# LHeC Physics Potential : Higgs/Top, BSM, PDFs, and the $\gamma\gamma$ Physics Opportunity

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e/mu-LHC proposal: initial discussion; Nov 11, 2025, CERN

# Outline

- The LHeC at the Frontline of Particle Physics
- Higgs Boson & Top-Quark Physics at the LHeC
- Precision SM & Strong Sensitivity to the BSM scenarios
- Precision QCD and proton PDF Program at the LHeC
- High-rate $\boldsymbol{\gamma\gamma}$ Factory within $ep$ at the LHeC & $\mu p$ at the $\mu$LHC

# The LHeC at the frontline of particle physics

- The LHeC is designed to move the field of DIS to the energy and intensity frontier of particle physics & LHeC Luminosity ≈ **1000** × HERA.
- LHeC will have a strong Higgs physics program and will provide percent-level precision studies of the Higgs mechanism.
- As a powerful lab for Electroweak Physics (EWK), LHeC will provide unique precision measurements in the EWK sector.
- It will deliver high-accuracy determinations of key SM parameters, crucial for analyses at the LHC and beyond.
- It will offer strong sensitivity to BSM scenarios and will have its own discovery potential for New Physics.
- It also gives access to photon-photon ($\gamma\gamma$) physics & precision $\gamma\gamma \to \ell\ell/\tau\tau/WW/ZZ/H$ with clean kinematics.
- Due to enhanced luminosity, large energy and the clean hadronic final states, ⇉ LHeC is NOT just a DIS super-collider.
- Selected highlights of all these aspects will be presented and discussed in this talk.


The Large Hadron electron Collider as a bridge project for CERN, 2503.17727 [hep-ex].
The Large Hadron-Electron Collider at the HL-LHC, 2007.14491 [hep-ex].
An electron-hadron collider at the high-luminosity LHC, 2503.20475 [hep-ex].

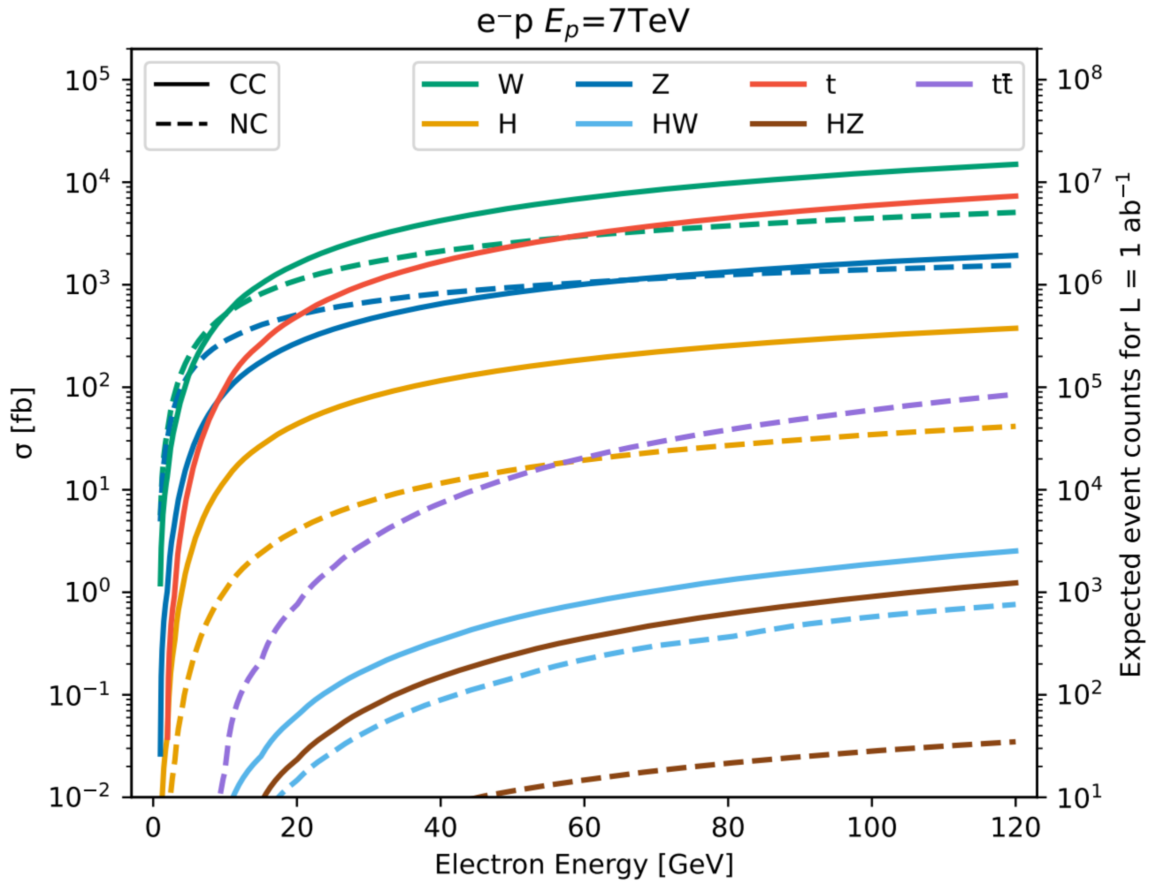
# The LHeC at the frontline of particle physics

- The high center-of-mass energy $\sqrt{s}$=1.2 TeV, together with the large integrated luminosity, enables the measurement of a large variety of processes:

- Inclusive production cross sections for prompt Z and $W^{\pm}$ bosons, the Higgs boson (H), single top-quark production (t), top-quark pair production ($t\bar{t}$); the cross sections for HZ and HW production, …

- LHeC will play as a very powerful lab for Electroweak Physics & Higgs physics and precision SM/BSM parameters!

LHeC as a general-purpose experiment at CERN




Selected inclusive production cross sections for an electron-proton collider at the HL-LHC as a function of the electron beam energy $E_e$.

The Large Hadron electron Collider as a bridge project for CERN, 2503.17727 [hep-ex].

# Higgs Boson Physics

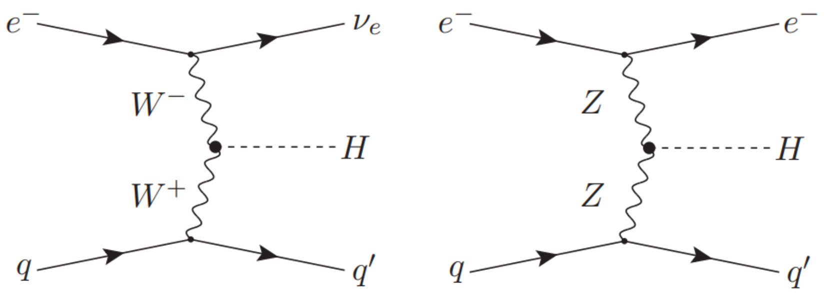
DIS provides a theoretically clean environment for Higgs production in electron-proton collisions, with minimal QED and QCD corrections.

At the LHeC, the Higgs boson is mainly produced via CC interactions through the t-channel process $W^+W^- \to H$, with a smaller but measurable contribution from NC interactions.

The Higgs production cross section at the LHeC is about 200 fb, comparable to the $e^+e^- \to HZ$ cross section at 250 GeV.

For the nominal integrated luminosity of 1 $\mathrm{ab}^{-1}$, around $2 \times 10^5$ Higgs bosons become available for analysis

The Large Hadron electron Collider as a bridge project for CERN, 2503.17727 [hep-ex].




Higgs boson production in charged (left) and neutral (right) current DIS.

Higgs production in a clean environment - CC/NC production with low pile-up!

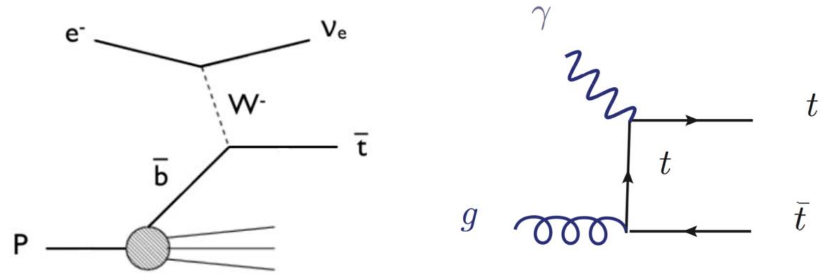
The LHeC as a Higgs Boson Factory, IPAC2013.

# Top-Quark Physics

- High-energy electron-proton colliders provide a unique environment for probing the electroweak interactions of the top quark, with the LHeC standing out as a powerful single-top production facility.

- At the LHeC, the CC single top production cross section is around 1.9 pb. This substantial production rate enables high-precision measurements of the Wtb coupling.

- The second important production mode for top quarks at the LHeC is photoproduction of top-antitop quark pairs ($t\bar{t}$), where a total cross section of 0.05 pb is expected at the LHeC.

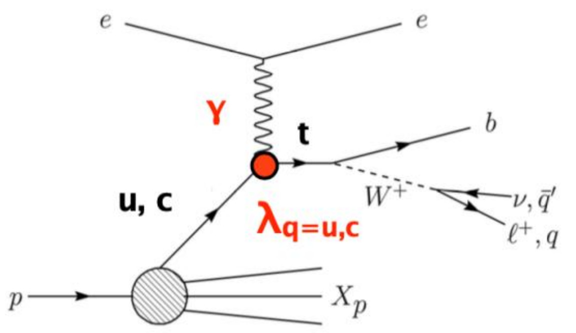



Top quark production in CC DIS & $t\bar{t}$ photoproduction.

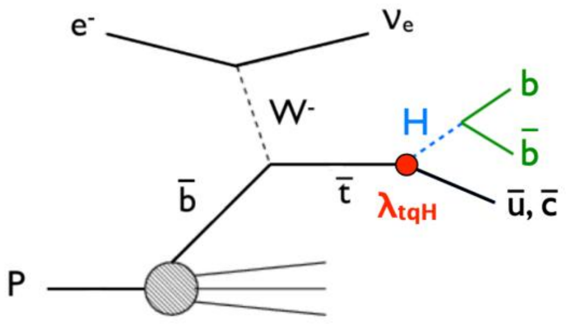

The Large Hadron electron Collider as a bridge project for CERN, 2503.17727 [hep-ex].
The Large Hadron-Electron Collider at the HL-LHC, 2007.14491 [hep-ex].
Overview of top quark physics at the ep colliders, 1710.06260 [hep-ph].

# Top Quark FCNC at the LHeC

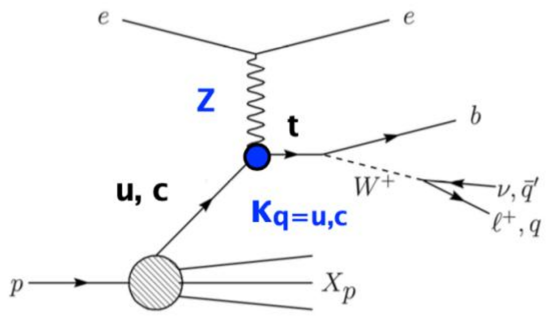
- The top quark Flavour Changing Neutral Currents (FCNCs) interactions are also extremely suppressed in the SM, which renders them a good test of New Physics.



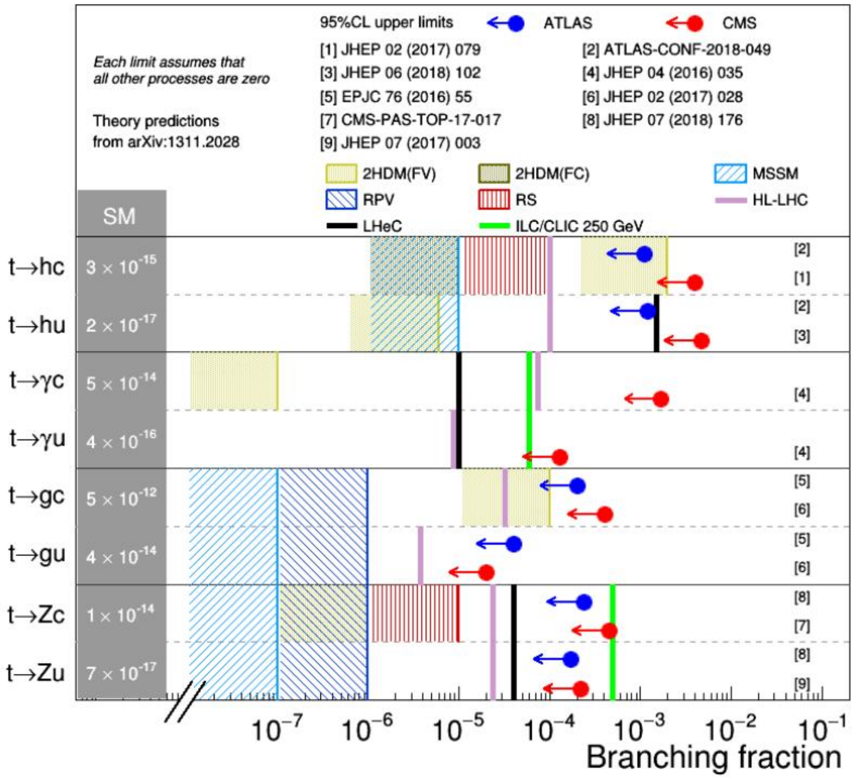

$tq\gamma$




$tqH$




$tqZ$

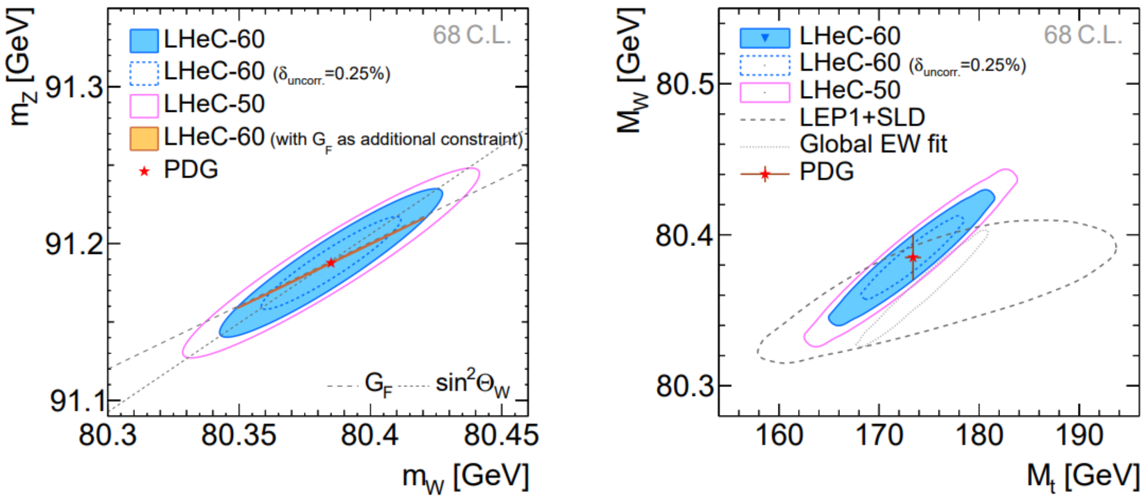



Summary of 95% C.L. limits on top FCNC $tqH$, $tqZ$ and $tq\gamma$ at the LHeC.

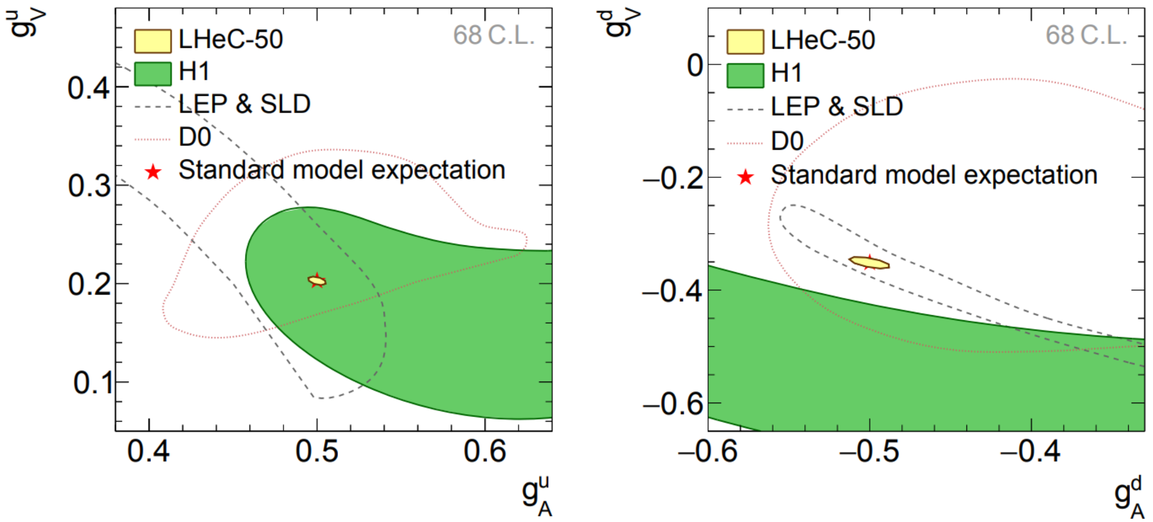
Top quark FCNC couplings at future circular hadron electron colliders, 1701.06932 [hep-ph]

# Precision SM Physics

- With LHeC inclusive NC and CC DIS data, unique measurements of electroweak parameters can be performed with highest precision.




Simultaneous determination of the W-boson and Z-boson masses from LHeC60 or LHeC-50 data (left); simultaneous determination of the top-quark mass and W-boson mass from LHeC60 or LHeC-50 data (right).

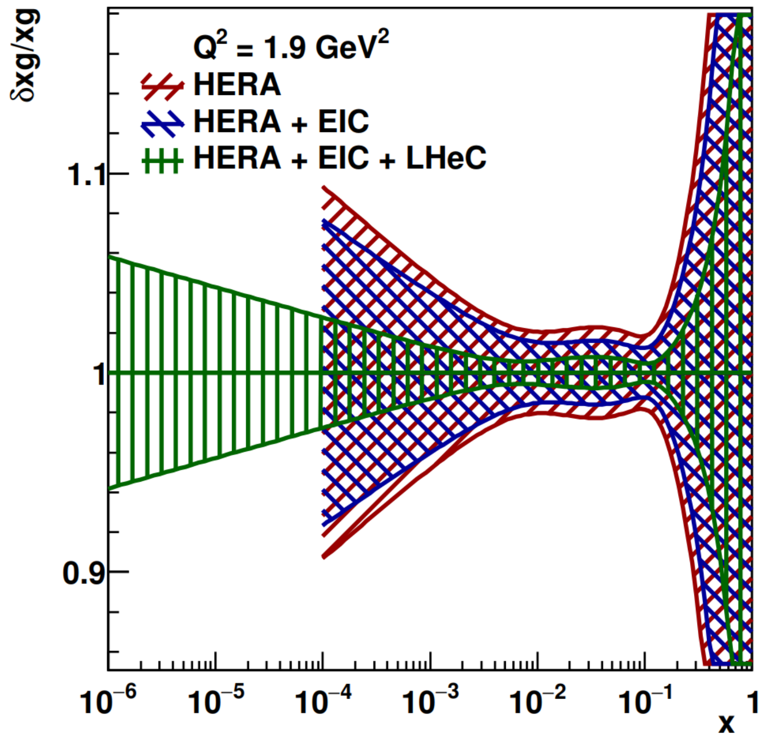



Weak NC vector and axial-vector couplings of u-type (left) and d-type quarks (right) at 68 % confidence level (CL) for simulated LHeC data. The LHeC expectation is compared with results from the combined LEP+SLD experiments, a single measurement from D0 and one from H1.

The Large Hadron electron Collider as a bridge project for CERN, 2503.17727 [hep-ex].
Electroweak physics in inclusive deep inelastic scattering at the LHeC, 2007.11799 [hep-ph].

# Precision QCD at LHeC

- LHeC will have strong program for the precision QCD, determination of the proton PDFs and the strong coupling constant through inclusive DIS measurements.

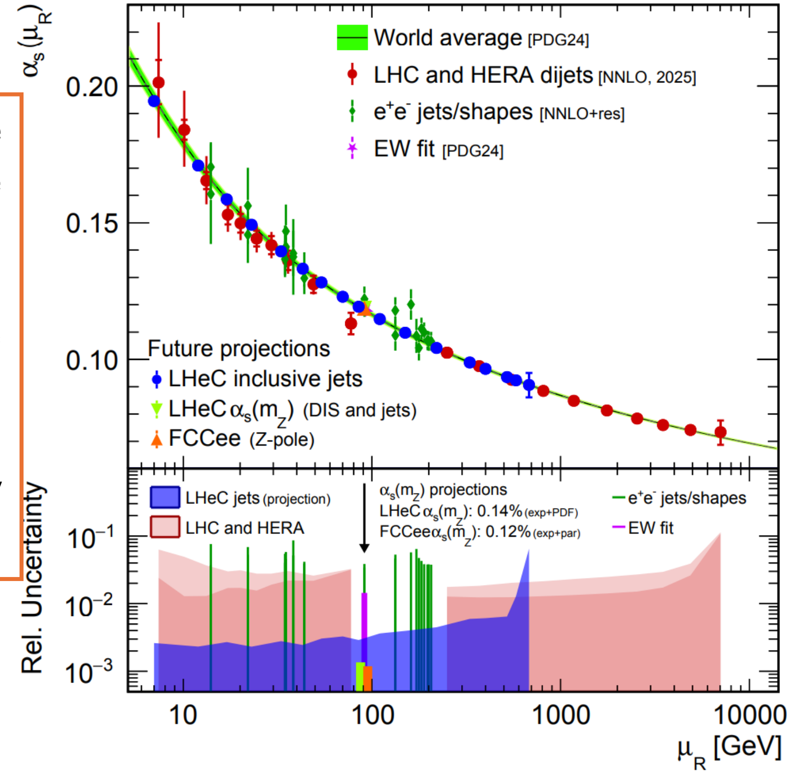



Uncertainty in the determination of the gluon distribution in fits to HERA data plus EIC projections plus LHeC.

DIS@LHeC is the ideal place for determining PDFs and the strong coupling constant.

Resolve the patron structure of the proton completely!

It could serve as a high-energy electron-ion (eA) collider.



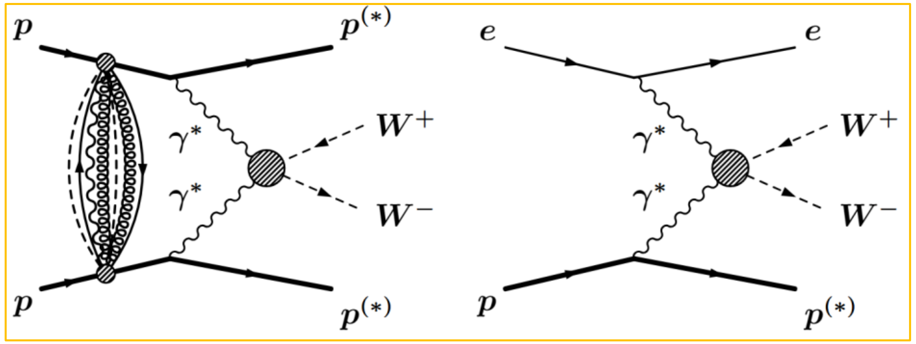

Expected measurement of $\alpha_s(\mu_R)$ and corresponding relative uncertainties at the LHeC compared with presently available measurements and the world average value.

# High-rate $\gamma\gamma$ factory within *ep* at the LHeC

- Comprehensive survey of studies of high energy photon-photon interactions at the LHeC, for the photon-photon center-of-mass energy of up to 1 TeV.

- Wide spectrum of $\gamma\gamma$ processes will be studied at the LHeC, including, in particular, the exclusive production of lepton pairs, Higgs boson, W and Z bosons, $t\bar{t}$, as well as pairs of charged supersymmetric particles.

- Very high statistics of these processes are expected to be achieved at the LHeC.




Feynman diagrams representing the exclusive $W^{\pm}$ boson pair production via photon-photon fusion at the LHC (left) and future collider LHeC (right).

L. Forthomme, H. Khanpour, K. Piotrzkowski, Y. Yamazaki, "*High energy $\gamma\gamma$ interactions at the LHeC*", paper in preparation.
High energy $\gamma\gamma$ interactions at the LHeC, PoS DIS2024 (2025) 269.

# Equivalent Photon Approximation (EPA)

- The calculations of cross-sections can be performed using the Equivalent Photon Approximation (EPA).

- In this approach, the cross-sections are factorized in a manner similar to the partonic framework used for hadron-hadron collisions in perturbative QCD.
- The total cross-section, proceeding via photon-photon fusion, can be accurately calculated by a convolution of the equivalent photon fluxes for leptons (electron/muon) and protons, $\Phi_l(y_l)$ and $\Phi_p(y_p)$, respectively, multiplied by the appropriate photon-photon cross-section $\sigma_{\gamma\gamma}(W)$,

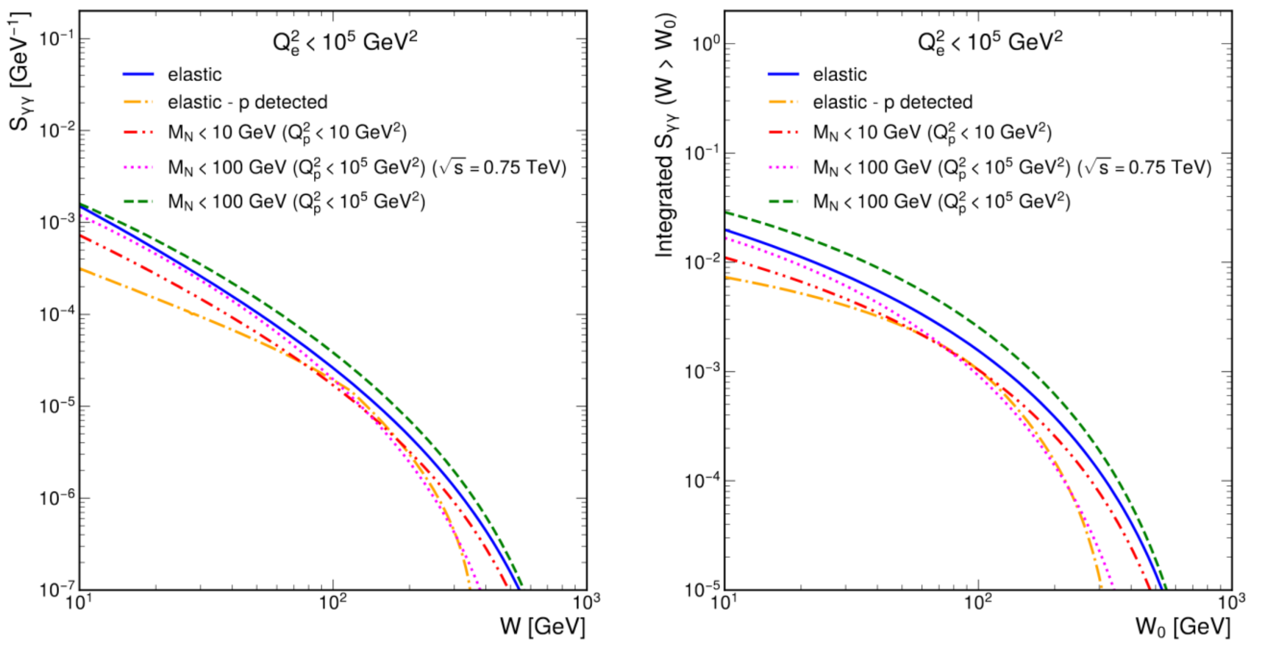
$$\sigma_{ep} = \int \mathrm{d}y_e \mathrm{d}y_p \Phi_e(y_e)\Phi_p(y_p)\,\sigma_{\gamma\gamma}(W) \;=\; \int \mathrm{d}W\,S_{\gamma\gamma}\sigma_{\gamma\gamma}\,,$$

- W is photon-photon center of mass energy
- Photon fractional energies $y_l = \frac{E_{\gamma(l)}}{E_l}$ ; $y_p = \frac{E_{\gamma(l)}}{E_l}$

The two-photon particle production mechanism, Phys. Rept. **15** (1975) 181.
Improved the Weizsäcker-Williams Approximation in Electron-Proton Collisions, Phys. Lett. B **319** (1993) 339, [hep-ph/9310350].

# Luminosity Spectrum $S_{\gamma\gamma}$

- It represents the fraction of the ep luminosity available for $\gamma\gamma$ collisions.
- Large fraction the total $\gamma\gamma$ luminosity → To makes the LHeC an excellent place to study the photon-photon interactions → An extraordinary $\gamma\gamma$ collider!
- The production rate of massive objects is limited by the photon luminosity at high invariant mass & however, they could be produced in a very clean experimental environment.



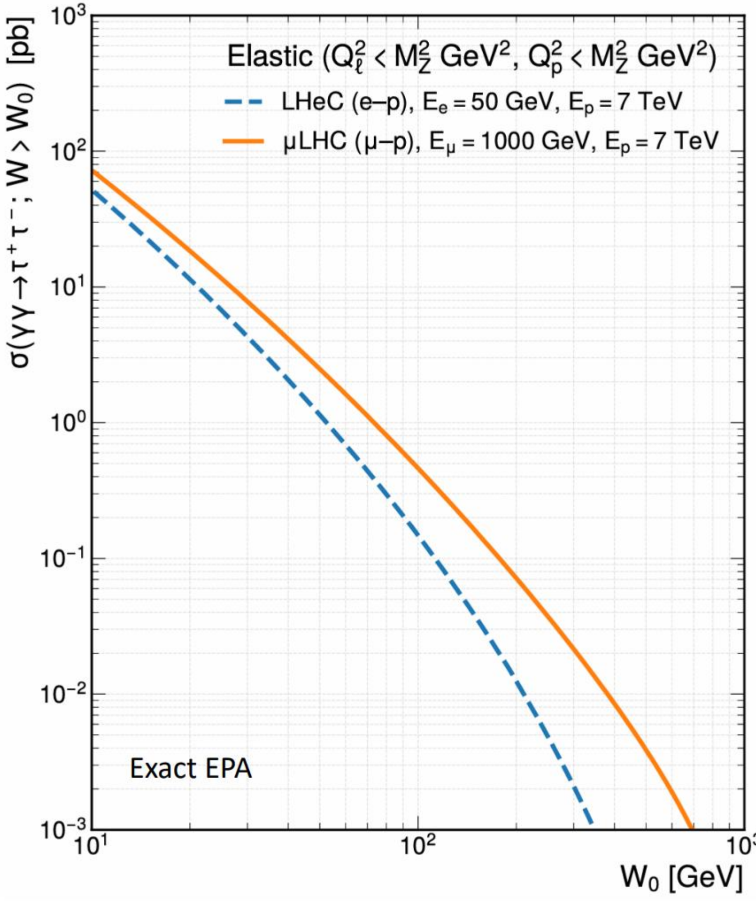

(left) Elastic luminosity spectrum $S_{\gamma\gamma}$ at the LHeC as well as three inelastic luminosity spectra where the dissociative mass $M_N$ < 10, 100, and 300 GeV is assumed; (right) corresponding integrated luminosity spectra as a function of the minimal $\gamma\gamma$ center-of-mass energy, $W_0$. An inelastic case for LHeC@0.75 TeV* is also shown.

L. Forthomme, H. Khanpour, K. Piotrzkowski, Y. Yamazaki, "*High energy $\gamma\gamma$ interactions at the LHeC*", paper in preparation.

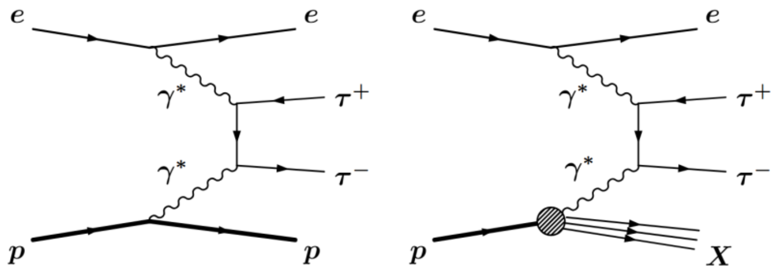
*An electron-hadron collider at the high-luminosity LHC, 2503.20475 [hep-ex]

# Photon-photon factory of τ pairs

$\sigma^{el}$(LHeC@1.2 TeV) = 50.3 pb
$\sigma^{el}$($\mu$LHC@5.3 TeV) = 70.3 pb




Elastic τ+τ− production cross sections (in pb) at the LHeC@1.2 TeV and $\mu$LHC@5.3 TeV.




Feynman diagram for the elastic (left), and dissociative (right) two-photon production of τ pairs at the LHeC.

The production of lepton pairs ($\gamma\gamma \rightarrow l^+l^-$) is dominated in most of the phase space reachable experimentally by the two-photon Bethe-Heitler (2-γ BH) & In the high-mass region → Z exchange production process is dominant.

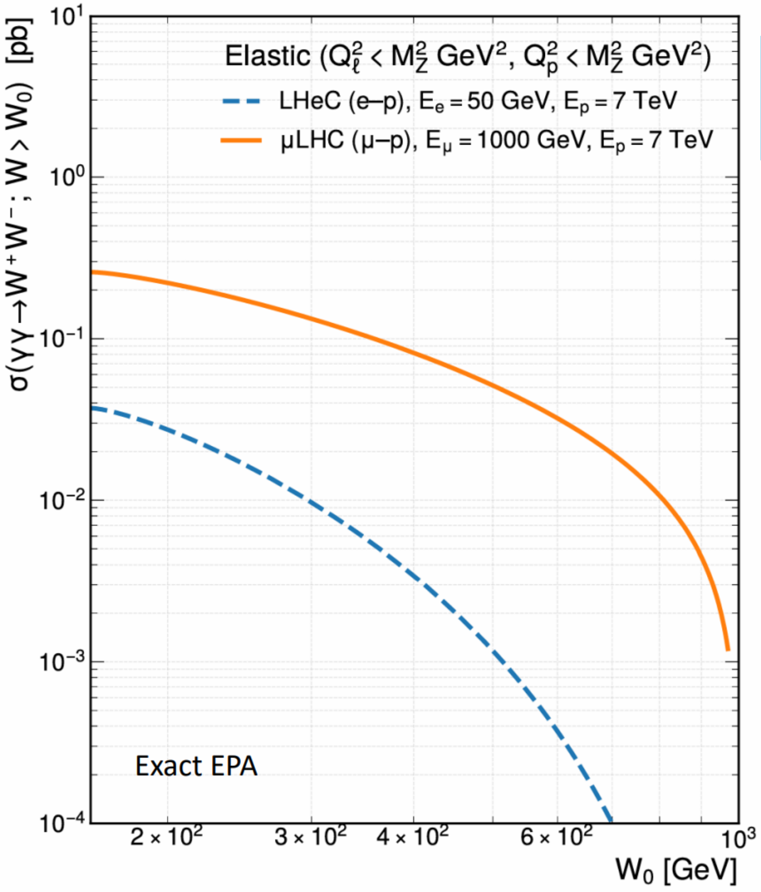
Very large statistics of elastic (and inelastic) τ+τ− pairs will be produced for $W_0$ > 10 GeV at the LHeC and $\mu$LHC.

| $\sigma^{\rm el}$ (pb) | $Q^2_{e,p} < 10$ GeV$^2$ $W_0 = 10$ GeV | $Q^2_{e,p} < 10$ GeV$^2$ $W_0 = 100$ GeV |
|---|---|---|
| EPA | 46.03 | 0.111 |
| CepGen (LPAIR, dipole FF) | 45.52 | 0.109 |
| GRAPE (BH) | 46.30 | 0.111 |
| GRAPE (BH+ISR) | 46.88 | 0.113 |
| GRAPE (EW) | 46.53 | 0.111 |
| GRAPE (EW+ISR) | 47.05 | 0.114 |

| $\sigma^{\rm inel}$ (pb) | Str.fun. modeling | $Q^2_{e,p} < 10$ GeV$^2$, $M_N < 3$ GeV $W_0 = 10$ GeV | $Q^2_{e,p} < 10$ GeV$^2$, $M_N < 3$ GeV $W_0 = 100$ GeV |
|---|---|---|---|
| EPA | ALLM | 12.20 | 0.046 |
| | LUX-like | 11.63 | 0.043 |
| CepGen (LPAIR) | Suri-Yennie | 12.74 | 0.048 |
| GRAPE (BH) | Hybrid | 11.52 | 0.045 |
| GRAPE (BH + ISR) | Hybrid | 12.53 | 0.047 |
| GRAPE (EW) | Hybrid | 11.54 | 0.045 |
| GRAPE (EW + ISR) | Hybrid | 12.77 | 0.047 |

Elastic (top) and inelastic (bottom) τ+τ− production cross sections (in pb) at the LHeC calculated using the EPA approach for a minimum two-photon invariant mass of $W_0$ = 10 and 100 GeV. Excellent performance of EPA for all cases handled by LPAIR and GRAPE.

# Exclusive production of W-boson pairs



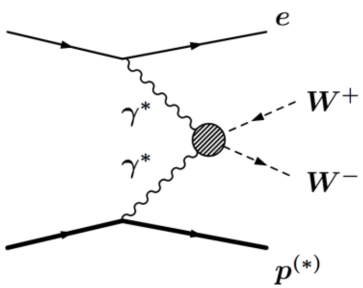

Elastic $W^{\pm}$ production cross sections (in pb) at the LHeC@1.2 TeV and $\mu$LHC@5.3 TeV.

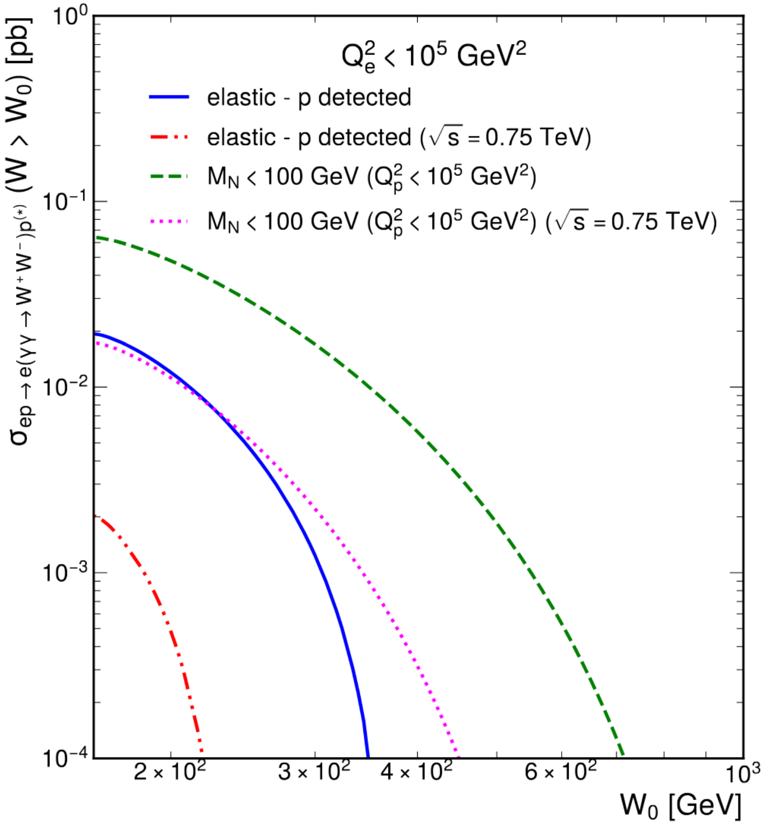
$\sigma^{el}$(LHeC@1.2 TeV) = 0.037 pb
$\sigma^{el}$($\mu$LHC@5.3 TeV) = 0.258 pb

$\gamma\gamma \to W^+W^-$ already broadly studied at the LHC phase space e.g. [CMS: CMS-PAS-SMP-24-019, ATLAS: Phys. Lett. B 816 (2021) 136190].

LHeC and $\mu$LHC cleanliness allowing precision probe of γγWW couplings in respect to the LHC case.

Feynman diagrams representing the exclusive production of W-boson pairs via photon-photon fusion at the LHeC.




The $W^{\pm}$ boson pair production cross sections at the LHeC, through the tagged elastic process ($0.01 < y_p < 0.1$) as well as the inelastic production.

# Anomalous triple/quartic gauge couplings

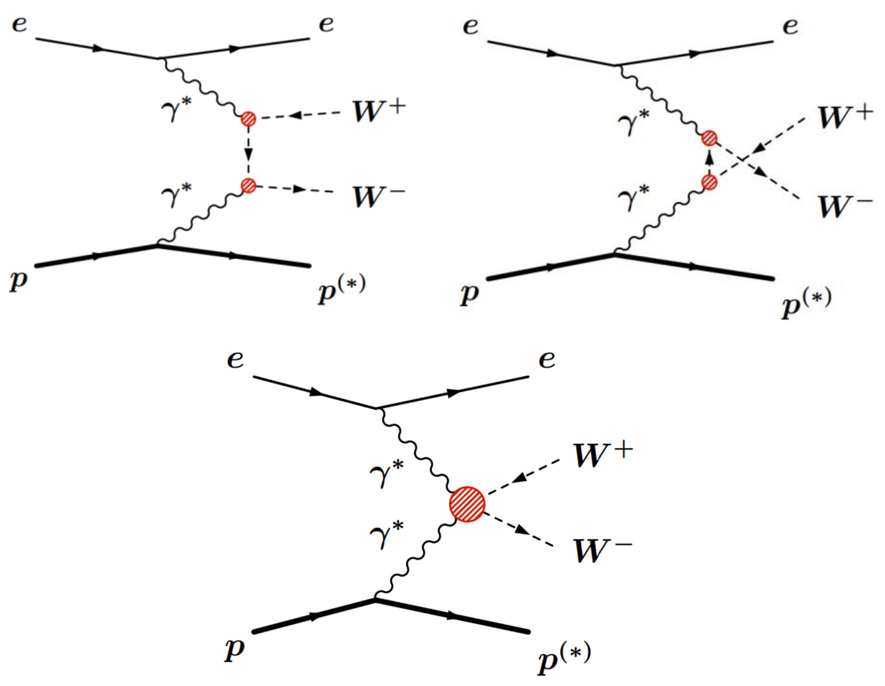
- In the EFT formalism, New Physics effects contributing to aQGCs are parameterized using higher-dimensional operators.
- The lowest-order modifications to quartic gauge couplings, which do not simultaneously induce triple gauge boson interactions, appear only atdimension-8.
- The general effective Lagrangian that governs these interactions is expressed as

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{f_i}{\Lambda^4}\mathcal{O}_i$$

- The general form of the effective Lagrangian for anomalous quartic gauge couplings is given by,

$$\mathcal{L}_{\text{aQGC}} = \sum_{j=0}^{1} \frac{f_{S,j}}{\Lambda^4}\mathcal{O}_{S,j} + \sum_{j=0}^{7} \frac{f_{M,j}}{\Lambda^4}\mathcal{O}_{M,j} + \sum_{j=0}^{9} \frac{f_{T,j}}{\Lambda^4}\mathcal{O}_{T,j}.$$

CMS-PAS-SMP-24-019

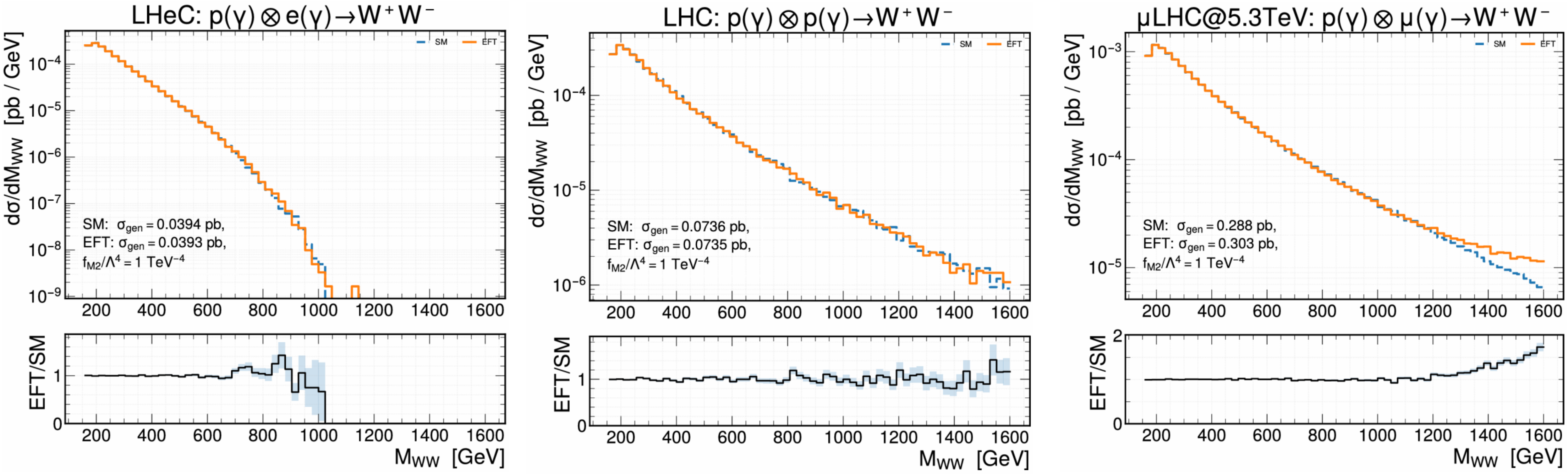



Clean observables: In $\gamma\gamma \rightarrow W^+W^-$, the aQGCs mainly boost the high-$M_{WW}$ and high-$p_T$ tails.

Elastic and dissociative $\gamma\gamma \rightarrow W^+W^-$ production in the clean electron-proton environment is a powerful test bench for anomalous triple and quartic gauge couplings.

# $\gamma\gamma \to W^+W^-$ as an aQGC probe at three machines

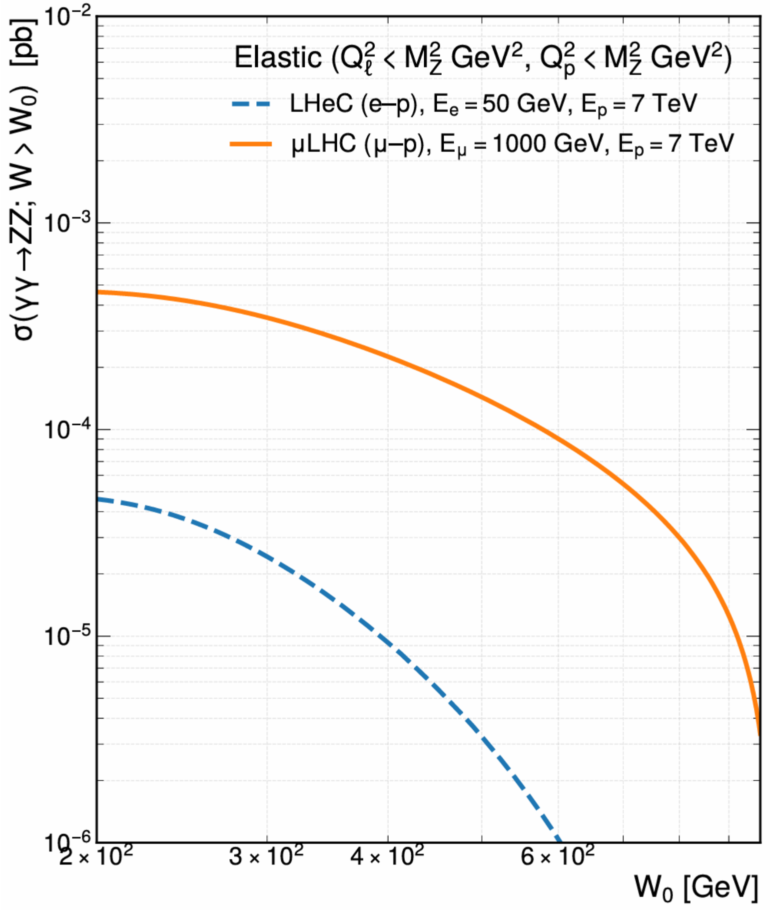
- Key pattern: EFT effects are tiny at low $M_{WW}$ but grow rapidly in the high-mass tail, giving a clean shape handle on aQGCs.
- All machines highlights robust sensitivity to quartic gauge couplings; each facility contributes a different strength.
- LHeC : lowest backgrounds, precise kinematics, potential proton/electron tagging
- μLHC has the largest yield and hardest tail, hence the strongest statistical reach.




Generator-level $M_{WW}$ spectra for LHeC (ep), LHC (pp) and $\mu$LHC@5.3 TeV. The orange curve includes a dim-8 EFT, the blue curve is SM. Lower panels show EFT/SM.

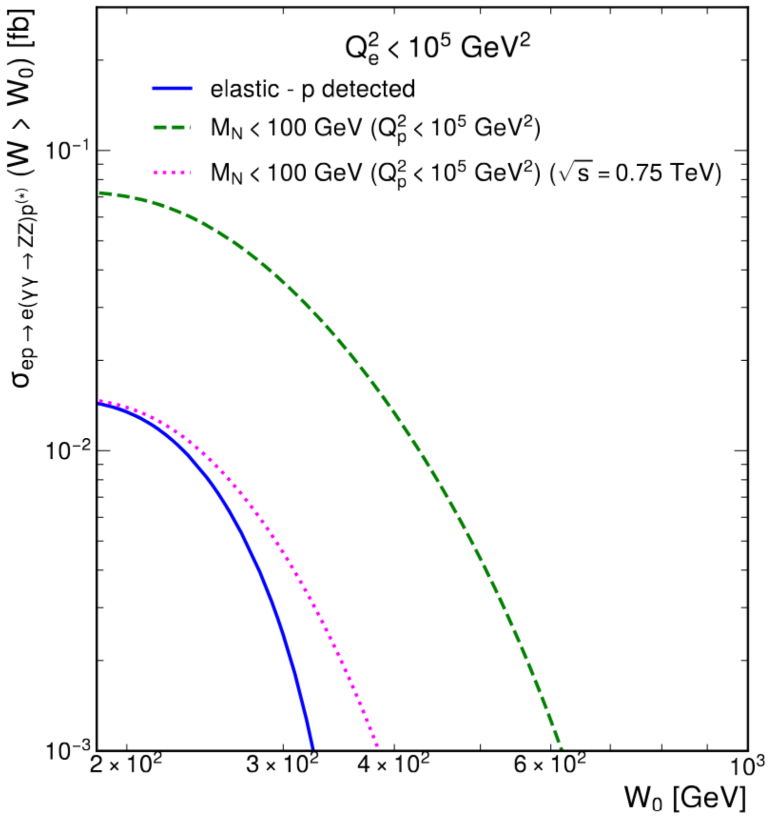
# Unique Z boson laboratory

$\sigma^{el}$(LHeC@1.2 TeV) = 0.046 fb
$\sigma^{el}$($\mu$LHC@5.3 TeV) = 0.463 fb




Elastic $ZZ$ production cross sections (in fb) at the LHeC@1.2 TeV and $\mu$LHC@5.3 TeV.

- In SM, $\gamma\gamma \to ZZ$ not allowed at tree level, LHeC's $\gamma\gamma \to ZZ$ is a pure one-loop SM process.
- High-mass tails of $M_{ZZ}$ at the LHeC are sensitive to nQGCs ($ZZ\gamma\gamma$).
- LHeC (and $\mu$ LHC) uniquely would accesses the ZZ high-mass regime, turning ep ($\mu p$) into a precision Z-boson laboratory.

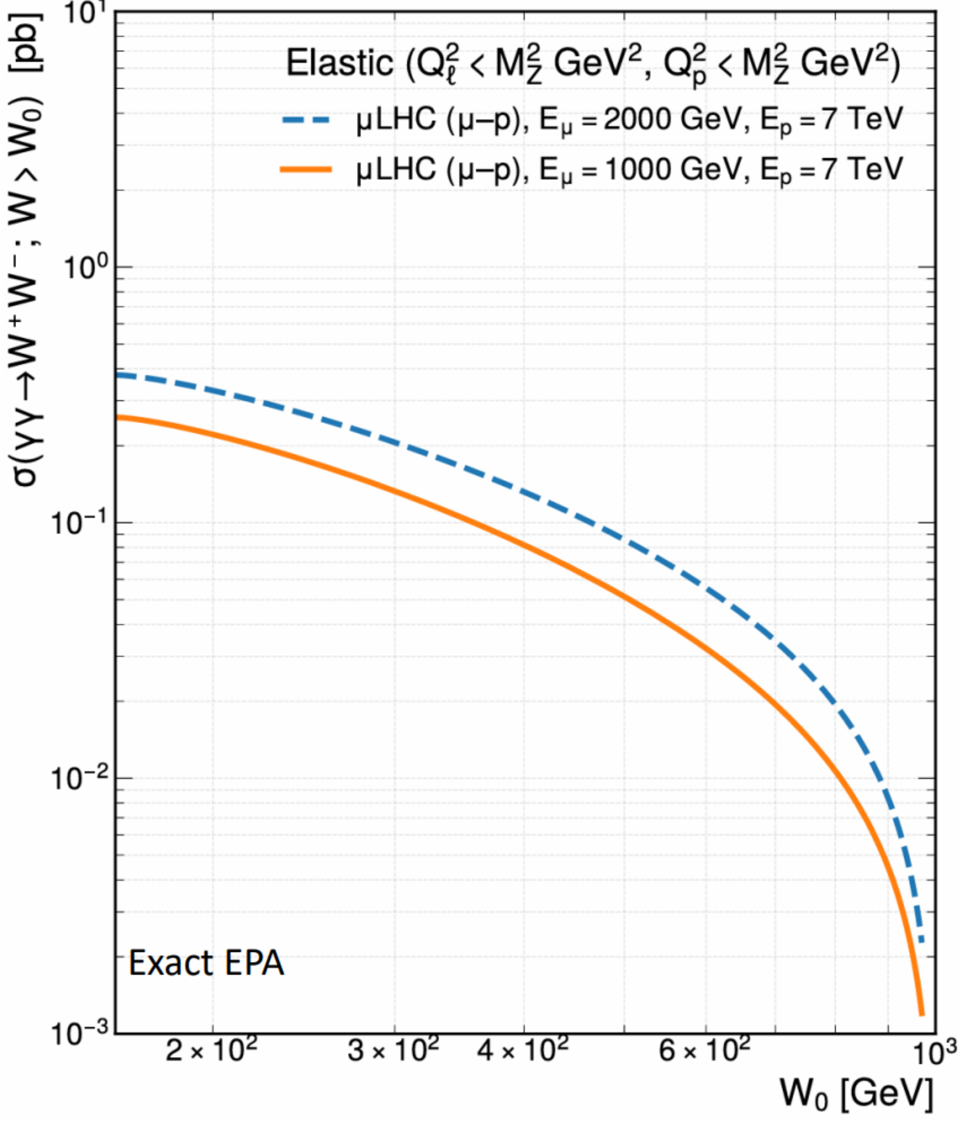



The Z-boson pair production cross sections (in fb), through the tagged elastic process($0.01 < yp < 0.1$) and the inelastic production. The corresponding inelastic result for LHeC working at the center-of-mass energy of $\sqrt{s}$ =0.75 TeV is also shown.

# $\gamma\gamma \to W^+W^-$
# $\mu$LHC@5.3 TeV vs $\mu$LHC@7.5 TeV

- μp collider in two modes: $E_\mu = 1$ TeV ($\sqrt{s} \approx 5.3$ TeV) and $E_\mu = 2$ TeV ($\sqrt{s} \approx 7.5$ TeV) with $E_p = 7$ TeV. We study elastic $\gamma\gamma \to W^+W^-$ using an exact EPA; both muon and proton remain intact (elastic form-factor regime).
- The 7.5 TeV option yields a harder spectrum and larger σ at the same $W_0$.
- Higher $\sqrt{s}$ boosts the effective $\gamma\gamma$ luminosity and extends the $M_{WW}$ reach; the high-mass tail grows markedly, where EFT effects scale fastest.
- aQGC sensitivity: The enhanced tail at 7.5 TeV amplifies the EFT/SM ratio and strengthens shape-based constraints on dim-8 operators.

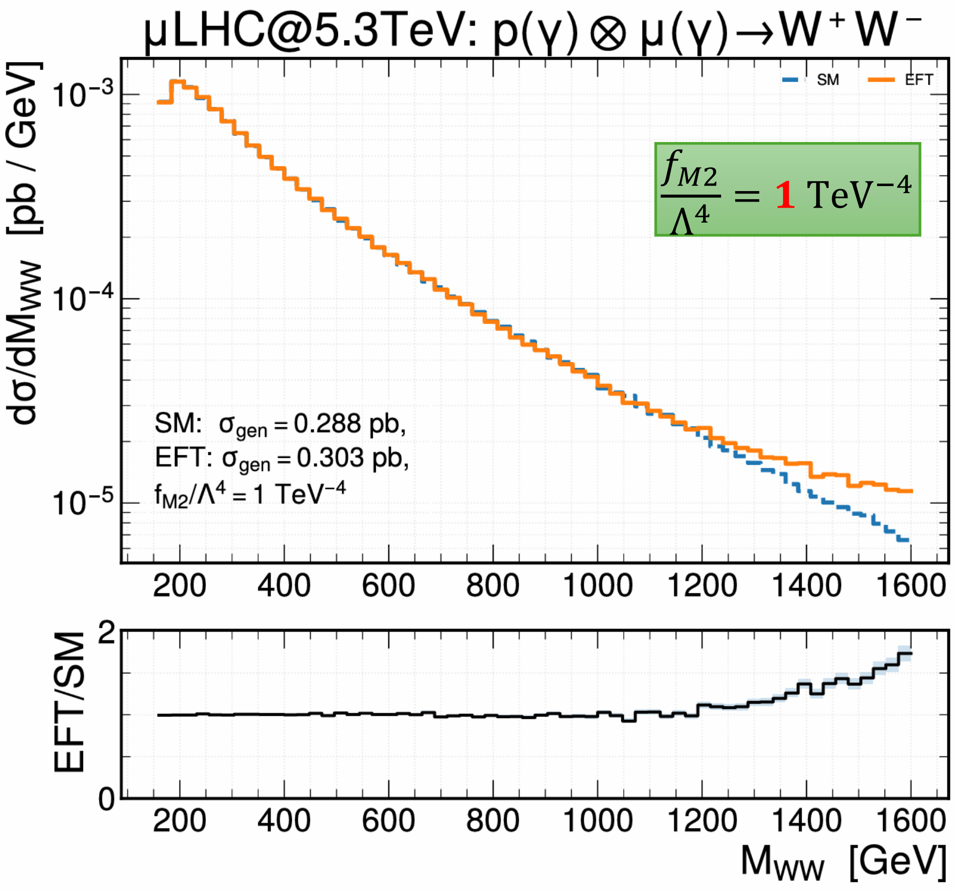
$\sigma^{el}(\mu\text{LHC@7.5 TeV}) = 0.378$ pb
$\sigma^{el}(\mu\text{LHC@5.3 TeV}) = 0.258$ pb

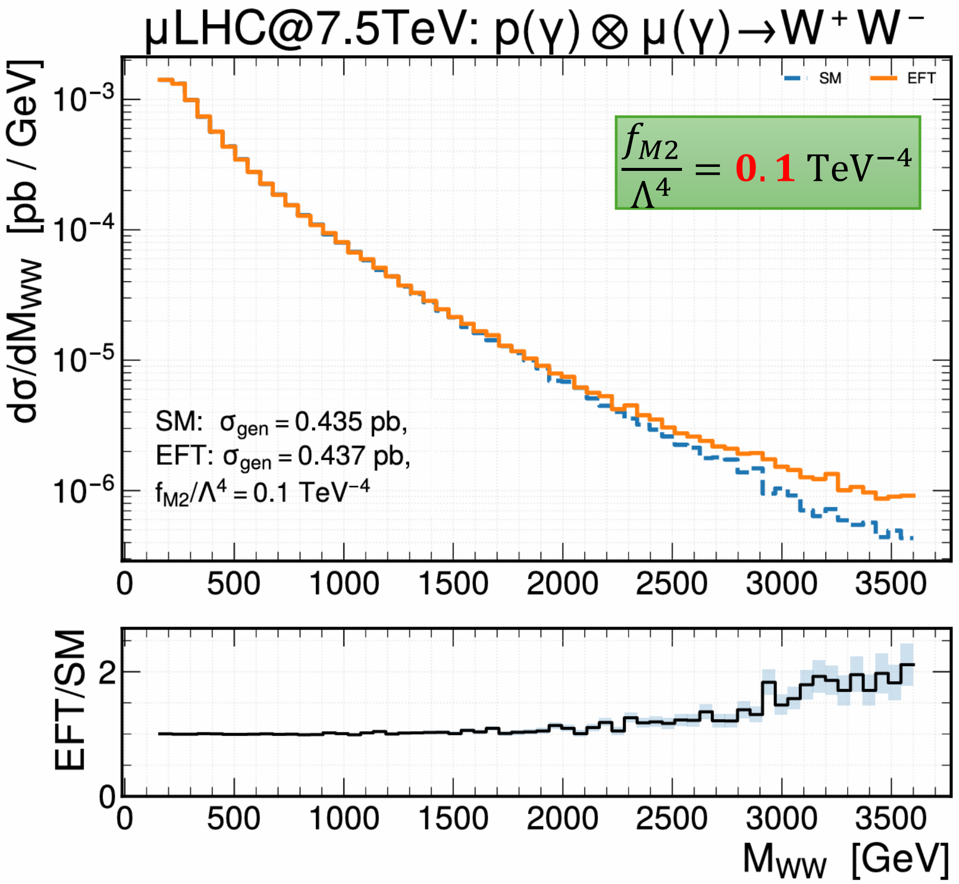


# $\gamma\gamma \to W^+W^-$

# $\boldsymbol{\mu}$LHC@5.3 TeV vs $\boldsymbol{\mu}$LHC@7.5 TeV

$\boldsymbol{\mu}$LHC@7.5 TeV gives a harder $M_{WW}$ tail and larger rate, extending sensitivity well beyond 2-3 TeV; ideal for shape-based aQGC limits.

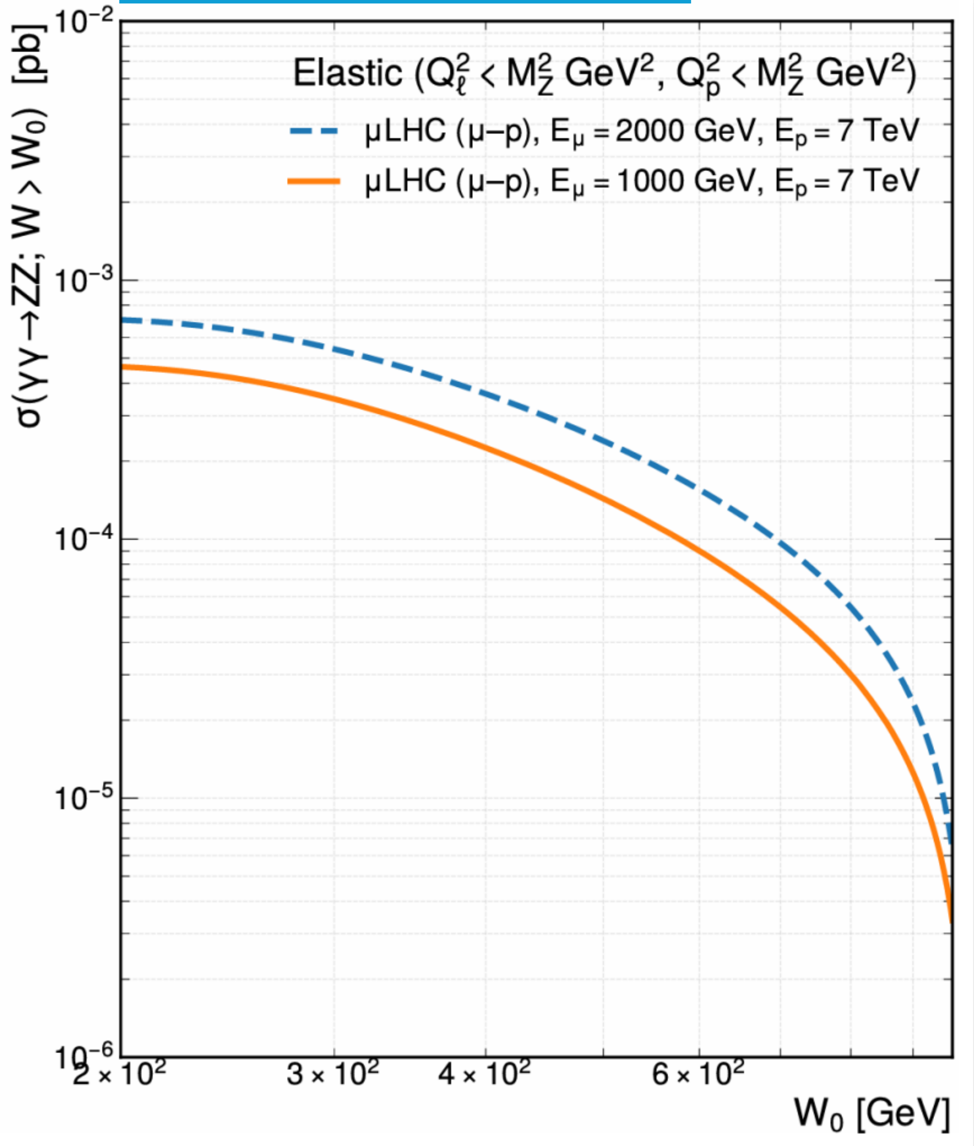



Generator-level spectrum for $M_{WW}$ for elastic $\gamma\gamma \to W^+W^-$ at the $\boldsymbol{\mu}$**LHC@5.3 TeV** and $\boldsymbol{\mu}$**LHC@7.5 TeV** for the SM and a dim-8 EFT.

$\sigma^{el}(\mu LHC@7.5\ TeV) =\ 0.703\ fb$
$\sigma^{el}(\mu LHC@5.3\ TeV) =\ 0.463\ fb$

# $\gamma\gamma \to ZZ$
# $\mu$LHC@5.3 TeV vs $\mu$LHC@7.5 TeV




- Setup & observable: Elastic $\gamma\gamma \to ZZ$ in μp collisions, using an exact-EPA calculation with elastic photon virtualities; plot shows σ($W$>$W_0$) vs $W_0$ for $\mu$LHC@5.3 TeV vs $\mu$LHC@7.5 TeV.
- Raising $\sqrt{s}$ hardens the spectrum, the gain is largest in the high-$M_{ZZ}$ tail & High-mass region is sensitive to neutral QGCs ($ZZ\gamma\gamma$) in dim-8 EFT via shape fits.
- Big picture: 7.5 TeV mode offers superior tail reach and aQGC sensitivity, while 5.3 TeV remains statistics-rich and operationally simpler - together they chart a clean $\gamma\gamma$ lab for neutral gauge-boson dynamics.

# Summary : Why LHeC?

- A TeV electron-proton factory, HL-LHC compatible, $\sqrt{s}$=1.2 TeV with an electron beam on 7 TeV protons; with $\mathcal{O}(1\ \text{ab}^{-1})$ program - the "bridge" that cleanly fits between HL-LHC and FCC.
- Clean environment → precision by design low pile-up, and vanishing Drell–Yan backgrounds for $\gamma\gamma$: measurements are statistically powerful.
- Global-PDF game-changer: LHeC DIS data collapse PDF uncertainties across x and $Q^2$; jets in DIS push $\alpha_s$ and QCD parameters to unprecedented precision.
- Higgs Boson, top quark and Electroweak precision machine.
- Embedded $\gamma\gamma$ factory at the electron-proton with high-rate $\gamma\gamma \rightarrow \ell\ell/\tau\tau/WW/ZZ/H$ and clean kinematics.
- μLHC concept: collide 1 TeV muon with 7 TeV proton $\sqrt{s}$=5.3 TeV, extending small-x & high-$Q^2$ reach and hard $\gamma\gamma$ tails beyond LHeC.


Thank you!