Double ALP production into 4γ at the LHC

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Motivations

Double ALP

First exploration of *non-resonant double-ALP production* ($pp \to aa$), which naturally probes ***dimension-6*** operators and extends the study beyond the well-explored dimension-5 scenario.

4γ-signature

The 4γ final state emerging from ALP photon decay ($a \to \gamma\gamma$) provides a ***clear signal***, with ***minimal background***, allowing us to probe ***ALP-photon interaction***.

Broadening previous Higgs Resonant ALP searches

We ***recast the existing limits*** on ALP-photon interaction coupling obtained in the ATLAS analysis [1] from double ALP production via a resonant Higgs ($h \to aa$), by allowing for ***ALP decay into gluons*** $a \to gg$.

ALP-operators & Signal

We assume ***CP-even interactions*** and ***negligible couplings to fermions***. The ***amplitude*** for double-ALP production ***scales*** as $\sim \Lambda_a^{-2}$ (with one inverse power of Λ_a per ALP insertion). Consequently, the ***relevant contributions*** arise from [2]:

Dimension five operators

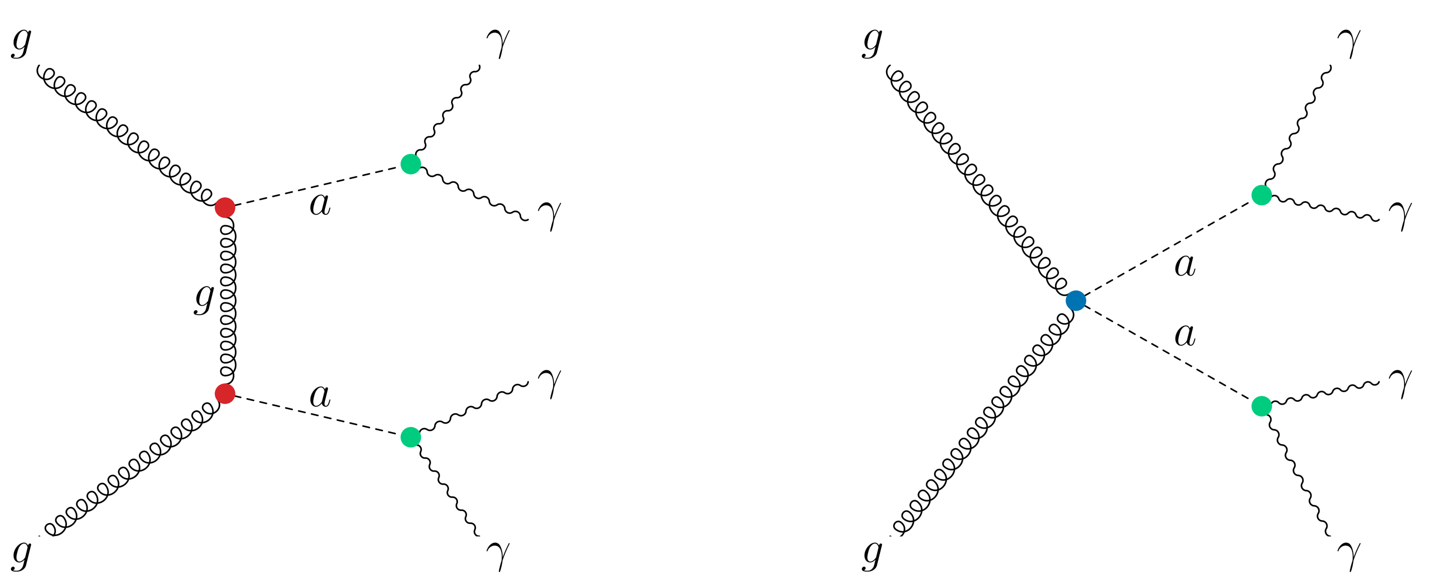
- $\widetilde{\mathcal{O}}_{G1} = \widetilde{C}_{G1} \dfrac{a}{\Lambda_a} G^a_{\mu\nu} \widetilde{G}^{a,\mu\nu}$
- $\mathcal{O}_{\gamma\gamma} = C_{\gamma\gamma} \dfrac{a}{\Lambda_a} F_{\mu\nu} \widetilde{F}^{\mu\nu}$

Dimension six operators

- $\mathcal{O}_{ah} = C_{ah} \dfrac{\partial_\mu a \, \partial^\mu a}{\Lambda_a^2} \Phi^\dagger \Phi$
- $\mathcal{O}_{G2} = C_{G2} \dfrac{a^2}{\Lambda_a^2} G^a_{\mu\nu} G^{a,\mu\nu}$

Signal from non-resonant ALP production

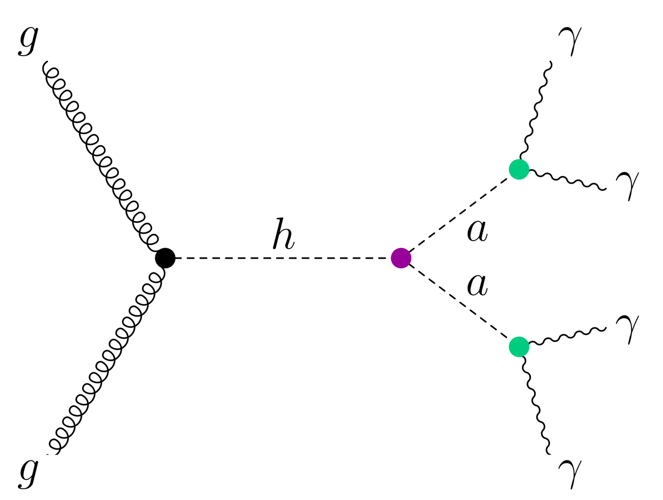
$$\mathcal{N} = \mathcal{L}\, \epsilon^{\text{reco}}\, \epsilon^{\text{cuts}}\, \sigma_{pp \to aa}(m_a, \widetilde{C}_{G1}, C_{G2})\, \text{Br}^2_{a \to \gamma\gamma}(m_a, C_{\gamma\gamma}, \widetilde{C}_{G1})$$



$gg \to aa \to 4\gamma$

Signal from resonant-Higgs ALP production

$$\mathcal{N} = \mathcal{L}\, \epsilon^{\text{reco}}\, \epsilon^{\text{cuts}}\, \sigma_{pp \to h}\, \text{Br}_{h \to aa}(m_a, C_{ah}) \text{Br}^2_{a \to \gamma\gamma}(m_a, C_{\gamma\gamma}, \widetilde{C}_{G1})$$



$pp \to h \to aa \to 4\gamma$

- ϵ^{cuts}: *Selection efficiency after cuts*
- ϵ^{reco}: *Photon reconstruction efficiency*
- $\mathcal{L}$: *Luminosity*

Detector Geometry Effects

Weakly-interacting/light ALPs can become ***long-lived ALPs*** and ***escape the detector volume*** before decaying, resulting in a ***reduced observed signal*** [3,4].

Probability of ALP-Pair Decaying Inside the Detector Volume

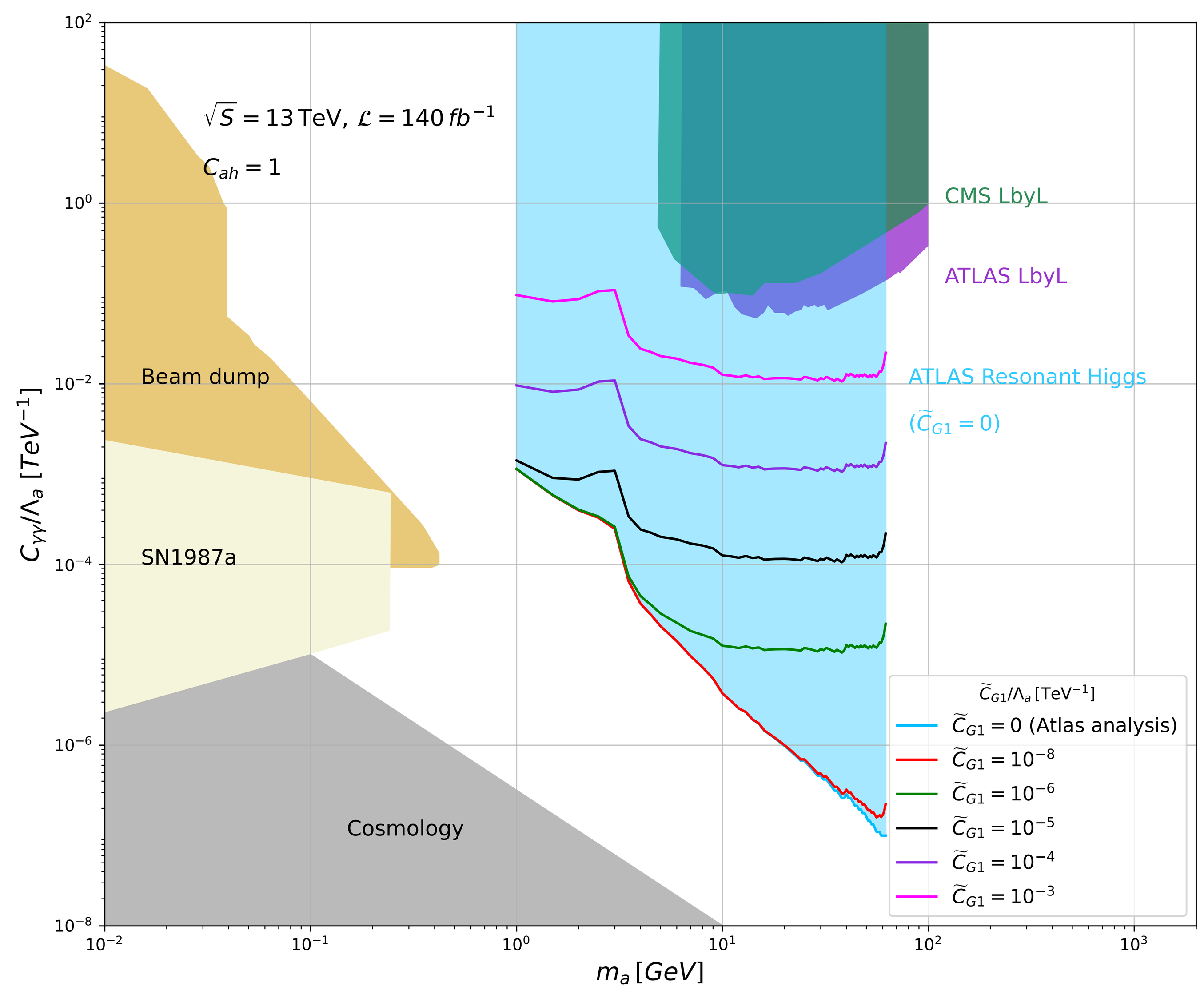
$$P_{aa} = \left(1 - e^{-L_{\text{det}}/L_a^\perp}\right)^2, \quad L_a^\perp = \frac{|p_T|}{m_a \Gamma_a} \hbar c$$

- L_{det}: Electromagnetic calorimeter length ($L = 2\,\text{m}$ for ATLAS)
- $L_a^\perp$: transverse decay length of the ALP

Results

Recasting ATLAS's upper limits [1] from Resonant-Higgs ALP production

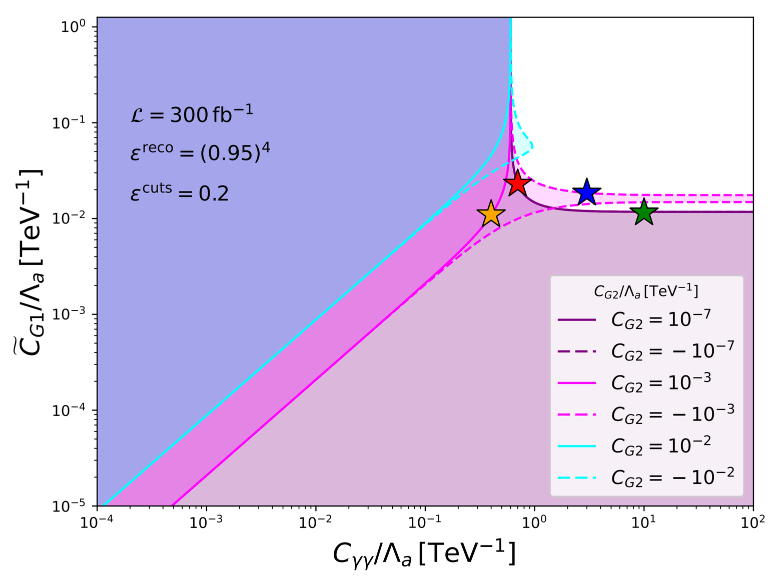
- **Baseline (ATLAS):** assumes $\text{Br}(a \to \gamma\gamma) = 1$ in $h \to aa \to 4\gamma$
- **Our extension:** Allowing for $a \to gg$ (non-zero gluonic coupling $\widetilde{C}_{G1}$), modifying $\text{Br}(a \to \gamma\gamma)$
- **Result:** Opening $a \to gg$ substantially ***weakens*** the ***existing upper limits*** on $C_{\gamma\gamma}$.



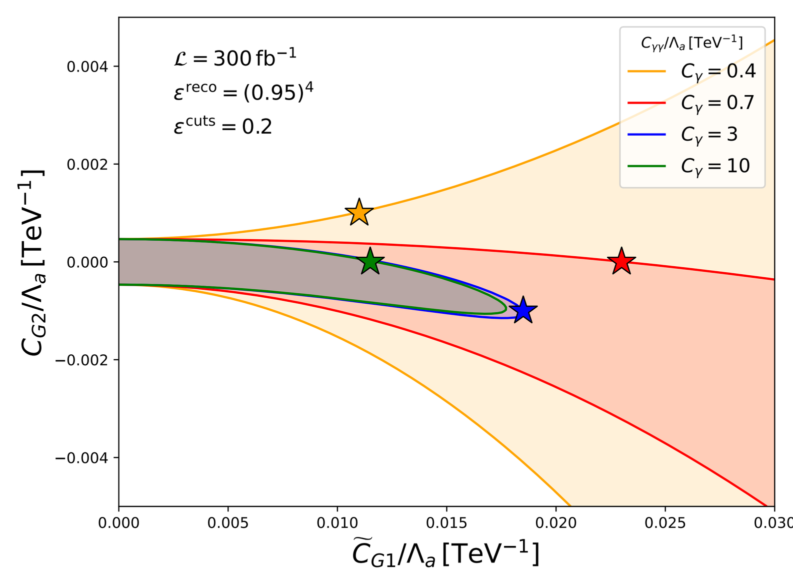
Coloured Regions ⟶ Excluded Regions

Upper limits from non-resonant ALP analysis

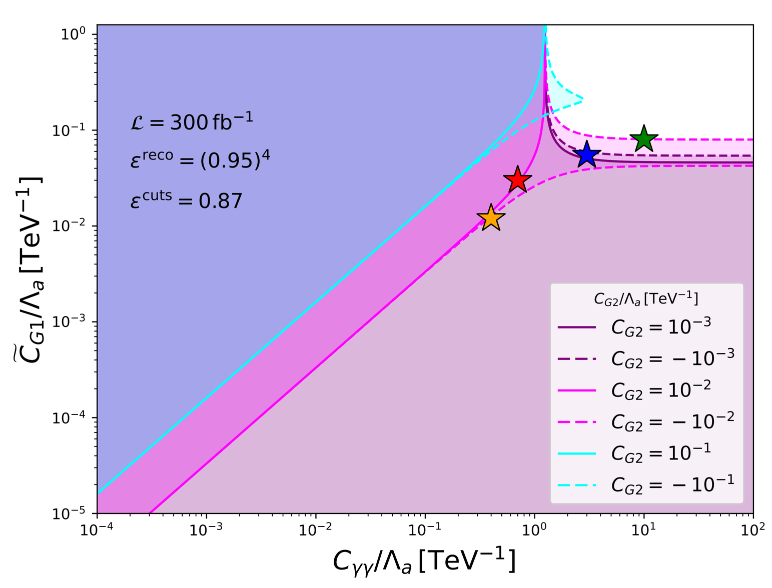
- **Baseline:** *allowed regions* at 95%-CL are defined by requiring: $\mathcal{N} \leq 3$, since ***SM background is negligible***.
- **Result C_{G2}:** We present the **first upper limits** on the C_{G2} coupling, reaching sensitivities of order $\sim 10^{-3}$.
- **Result $C_{\gamma\gamma}$:** Bounds on $C_{\gamma\gamma}$ extend the ***mass reach*** (up to $1\,\text{TeV}$) ***beyond*** the ***ATLAS analysis*** (up to $62\,\text{GeV}$).
- **Comment:** Even fixing one of the three parameters, the ***allowed region*** can be ***unbounded***.



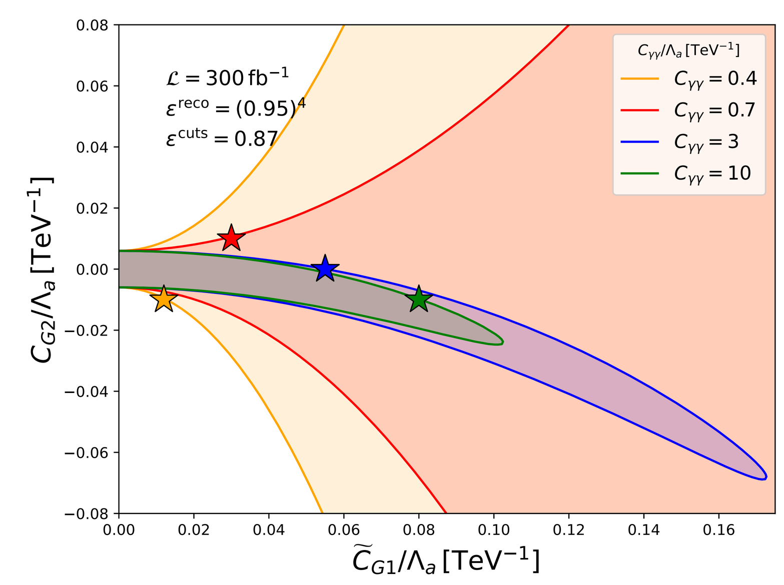
$m_a = 30\,\text{GeV}$



$m_a = 30\,\text{GeV}$



$m_a = 1000\,\text{GeV}$



$m_a = 1000\,\text{GeV}$

Coloured Regions⟶ Allowed Regions

References

[1] ATLAS Collaboration, *Search for short- and long-lived axion-like particles in $H \to aa \to 4\gamma$ decays*, 2023.
[2] R. D. Peccei, H. R. Quinn, *CP Conservation in the Presence of Pseudoparticles*, 1977.
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[5] J. Bonilla, I. Brivio, M. B. Gavela, V. Sanz, *One-loop corrections to ALP couplings*, 2021.