamma$ interactions is higher at the LHC, however tagging $\gamma\gamma$ events at the highest photon-photon CM energy ($W$) is not possible and the suppression due to re-scattering becomes large.

Event **pileup is very low at the LHeC** – it is only 5% at the highest $ep$ luminosity of $2.3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$.

This is not only allowing to **use calorimetry for the selection** of exclusive production and to **suppress** backgrounds, but will also significantly **increase** detection efficiencies, including $\gamma\gamma$ tagging!
High energy $\gamma\gamma$ colliders: Equivalent Photon Approximation

\[ \sigma_{ep} = \int dW S_{\gamma\gamma} \sigma_{\gamma\gamma} \]

\[ S_{\gamma\gamma} = \frac{2}{W} \int_{W^2/s}^{1} dy_e \Phi_e(y_e) y_p \Phi_p(y_p) \]

EPA: Budnev et al. (1975)

$S_{\gamma\gamma}$ is analogous to the partonic luminosity, and its integral \( \int_{W_0}^{\sqrt{s}} dW S_{\gamma\gamma} \) provides a fraction of the $pp$ luminosity "available" for $\gamma\gamma$ collisions above $W_0$

Note: There are elastic and inelastic (when the proton dissociates to $p^*$) contributions to $S_{\gamma\gamma}$
LHeC as a high energy $\gamma\gamma$ collider

Very high LHeC luminosity is the key here ⇒ more than 1 ab$^{-1}$ (= 1000 fb$^{-1}$) is expected for $ep$ collisions.

Incident electrons will have “only” 50 GeV, but higher equivalent photon flux, as approximately:

$$S_{\gamma\gamma} \propto \ln\left(\frac{Q_{\text{max},e}}{Q_{\text{min},e}}\right)\ln\left(\frac{Q_{\text{max},p}}{Q_{\text{min},p}}\right)$$

where $Q_{\text{min}} \propto m^2$, and $Q_{\text{max},e}$ can be very high

For $W < 50$ GeV the fully exclusive $\gamma\gamma$ luminosity spectrum is **higher** at the LHeC than at the HL-LHC!
**LHeC as a very unique, generic high energy $\gamma\gamma$ collider**

Wide spectrum of $\gamma\gamma$ processes will be studied at the LHeC:

- $\gamma\gamma \rightarrow \gamma\gamma$ : orders of magnitude higher statistics than for $PbPb$ at the HL-LHC + $\gamma\gamma$ tagging ⇒ kinematic fitting
- $\gamma\gamma \rightarrow \tau^+\tau^-$ : orders of magnitude higher statistics than for $PbPb$ at the HL-LHC + $\gamma\gamma$ tagging ⇒ new decay modes
- $\gamma\gamma \rightarrow Z$ : search for the anomalous single Z boson exclusive production
- $\gamma\gamma \rightarrow ZZ$ : possibility of first ever detection + stringent limits on anomalous quartic gauge couplings (aQGCs) using semi-leptonic decay modes, $ZZ \rightarrow l^+l^-jj$
- $\gamma\gamma \rightarrow W^+W^-$ : measurements of semi-leptonic decay modes, $W^+W^- \rightarrow l\nu jj$, will allow for a use of Optimal Observable methods (even with single $\gamma\gamma$ tagging) for probing aQGCs; yet high statistics (≈ as at the HL-LHC) is expected for fully leptonic $W^+W^-$ decays + tagging
LHeC: $\gamma\gamma \rightarrow \tau\tau$ and $\gamma\gamma \rightarrow W^+W^-$

Very large statistics:

$\Rightarrow$ 30 million elastic $\tau\tau$ pairs produced for $W > 10$ GeV at 1 ab$^{-1}$

$\approx 100,000$ for $W > 100$ GeV
LHeC: $\gamma\gamma \rightarrow \tau\tau$ and $\gamma\gamma \rightarrow W^+W^-$

Large statistics:
$\Rightarrow$ > 100 000 W boson pairs produced at 1 ab$^{-1}$
$\approx$ 20 000 for $W > 500$ GeV

Inelastic production dominant
FCC-eh case

$60 \times 50000 \text{ GeV}^2 \rightarrow 3.5 \text{ TeV } ep \text{ collider}$
delivering very high luminosity
concurrently with $pp$ collisions
LHeC vs. FCC-eh

$O_e^2 < 10000.0/10000.0\text{GeV}^2$

- Elastic
- Inelastic $M_N < 10.0\text{GeV}$
- Inelastic $M_N < 100.0\text{GeV}$
- Inelastic $M_N < 1000.0\text{GeV}$

$S_{YY}[1/\text{GeV}]$

$W [\text{GeV}]$

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$S_{YY}[1/\text{GeV}]$

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\( ep (\&eA) \) luminosity

As was shown at HERA, \( ep \) bremsstrahlung can be used to measure \( ep \) luminosity with high precision, at \( \lesssim 1\% \).

However, rates of high energy bremsstrahlung will be extremely high at the LHeC/FCC-\( eh \), well in excess of 1 GHz, and in addition strong Beam-Size Effect will take place – effective bremsstrahlung suppression at high energies due to small lateral beam-sizes of both colliding beams:

Event rate = Luminosity \( \times \) cross section

where colliding particles are represented by PLANE waves – but this assumption breaks down if the lateral beam sizes are comparable to relevant impact parameter of a process. Its understanding can be deeply tested by measuring the bremsstrahlung spectrum while displacing a hadron beam.

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See, for example:


https://iopscience.iop.org/article/10.1088/1748-0221/16/09/P09023
Summary and outlook

LHeC will complete the HL-LHC science in a very profound and relevant way, in the QCD and Electroweak sectors.

**LHeC offers practically ideal conditions for studying high energy $\gamma\gamma$ interactions**

Scientific potential of $\gamma\gamma$ physics at the LHeC, both in testing the electroweak theory and for searches of signals of New Physics, will be further explored.

*STAY TUNED!*
Backup slides
HL-LHC (and FCC-hh) as a high energy $\gamma\gamma$ collider: **challenges & limitations**

HL-LHC will provide 10 times bigger integrated luminosity, but:

- $S_{\gamma\gamma}$ only marginally higher (thanks to $13 \rightarrow 14$ TeV increase)
- PU yet 4 times higher ($\approx 140$) than for Run 2 – but new tracking with ps resolution timing should cope well with it
- Very high event pileup will make tagging with forward protons even more tricky – **ps resolution timing detectors** will help – however, the problem of overall efficiency loss still persists

**re-scattering aka survival probability**

Major limitations for the high luminosity $pp$ case of a $\gamma\gamma$ collider:

- **Only** tracks can be used for the selection of (quasi-)exclusive production
- **Only** exclusive charged dilepton states could be successfully measured so far (after 10-year efforts)
- And, the **re-scattering suppression** is large and uncertain, especially at very large $W$
**ep Luminosity**

Using *Van der Meer scans*:

- Longitudinal view
- Transverse view

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See poster #40 by K.P. and M. Przybycień

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**LHeC layout’12**

![Diagram showing ep interactions with longitudinal and transverse views](image)

Using *Van der Meer scans*:

- Longitudinal view
- Transverse view

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**EIC 1**
- $E_e = 10$ GeV
- $E_p = 275$ GeV
- $\sigma_x = 93 \mu$m
- $\sigma_y = 7.8 \mu$m

**EIC 2**
- $E_e = 18$ GeV
- $E_p = 275$ GeV
- $\sigma_x = 50 \mu$m
- $\sigma_y = 5 \mu$m

**HERA**
- $E_e = 30$ GeV
- $E_p = 820$ GeV
- $\sigma_x = 290 \mu$m
- $\sigma_y = 65 \mu$m
- $\sigma_y^2 = 77 \mu$m

**LHeC**
- $E_e = 50$ GeV
- $E_p = 7000$ GeV
- $\sigma_x = 5 \mu$m
- $\sigma_y = 5 \mu$m