# High energy $\gamma\gamma$ interactions at the LHeC

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# Large Hadron-electron Collider

- LHeC is to operate at center-of-mass energy of 1.2 TeV and is expected to deliver integrated electron-proton luminosity of about 1 ab$^{-1}$
- It offers clean experimental environment $\Rightarrow$ negligible event pileup + possibility of data streaming ("no triggers"!)

| Parameter | Unit | LHeC | | | | FCC-eh | |
|---|---|---|---|---|---|---|---|
| | | CDR | Run 5 | Run 6 | Dedicated | $E_p$=20 TeV | $E_p$=50 TeV |
| $E_e$ | GeV | 60 | 30 | 50 | 50 | 60 | 60 |
| $N_p$ | $10^{11}$ | 1.7 | 2.2 | 2.2 | 2.2 | 1 | 1 |
| $\epsilon_p$ | $\mu$m | 3.7 | 2.5 | 2.5 | 2.5 | 2.2 | 2.2 |
| $I_e$ | mA | 6.4 | 15 | 20 | 50 | 20 | 20 |
| $N_e$ | $10^9$ | 1 | 2.3 | 3.1 | 7.8 | 3.1 | 3.1 |
| $\beta^*$ | cm | 10 | 10 | 7 | 7 | 12 | 15 |
| Luminosity | $10^{33}$ cm$^{-2}$s$^{-1}$ | 1 | 5 | 9 | 23 | 8 | 15 |

Figure: Principal parameters for LHeC [J. Phys. G 48 (2021) 11, 110501] as well as for FCC-eh.

- Providing high energy *electron-hadron* collisions is also part of ongoing studies of Future Circular Collider (FCC) running in FCC-eh mode with center-of-mass energies yet significantly higher than at LHeC [Eur. Phys. J. C 79 (2019) 474].

# Detector for electron-hadron AND hadron-hadron collisions

- Design of special interaction region allowing for both electron-hadron and hadron-hadron collions at HL-LHC was proposed, together with corresponding "general-purpose" detector [Eur. Phys. J. C 82 (2022) 1, 40]:

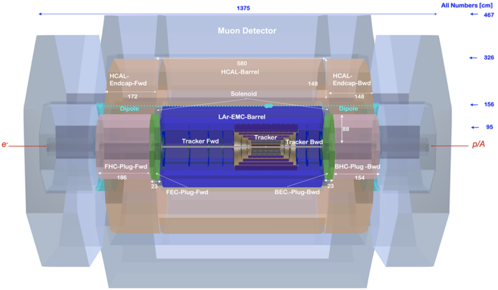



Figure: Side view of updated baseline LHeC detector concept, providing overview of main detector components and their locations.

| LHeC Tracker Part | $\eta_{max}$ | $\eta_{min}$ | $\#\text{Layers}_{\text{Barrel}}$ |
|---|---|---|---|
| Inner Barrel | | | |
| pix | 3.3 | − 3.3 | 2 |
| $\text{pix}_{\text{macro}}$ | 2. | − 2. | 4 |
| strip | 1.3 | − 1.3 | 4 |
| | | | $\#\text{Rings}_{\text{Wheels}}$ |
| End Caps | | | |
| pix | 4.1/− 1.1 | 1.1/− 4.1 | 2 |
| $\text{pix}_{macro}$ | 2.3/− 1.4 | 1.4/− 2.3 | 1 |
| strip | 2./− 0.7 | 0.7/− 2. | 1–4 |
| pix | 5.2 | 2.6 | 2 |
| Fwd Tracker | | | |
| $\text{pix}_{\text{macro}}$ | 3.4 | 2.2 | 1 |
| strip | 3.1 | 1.4 | 4 |
| pix | − 2.6 | − 4.6 | 2 |
| Bwd Tracker | | | |
| $\text{pix}_{\text{macro}}$ | − 2.2 | − 2.9 | 1 |
| strip | − 1.4 | − 2.5 | 4 |
| Total $\eta_{\text{max/min}}$ | 5.2 | − 4.6 | |

Figure: Tracker parts in revised LHeC detector configuration.

- **Note very large tracking coverage in pseudo-rapidity!**

For more details see dedicated contributions at this conference – **#1038** *The LHeC: Basic Concepts and Layout of the Machine*, and **#1319** *A detector for future DIS at the energy frontier.*

# Unique Physics at the LHeC

- LHeC offers extremely rich scientific program of its own as well as provides means to significantly improve scientific outcome at LHC!
- Just two highlights here:

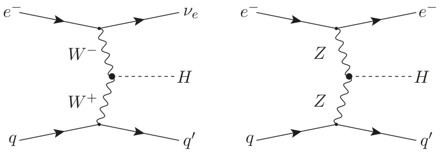



Figure: Higgs boson production at LHeC via *WW* and *ZZ* fusion – its large cross-section allows to study also "difficult" Higgs decay channels.

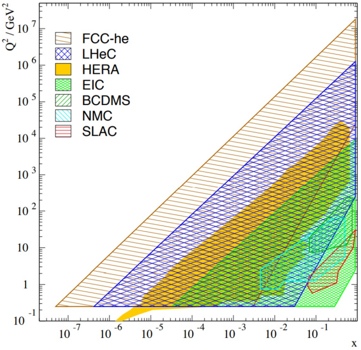



Figure: DIS kinematic plane for *ep* experiments.

- For more details see dedicated contributions at this conference – **#1314** *The general-purpose LHeC and FCC-eh high-energy precision programme: Top and EW measurements*, **#1312** *The LHeC and FCC-eh experimental program*, **#1309** *Proton and nuclear structure from EIC and HERA to LHeC and FCC-eh*, and **#1316** *Higgs precision physics in electron–proton scattering at CERN.*

# Science@LHeC – Quick Summary

- LHeC represents much more than ”just” a DIS super-collider $\rightarrow$ it also provides a cutting-edge laboratory for exploring electroweak and Higgs physics, and for making unique searches of Beyond Standard Model (BSM) physics.
- LHeC opens research fields in DIS at new energy and intensity frontiers $\rightarrow$ it extends kinematic range in electron-hadron scattering by orders of magnitude.
- LHeC serves also as high-energy electron-ion (*eA*) collider – nuclear effects can be optimally investigated using updated detector concept allowing $\rightarrow$ studies of *eA* and *AA* interactions using same setup.
- Note: Thanks to clean experimental conditions, triggering/selection/reconstruction of many specific/exclusive final states is feasible.
- Reminder: LHeC luminosity exceeds that of HERA by a factor of approximately 1000!

# High energy $\gamma\gamma$ interactions at the LHeC

- Studies of high energy photon-photon interactions can be performed at LHeC for $\gamma\gamma$ center-of-mass energy of up to almost 1 TeV (and well beyond that at FCC-eh !).
- Wide spectrum of $\gamma\gamma$ processes can be studied, including for example exclusive production of lepton pairs, Higgs bosons, W and Z boson pairs as well as pairs of charged supersymmetric particles.
- High event statistics is (often) expected.

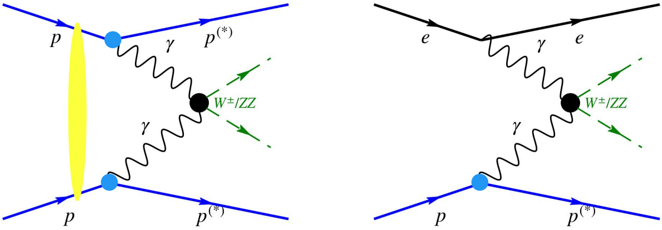



Figure: Exclusive W and Z boson pair production via photon-photon fusion at LHC (left) and LHeC (right). Additional exchange between protons (yellow band) represents hadronic re-scattering, absent in $ep$ collisions.

# *Equivalent Photon Approximation* (EPA)

- In EPA [Phys. Rept. 15 (1975) 181-281], cross-sections for two-photon production in electron-proton collisions are calculated by convoluting electron and proton equivalent photon fluxes, $\Phi_e$ and $\Phi_p$, respectively, with photon-photon cross-section $\sigma_{\gamma\gamma}$:

$$\sigma_{ep} = \int \mathrm{d}y_e \mathrm{d}y_p \Phi_e(y_e)\Phi_p(y_p)\sigma_{\gamma\gamma}(W)$$

$$= \int \mathrm{d}W S_{\gamma\gamma}\sigma_{\gamma\gamma}(W)\,,$$

where respective photon fractional energies $y_e = E_{\gamma(e)}/E_e$, $y_p = E_{\gamma(p)}/E_p$, and $\gamma\gamma$ luminosity spectrum $S_{\gamma\gamma}$ is equal to flux convolution at photon-photon center-of-mass energy $W = \sqrt{y_e y_p s}$,

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

where $\sqrt{s} = 1.2$ TeV at LHeC.

$\rightarrow$ notion of $S_{\gamma\gamma}$ is analog to partonic luminosities for hadron-hadron collisions.

# Photon fluxes for electrons and protons, $\Phi_e$ and $\Phi_p$

- It is assumed above that $\sigma_{\gamma\gamma}$ is not sensitive to photon virtualities, so fluxes could be integrated over photon $Q^2$:

$$\Phi_\gamma(y) = \frac{\alpha}{\pi y} \int \frac{\mathrm{d}Q^2}{Q^2} \left[ (1-y) \left(1 - \frac{Q^2_{\min}}{Q^2}\right) F_E(Q^2) + \frac{y^2}{2} F_M(Q^2) \right],$$

  where $\alpha$ is the fine-structure constant and $F_E$, $F_M$ are the electric and magnetic form factors, respectively.

- *Elastic* scattering: For electrons $F_E = F_M = 1$, and for protons, within dipole approximation, $F_M = G_M^2$ and $F_E = (4M_p^2 G_E^2 + Q^2 G_M^2)/(4M_p^2 + Q^2)$.

- *Inelastic* scattering: Proton dissociates into states of invariant mass $M_N > M_p$, $F_E = \int dx F_2/x$ and $F_M = \int dx F_2/x^3$, where $F_2(x, Q^2)$ is proton structure function and $M_N^2 - M_p^2 = Q^2(1/x - 1)$.

- `ALLM` $F_2$ parametrization is used, which provides good description of DIS data for kinematical region of $10^{-6} < x < 0.85$ and $0 \leq Q^2 < 5000$ GeV$^2$ [arXiv:hep-ph/9712415] – `ALLM` is based on fits to experimental data on total $\gamma^{(*)}p$ cross-sections.

# Luminosity spectrum $S_{\gamma\gamma}$ & its integral $\int dW\, S_{\gamma\gamma}$

- Integral of $S_{\gamma\gamma}$ represents fraction of $ep$ luminosity "available" for $\gamma\gamma$ collisions above some minimal $W_0$ (assuming constant $\sigma_{\gamma\gamma}$)
- $s$ smaller at LHeC than at LHC is compensated by electron photon flux much larger than proton one $\rightarrow$ *elastic* $S_{\gamma\gamma}(\mathrm{LHeC}) > S_{\gamma\gamma}(\mathrm{LHC})$ for $W \lesssim 100$ GeV !

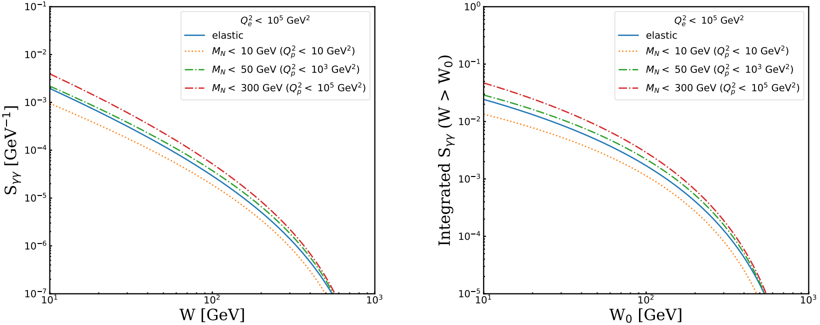


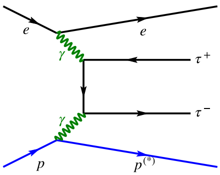

Figure: (Left) Elastic and inelastic luminosity spectra at the LHeC; (Right) integrated luminosity spectra, $\int dW\, S_{\gamma\gamma}$, as a function of minimal $\gamma\gamma$ center-of-mass energy $W_0$.

# Exclusive two-photon production of pairs of charged particles

- At high energies, *W*-dependence of cross-sections for pair production via $\gamma\gamma$ fusion depends strongly on produced particles' spin: for vector particles (as $W^+W^-$) $\sigma_{\gamma\gamma}$ is constant, for fermions is falling as $W^{-1}$ and for scalars as $W^{-2}$

  $\rightarrow$ about 100 000 *W* boson pairs will produced at LHeC via $\gamma\gamma$ fusion, offering very powerful test-bench for anomalous quartic gauge couplings $\gamma\gamma WW$

  $\rightarrow$ whereas $> 10^8$ $\tau$ pairs offer unique sensitivities to $\tau$ anomalous electric and magnetic moments



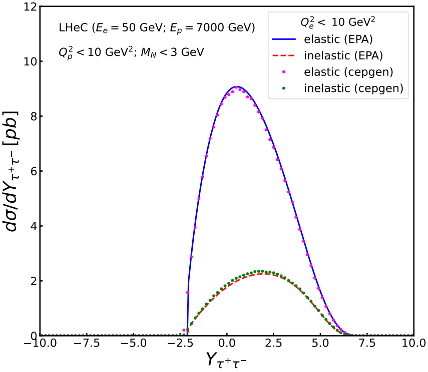
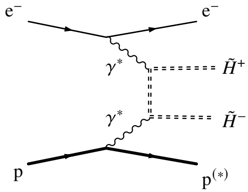




Figure: Production of $\tau$ pairs (via $\gamma\gamma \rightarrow \tau^+\tau^-$) at the LHeC – pairs' rapidity distributions.

# Two-photon exclusive production of supersymmetric pairs

- Exclusive production of pairs of charged supersymmetric particles, via photon-photon fusion, offers exciting potential at LHeC:



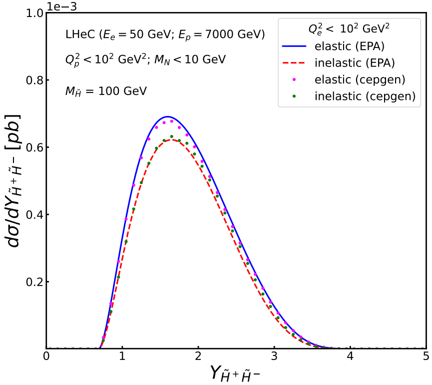




Figure: Production at the LHeC of higgsiono pairs via $\gamma\gamma$ fusion – pairs' rapidity distributions.

- Note: very good agreement Lpair vs. Grape ME generators too, with ISR corrections only at $\approx 5\%$

- LHeC offers unique conditions for studying high energy photon-photon interactions:

  $\rightarrow$ very low event pileup and data streaming allow to measure two-photon exclusive production with high efficiency;

  $\rightarrow$ high efficiency and large photon-photon luminosities make LHeC ideal laboratory for $\gamma\gamma$ physics;

  $\rightarrow$ LHeC provides excellent prospects for studying exclusive two-photon production of lepton pairs, pairs of W and Z bosons, and for searches of charged supersymmetric/BSM particles.

- High energy $\gamma\gamma$ physics at LHeC will significantly enhance its scientific potential.


Thank you

# Event generators used for high energy photon-photon interactions@LHeC

- Lpair [S. P. Baranov, O. Duenger, H. Shooshtari and J. A. M. Vermaseren, Proceedings, Workshop on Physics at HERA, vol. 3, p. 1478, 1991.].
  - Generator for lepton pair production in lepton-lepton, lepton-hadron and hadron-hadron collisions via two-photon Bethe–Heitler process.
- GRAPE [T. Abe, Comput. Phys. Commun. 136 (2001) 126-147, [arXiv:hep-ph/0012029 [hep-ph]]].
  - ME generator for dilepton production in $ep$ collisions according to EWK matrix elements at tree level (including $\gamma$ and $Z$ exchanges), simulates also ISR/FSR.
- CepGen [L. Forthomme, Comput. Phys. Commun. 271 (2022) 108225, arXiv:1807.06059 [hep-ph]].
  - Generator of generic central exclusive events for photon-photon physics at the LHC.
  - Integration with Lpair/GRAPE for the electron-proton collision is in progress.
  - CepGen repository can be found in: https://github.com/cepgen/cepgen.