Two-photon interactions at the LHeC

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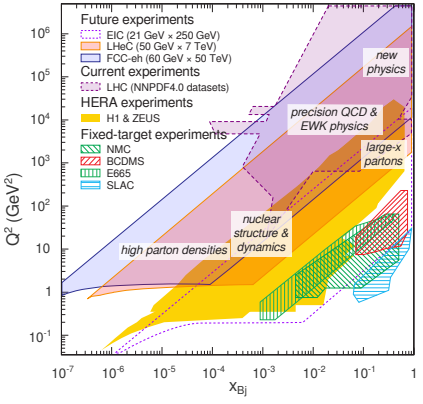
Introduction – Future e-h colliders?

Multiple tracks for **(polarised/unpolarised) electron-hadron machines** in the 21st Century, incl. some presented at this workshop:

- **EIC** @ BNL [1, 2, 3, 4, 5, …]
  10 − 18 GeV (e^-) $\oplus$ $\mathcal{O}$(100 GeV) (A) ($\sqrt{s} \sim 20 - 140$ GeV) $\Rightarrow$ 2030s
- **LHeC** + **FCC-eh** @ CERN [6, 7, 8, 9]
  50 GeV (e^-) $\oplus$ 7 TeV (p) for LHeC ($\sqrt{s} \sim 1.3$ TeV) $\Rightarrow$ 2040-2050s
  20 GeV (e^-) — @ phase-1 LHeC ($\sqrt{s} \sim 0.75$ TeV) arXiv:2503.20475
  60 GeV (e^-) $\oplus$ 100 TeV (p) for FCC-eh ($\sqrt{s} \sim 3.5$ TeV)
- **LHμC** @ CERN [10, 11, 12]
- **CEPC-SehC**



In particular, LHeC is expected to deliver an integrated e-p luminosity of ~ 1 ab^{-1} over its lifespan

LHeC physics case

Rich playground for high precision **electroweak & QCD** studies at the TeV scale

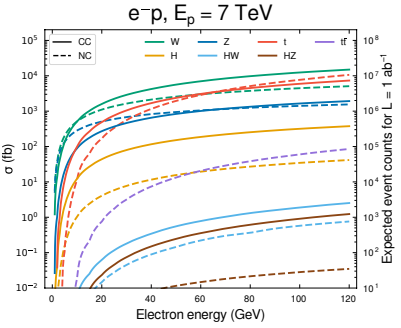
- best limits on m_W, m_Z, aTGCs
- studies of top quark properties (coupling, mass, ...) through DIS/FCNCs/diffractive production processes
- DIS CC/NC Higgs production to study its characteristics
- extensive DIS/QCD programme at broad x_{Bj}, or high-Q^2 values

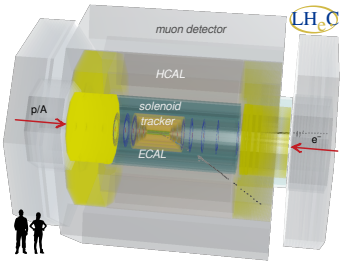
Much more than a super-HERA collider

- $\mathcal{L}_{\mathrm{LHeC}} > 10^3 \mathcal{L}_{\mathrm{HERA}}$
- high discovery potential for new physics
- can also operate in electron-ion mode

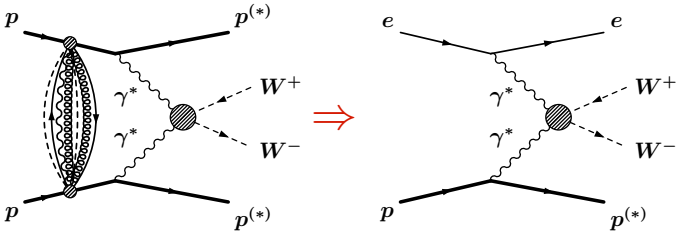
More details about main LHeC prospects: see N. Armesto's [7, 8], C. Gwenlan's [9], and K. Wichmann's [10] talks

⊕ NEW **"LHeC as a bridge"** white paper arXiv:2503.17727 [hep-ex]





$\gamma\gamma$ physics: proton-proton vs. lepton-proton



Given the **good sensitivity** shown by $\gamma\gamma$ **searches at LHC**, transposition to the e-h / LHeC case simplifies the problem:

- very low event pileup, ensuring an even **cleaner final state** in e-p than p-p
- barely any hadronic re-scattering activities spoiling the rapidity gap between the central system & forward scattered beam particles
- beam-beam interaction largely reduced: mostly soft-scale corrections through ISR

Theoretical framework – EPA

Common framework introduced to factor the **central, two-photon process matrix element** out of the **total e-p cross section**:

- both operational (with limitations) in electron-hadron, or hadron-hadron
- basic formalism:

$$\sigma(ep \to e(\gamma\gamma \to X)p^{(*)}) = \int \mathrm{d}y_e \Phi_e(y_e) \int \mathrm{d}y_p \Phi_{p^{(*)}}(y_p)\, \sigma_{\gamma\gamma\to X}(W \equiv \sqrt{s y_e y_p}) = \int \mathrm{d}W\, S_{\gamma\gamma}(W)\sigma(W),$$

with $\gamma\gamma$ **luminosity spectrum** $S_{\gamma\gamma}$ as convolution of photon-from-electron & photon-from-proton fluxes:

$$S_{\gamma\gamma}(W) = \frac{2}{W}\int_{W^2/s}^{1} \mathrm{d}y_e\; \Phi_e(y_e) y_p \Phi_p(y_p) = \frac{2W}{s}\int_{W^2/s}^{1} \mathrm{d}y_e \frac{\Phi_e(y_e)}{y_e}\; \Phi_p\left(\frac{W^2}{y_e s}\right),$$

- form factors-dependent photon fluxes:

$$\Phi(y) = \frac{\alpha_{\mathrm{em}}}{\pi}\frac{1}{y}\int \frac{\mathrm{d}Q^2}{Q^2}\left\{(1-y)\left(1-\frac{Q^2_{\mathrm{min}}}{Q^2}\right)F_E(Q^2) + \frac{y^2}{2}F_M(Q^2)\right\}$$

EPA – photon fluxes

- **Photon-from-electron** $\rightarrow$ trivial form factors: $F_M = F_E = 1$
- **Photon-from-proton**: elastic / dissociative (w/ proton fragmentation)
  - Elastic scattering: Sachs form factors-dependent:

$$F_E(Q^2) = \frac{4m_p^2 G_E{}^2 + Q^2 G_M{}^2}{4m_p^2 + Q^2}, \quad \text{and} \quad F_M(Q^2) = G_M{}^2$$

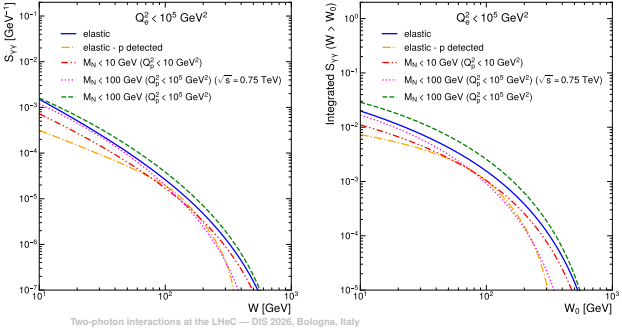
  - Inelastic scattering: nucleon structure functions-dependent ; at first order, only F_2-dependent:

$$F_E(Q^2) = \int \frac{\mathrm{d}x}{x} F_2(x, Q^2), \quad \text{and} \quad F_M(Q^2) = \int \frac{\mathrm{d}x}{x^3} F_2(x, Q^2)$$

E.g., for the **LHeC energy range**:

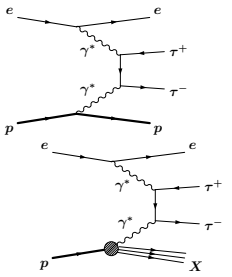
- ALLM F_2 parameterisation
  $(10^{-6} < x_{\mathrm{Bj}} < 0.85, Q^2 < 5000\ \mathrm{GeV}^2)$
  for inelastic scattering

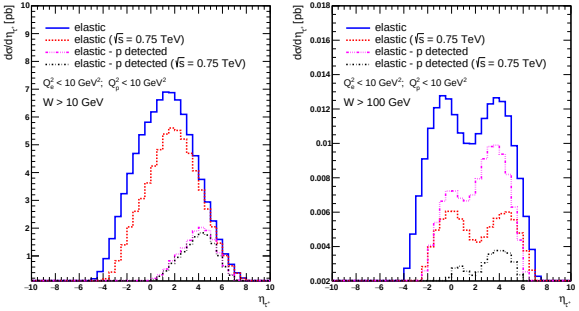
$\Rightarrow$ central system kinematics reach limited by $S_{\gamma\gamma}$ **behaviour at high-mass**



A couple of selected $\gamma\gamma$ physics cases

Physics case 1: $\gamma\gamma \to \tau^+\tau^-$

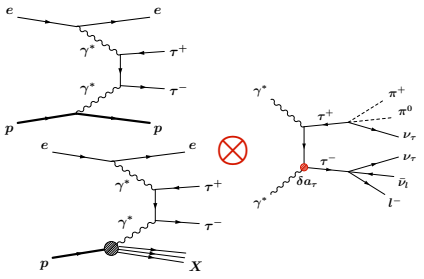


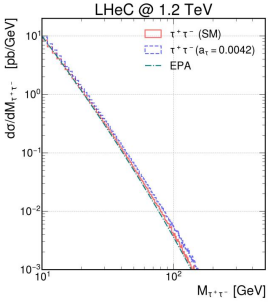


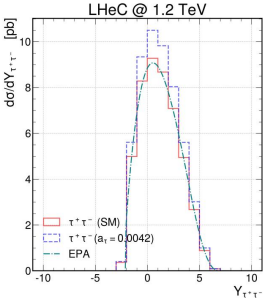
LHeC (1 ab^{-1}): $\mathcal{O}(10^8)$ $\gamma\gamma \to \tau^+\tau^-$ events produced at $W > 10$ GeV, ~2×10^6 at $W > 50$ GeV

- ISR corrections: $\mathcal{O}(5\%)$
- main background from other lepton flavours in $\gamma\gamma \to \ell^+\ell^-$ (sensitivity enhanced for **semi-leptonic decay modes**), $\gamma\gamma \to W^+W^-$, $\gamma\gamma \to q\bar{q}$, NC DIS, photoproduction processes ...

Physics case 1: $\gamma\gamma \to \tau^+\tau^-$







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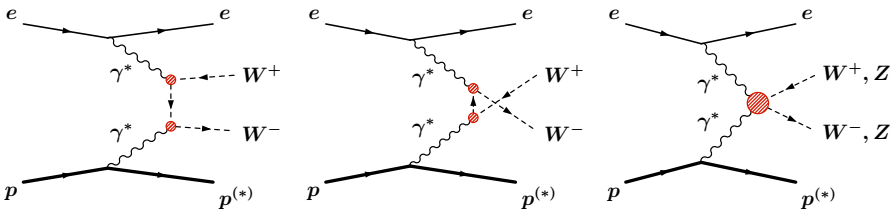
- precision probe of the τ/γ coupling, sensitive to anomalous **SMEFT deviations** of electromagnetic moment $\delta(a_\tau \equiv (g_\tau - 2)/2)$ [Rep. Prog. Phys. 87 (2024) 107801, arXiv:2503.19836 [hep-ex]]

Physics case 2: $\gamma\gamma \to W^+W^-/ZZ$



In the **high energy limit**, $\sigma_{\gamma\gamma}(W) \propto \begin{cases} c & \text{for vector particles} \\ 1/W & \text{for fermions} \\ 1/W^2 & \text{for scalar particles} \end{cases} \Rightarrow$ powerful test bench for the probing of anomalous triple/quartic gauge couplings

Physics case 2: $\gamma\gamma \to W^+W^-/ZZ$ (cont.)

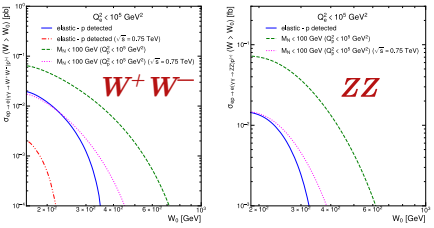
$\gamma\gamma \to W^+W^-$ already broadly studied in LHC phase space e.g. [CMS: JHEP 07 (2023) 229, ATLAS: Phys.Lett.B 816 (2021) 136190]

LHeC cleanliness allowing **precision probe** of γVV **&** $\gamma\gamma VV$ **couplings**

- **EFT models** predicting anomalous production processes (yield + differential kinematics distributions)
- in SM, $\gamma\gamma \to ZZ$ not allowed at tree level: ≥ 1 loop involved & $\sigma^{\mathrm{SM}}_{\gamma\gamma\to ZZ} \ll$

In terms of production cross section, LHeC **roughly a factor 3** lower than HL-LHC, but with much more cleaner final state

- unleashes semi-leptonic and fully hadronic decays as in CEP $\tau^+\tau^-$ search, **without requirement of forward beam remnants detection**
- main sources of background: **inclusive top quark** production (single-top, $t\bar{t}$), **associated** $V + j$ **and** $VV + j$ production, exclusive SM $\gamma\gamma \to W^+W^-/\tau^+\tau^-/t\bar{t}, \ldots$
- new selections can profit from specific topology of asymmetric e-p collisions



	$\sigma^{ep}_{\mathrm{el}}$ (fb)	$\sigma^{pp}_{\mathrm{el}}$ (fb)
$\gamma\gamma \to W^+W^-$	33.4	101.6
$\gamma\gamma \to ZZ$	0.033	0.145

Cross-sections for elastic $\gamma\gamma \to VV$ production at HL-LHC ($\sqrt{s}$ = 14 TeV), and LHeC (E_e = 50 GeV, $\sqrt{s}$ = 1.3 TeV)

Summary and outlook

Broad physics case for $\gamma\gamma$ **physics at electron-hadron colliders**

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

- very low event pileup and data streaming allow to measure two-photon exclusive production with high efficiency ;
  - addition of forward proton/shower detectors for exclusivity selection is a plus
- large photon-photon luminosities makes it an **ideal laboratory for $\gamma\gamma$ physics** ;
- excellent prospects for the study of exclusive two-photon production of lepton pairs, pairs of W and Z bosons, and for other searches (e.g. charged supersymmetric/BSM particles).

High energy $\gamma\gamma$ physics will also significantly **enhance LHeC scientific potential**

- with accelerated (bridge) LHeC, will complement HL-LHC scientific endeavours, particularly in QCD & electroweak sectors
- staged, E_e = 20 GeV also very competitive for $\gamma\gamma$ searches, given limited (high-η)

Thanks for your attention!

Spares

Abstract

An overview of the prospects for unique studies of photon-photon interactions at LHeC will be presented.

Profiting from the clean experimental environment and high luminosity at the LHeC, it will be possible to conduct stringent tests of electroweak interactions as well as meaningful searches for possible deviations from Standard Model.

In particular, the cases of two-photon production of pairs of W and Z boson, tau leptons and supersymmetric particles will be discussed.

Other approaches for $\gamma\gamma \to X$ predictions

According to the process, other techniques can be implemented for a more precise prediction of $\gamma\gamma$ processes

E.g. "HERA" Monte Carlo generators for $\gamma^{(*)}\gamma \to \ell^+\ell^-$:

LPAIR[1]

- **pros**: **full matrix element** computation, suitable for e-p as for p-p (using electromagnetic form factors/DIS structure functions)
- **cons**: only **Bethe-Heitler** production implemented, no ISR/EW corrections, Suri & Yennie as only continuum SF

$\Rightarrow$ now implemented in CepGen[2]

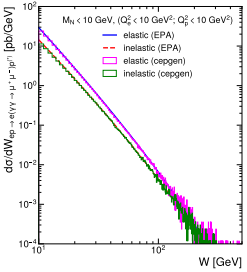
GRAPE[3]

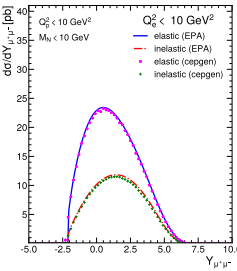
- **pros**: same approach as LPAIR (full matrix element computation), with all helicity amplitudes ; also includes **ISR/EW corrections** (incl. Z exchanges) ; accounts for **beam polarisation**
- **cons**: severely outdated stack, very slow and numerically unstable for corner cases of the phase space

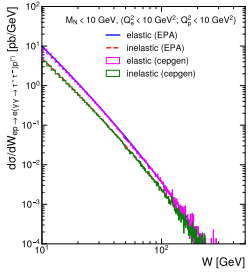
$\Rightarrow$ implementation in CepGen under validation

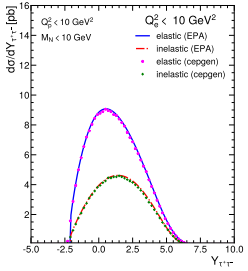
[1] Nucl.Phys.B 229 (1983) 347
[2] Comput.Phys.Commun. 271 (2022) 108225, arXiv:1808.06059 [hep-ph]
[3] Comput.Phys.Commun. 136 (2001) 126, arXiv:hep-ph/0012029

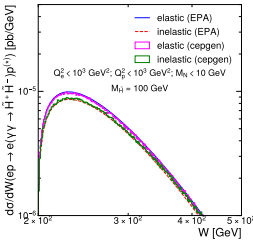
Validation: EPA vs. LPAIR

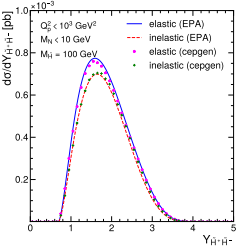












- at first order, EPA reproduces all ME-level observables
- low-mass objects (e.g. muons/electrons) → higher sensitivity to photon virtuality
- **correction needed** for this case to handle high-Q^2 part of the spectrum