High-energy two-photon interactions at future ep colliders

EPS-HEP 2025, Marseille, France

L. Forthomme, H. Khanpour, K. Piotrzkowski (AGH University of Kraków), Y. Yamazaki (Kobe University)

7-11 Jul 2025

Introduction – Future e-h colliders?

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

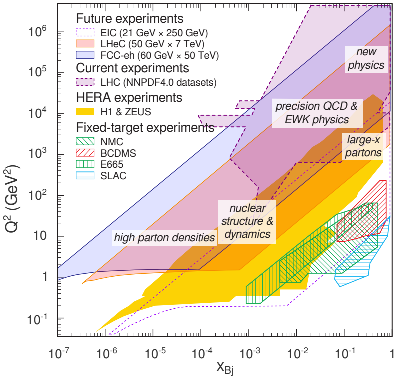
- **EIC** @ BNL [1]

  10 — 18 GeV (e^-) $\oplus$ $\mathcal{O}$(100 GeV) (A) ($\sqrt{s} \sim 20 - 140$ GeV) $\Rightarrow$ 2030s

- **LHeC** + **FCC-eh** @ CERN [2, 3, 4, 5, 6, 7, 8]

  50 GeV (e^-) $\oplus$ 7 TeV (p) for LHeC ($\sqrt{s} \sim 1.3$ TeV) $\Rightarrow$ 2040-2050s
  20 GeV (e^-) $\oplus$ 7 TeV (p) phase-1 LHeC ($\sqrt{s} \sim 0.75$ TeV) arXiv:2503.20475
  60 GeV (e^-) $\oplus$ 100 TeV (p) FCC-eh ($\sqrt{s} \sim 3.5$ TeV)

- **CEPC-SehC**



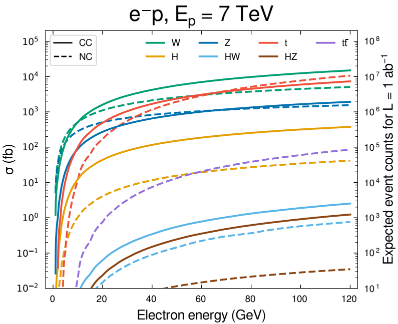
LHeC, in particular, would deliver an **integrated e-p luminosity** of ~ 1 ab^{-1} over its ~ decade long lifespan

LHeC physics case

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

(see LHeC's poster, Nestor's talks [1, 2], Christian's [1, 2] talks @ this conference)

- 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

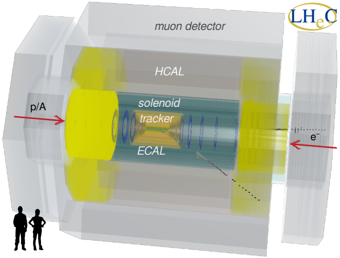


Much more than a super-HERA collider

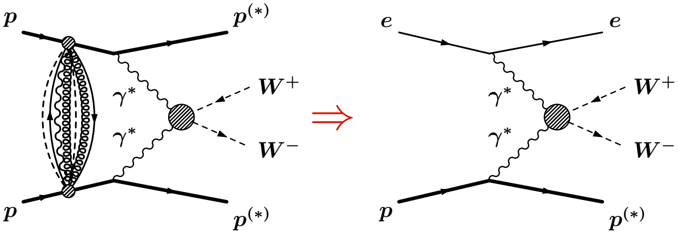
- $\mathcal{L}_{\text{LHeC}} > 10^3 \mathcal{L}_{\text{HERA}}$
- high discovery potential for new physics
- can also operate in electron-ion mode

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

(see Jorgen's talk @ Accelerators for HEP session on Wednesday)



$\gamma\gamma$ physics at e-p colliders



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

- very low event pileup, ensuring a very **clean final state**
- 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 corrections from ISR

Theoretical tools

Theoretical framework – EPA

Factorisation of the **central, two-photon process matrix element** from the **total e-p cross section**:

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

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

where the $\gamma\gamma$ **luminosity spectrum** $S_{\gamma\gamma}$ is the convolution of both photon-from-electron, and photon-from-proton fluxes:

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

with 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**: 2 types of γ emission: elastic / dissociative (w/ proton fragmentation)
  - Elastic scattering: Sachs form factors-dependent:

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

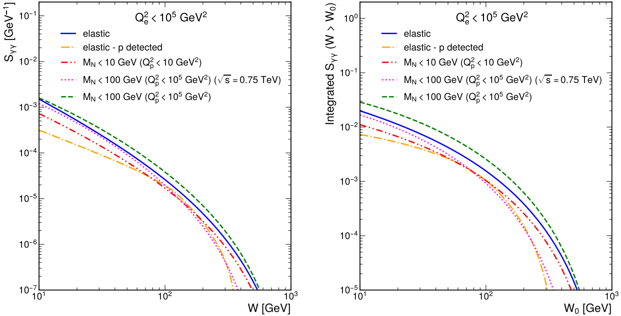
  - Inelastic scattering: nucleon structure functions-dependent ; at first order, only F_2-dependent:

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

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

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

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



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

According to the process, other techniques can be implemented (e.g. in CepGen[1]) for a more precise prediction of $\gamma\gamma$ processes

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

LPAIR[2]

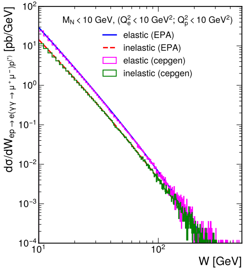
- **pros**: **full matrix element** computation, suitable for e-p as for p-p (using electromagnetic form factors/DIS structure functions)
- **cons**: only **Bethe-Heitler** production implemented, no ISR/EW corrections, Suri & Yennie as only continuum SF

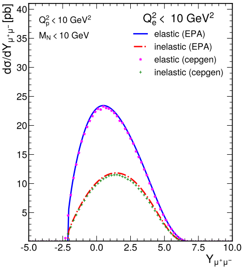
GRAPE[3] (implementation in CepGen under validation)

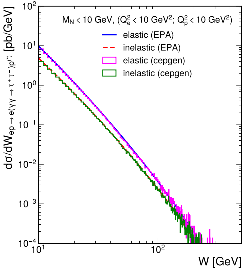
- **pros**: same approach as LPAIR (full matrix element computation), with all helicity amplitudes ; also includes **ISR/EW corrections** (incl. Z exchanges) ; accounts for **beam polarisation**
- **cons**: severely outdated stack, very slow and numerically unstable for corner cases of the phase space

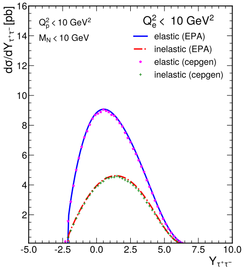
[1] Comput.Phys.Commun. 271 (2022) 108225, arXiv:1808.06059 [hep-ph]
[2] Nucl.Phys.B 229 (1983) 347
[3] Comput.Phys.Commun. 136 (2001) 126, arXiv:hep-ph/0012029

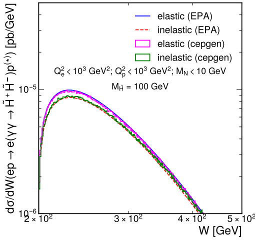
Validation: EPA vs. LPAIR

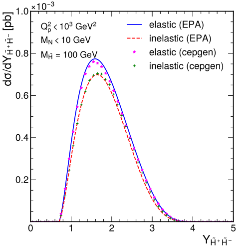












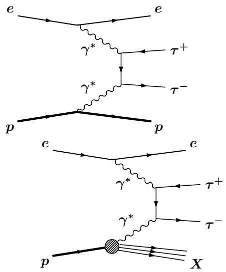
At first order, **excellent performance of EPA** for all cases handled by LPAIR

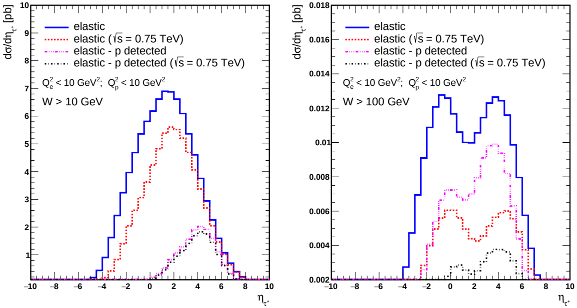
However, for low-mass objects (e.g. muons/electrons), photon virtuality play a larger role

$\Rightarrow$ **correction needed** for this case to handle high-Q^2 part of the spectrum

A (selected) digest of $\gamma\gamma$ processes to be studied at future e-h facilities

Physics case 1: $\gamma\gamma \to \tau^+\tau^-$ H. Khanpour *et al*, paper in preparation

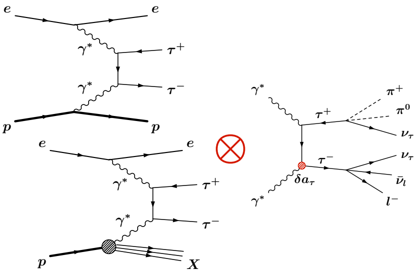


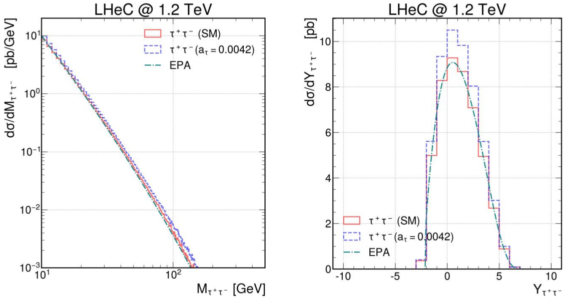


LHeC (1 ab^{-1}): $\mathcal{O}(10^8)$ $\gamma\gamma \to \tau^+\tau^-$ events produced at $W > 10$ GeV, ~2×10^6 at $W > 50$ GeV

- magnitude of ISR corrections at the order of 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: $\gamma\gamma \to \tau^+\tau^-$ H. Khanpour *et al*, paper in preparation

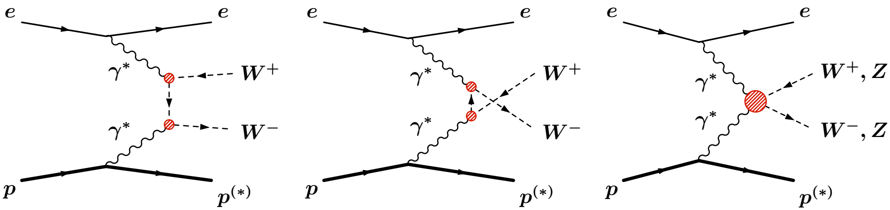




LHeC (1 ab^{-1}): $\mathcal{O}(10^8)$ $\gamma\gamma \to \tau^+\tau^-$ events produced at $W > 10$ GeV, ~2×10^6 at $W > 50$ GeV

- magnitude of ISR corrections at the order of 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 ...
- allows to probe with high precision 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: $\gamma\gamma \to W^+W^- / ZZ$ H. Khanpour *et al*, paper in preparation



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.) H. Khanpour *et al*, paper in preparation

AGH

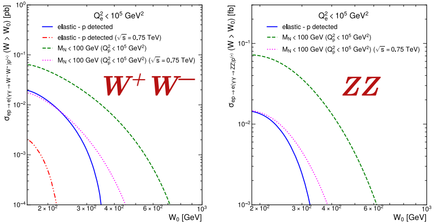
$\gamma\gamma \to W^+W^-$ already broadly studied in LHC phase space e.g. [CMS: JHEP 07 (2023) 229, ATLAS: Phys.Lett.B 816 (2021) 136190]

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 $\gamma\gamma \to W^+W^-$, $\gamma\gamma \to \tau^+\tau^-$, $\gamma\gamma \to t\bar{t}$, …
- 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)

More in Hamzeh's presentation on Tuesday

Physics case 3: Two-photon production of supersymmetric pairs H. Khanpour *et al*, paper in preparation

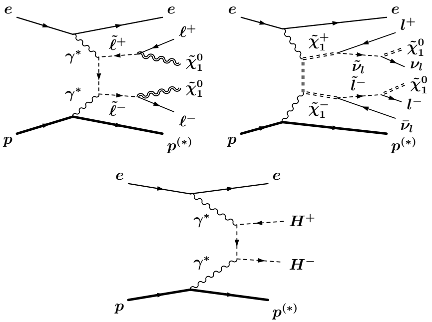
- Same electromagnetic coupling as any SM **charged particle emission from photons**

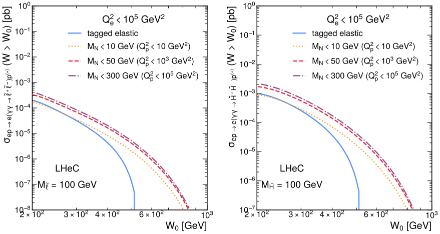
  e.g. **for fermions**, with $\beta^2 = 1 - 4m_f^2/\hat{s}$:

$$\sigma(\gamma\gamma \to f\bar{f})(w_{\gamma\gamma}) \sim \frac{\beta}{w_{\gamma\gamma}} \left(\frac{3-\beta^4}{2\beta} \ln\left(\frac{1+\beta}{1-\beta}\right) - 2 + \beta^2 \right),$$

  and equivalently for bosons

- Dependence on SUSY object (charginos $\tilde{\chi}^{\pm}$, sleptons $\tilde{l}^{\pm}$, 2HDM $H^{\pm}$…) mass and electromagnetic charge
  - mass range for SUSY/BSM objects searches driven by two-photon centre-of-mass energy reachable at LHeC/FCC-eh/…





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 at LHeC 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

Thanks for your attention!

Spares

Abstract

High energy two-photon processes provide unique opportunity for studying with high precision the electroweak sector of particle interactions at future colliders.

Future facilities such as the LHeC, FCC-eh, or the eh-CEPC, will ensure very advantageous experimental conditions and at the same time provide high two-photon luminosities, reaching the TeV scale.

In this talk we will give an overview of expected performance of these colliders in that context. In addition, the impact of tagging two-photon processes using very forward detectors will also be presented.