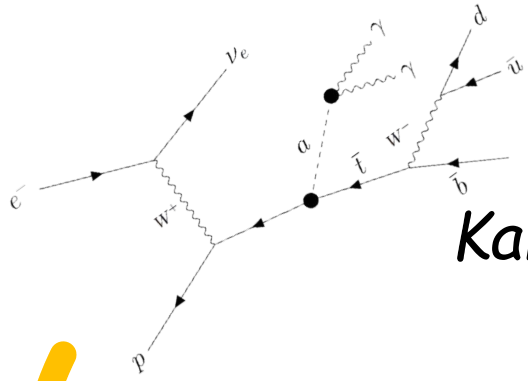
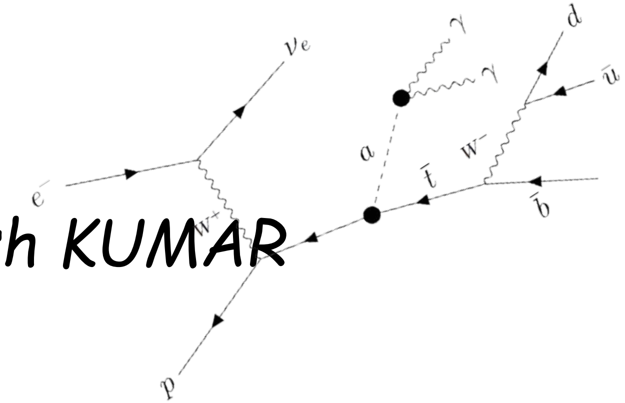
Probing ALPs couplings to top-quark at future e- p colliders





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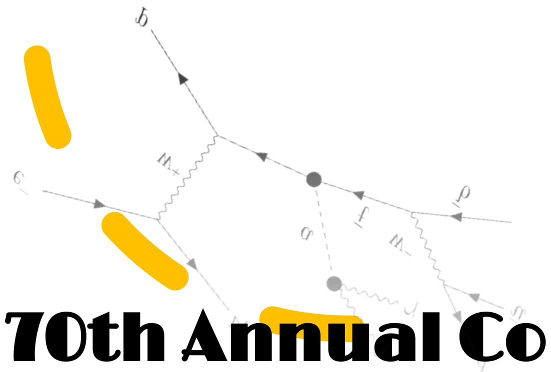
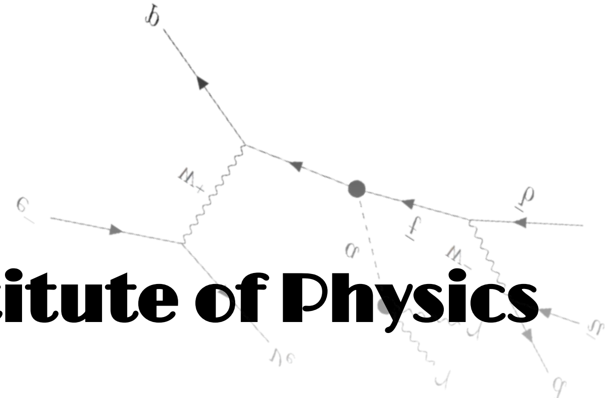




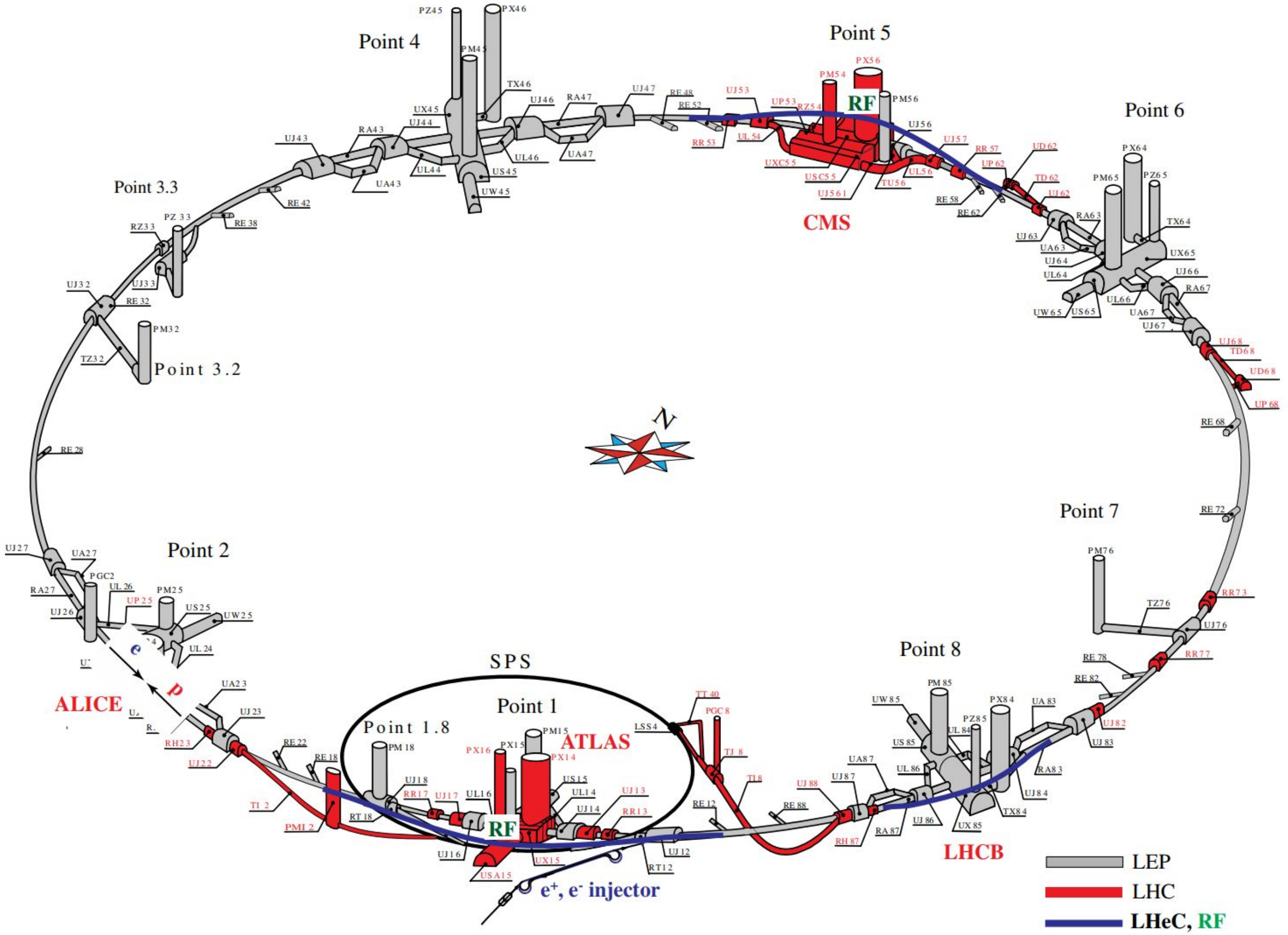
70th Annual Conference of the South African Institute of Physics

Overview

- LHeC Environment
- What are ALPs?
- Previous Studies & Motivation
- Signal Process & Top polarisation
- Analysis, Observable and Results
- Summary & Conclusion

LHeC Environment

- The LHeC – proposed to deliver 7 TeV proton beam and 40-150 GeV electron beam, delivering $\sqrt{s} \approx 1.3$ TeV and maximum $1\ \text{ab}^{-1}$ of integrated luminosity.
- Providing cleaner environment than LHC; no pileup; reduced QCD background.



What are ALPs?

- **Axion-Like Particles (ALPs) are pseudo-Nambu Goldstone bosons arising from the spontaneous breaking of global symmetries in many BSMs: axion (PQ Symmetry), majoron (dynamic neutrino masses , lepton number), string theory, flavon (flavour symmetry), extra dimensions, etc….**
- **The Lagrangian consist of all SM states + a single ALP field** a **and is gauge invariant under** $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ **derivative and anomalous couplings to SM particles:**

$$\mathcal{L}_{ALP} = \mathcal{L}_{SM} + \frac{1}{2}(\partial a)^2 - \frac{1}{2}m_a^2 a^2 + \left(\frac{\partial_\mu a}{f_a}\right) \times SM^\mu + \left(\frac{a}{f_a}\right) \times V^{\mu\nu}\tilde{V}_{\mu\nu}$$

- **ALPs can solve (i) the Strong CP problem , (ii) serve as Dark Matter candidate, etc.**

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Symmetry breaking scale or ALP decay constant

V = G, W, B. Analogous coupling-like interactions to gauge bosons (gg, $\gamma\gamma$, Zγ, WW, BB)

- ALPs can solve (i) the Strong CP problem , (ii) serve as Dark Matter candidate, etc.

Previous Analysis

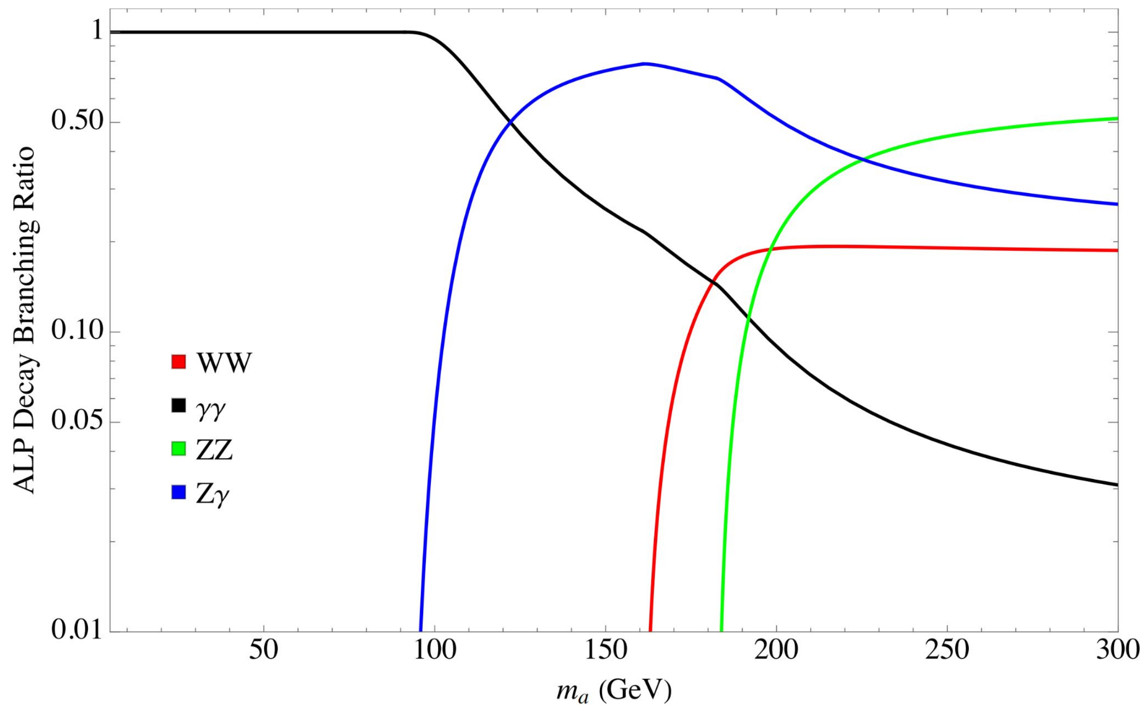
- The relevant decay width are modelled as follows:

$$\Gamma(a \to \gamma\gamma) \equiv \Gamma_{\gamma\gamma} = \frac{e^4}{4\pi f_a^2} |g_{\gamma\gamma}|^2 m_a^3$$

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

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

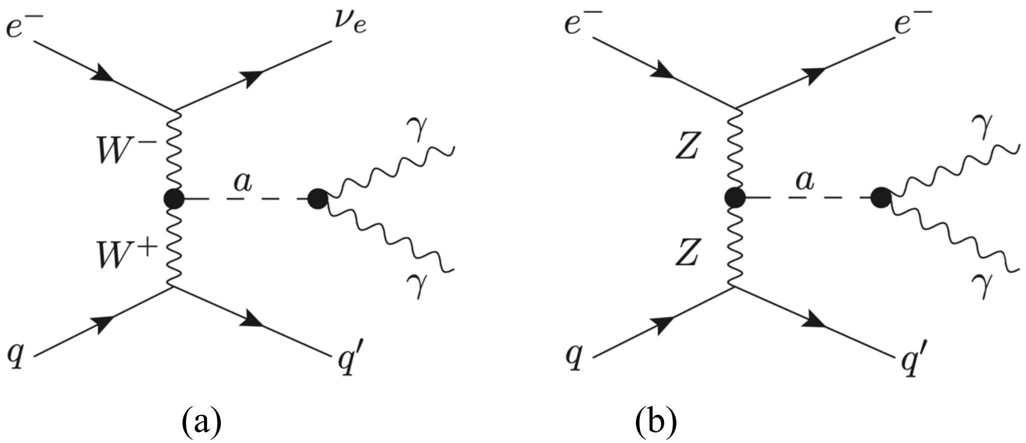
$$\Gamma(a \to W^+W^-) \equiv \Gamma_{WW} = \frac{e^4}{8\pi f_a^2 s_{\theta_W}^4} |g_{WW}|^2 m_a^3 \left(1 - 4\frac{m_W^2}{m_a^2}\right)^{\frac{3}{2}}$$



arXiv:2307.00394v1 / https://link.springer.com/article/10.1140/epjc/s10052-024-12401-9

Previous Analysis

- **Focused on ALP production in:**
  - **Charged Current (CC) through (a)** $W^{\pm}$ **- Fusion**
  - **Neutral Current (NC) through (b)** $ZZ, \gamma Z$ and $\gamma\gamma$



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

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Previous Analysis

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

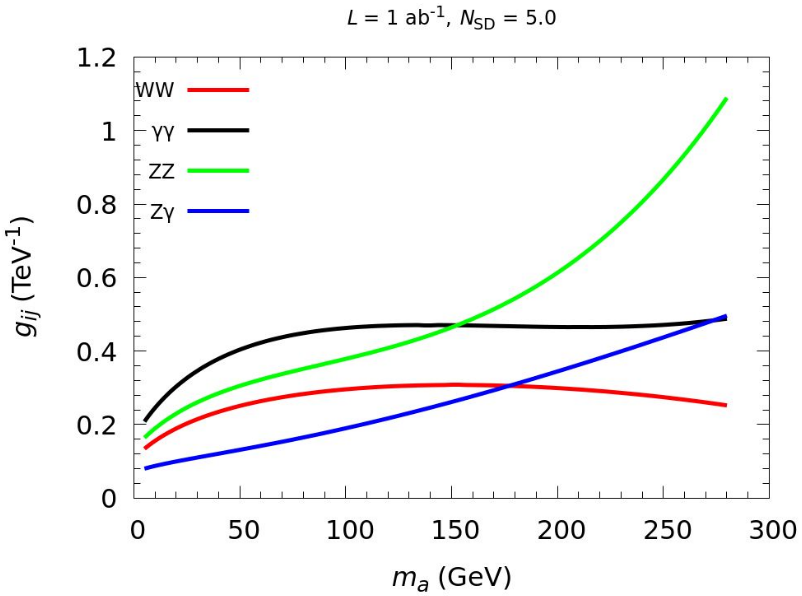
$$N_{\mathrm{SD}} = \frac{S}{\sqrt{S + B + (\delta_s \cdot S)^2 + (\delta_s \cdot B)^2}}$$

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

$$\chi^2 = \sum_{k=1}^{n} \left(\frac{N_k(g_{ij}) - N_k^{\mathrm{SM}}}{\Delta N_k} \right)^2$$

Where

$$\Delta N_k = \sqrt{N_k^{\mathrm{SM}} \left(1 + \delta_s^2 N_k^{\mathrm{SM}}\right)}$$



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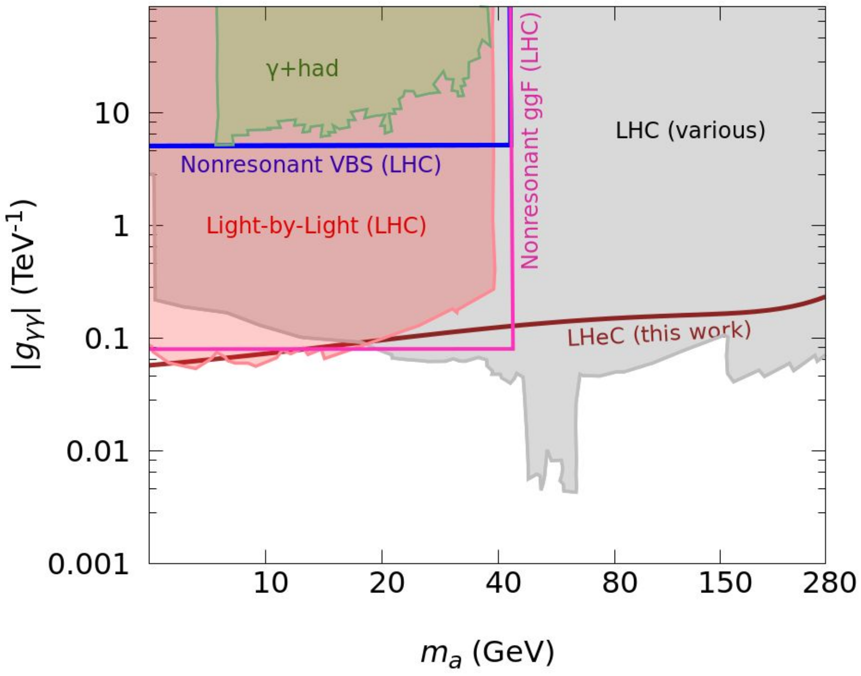

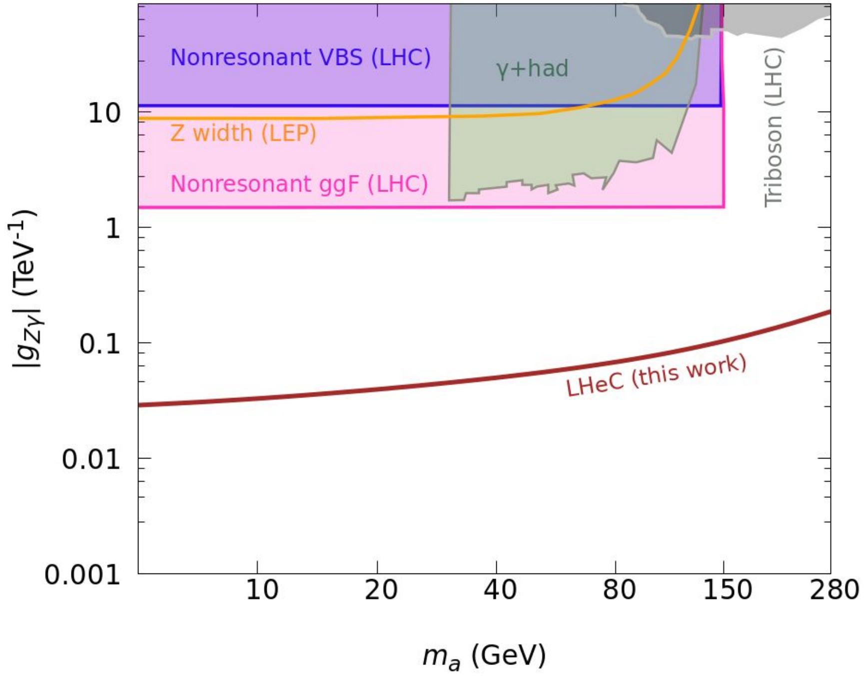

- $g_{Z\gamma}$ **provided best overall but not better than ALP-SMEFT and** $g_{\gamma\gamma}$ **provided the poorest constraints.**

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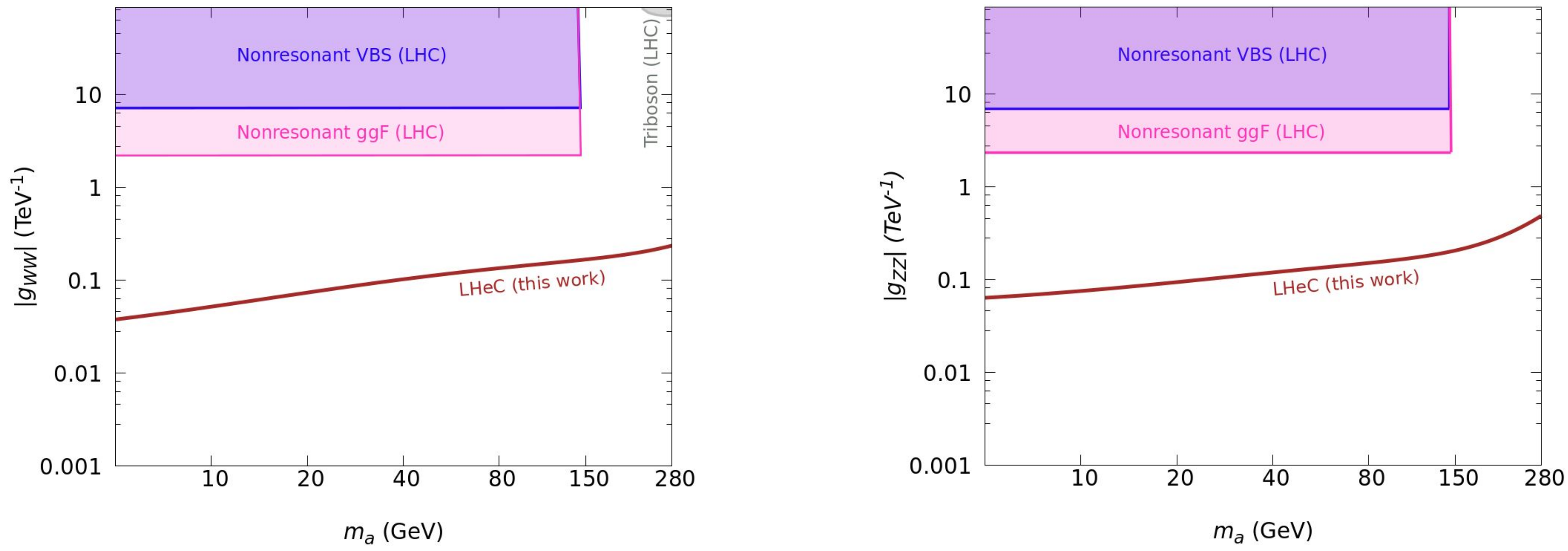
Previous Analysis



- g_{WW} and g_{ZZ} **provided better sensitivity when compared to available studies.**

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Motivation

- Most existing ALP searches (LHC diphoton resonances, beam-dump experiments, astronomical bounds) constrain $C_{\gamma\gamma}/f_a$ and light-quark/gluon couplings – Top quark coupling C_{tt}/f_a remains largely unconstrained.
  - Producing an ALP alongside an on-shell top quark requires partonic energies beyond what most existing photon/gluon-fusion based searches are built to probe.
- C_{tt}/f_a is theoretically well motivated in its own right – composite and PQ-type constructions often couple ALPs preferentially to the heaviest SM states.

Top polarisation: a unique handle

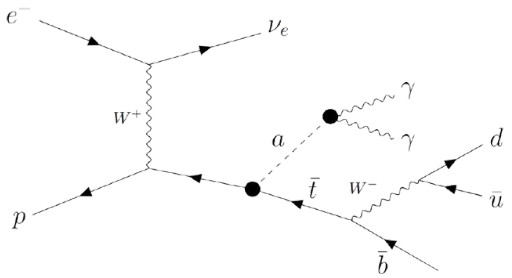
- **Because the ALP is produced in association with top quark we get access to the top's polarisation/spin information as an extra discriminating observable.**
  - This is something the photon or gluon-fusion ALP production simply doesn't have.
- **Top polarisation is measured via the angular distribution of its decay products in the top rest frame:** $\cos\theta^*$**, the angle between the top's spin-analyser direction and its momentum (helicity frame).**
  - Spin analyser used - Hadronic channel: the anti-b quark direction $\cos\theta^*_{\bar{b}}$
  - Spin analyser used - Leptonic channel: The charged lepton l^- from $\bar{t} \to \bar{b} l^- \bar{\nu}_l$, boosted into the $\bar{t}$ rest frame $(\cos\theta^*_\ell)$.
- **This observables feed directly into the** χ^2 **analysis – sharpening sensitivity to** C_{tt}/f_a **beyond a simple rate-counting search.**

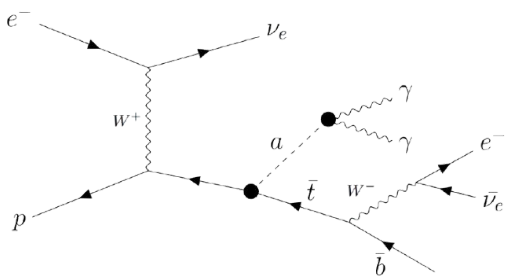
$$\chi^2 = \sum_i \left(\frac{S_i\, C_{tt}^2}{\sigma_{\mathrm{tot},i}} \right)^2, \qquad \sigma_{\mathrm{tot},i} = \sqrt{\sigma^2_{\mathrm{stat},i} + \sigma^2_{\mathrm{sys},i}}$$

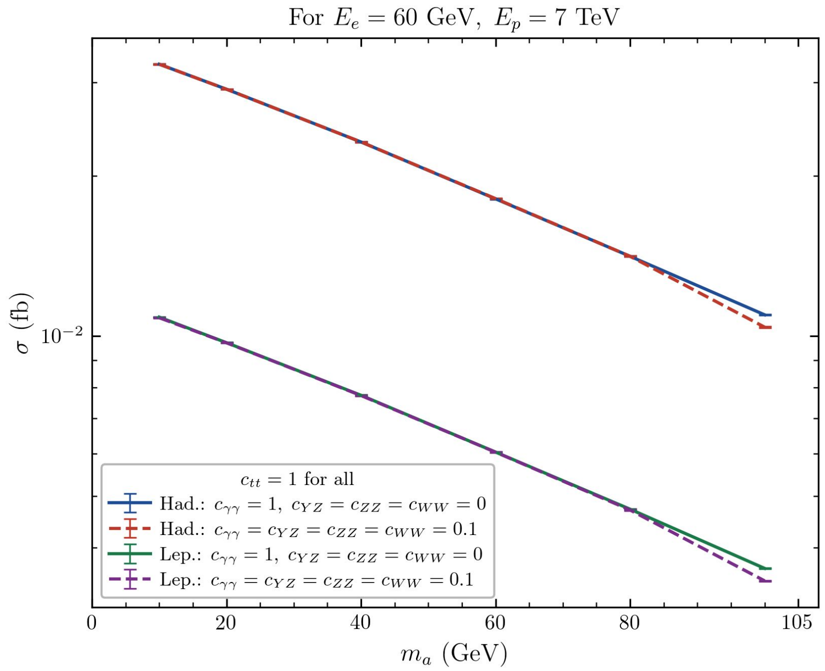
- **Statistical and Systematic uncertainties combined in a quadrature (** $\delta_s = 5\%$ **), with** χ^2 **scanned until** $\chi^2 < 3.84$ (95% CL, 1 dof)

Signal Process & Top Polarisation

- The signal process: $p\, e^{-} \to \bar{t}\, a x\, \nu_e$



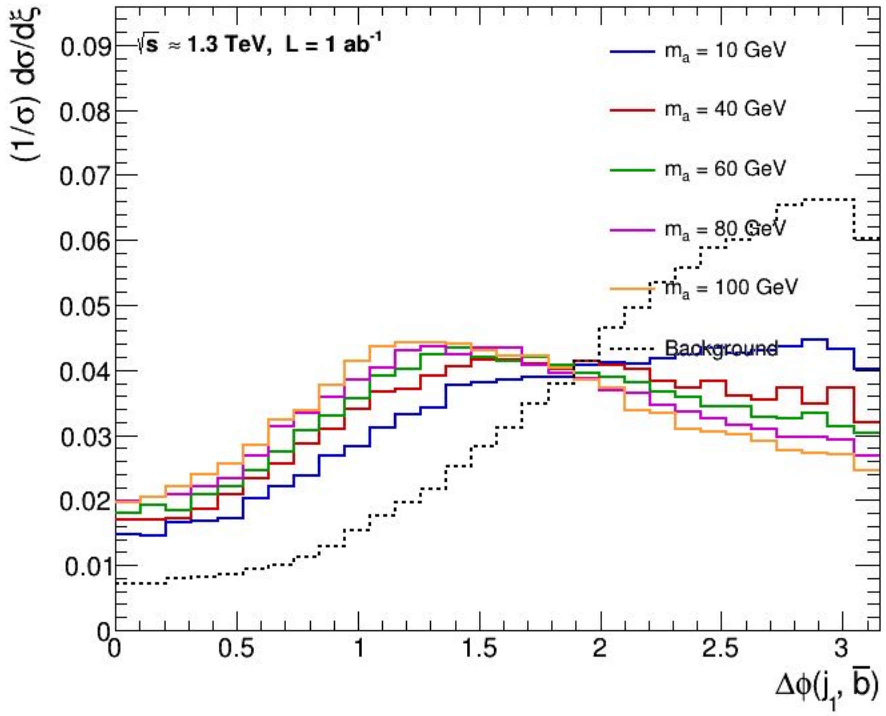


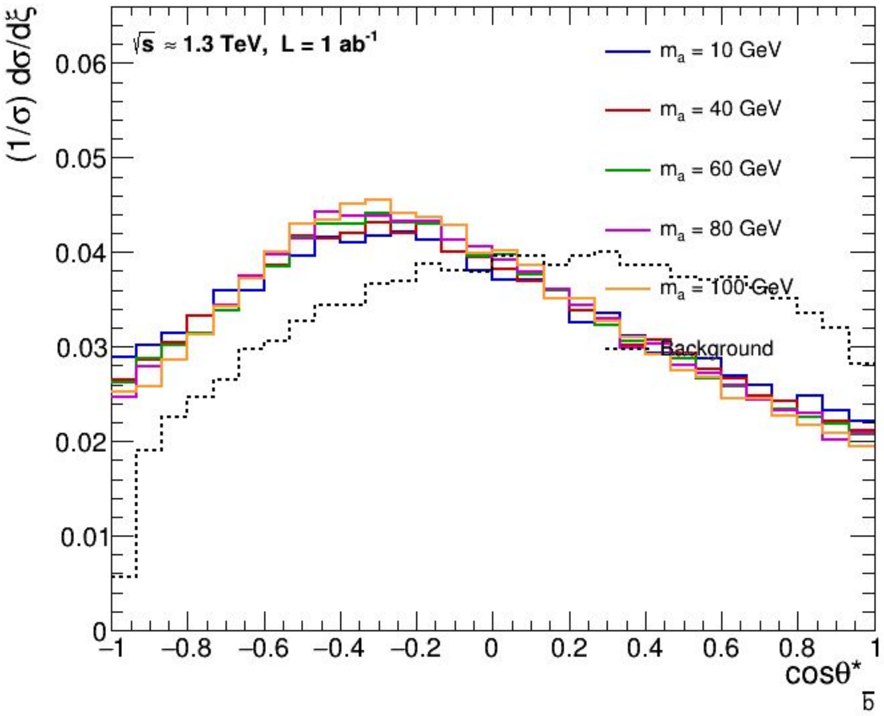


- To optimize signal events over leading SM backgrounds, additional cuts were applied as follows:

$$p_T(\gamma_1, \gamma_2) > 5 \text{ GeV} \qquad 0.5 < |\eta(\gamma_1, \gamma_2)| < 5.0 \qquad M(\gamma\gamma) - m_a < 3 \text{ GeV}$$

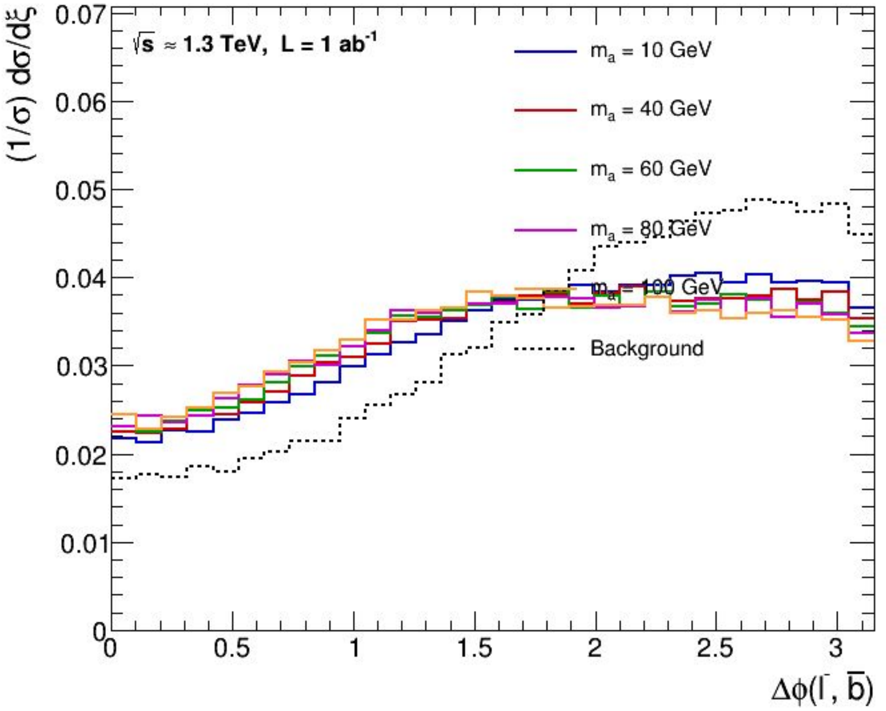
Analysis, Observable and Results

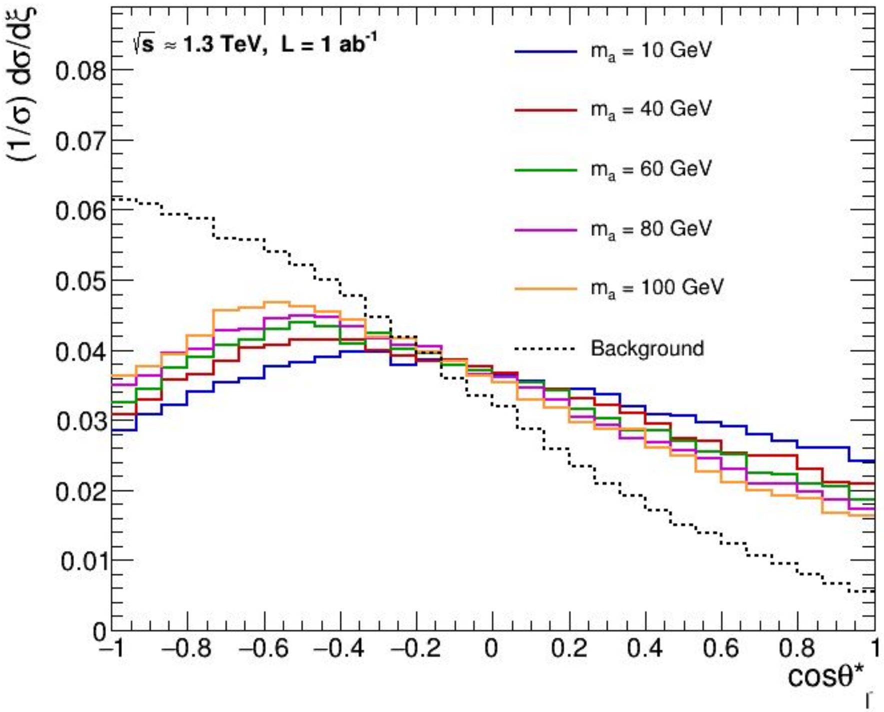




- **Second most sensitive kinematic distributions for the hadronic channel.**

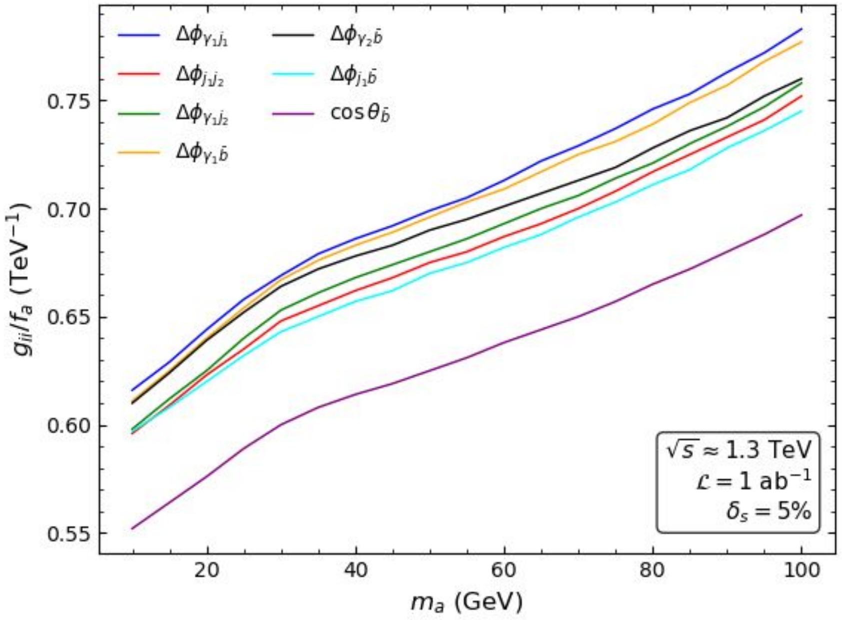
Analysis, Observable and Results

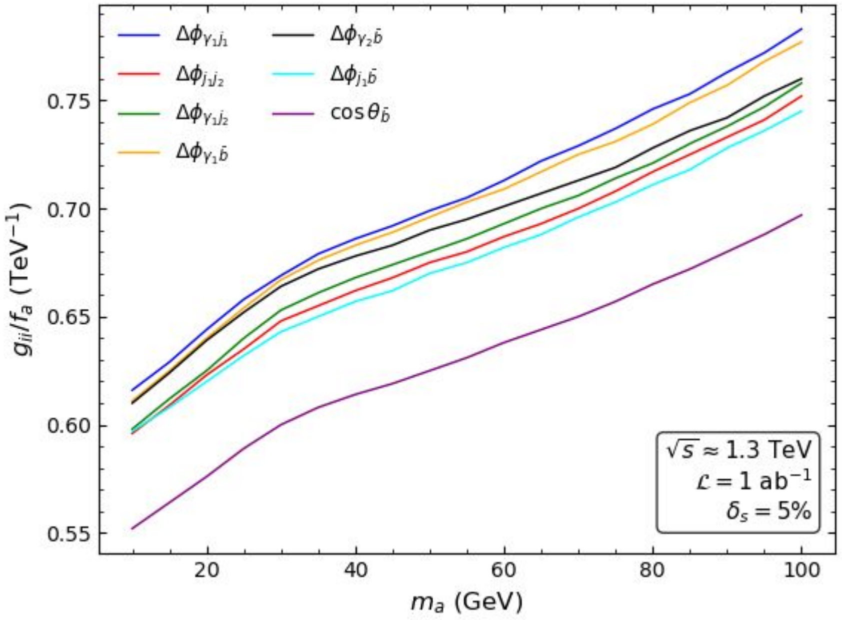




- **Second most sensitive kinematic distributions for the leptonic channel.**

Analysis, Observable and Results





- **The 95% C.L. contours are shown in the $g_{ii}/f_a - m_a$ plane with the observable based on χ^2-analysis for one-bin and multiple-bin with integrated luminosity of $1\ \mathrm{ab}^{-1}$ for hadronic channel**

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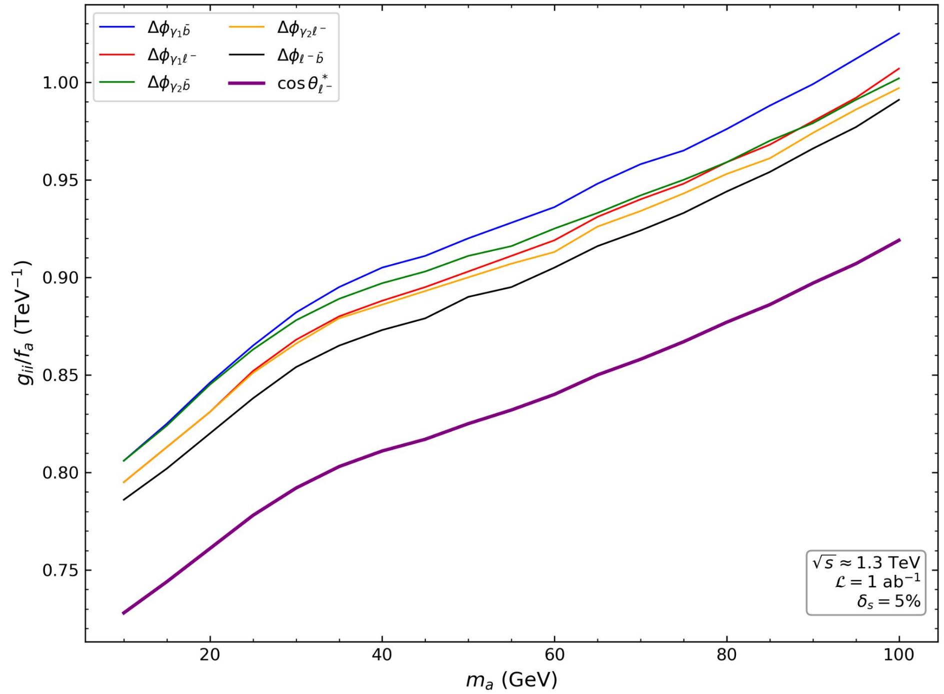

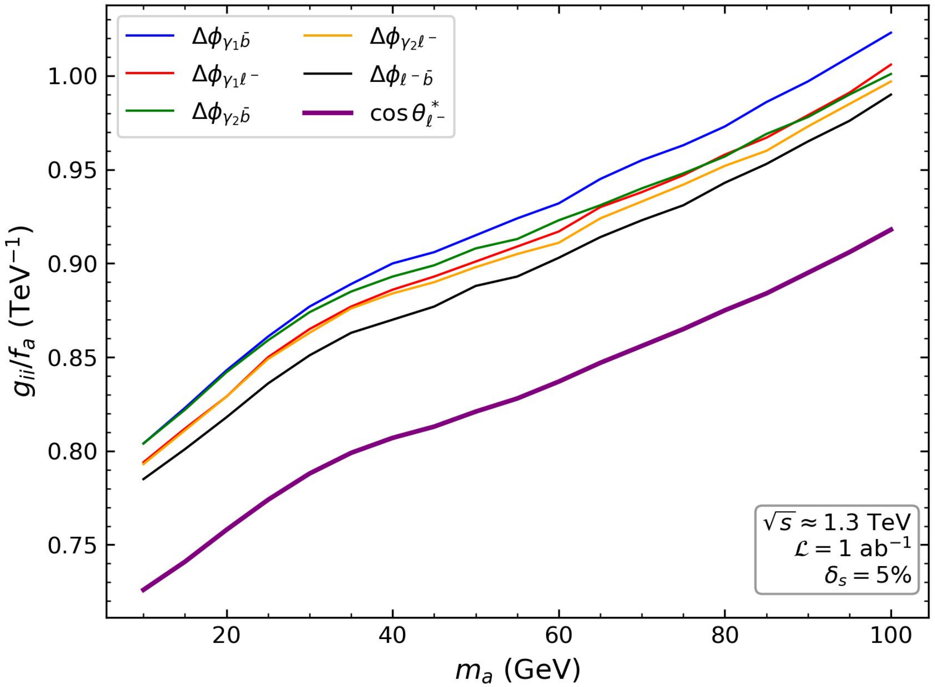

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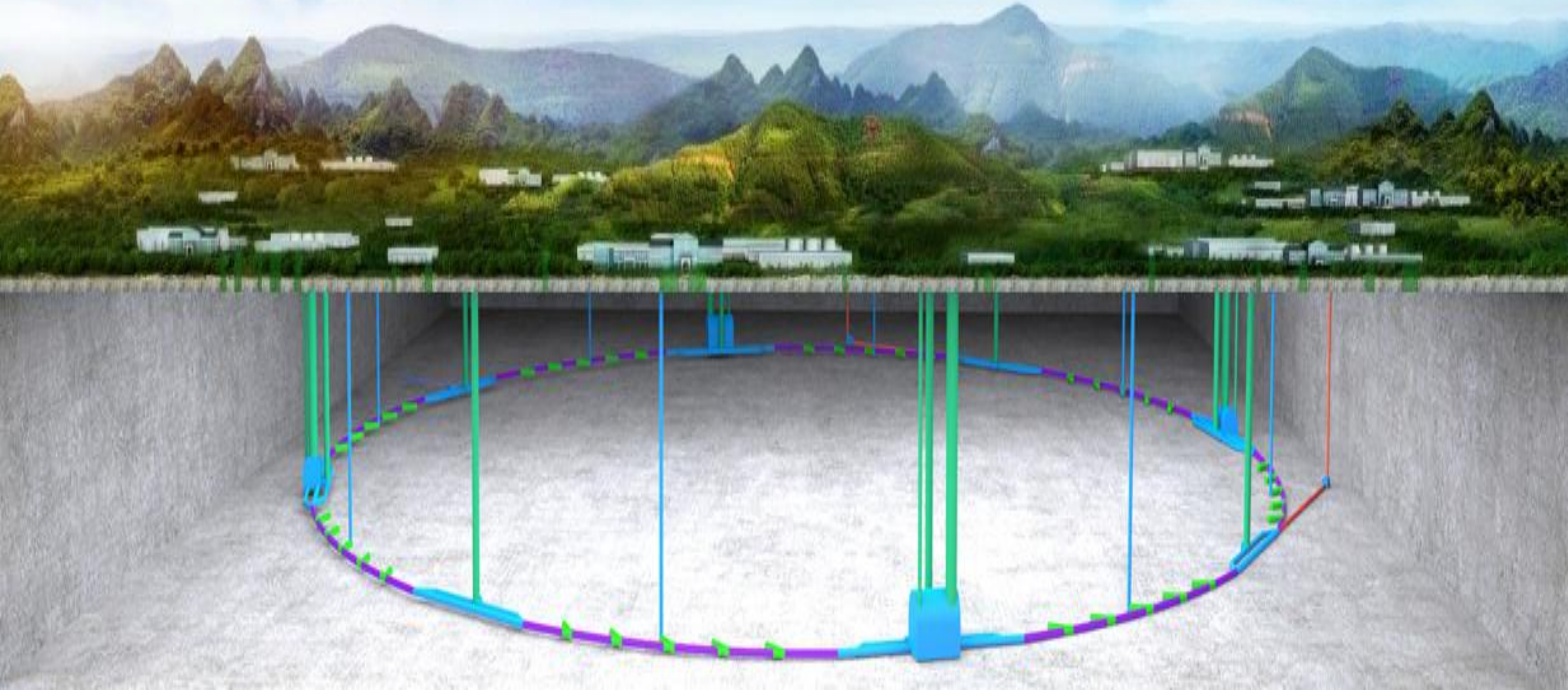
Summary and Conclusion

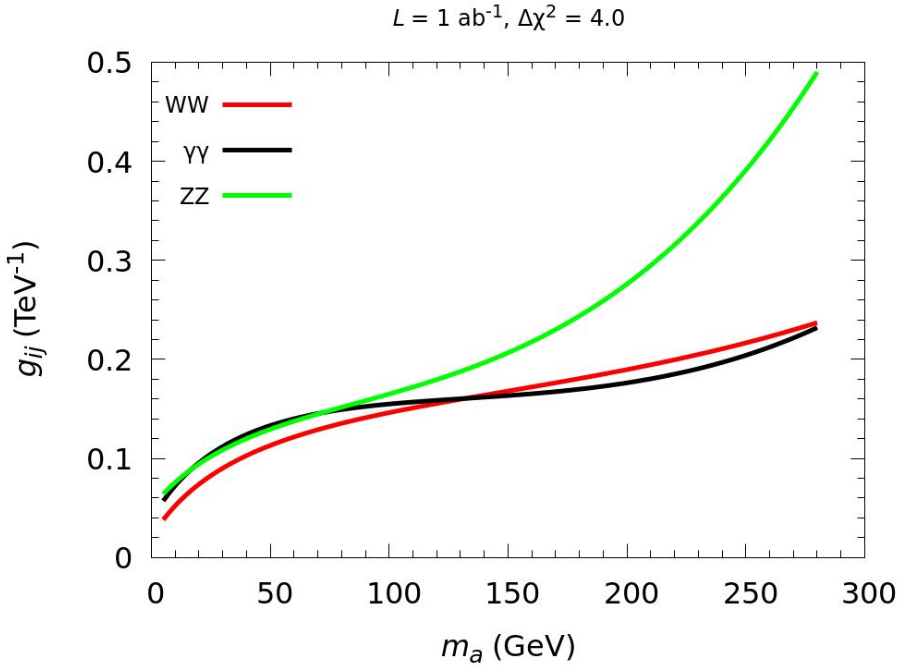
- We provide a detailed study of ALP production via the top-quark coupling at the LHeC.
- Hadronic channel: the multi-bin limits on C_{tt}/f_a range from ~0.55 to 0.70 TeV^{-1}.
- Leptonic channel: the limits range from ~0.73 to 0.92 TeV^{-1}.
- We provide the first probes of C_{tt}/f_a in a production mode and energy regime largely unexplored.

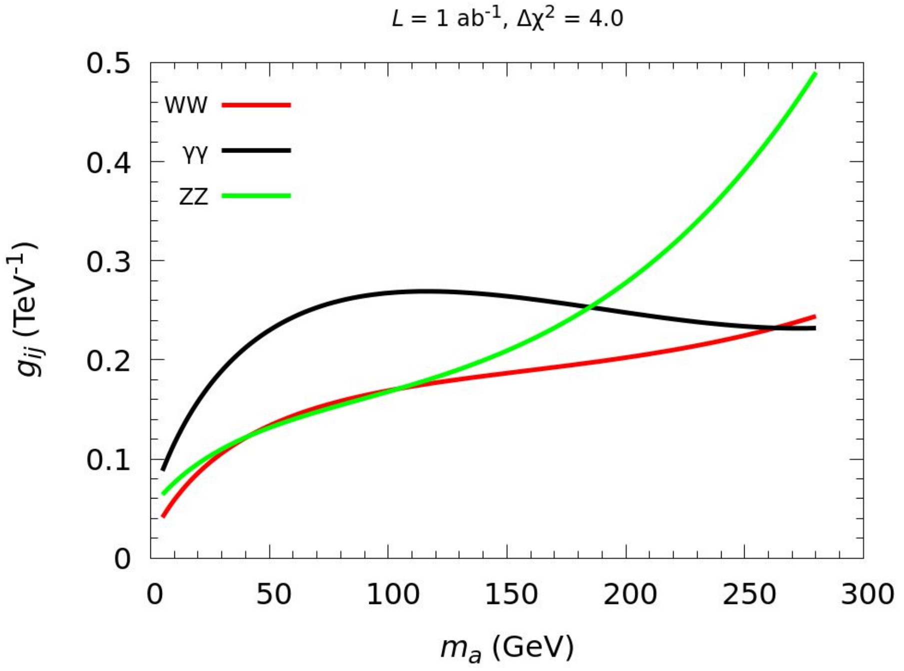
Further Questions?

Additional Slides



Extra Slides





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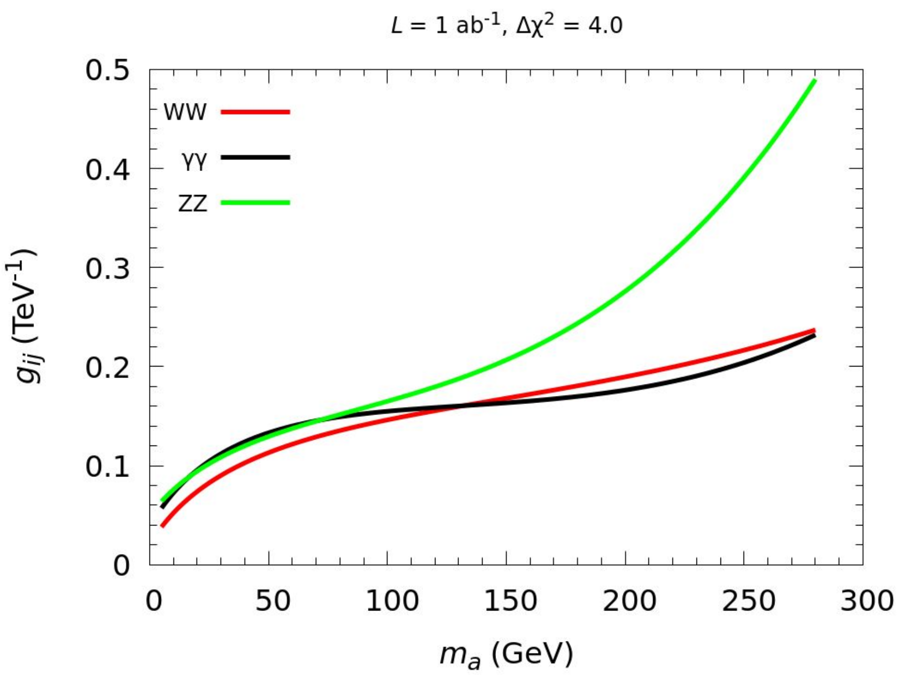
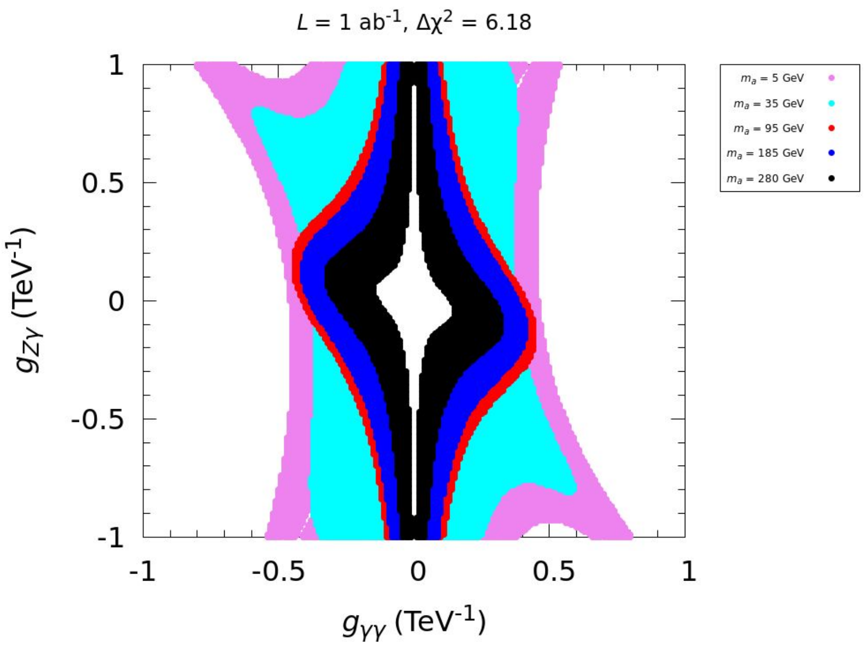


Extra Slides

$$\sigma_{BSM} = g_{\gamma\gamma}^2 (g_i^2 \sigma_i + g_i g_{\gamma\gamma} \sigma_{i\gamma\gamma} + g_{\gamma\gamma}^2 \sigma_{\gamma\gamma})$$

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



ALP Decay Modes