ALPs at Future $e^{-}p$ Colliders

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WITS UNIVERSITY

ATLAS EXPERIMENT

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Axion-Like Particles

- Axion-Like Particles (or ALPs) are **neutral pseudo scalar** pseudo-nambu Goldstone bosons.

- Interaction to SM particles arise from explicit **Global Peccie-Quinn $U(1)_{PQ}$** symmetry.

- Either shift invariant and/or anomalous couplings interactions

$$\begin{cases} \dfrac{\partial_\mu a}{f_a}\bar{\psi}\gamma^\mu\psi \\ \dfrac{a}{f_a}X_{\mu\nu}\widetilde{X}^{\mu\nu} \end{cases}$$

- ALPs interactions with SM particles have a derivative character: They grow with momentum

Motivations for Axions and ALPs

Axion-Like Particles

$$\mathcal{L}_{eff} \supset e^2 \frac{a}{f_a} g_{\gamma\gamma} F_{\mu\upsilon}\tilde{F}^{\mu\upsilon} + \frac{2e^2}{c_w s_w}\frac{a}{f_a} g_{\gamma Z} F_{\mu\upsilon}\tilde{Z}^{\mu\upsilon} + \frac{e^2}{s_w^2 c_w^2}\frac{a}{f_a} g_{ZZ} Z_{\mu\upsilon}\tilde{Z}^{\mu\upsilon} + \frac{e^2}{s_w^2}\frac{a}{f_a} g_{WW} W_{\mu\upsilon}\widetilde{W}^{\mu\upsilon}$$

f_a = 1 TeV : New Physics Scale

- Classical Searches: ALPs coupling to gluons and photons

$$WW, ZZ, \gamma Z \text{ and } \gamma\gamma$$

- ALPs couplings to EWK bosons:

$$g_{\gamma\gamma} = C_{WW} + C_{BB}, \qquad g_{Z\gamma} = c_w^2 C_{WW} - s_w^2 C_{BB},$$

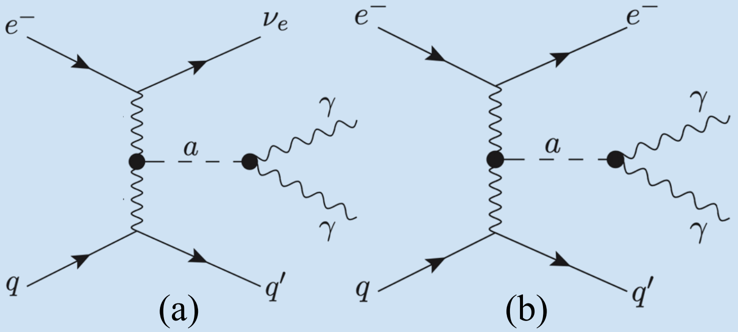
$$g_{ZZ} = c_w^4 C_{WW} + s_w^4 C_{BB},. \qquad g_{WW} = C_{WW}.$$

- ALP-gauge interactions at ATLAS and CMS:
  - Mono-X
  - Resonant

- **New Idea: Non-resonant**

Our Approach

- Leading order and matrix-element level singe ALP production in
  - Charged Current (CC) through (a) $W^{\pm}$ - Fusion
  - Neutral Current (NC) through (b) $ZZ, \gamma Z$ and $\gamma\gamma$.



$$q, q' \equiv u, \bar{u}, d, \bar{d}, s, \bar{s} \text{ or } b\bar{b}$$

- Signals independent on ALP mass and width up to

$$m_a \ll 300\ GeV$$

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Our Approach

- The relevant decay width are modelled as follows:

$$\Gamma(a \longrightarrow \gamma\gamma) \equiv \Gamma_{\gamma\gamma} = \frac{e^4}{4\pi f_a^2} \left|g_{\gamma\gamma}\right|^2 m_a^3., \qquad \Gamma(a \longrightarrow \gamma Z) \equiv \Gamma_{\gamma Z} = \frac{e^4}{2\pi f_a^2 c_{\theta_W}^2 s_{\theta_W}^2} \left|g_{\gamma Z}\right|^2 m_a^3 \left(1 - \frac{m_Z^2}{m_a^2}\right)^3$$

$$\Gamma(a \longrightarrow ZZ) \equiv \Gamma_{ZZ} = \frac{e^4}{4\pi f_a^2 c_{\theta_W}^4 s_{\theta_W}^4} |g_{ZZ}|^2 m_a^3 \left(1 - 4\frac{m_Z^2}{m_a^2}\right)^{3/2},$$

$$\Gamma(a \longrightarrow W^{\pm}) \equiv \Gamma_{W^{\pm}} = \frac{e^4}{8\pi f_a^2 s_{\theta_W}^4} |g_{WW}|^2 m_a^3 \left(1 - \frac{m_W^2}{m_a^2}\right)^{3/2}$$

NOTE: We considered variable decay widths

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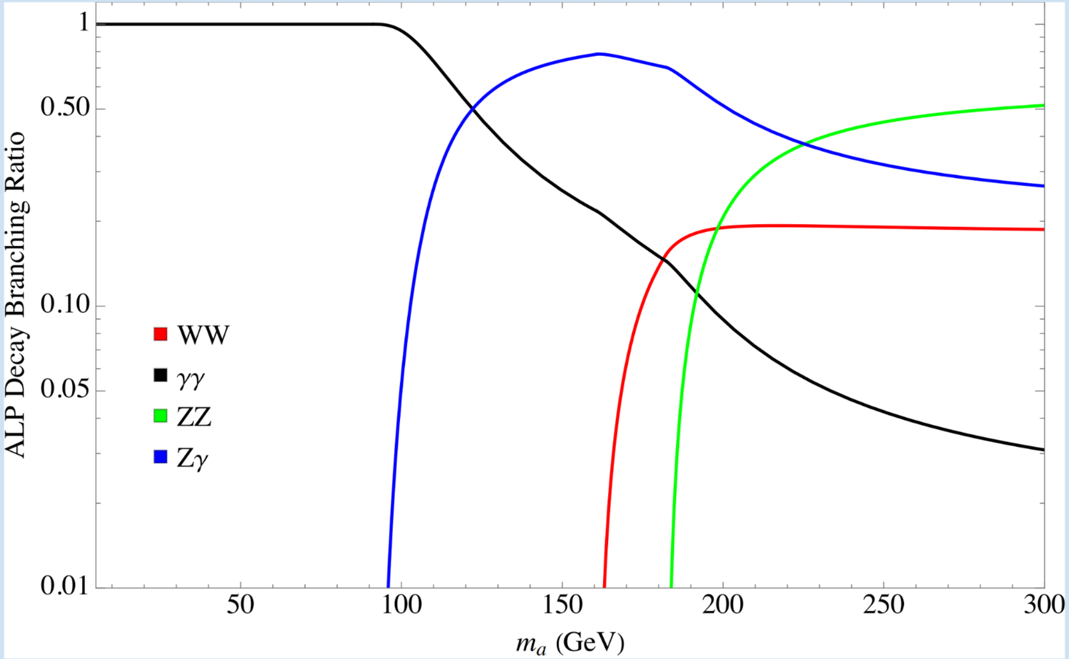
Our Approach



- Branching ratio for the considered ALPs production channels.

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Our Approach

- The local significance and discovery limits are given as follows:

$$N_{SD} = \frac{S}{\sqrt{S + B + (\delta_S \cdot S)^2 + (\delta_S \cdot B)^2}}$$

- The χ^2 definition used to constraint ALP-gauge couplings g_{ij} is given as:

$$\chi^2 = \sum_{k=1}^{n} \left(\frac{N_k(g_{ij}) - N_k^{SM}}{\Delta N_k} \right)^2, \qquad \Delta N_k = \sqrt{N_k^{SM}(1 + \delta_S^2 N_k^{SM})}$$

Note: 2 cases considered – (1) **one-bin χ^2 analysis** and (2) **multiple-bin χ^2 analysis**.

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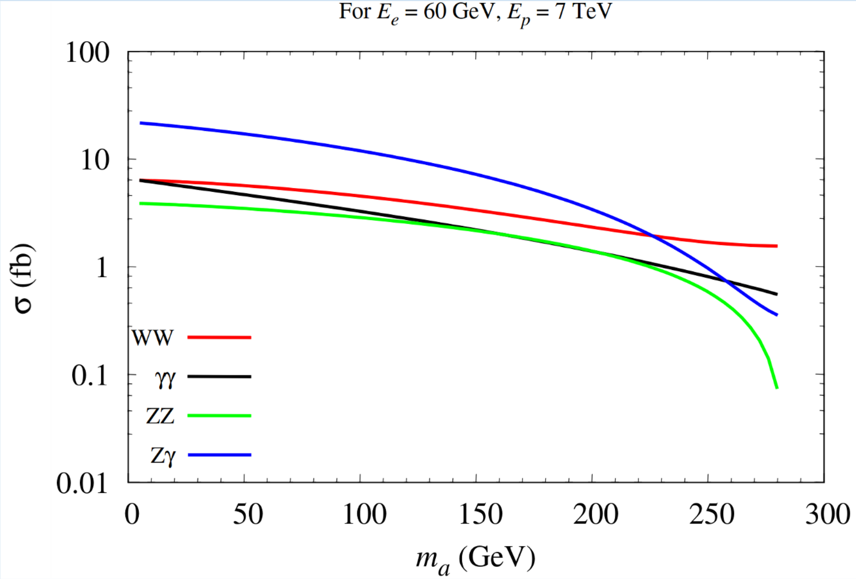
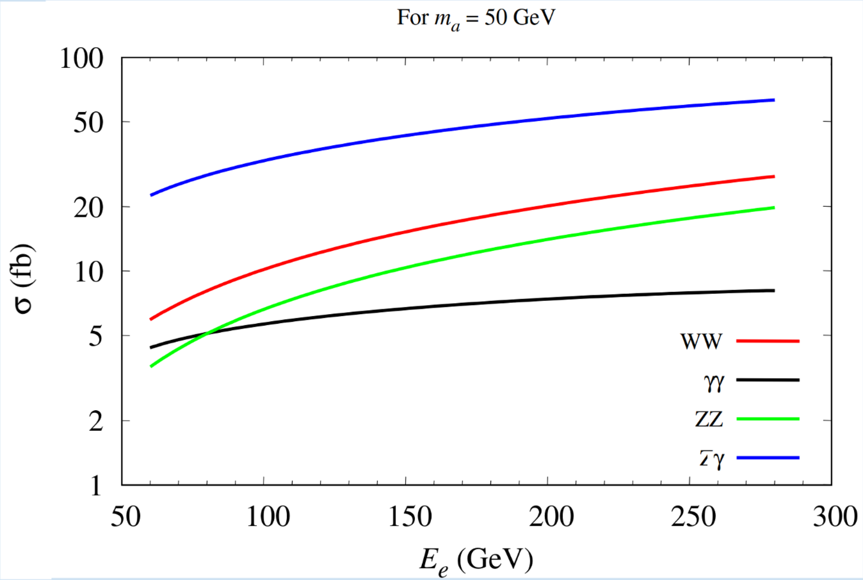
Our Approach





- ***$Z\gamma$*** **Can not be separate at production level due to the interference of** ***$\gamma\gamma$***

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ALP production in $e^{-}p$ collider

- ALP-gauge couplings are probed by direct production of ALP through VBF processes.

- We base our study on LHeC environment, employing **7 TeV** proton beam from LHC and electrons from Energy Recovery Linac (ERL): $\sqrt{s} = 1.3$ **TeV**.

FeynRules ⟶ **MadGraph5_aMC@NLO** ⟶ **Pythia-PGS** ⟶ **Delphes**

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Analysis, Observable and Results

- To optimize signal events over leading SM backgrounds, additional cuts were applied as follows:
  - for all channels: $p_T^{j,e^-,\gamma} > 20\ GeV$
  - $\boldsymbol{WW}$: $0 < |\eta_\gamma| < 3,\ \ 0 < |\eta_j| < 4$
  - $\boldsymbol{\gamma\gamma}$: $-2 < |\eta_\gamma| < 3, -2 < |\eta_j| < 5, -2.5 < |\eta_{e^-}| < 2$
  - $\boldsymbol{ZZ}$: $0 < |\eta_\gamma| < 3,\ \ 0 < |\eta_j| < 5,\ \ \ 0 < |\eta_{e^-}| < 5$
  - $\boldsymbol{\gamma Z}$: $0 < |\eta_\gamma| < 3,\ 0 < |\eta_j| < 5,\ \ -2.5 < |\eta_{e^-}| < 1$
- Analysis was performed at 5% allowed systematic error, $1ab^{-1}$ luminosity and 80% left polarized electron beam

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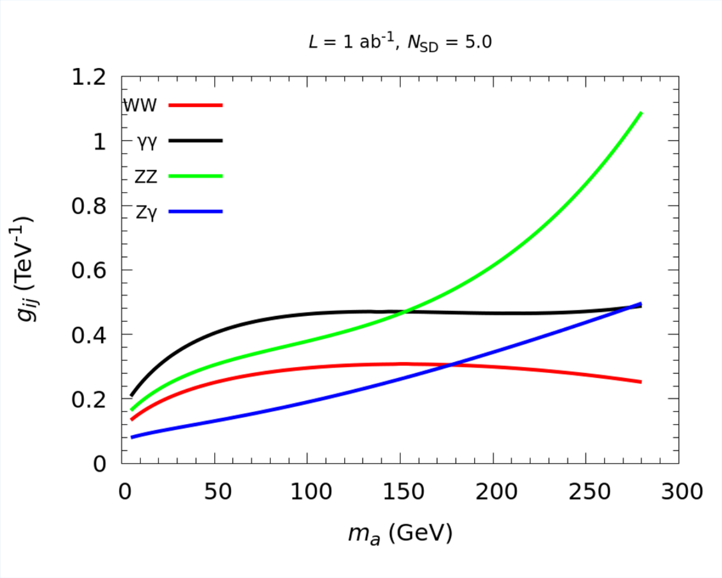
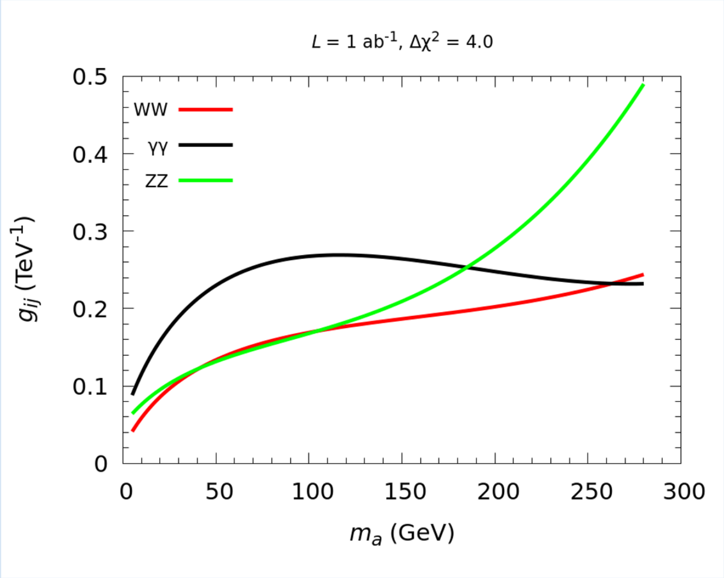
Analysis, Observable and Results





- **Upper bounds on effective couplings as a function of Axion mass, based on the local significance at 5σ discovery limit (left) and total differential cross section (right).**

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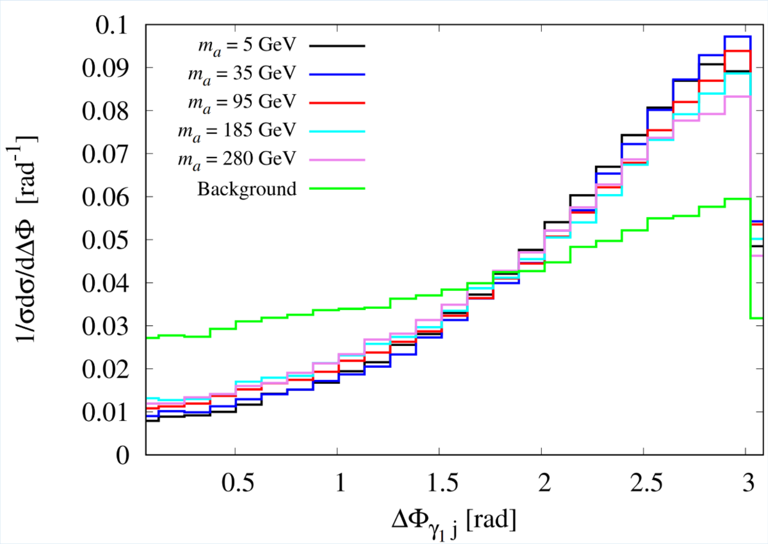
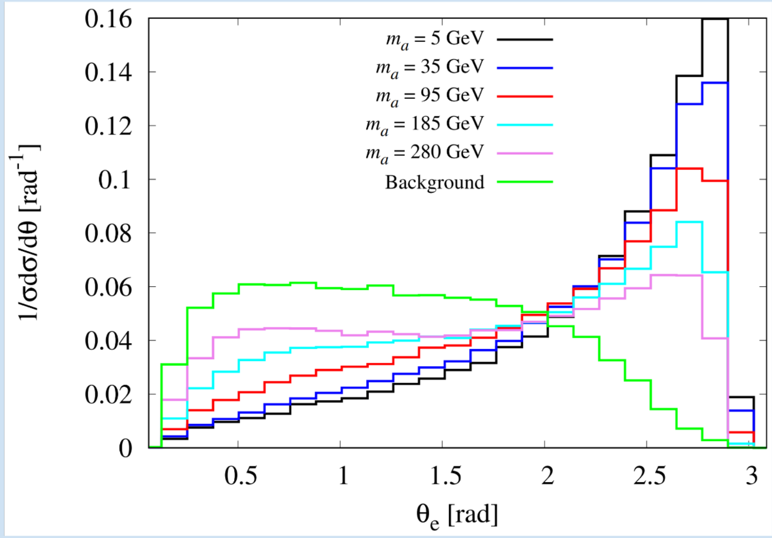
Analysis, Observable and Results





- **Differential distributions for WW-fusion and $\gamma\gamma$ -fusion, respectively.**

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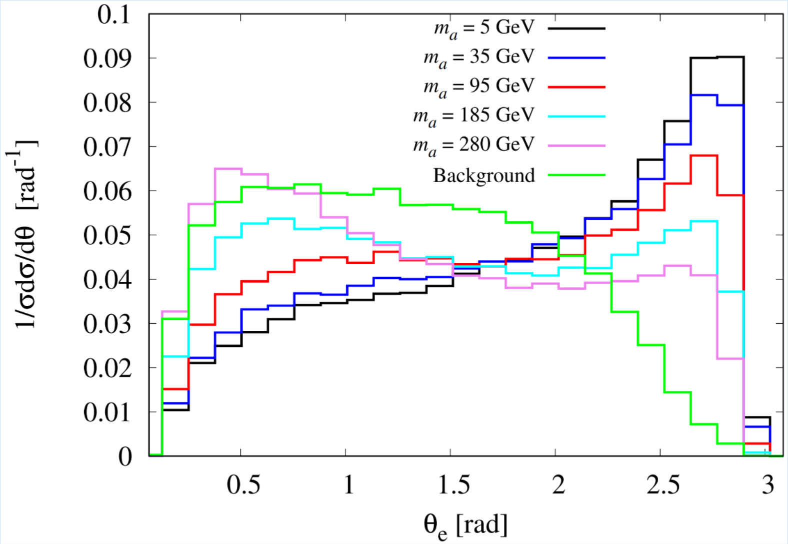
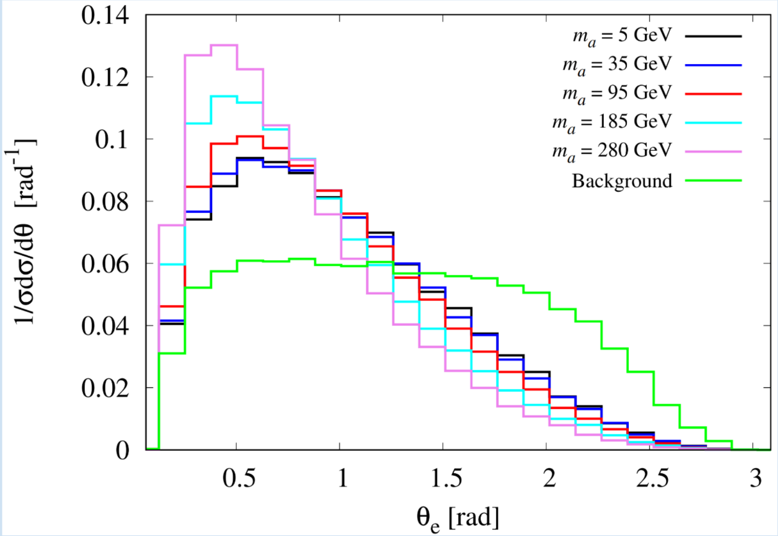
Analysis, Observable and Results





- **Differential distributions for $Z\gamma$ - fusion and ZZ - fusion, respectively.**

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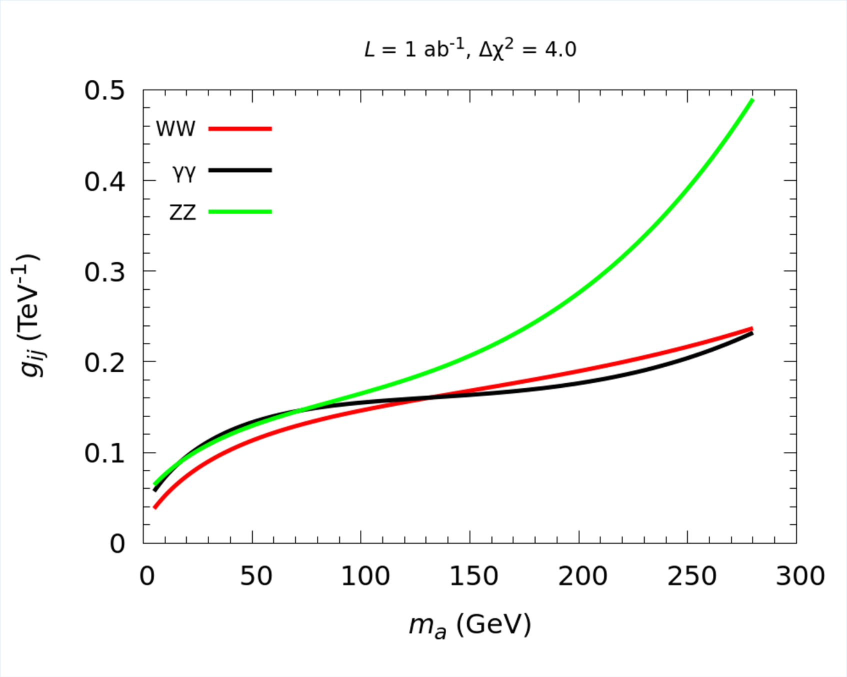
Analysis, Observable and Results



- **Upper bounds on effective couplings, g_{ij} as a function of axion mass, m_a based on sensitive differential distributions**

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Analysis, Observable and Results

- The $g_{\gamma Z} = g_i$ and $g_{\gamma\gamma}$ separation problem was solved by considering:

$$\sigma_{BSM} = g_{\gamma\gamma}^2(g_i^2\sigma_i^2 + g_i g_{\gamma\gamma}\sigma_{i\gamma\gamma} + g_{\gamma\gamma}^2\sigma_{\gamma\gamma})\times\mathcal{B}_{a\to\gamma\gamma}$$

$g_{\gamma\gamma}$	$g_{\gamma Z} = g_i$
1	1
1	0
-1	1

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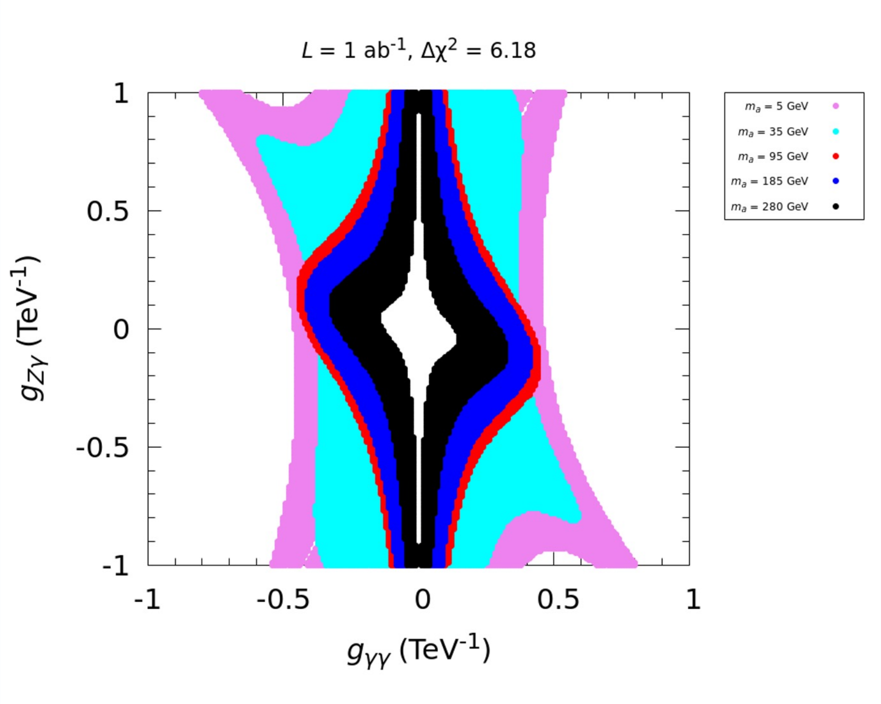
Analysis, Observable and Results



- **2-parameter upper bound with all 3 cases taken into consideration due to the SEPARATION PROBLEM**

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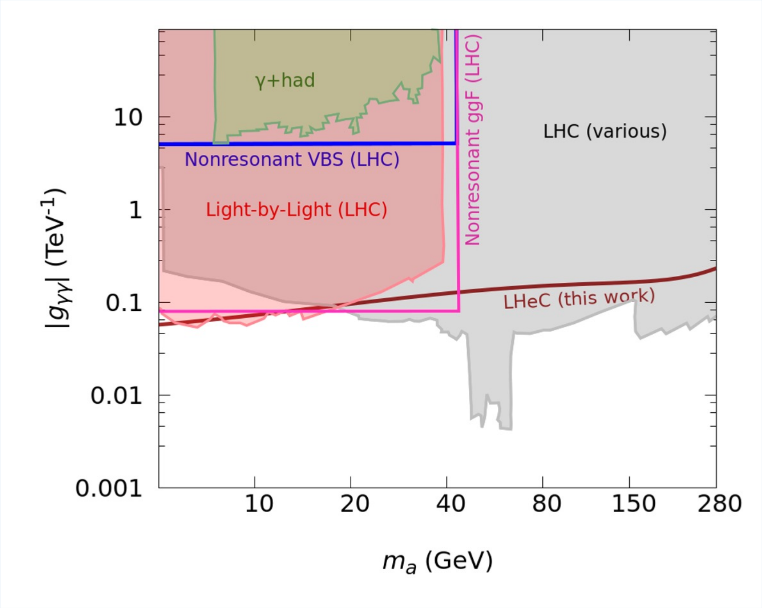
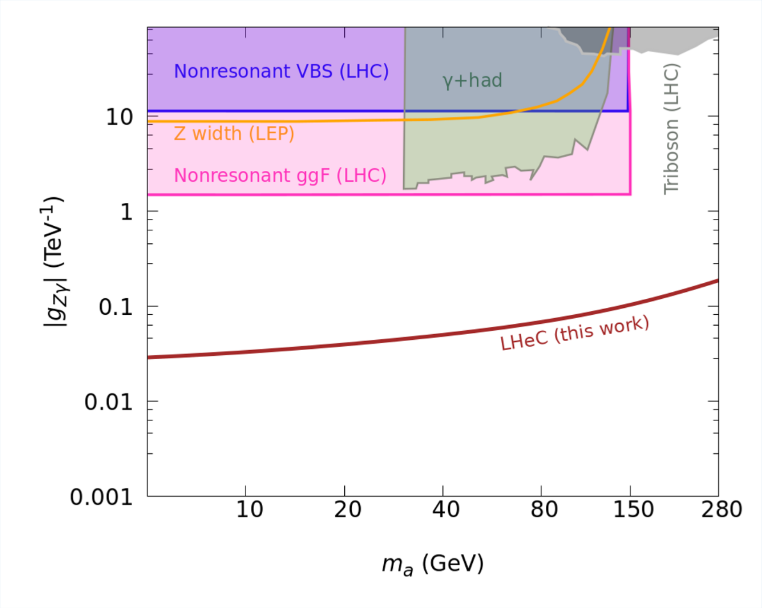
Experimental Comparison





- Various LHC, Light-by-light scattering (LHC), Nonresonant VBS, Nonresonant ggF (LHC), γ + had (LHC) , LHeC (This work), Triboson (LHC) and Z width (LEP).

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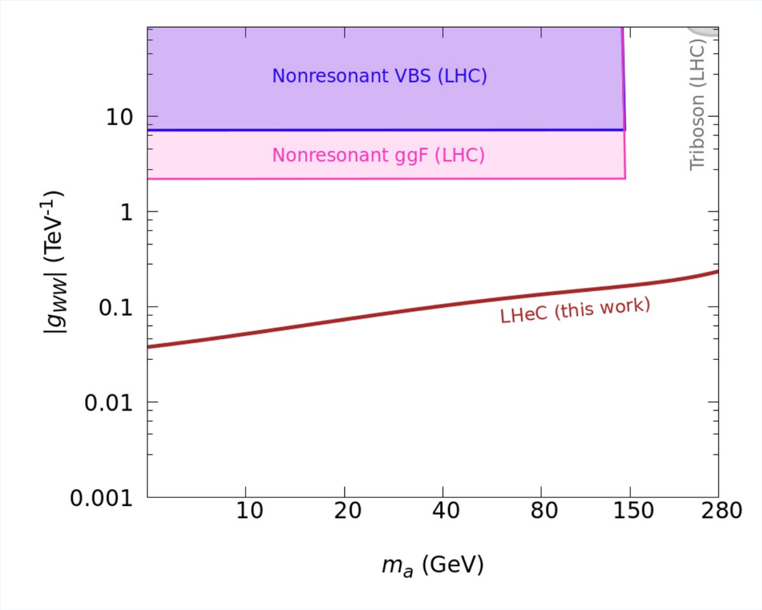
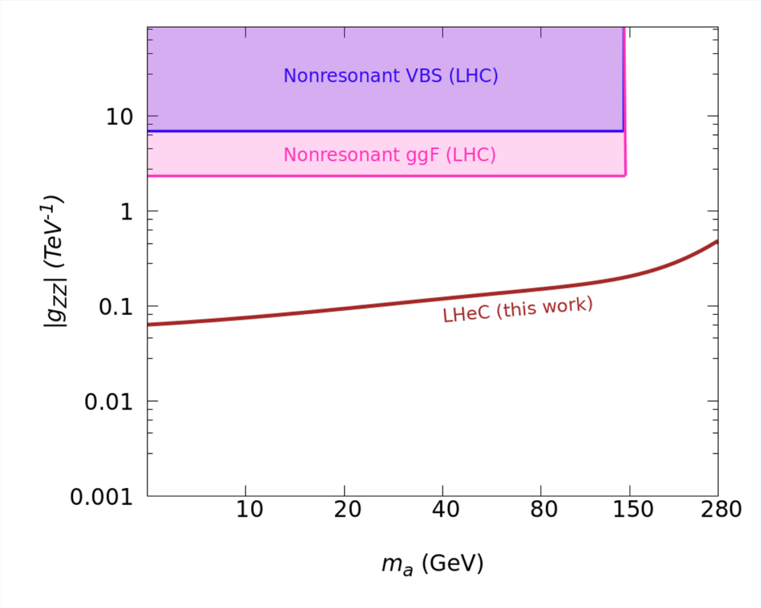
Experimental Comparison





- **Nonresonant VBS**, **Nonresonant ggF (LHC)**, **Triboson (LHC)**

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Conclusion

- We conclude that a electron-proton collider running at high energies with a high luminosity would have great potential in searching for the ALPs.

- These limits serve as approximate predictions that can be investigated further if the electron energy (E_e) is increased to higher values.

- The limits on g_{WW}, g_{ZZ} and $g_{\gamma Z}$ comparing to available studies in different collider scenario are better at LHeC for considered range of ma, whereby, the limits on $g_{\gamma\gamma}$ are competitive with respect to few scenario.

- VBF process used to probe ALPs provides a complementary window to the opportunities offered by other high energy collider experiments.

- Although, exploring high masses beyond 200 GeV is less likely due to the limited cross section achievable with the available energy and luminosity

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Welcome to the "Future"

Thank You!

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