DI-HIGGS PRODUCTION VIA AXION-LIKE PARTICLES

Collaborators: Fabian Esser, Maeve Madigan, Verónica Sanz and Maria Ubiali.

8th Red LHC workshop, Thursday 30th May, 2024

Alexandre Salas-Bernárdez

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28 – 30 May 2024 @ U. Complutense (Madrid)

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Based on *"Di-Higgs production via Axion-Like Particles"*,
2404.08062

Introduction

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Axion-Like Particles for BSM physics

BSM phenomena to be explained

- Dark matter.

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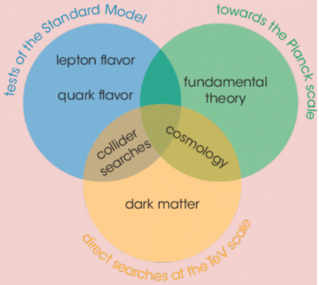

ALPs are strong candidates for SM extensions:

- Introduced for solving the strong CP problem (?).
- ALPs appear in scenarios of global symmetry breaking in new confining sectors (pNGB).

Di-Higgs in the chiral ALP

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Linear vs. chiral ALP: linear (SMEFT-like) 1701.05379

Linear ALP theory (expansion in terms of the inverse of the ALP scale f_a). Dimension-five interactions with the SM gauge fields,

$$\mathcal{L} \supset -\frac{a}{f_a}\left(c_{\tilde{B}} B_{\mu\nu}\tilde{B}^{\mu\nu} + c_{\tilde{W}} W^a_{\mu\nu}\tilde{W}^{a,\mu\nu} + c_{\tilde{G}} G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}\right) \ .$$

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Coupling to the Higgs doublet, H,

$$\mathcal{O}_{aH} = i\left(H^\dagger \overleftrightarrow{D}_\mu H\right)\frac{\partial^\mu a}{f_a} \ ,$$

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$$\mathcal{O}_{aH} = i\left(H^\dagger \overleftrightarrow{D}_\mu H\right)\frac{\partial^\mu a}{f_a} \ ,$$

which leads to fermionic couplings proportional to the Yukawas,

$$\mathcal{O}_{a\Psi} = i\frac{a}{f_a}\left(\bar{Q}_L Y_U \tilde{H} u_R + \ldots\right) + h.c.$$

Linear vs. chiral ALP: chiral (HEFT-like) 1701.05379

We find 17 possibilities for coupling the ALP to SM fields,

$$\mathcal{L}_{\rm chiral} = \sum_{i=\tilde{B},\tilde{W},\tilde{G}} c_i\,\mathcal{O}_i + \sum_{j=1}^{17} c_j\,\mathcal{O}_j\,,$$

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$$\mathcal{F}_i(h) = 1 + a_i\,\frac{h}{v} + b_i\,\left(\frac{h}{v}\right)^2 + \dots\,,$$

New couplings: c_{2D}, which induces $Z^\mu \partial_\mu a$.

Other relevant operators: such as the operator c_{17} which accompanies $\frac{1}{f_a}\,V_\mu \partial^\mu \Box a$.

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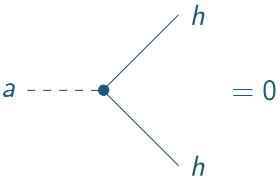
CP conserving ALP interactions

ALPs are pseudoscalar particles (0^-).



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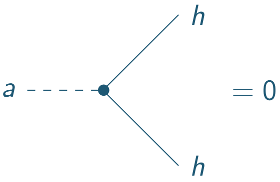

⇒**Need for an extra γ or Z boson.**

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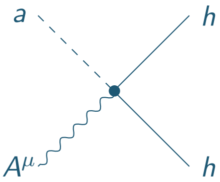

$$\frac{1}{2\pi v^2 f_a}\left(\tilde{b}_3 c_W + \tilde{b}_{10} s_W\right)\left(p_\gamma^\mu p_a^2 - p_\gamma^2 p_a^\mu\right) \overset{\text{on shell}}{=} 0$$

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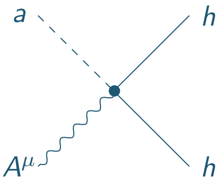

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This is due to CP conservation $\Rightarrow$
$0^- \longrightarrow 0^-$ which needs **longitudinal polarization** of outgoing vector boson.

Process of this analysis

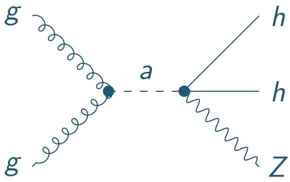
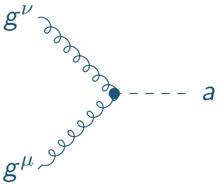


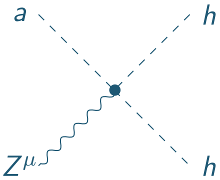
Figure 1: Feynman diagram for di-Higgs production with an associated Z-boson via a non-resonant ALP.

ALP from gg fusion



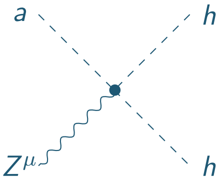
$$-\frac{4i}{f_a} c_{\tilde{G}}\, p_{g1\,\alpha} p_{g2\,\beta}\, \varepsilon^{\mu\nu\alpha\beta}$$

Di-Higgs from ALP



$$\frac{g}{4\pi^2 c_W v^2 f_a}\Big[p_{hh}^\mu(p_a^2\tilde{b}_{11} + p_a\cdot p_{hh}\tilde{b}_{14}) + p_a^\mu(p_{hh}^2\tilde{b}_{13} + p_a\cdot p_{hh}\tilde{b}_{12})$$
$$+ 2\tilde{a}_{16}(p_{h1}^\mu p_a\cdot p_{h2} + p_{h2}^\mu p_a\cdot p_{h1}) + 4\tilde{a}_{15}p_a^\mu p_{h1}\cdot p_{h2}$$
$$- p_a^\mu(16\pi^2 v^2\tilde{\boldsymbol{b}}_{2\boldsymbol{D}} - \tilde{\boldsymbol{b}}_{17}p_a^2) + 2\pi s_{2W}\tilde{b}_{310}(p_Z^2 p_a^\mu - p_Z^\mu p_a\cdot p_Z)/e\Big]$$

Di-Higgs from ALP



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Many structures! We choose 3 relevant Benchmarks.

Benchmarks of this analysis

Benchmark 1: $\tilde{b}_{3,10-17} = \tilde{a}_{15,16} = \tilde{b}_{2D} = 1$,

Benchmark 2: $\tilde{b}_{2D} = 1$, all others set to zero,

Benchmark 3: $\tilde{b}_{17} = 1$, all others set to zero.

ALP to di-Higgs in $b\bar{b}\gamma\gamma$

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ATLAS analysis: 2310.12301

Up to date there is no search with HHZ final state.

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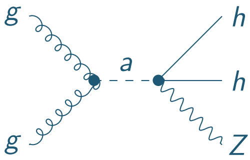
ATLAS does not place explicit vetoes on missing energy, and the veto on additional jets is quite lax.

Limits from ATLAS data



We will denote the combination of gluon and electroweak bosons with the letter c, namely

$$c \equiv c_{\tilde{G}}\, c_{3B}\,,$$

The partonic cross section scales as

$$\hat{\sigma}(gg \to a \to h\, h\, Z) \propto \hat{s}^3\, \frac{c_{\tilde{G}}^2\, c_{3B}^2}{v^4 f_a^4}\,.$$

Limits from ATLAS data

We now compare the total number of measured events ($n_{\rm obs}$) to the background estimate provided by ATLAS $n_{\rm BG}$, and our signal prediction $n_{\rm s}$, which depends on the combination c/f_a^2.

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$$\chi^2\left(\frac{c}{f_a^2}\right) = \left(\frac{n_{\rm obs} - n_{\rm BG} - n_{\rm s}(c/f_a^2)}{\Delta_{\rm BG}}\right)^2 ,$$

where $\Delta_{\rm BG}$ denotes the quadratic sum of the background uncertainties as provided by ATLAS.

Limits from ATLAS data

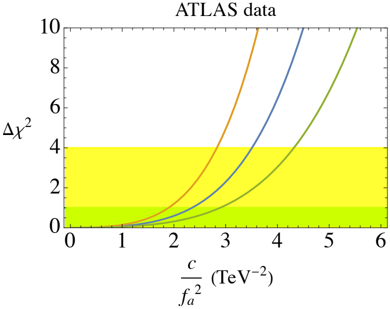

Figure 2: Dependence of $\Delta\chi^2$ on c/f_a^2. Benchmark 1 (blue line), Benchmark 2 (orange line) and Benchmark 3 (green line).

The limits corresponding to 2 standard deviations translate into

$$f_a > (0.53, 0.59, 0.48) \times \sqrt{c}\ \mathrm{TeV}$$

for Benchmark 1, Benchmark 2 and Benchmark 3, respectively.

ALP-mediated di-Higgs differential distributions

ATLAS analysis has differential distributions normalized to one and focused on regions defined by BDT classifiers, leaving insufficient details for comparing our signal events with the observed data.

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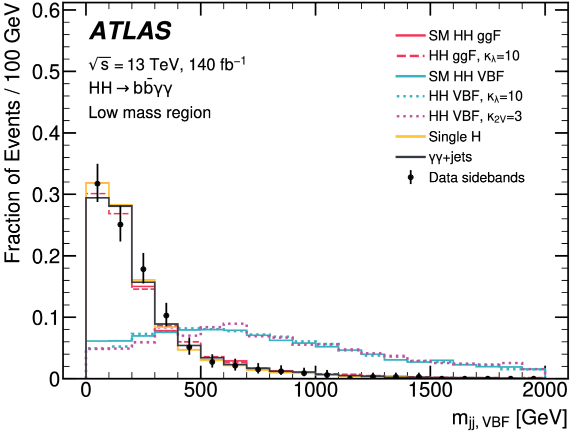
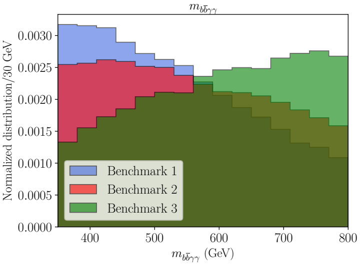
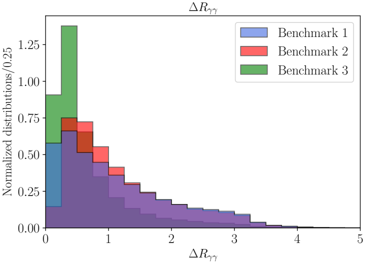


Differential Distributions





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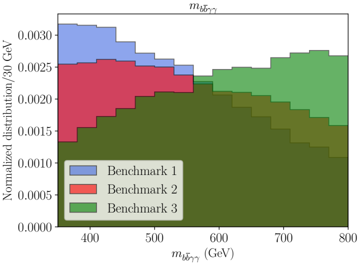

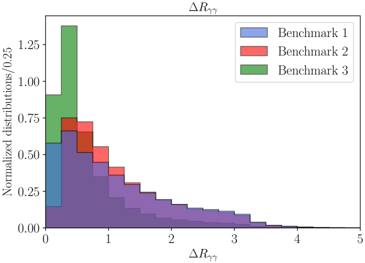

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In contrast to the EFT case (κ_{2V} modifier) analyzed by ATLAS, the ALP-mediated signal does not exhibit interference with the SM di-Higgs production.

A smoking gun for ALP to di-Higgs

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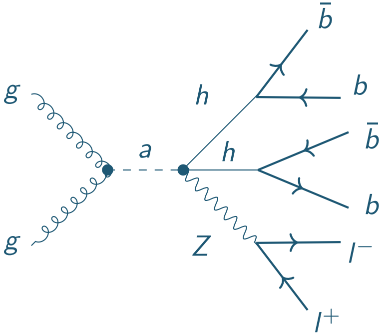
Dedicated search



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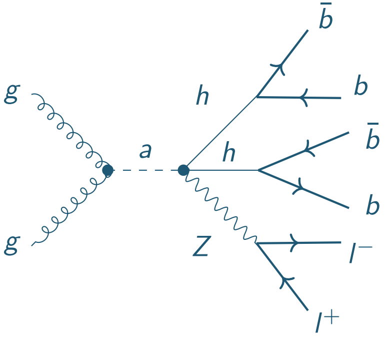
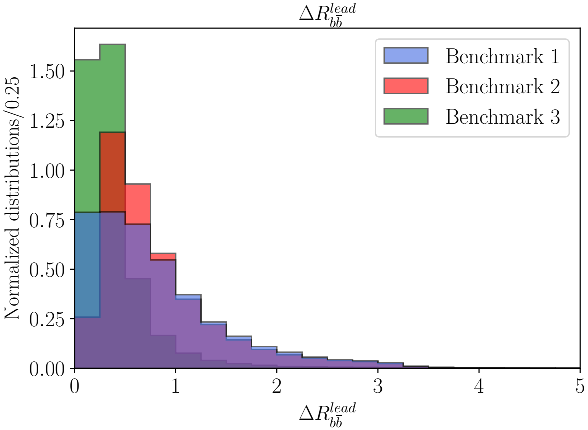


Need to estimate SM background with the relevant cuts.

Differential Distributions



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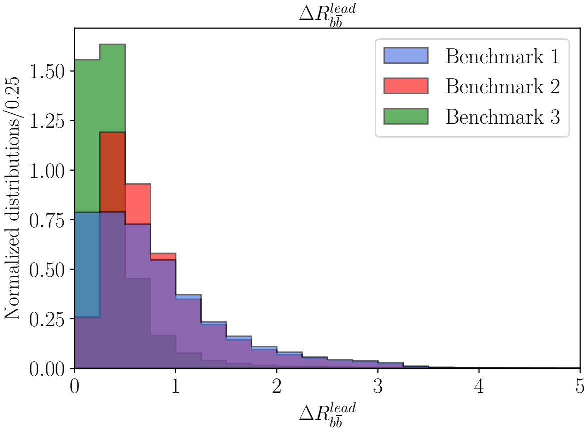

Highly collimated *b*s from the leading Higgs,

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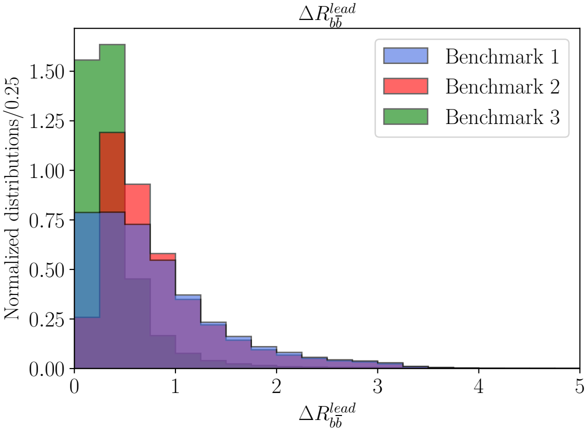
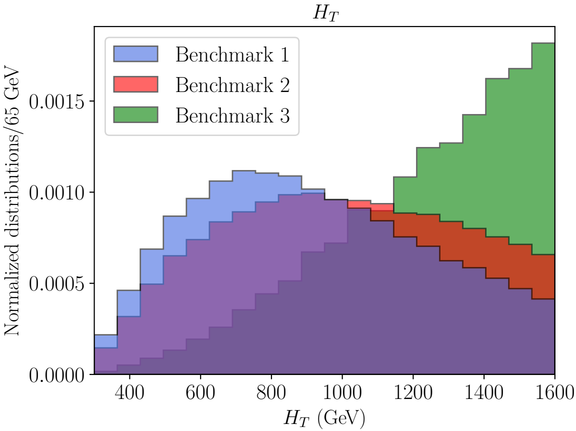


Highly collimated *b*s from the leading Higgs,
$\Rightarrow$ non isolation of *b* jets in many cases (fat jets).

Differential Distributions



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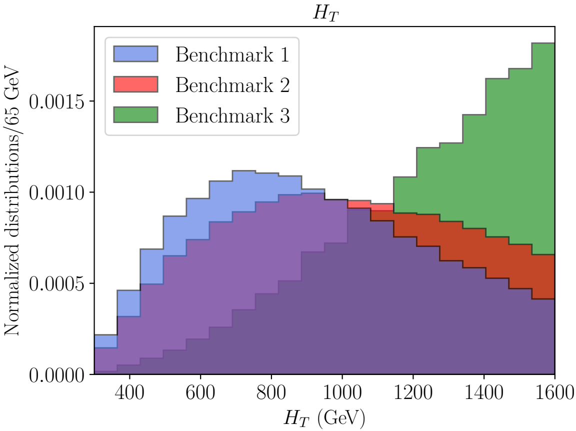

Cut $H_T > 500$ GeV, with good acceptance.

SM Background of $gg \to hhZ \to Z + 4b$ jets

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In 1303.6636 the authors propose a tagging algorithm for two Higgses into b-jets which could go from the fully resolved 4 b final state, to intermediate fat jet + 2 b-jets situation, and reaching the two fat jet case (around 50% efficiency across all channels).

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Finally, applying an additional cut on $H_T > 500$ GeV brings the cross section from 4 to around 2 fb.

Sensitivity estimate

We can assess the potential sensitivity of a dedicated analysis using Run 2 LHC data.

The typical cross section of the signal is

$$\sigma(pp \to hhZ)_{ALP} \simeq \left(\frac{c}{f_a^2\ (\mathrm{TeV})}\right)^2 (230 - 530)\ \mathrm{fb}\ .$$

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Comparing (Signal S vs Background B) this with the 2 fb cross section from the SM,

$$\frac{S}{\sqrt{B}} \simeq \frac{\sigma_{ALP}\,\mathrm{Br}(h \to b\bar{b})^2\,\sqrt{\mathrm{Br}(Z \to 2\ell)}}{\sqrt{\sigma_{SM}}}\,\epsilon_b^2\,\sqrt{\mathcal{L}}\ ,$$

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which produces a ($S/\sqrt{B} = 2$, 95% C.L) limit on the size of of ALP-mediated contribution

$$f_a \gtrsim\ 2.4\text{-}3.0 \times \sqrt{c}\ \mathrm{TeV}$$

which much more sensitive.

Linear ALP to di-Higgs through top loops

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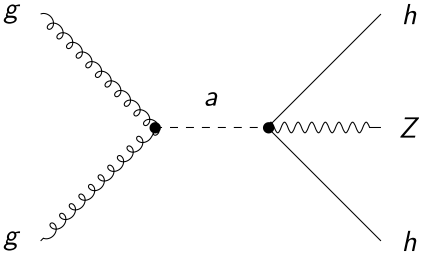
Comparing to linear theory



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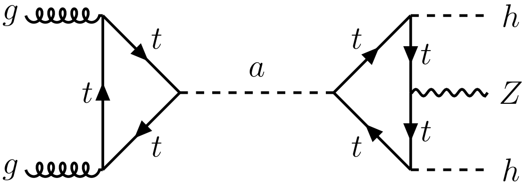

$$\mathcal{L} = -i\, c_t\, \frac{m_t a}{f_a} \left(\bar{t}\gamma^5 t\right)$$

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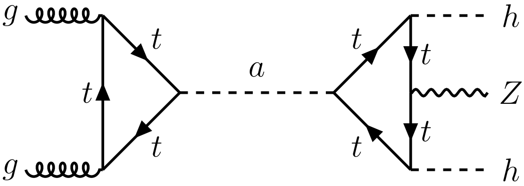

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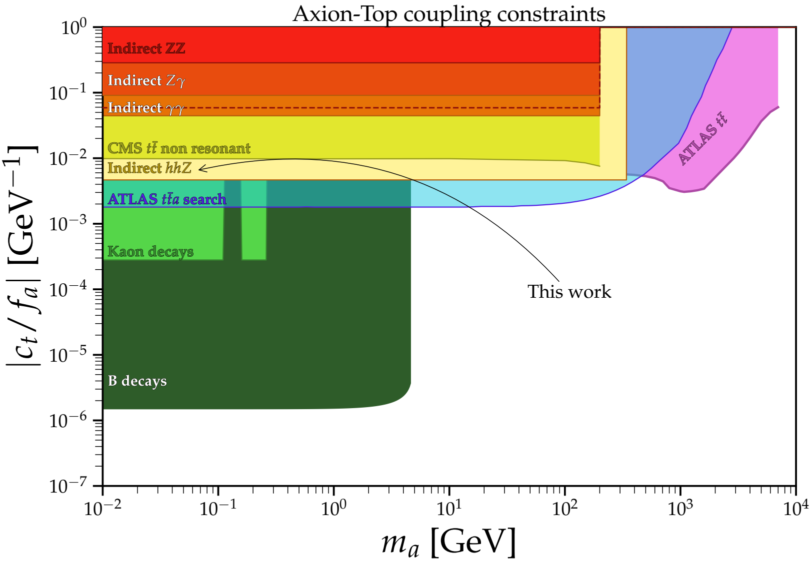
Using Naive Dimensional Analysis (NDA) we can interpret the results from the last section in terms of loop contributions as

$$\frac{c}{f_a^2} \simeq \frac{\alpha_s}{8\pi c_W} \frac{c_t^2}{f_a^2} \, .$$

Bounds on top-axion couplings



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Conclusions

- Di-Higgs production from ALPs needs an extra vector boson.
- Sensitivity would increase if ATLAS or CMS data and DD is made accessible.
- A dedicated search (f.e. HHZ) can place very strong limits on ALP couplings to Higgses.
- Results can be translated to the linear-ALP theory, placing competitive bounds.

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