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TWO-PHOTON PRODUCTION OF W-BOSON PAIRS AT THE LHEC AND SENSITIVITY TO ANOMALOUS GAUGE COUPLINGS

Zahra Abdy, Laurent Forthomme, Hamzeh Khanpour, Krzysztof Piotrzkowski

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INTRODUCTION & MOTIVATION

- LHeC : A high-energy & high-luminosity electron-proton collider at CERN
- High energy $\gamma\gamma$ interactions at the LHeC & Equivalent Photon Approximation (EPA)
- Two-photon production of W-boson pairs ($\gamma\gamma \rightarrow W^+W^-$)
- Sensitivity to the anomalous quartic gauge couplings (aQGC) at the LHeC
- Summary & Outlook

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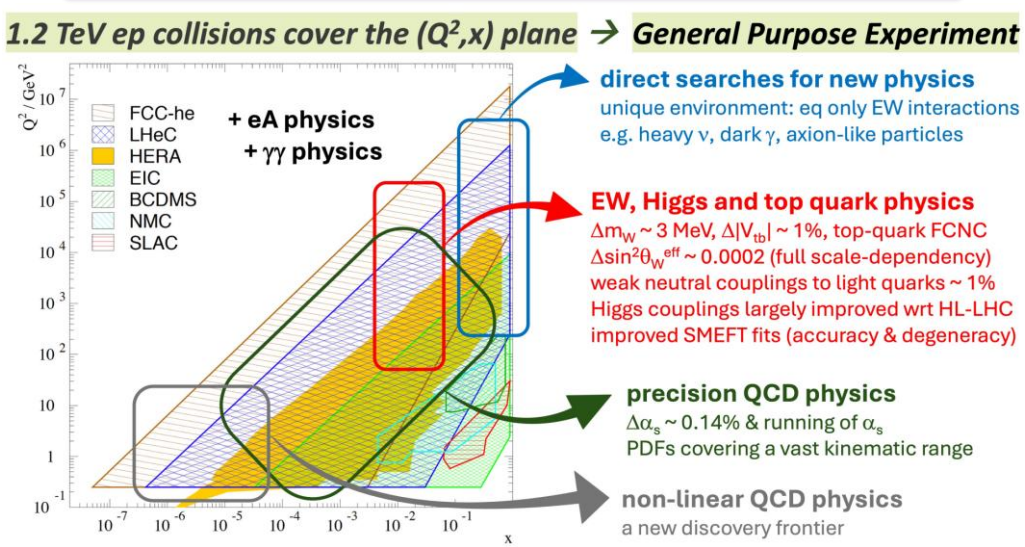
FUTURE LARGE HADRON-ELECTRON COLLIDER (LHEC)

- The future collider LHeC, planned at the LHC, is to operate at the center-of-mass energy of 1.2 TeV and is expected to deliver an integrated electron-proton luminosity of about 1 ab^{-1}.
- The LHeC is designed to move the field of DIS to the energy and intensity frontier of particle physics & LHeC Luminosity ≈1000×HERA.
- Very high electron-proton luminosity & Clean experimental environment & High statistics data event for the rare processes.

- LHeC as a general-purpose experiment at CERN



- The Large Hadron electron Collider as a bridge project for CERN, [arXiv: 2503.17727 [hep-ex]].
- ➢ An electron-hadron collider at the high-luminosity LHC, Kevin David J. André, Bernhard Holzer, Laurent Forthomme, Krzysztof Piotrzkowski, arXiv: 2503.20475 [hep-ex].

- LHeC ESPP'26 input: https://indico.cern.ch/event/1439855/contributions/6461616/
- ✓ Jorgen D'Hondt, LHeC, European Strategy for Particle Physics, Venice, June 2025

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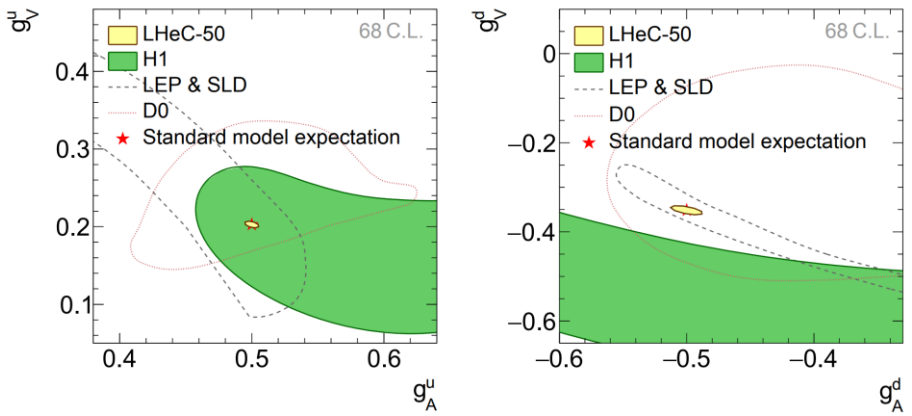
ELECTROWEAK PHYSICS AT THE LHEC

- Unique measurements of electroweak parameters

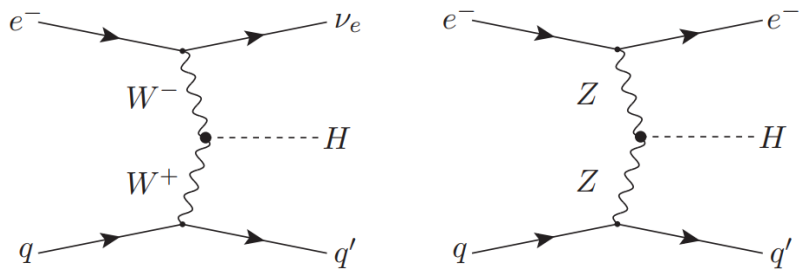
2503.17727 [hep-ex]



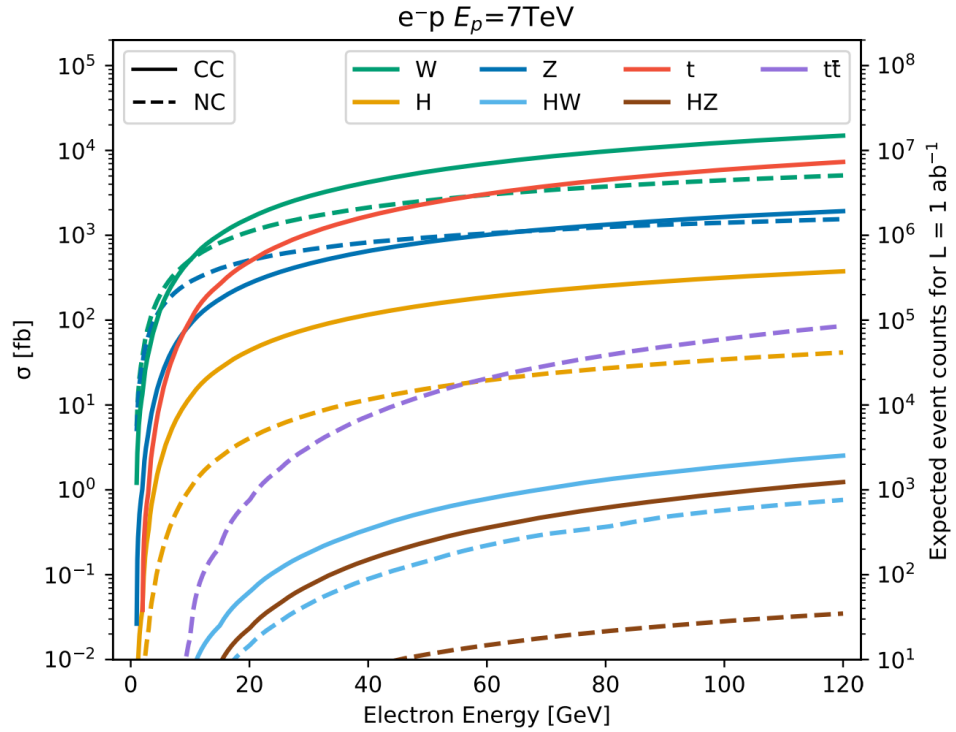
Higgs Physics at the LHeC

- Higgs boson production at LHeV: CC DIS & NC DIS

2007.14491 [hep-ex]



A GENERAL-PURPOSE EXPERIMENT



- LHeC has a strong Higgs physics program and its own discovery potential for New Physics & Very powerful lab for Electroweak Physics, top/Higgs physics & Beyond SM signatures ⇉ LHeC is NOT just a DIS super-collider!

BSM physics at the LHeC, Nestor Armesto, [EPS-HEP 2025]

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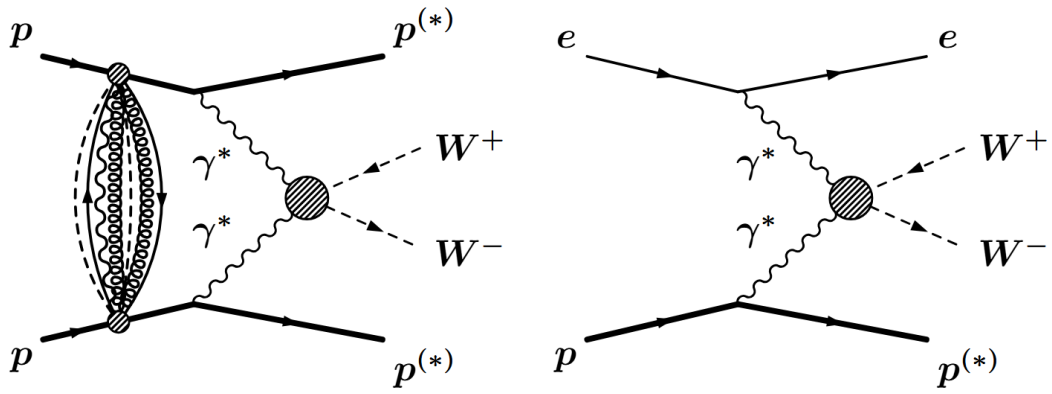
HIGH ENERGY $\gamma\gamma$ INTERACTIONS AT THE LHEC

- 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 γγ interactions at the LHeC*", paper in preparation.

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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 electrons and protons, $\Phi_e(y_e)$ 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 $y_e = \frac{E_{\gamma(e)}}{E_e}$; $y_p = \frac{E_{\gamma(p)}}{E_p}$

- 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].

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AQGC SENSITIVITY AT LHEC AND EFT FRAMEWORK

arXiv:1309.7890 [hep-ph]

- The general effective Lagrangian that governs $\gamma\gamma \to W^+W^-$ interaction is expressed as:

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

- These operators introduce new interaction vertices modifying the $\gamma\gamma \to W^+W^-$ process.

- The dimension-8 operators are often expressed using the coefficients $f_{S,j}$; $f_{M,j}$ and $f_{T,j}$ normalized by the new physics energy scale Λ^4.

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

Couplings (TeV^{-4})	CMS@13TeV@100 fb^{-1}
$\frac{f_{M0}}{\Lambda^4}$	66 (TeV^{-4})
$\frac{f_{M1}}{\Lambda^4}$	245 (TeV^{-4})
$\frac{f_{M2}}{\Lambda^4}$	9.8 (TeV^{-4})
$\frac{f_{M3}}{\Lambda^4}$	73 (TeV^{-4})

CMS and TOTEM Collaborations, 2211.16320 [hep-ex], *JHEP* 07 (2023) 229.

- Broadly studied at pp@LHC :
  - CMS@CERN : JHEP 07 (2013) 116, JHEP 08 (2016) 119, JHEP 07 (2023) 229.
  - ATLAS@CERN : Phys. Rev. D 94 (2016) 032011, Phys. Lett. B 816 (2021) 136190.

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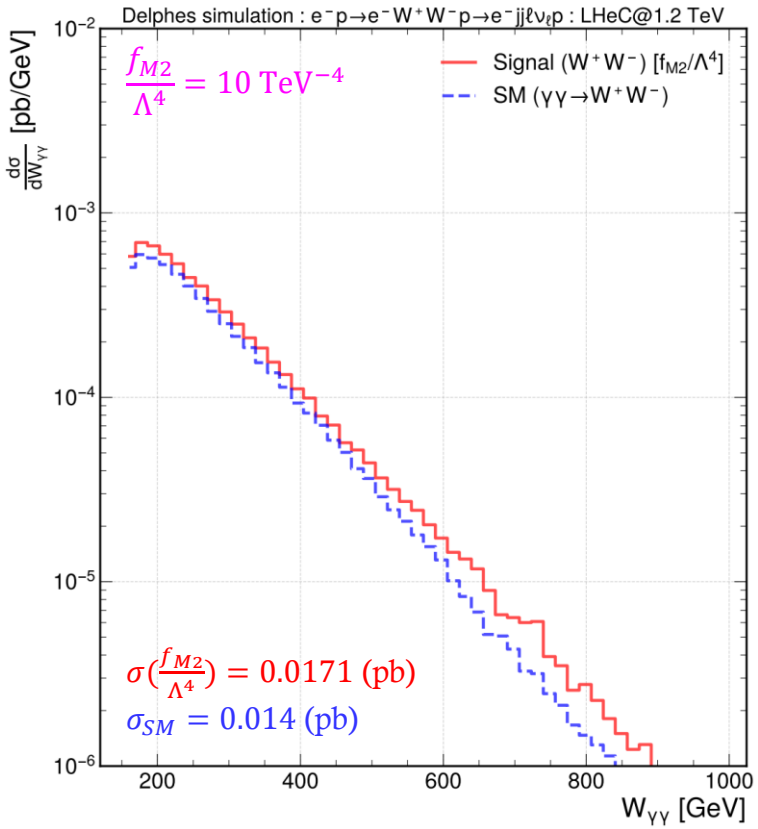
SIGNAL TOPOLOGY : AQGC@LHEC

- Semileptonic W-pair production is considered as a probe of aQGCs at the LHeC.

- Signal topology : $e^- p \to e^- W^+ W^- p \to e^- \, jj \, l\nu_l \, p$

Basic Event Selection

- ✅ Exactly one lepton (e or μ), $p_T^\ell > 10\ \mathrm{GeV},\ |\eta_\ell| < 5$
- ✅ Exactly two jets, $p_T^j > 10\ \mathrm{GeV},\ |\eta_j| < 5$
- 🔹 Missing Transverse Energy (MET): $\mathrm{MET} > 10\ \mathrm{GeV}$



- The differential cross-section $\frac{d\sigma}{dW}$ (pb/GeV) as a function of photon-photon center of mass energy $W_{\gamma\gamma}$ [GeV].

- A detector for top energy DIS, Laurent Forthomme [EPS-HEP 2025]

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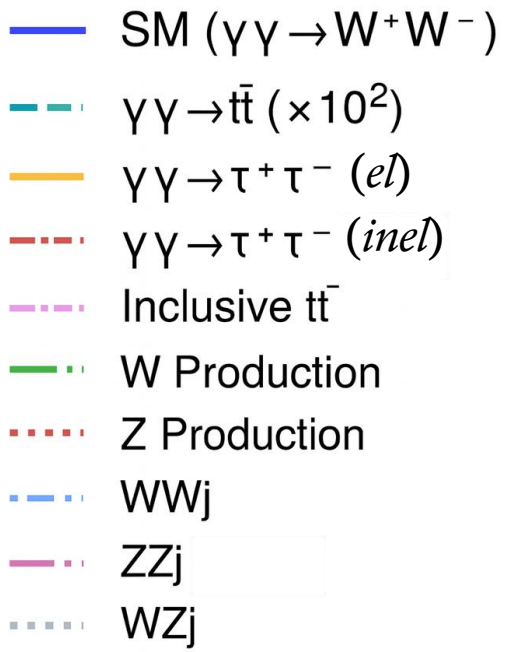
MAIN SOURCES OF BACKGROUNDS

- Exclusive backgrounds : SM $\gamma\gamma \to W^+W^-$ production, $\gamma\gamma \to \tau^+\tau^-$; $\gamma\gamma \to t\bar{t}$; …
- Inclusive backgrounds : Inclusive top quark production (single-top, $t\bar{t}$), associated V + j and VV + j production (V=W, Z).
- New event selections can profit from specific topology of asymmetric electron-proton collisions at LHeC.
- LHeC would offers significantly reduced backgrounds relative to proton-proton collisions at the LHC, enabling cleaner final states.



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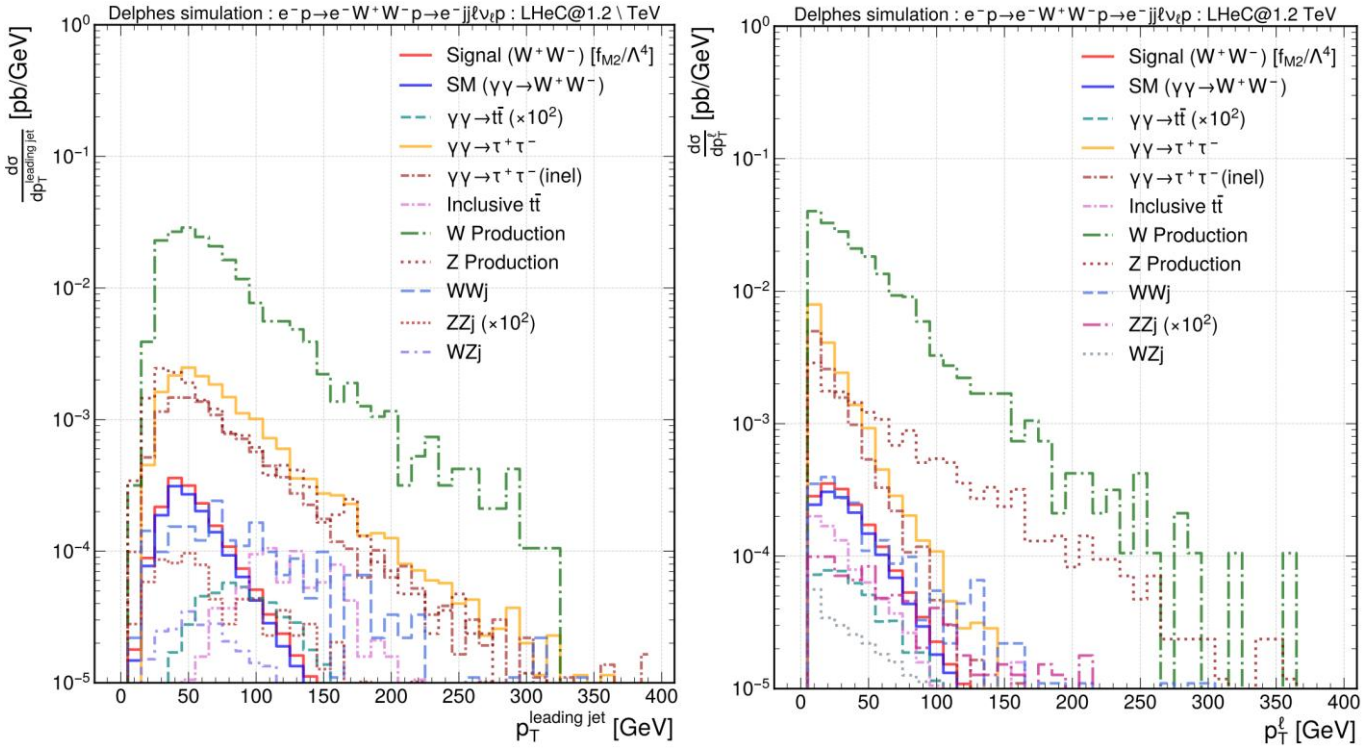
FAST SIMULATION

- Signal and background events are generated using MadGraph5_aMC@NLO.
- For the $\gamma\gamma \to \tau^+\tau^-$ (with full tau decays with Tauola), we used CepGen event generator [Laurent Forthomme :1808.06059 [hep-ph]].
- We apply a fast detector simulation using the Delphes framework.
- We use the dedicated LHeC detector card available on [https://delphes.github.io/].
- A set of kinematic variables is chosen to optimize signal-background discrimination.



- Transverse momentum distributions of the lepton and leading jet. Signal sample are generated with $\frac{f_{M2}}{\Lambda^4} = 10\ TeV^{-4}$, assuming all other operators are zero.

- A detector for top energy DIS, Laurent Forthomme (EPS-HEP 2025)

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MULTIVARIATE ANALYSIS (MVA)

- To enhance the discrimination between the aQGC-induced signal and Standard Model backgrounds, we employ a multivariate analysis (MVA) based on Boosted Decision Trees (BDTs).

- Key observables are selected to improve the performance of the BDT-based analysis.

- Variables with the highest discrimination power are prioritized using feature importance ranking from the trained BDT.

📊 Input Variables:

Input observables include kinematic and angular variables such as:

- p_T^j: Transverse momentum of the leading jet
- $p_T^{j_2}$: Transverse momentum of the subleading jet
- η^j, η^{j_2}: Pseudorapidity of the leading and subleading jets
- η^ℓ: Lepton pseudorapidity
- E_T^{miss}: Missing transverse energy (MET)
- m_{jj}: Invariant mass of the two jets
- $m_W^{\text{lep}} = m_{\ell\nu}$: Invariant mass of leptonic W
- $m_W^{\text{had}} = m_{jj}$: Invariant mass of hadronic W
- $m_{\ell\nu jj}$: Invariant mass of the full reconstructed WW system
- $\Delta R_{\ell j}$: Separation between lepton and jet
- $\Delta\eta_{jj}$: Rapidity difference between jets
- $\Delta\phi_{\ell,\text{MET}}$: Azimuthal angle between lepton and MET
- $\Delta\phi_{jj}$: Azimuthal angle between the jets
- $\Delta\phi_{W^{\text{lep}},W^{\text{had}}}$: Azimuthal angle between W^{lep} and W^{had}
- $\Delta\eta_{W^{\text{lep}},W^{\text{had}}}$: Rapidity difference between W bosons
- $m_T^{W^{\text{lep}}}$: Transverse mass of leptonic W
- H_T: Scalar sum of visible transverse momenta

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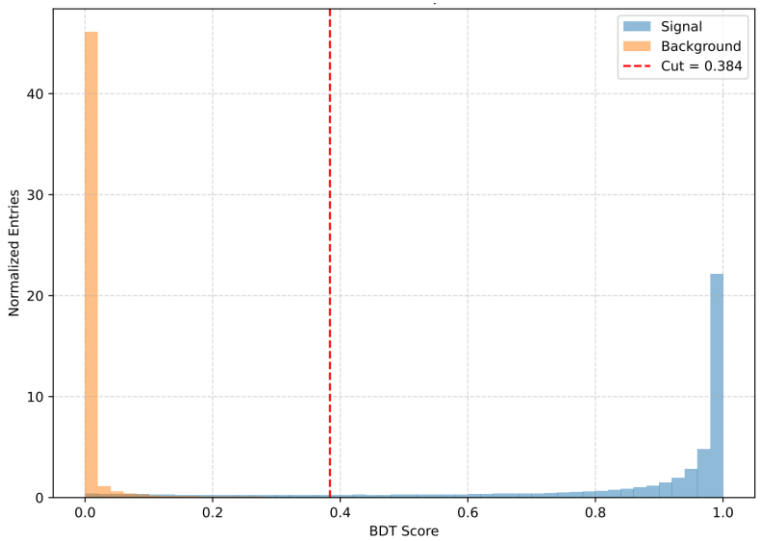
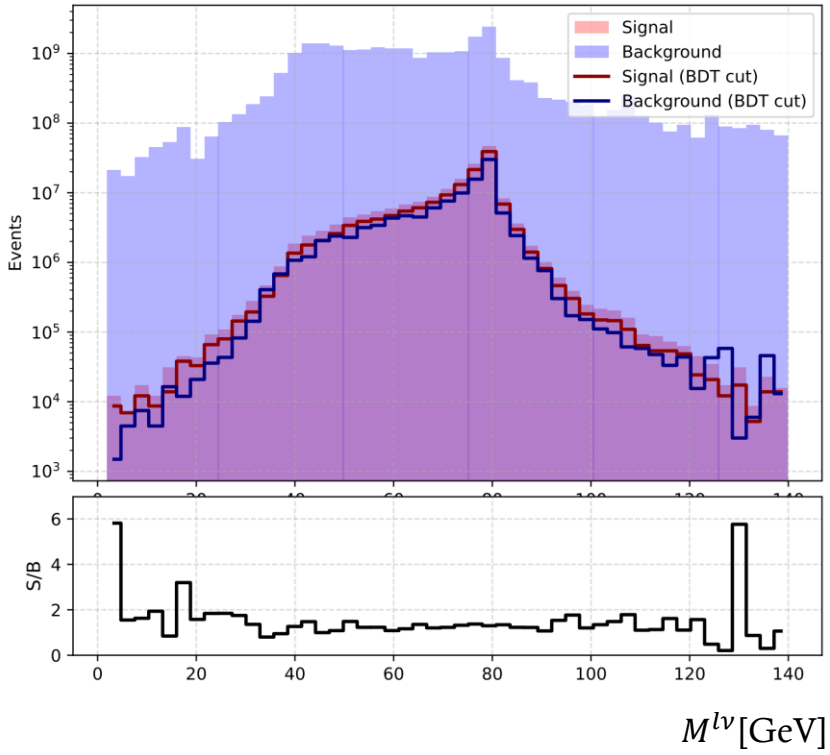
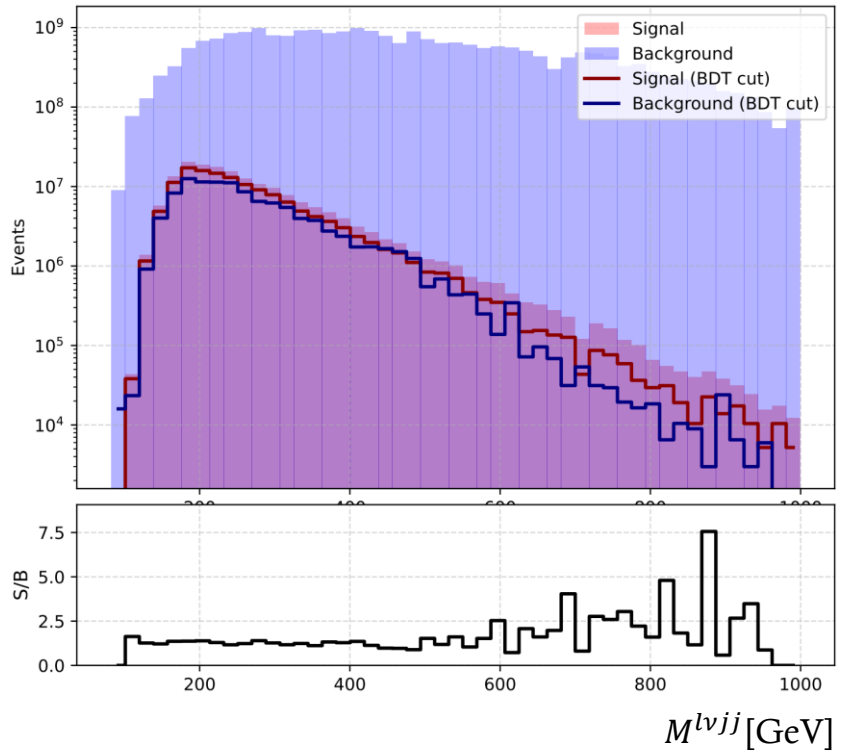
PRE VS. POST-SELECTION COMPARISON



- BDT Output Score & classifier discrimination power





- The distributions of selected kinematic observables before and after applying the BDT cut. Each plot compares the raw (pre-BDT) and selected (post-BDT) distributions for signal and background events. The lower panels display the corresponding signal-to-background ($\frac{S}{B}$) ratios after BDT selection.

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SUMMARY & OUTLOOK

- This study presents projections for probing dimension-8 anomalous quartic gauge couplings (aQGCs) at the LHeC through exclusive two photons production of W pairs, $\gamma\gamma \to W^+W^-$, with EPA-based modeling.
- Large photon-photon luminosities and center-of-mass energies up to 1 TeV, including low pile-up and clean experimental conditions make the LHeC an ideal environment for studying exclusive photon-induced interactions, such as $\gamma\gamma \to W^+W^-$.

- LHeC will significantly improve aQGC limits - and uniquely enable exploration beyond current experimental reach.
- Further, very significant background suppression will be achieved by implementing exclusivity conditions - (and by requesting detection of "elastic" protons). ✨ *Work in progress -- stay tuned...*

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THANK YOU!