Preliminary

Searches for Axions at ATLAS and CMS

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https://twiki.cern.ch/twiki/bin/view/AtlasPublic
https://cms-results-search.web.cern.ch

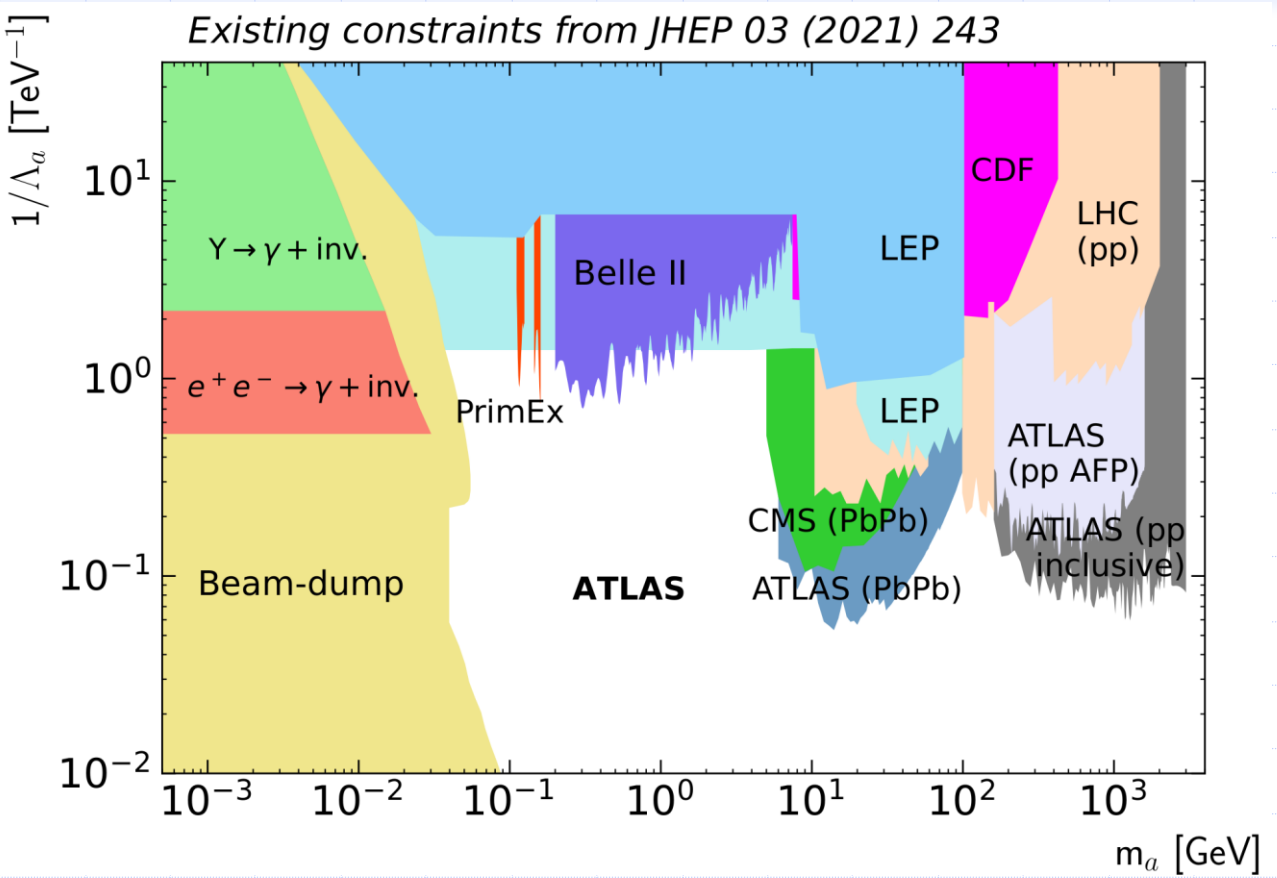
Outline

- Introduction: axions, axion-like particles (ALPs) and their collider signatures
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Axions and axion-like particles

- **Strong CP problem:** the SM allows a QCD θ-term, but the neutron EDM requires $|\bar{\theta}| < 10^{-10}$
- **Peccei–Quinn solution:** a spontaneously broken global $U(1)_{PQ}$ symmetry; the **axion** a is its pseudo-Nambu–Goldstone boson, $\bar{\theta}$ relaxes dynamically to zero
  - QCD axion: $m_a \approx 5.7\ \mu eV \times (10^{12}\ GeV / f_a)$, mass and couplings fixed by f_a
- **Axion-like particles (ALPs):** generic light pseudoscalars from broken global symmetries (string compactifications, composite and flavour models), with m_a and couplings **independent**
  - dark-matter candidates and mediators to a dark sector
- **Colliders** probe m_a ~ MeV – TeV and couplings to all SM particles, complementary to
  - haloscopes (searches for axions that make up the **dark matter halo** of our **Galaxy**),
  - helioscopes (searches for axions produced in the **Sun)** and
  - **beam dumps**



ATLAS, JHEP 07 (2023) 234, aux. Fig. 15

ALP effective Lagrangian and collider signatures

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$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{1}{2}m_a^2 a^2 + c_{GG}\frac{a}{f}G_{\mu\nu}\widetilde{G}^{\mu\nu} + c_{WW}\frac{a}{f}W_{\mu\nu}\widetilde{W}^{\mu\nu} + c_{BB}\frac{a}{f}B_{\mu\nu}\widetilde{B}^{\mu\nu}$$
$$+ \sum_F c_F \frac{\partial^\mu a}{f}\overline{F}\gamma_\mu F + \frac{c_{ah}}{f^2}(\partial a)^2 H^\dagger H + \frac{c_{Zh}}{f^3}(\partial_\mu a)\left(H^\dagger i D^\mu H + \text{h.c.}\right)H^\dagger H$$

Photon coupling $c_{\gamma\gamma} = c_{WW} + c_{BB}$; each Wilson coefficient selects a production mode and final state [Bauer, Neubert, Thamm, JHEP 12 (2017) 044; Brivio et al., EPJC 77 (2017) 572]

Coupling	Production and signature	Mass range probed
$c_{\gamma\gamma}$	$\gamma\gamma \to a \to \gamma\gamma$ in ultraperipheral Pb+Pb and in pp with forward protons	5 GeV – 2 TeV
c_{GG}, $c_{\gamma\gamma}$	$gg \to a \to \gamma\gamma$, boosted or merged diphotons	10 – 110 GeV, $X \to \varphi\varphi \to 4\gamma$
c_{Zh}	$H \to Za$, $a \to \gamma\gamma$, $\ell\ell$, hadrons	0.1 – 33 GeV
c_{ah}	$H \to aa \to 4\gamma$, 4τ, $\gamma\gamma\tau\tau$, $bb\tau\tau$, $\mu\mu\tau\tau$, 4b, 4e	10 MeV – 62 GeV
c_{tt}	$t\bar{t}a$ with $a \to \mu\mu$, $b\bar{b}$, $\tau\tau$; $gg \to a/\eta_t \to t\bar{t}$ near threshold	12 GeV – $2m_t$
small couplings	long-lived ALPs: displaced photons, jets, muons	$c\tau$ ~ mm – 10 m

ATLAS and CMS ALP search programme (Run 2)

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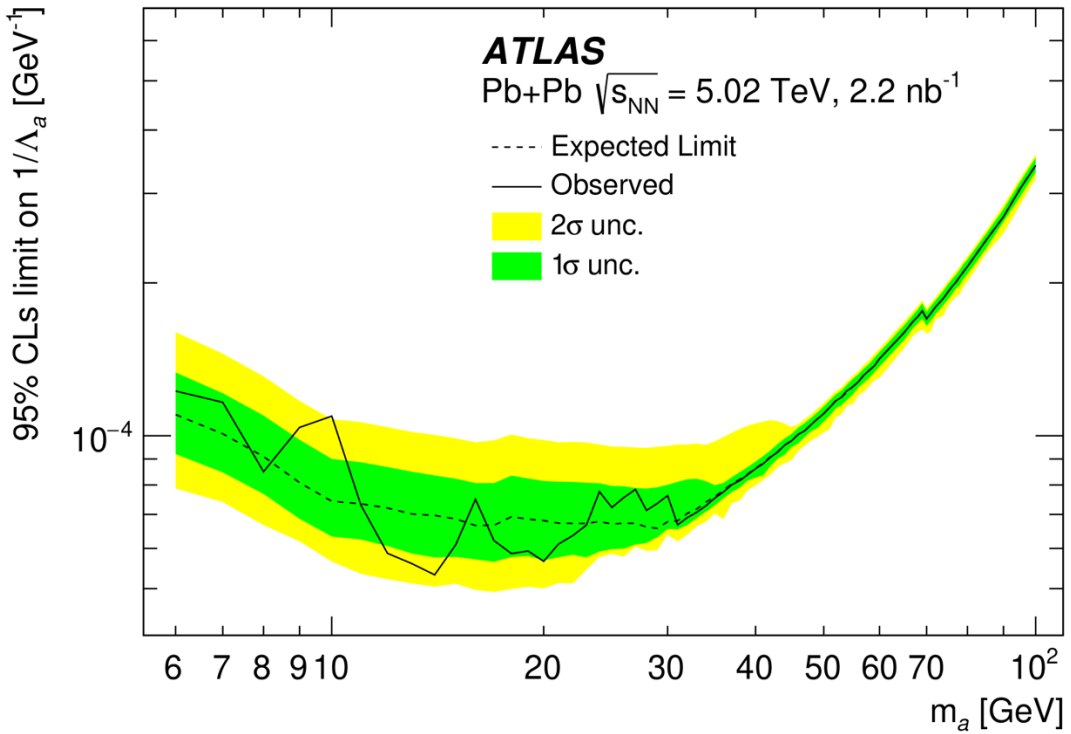
Signature	ATLAS	CMS
γγ → a → γγ (UPC Pb+Pb)	JHEP 03 (2021) 243	JHEP 08 (2025) 006
γγ → a with forward protons	JHEP 07 (2023) 234 (AFP)	PRD 110 (2024) 012010 (PPS)
Low-mass / merged diphotons	JHEP 07 (2023) 155; JHEP 01 (2025) 053	PLB 860 (2025) 139067; PRL 134 (2025) 041801
H → Za	PLB 850 (2024) 138536; PLB 868 (2025) 139671	PLB 852 (2024) 138582
H → aa → 4γ	EPJC 84 (2024) 742	—
H → aa → fermions	4τ: arXiv:2603.08323, PLB 870 (2025) 139843; γγττ: JHEP 03 (2025) 190; bbττ: PRD 110 (2024) 052013; 4b/6b: PRD 112 (2025) 072005	μμττ: arXiv:2609.12683; 4τ/2μ2τ: JHEP 04 (2026) 132; 4e: PRL 136 (2026) 181807; bbγγ: SUS-24-008; 4b: JHEP 06 (2024) 097
tt̄a	μμ: PRD 108 (2023) 092007; bb̄: EPJC 85 (2025) 886; ττ: arXiv:2607.28484	ℓℓ: PRD 110 (2024) 012013
tt̄ threshold (pseudoscalar)	arXiv:2601.11780; arXiv:2605.02341	Rep. Prog. Phys. 88 (2025) 087801; arXiv:2608.19546
Long-lived ALPs	ATL-PHYS-PUB-2025-007; PRD 112 (2025) 092001	EXO-24-016 (13.6 TeV, scouting)

Full Run-2 data sets: ≈ 140 fb^{-1} pp at $\sqrt{s}$ = 13 TeV per experiment; ≈ 2 nb^{-1} Pb+Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

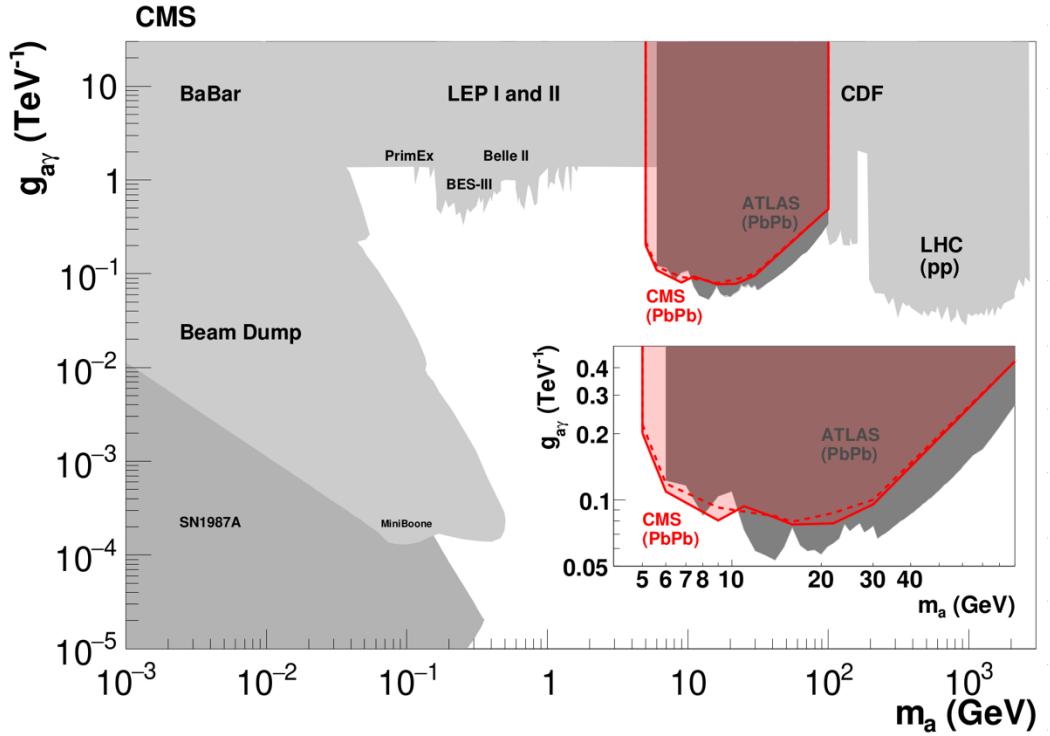
Light-by-light scattering in ultraperipheral Pb+Pb collisions

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- Coherent photon fluxes $\propto Z^2$ of the Pb ions: $\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$ with two back-to-back photons and nothing else in the detector
- **ATLAS** (2.2 nb^{-1}): most stringent limits for m_a = 6–100 GeV at publication, $\sigma(\gamma\gamma \rightarrow a \rightarrow \gamma\gamma)$ > 2–70 nb excluded
- **CMS** (1.7 nb^{-1}): 26 events observed (12.0 ± 2.9 bkg.), σ_{fid} = 107 ± 24 (stat) ± 13 (syst) nb; ALP limits for 5–100 GeV, most stringent for 5–10 GeV



ATLAS, JHEP 03 (2021) 243

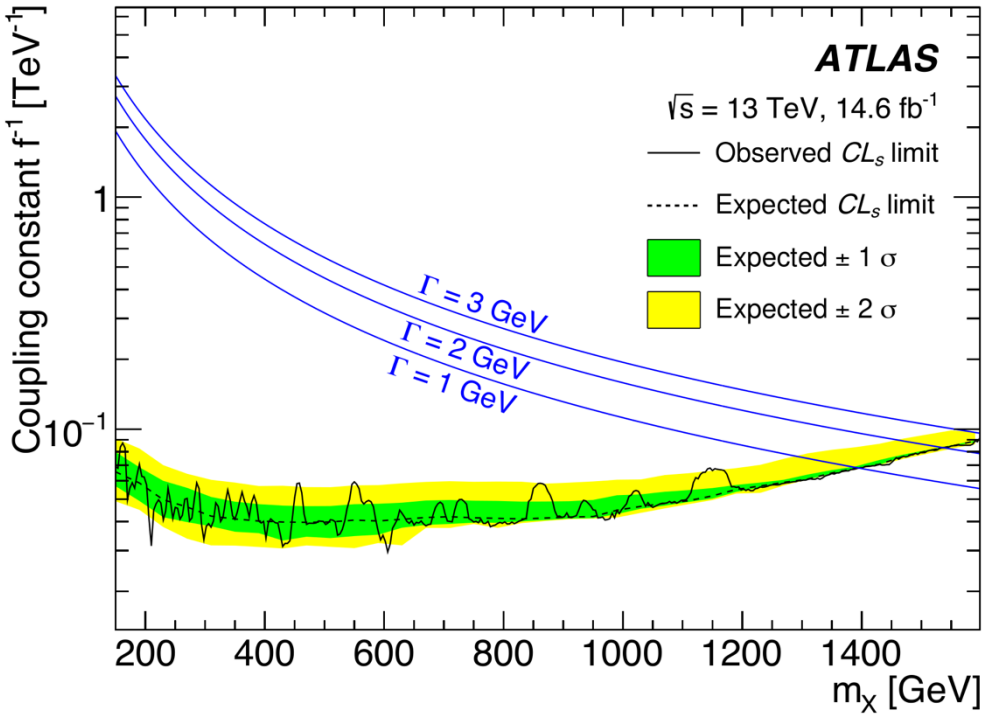


CMS, JHEP 08 (2025) 006

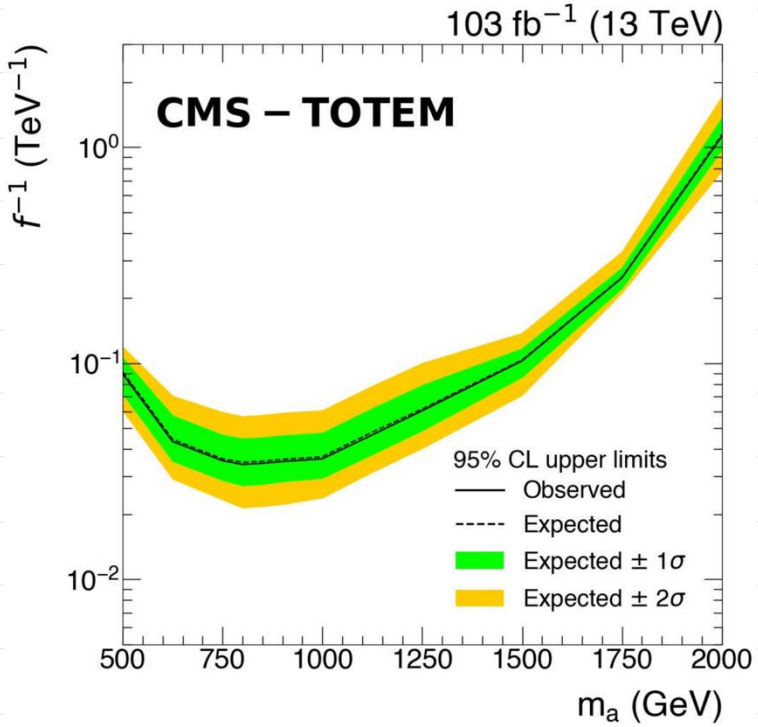
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ALP searches with forward-proton tagging

- pp → p(γγ → a → γγ)p: both protons stay intact and are measured in Roman-pot spectrometers; matching proton and diphoton kinematics removes inclusive backgrounds
- **ATLAS AFP** (14.6 fb^{-1}, 2017): 441 candidates, no resonance for m_a = 150–1600 GeV; ALP coupling f^{-1} > 0.04–0.09 TeV^{-1} excluded at 95% CL
- **CMS + TOTEM PPS** (103 fb^{-1}): $m_{\gamma\gamma}$ > 350 GeV, 1 candidate (1.1 exp.); f^{-1} > 0.03–1 TeV^{-1} excl., 0.5–2 TeV



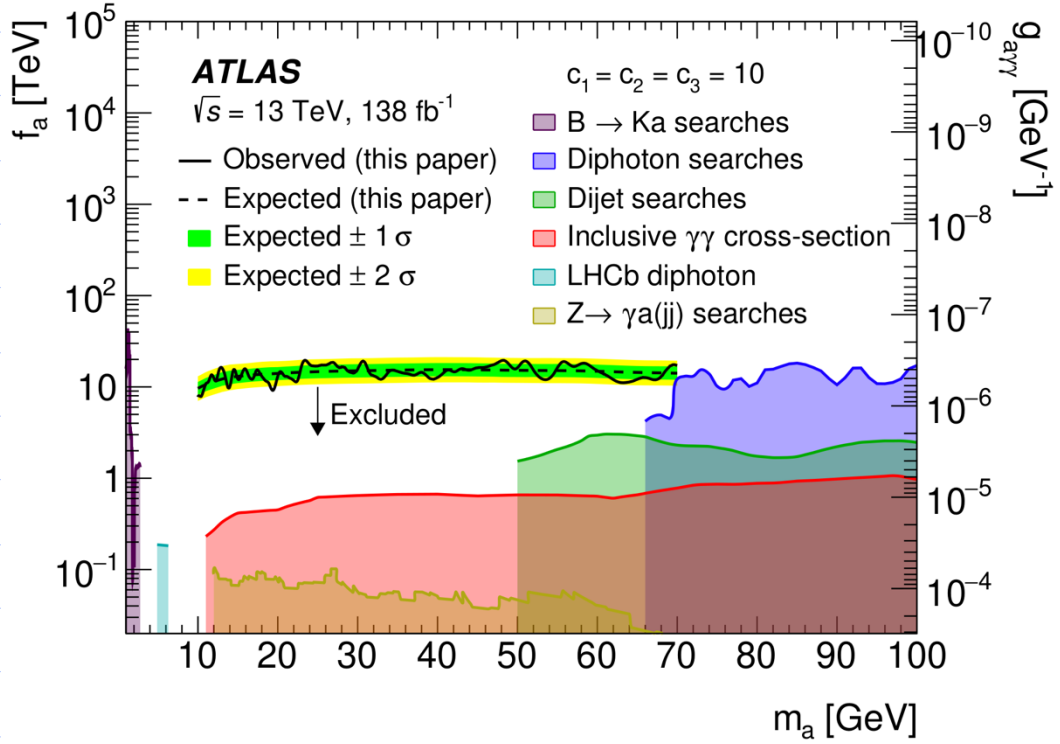
ATLAS, JHEP 07 (2023) 234



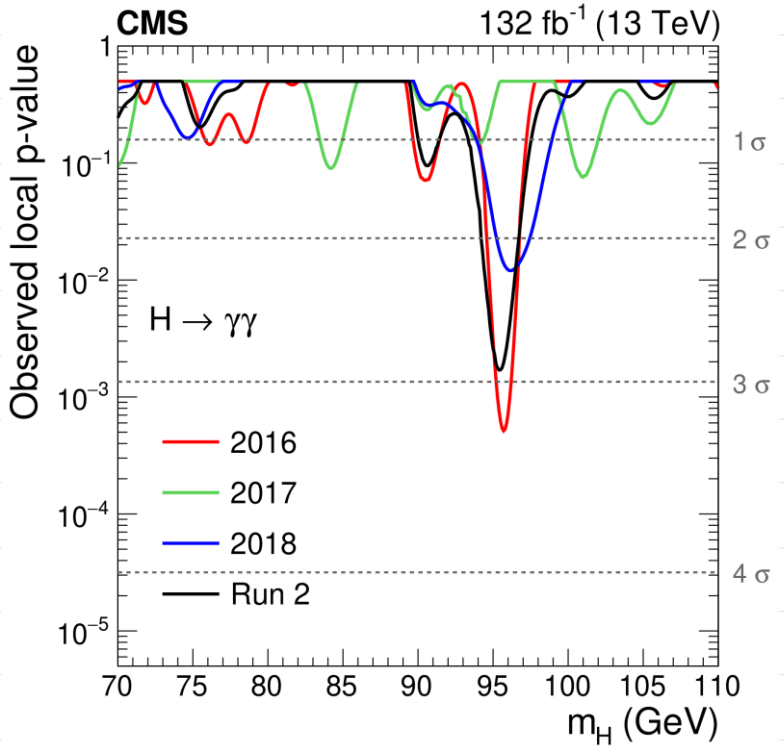
CMS-TOTEM, PRD 110 (2024) 012010

Low-mass and boosted diphoton resonances

- **ATLAS** boosted diphotons, 10–70 GeV (138 fb^{-1}): strongest bound on prompt ALPs coupling to gluons and photons; 66–110 GeV: $\sigma_{fid}\times B$ < 8–53 fb (JHEP 01 (2025) 053)
- **CMS** 70–110 GeV: largest deviation at 95.4 GeV, 2.9σ local (1.3σ global); X → φφ → (γγ)(γγ) with merged diphotons, m_X = 0.3–3 TeV (PRL 134 (2025) 041801)



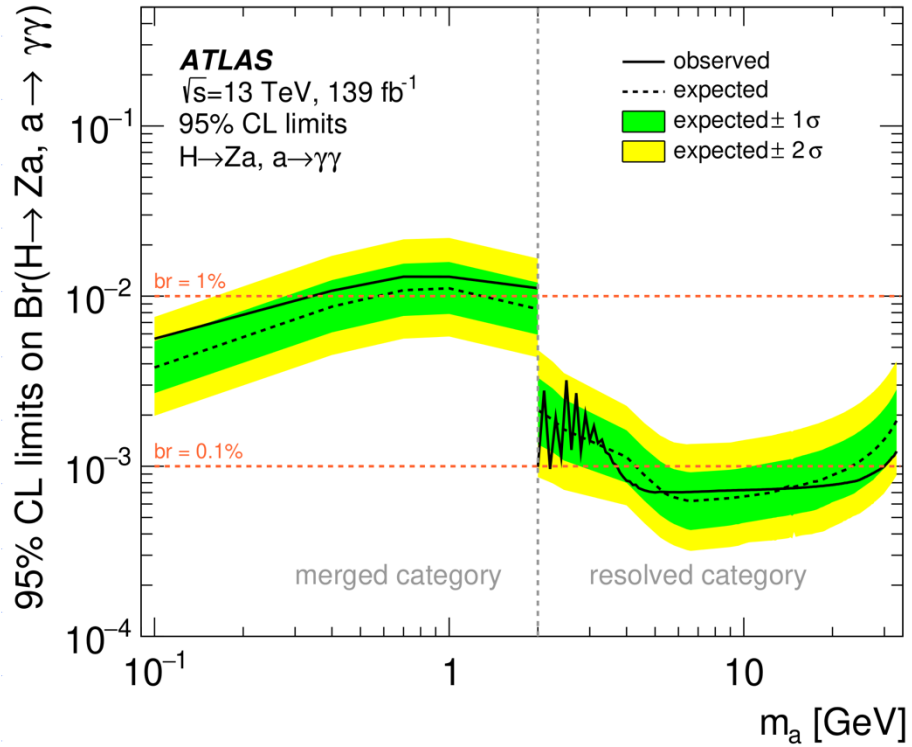
ATLAS, JHEP 07 (2023) 155



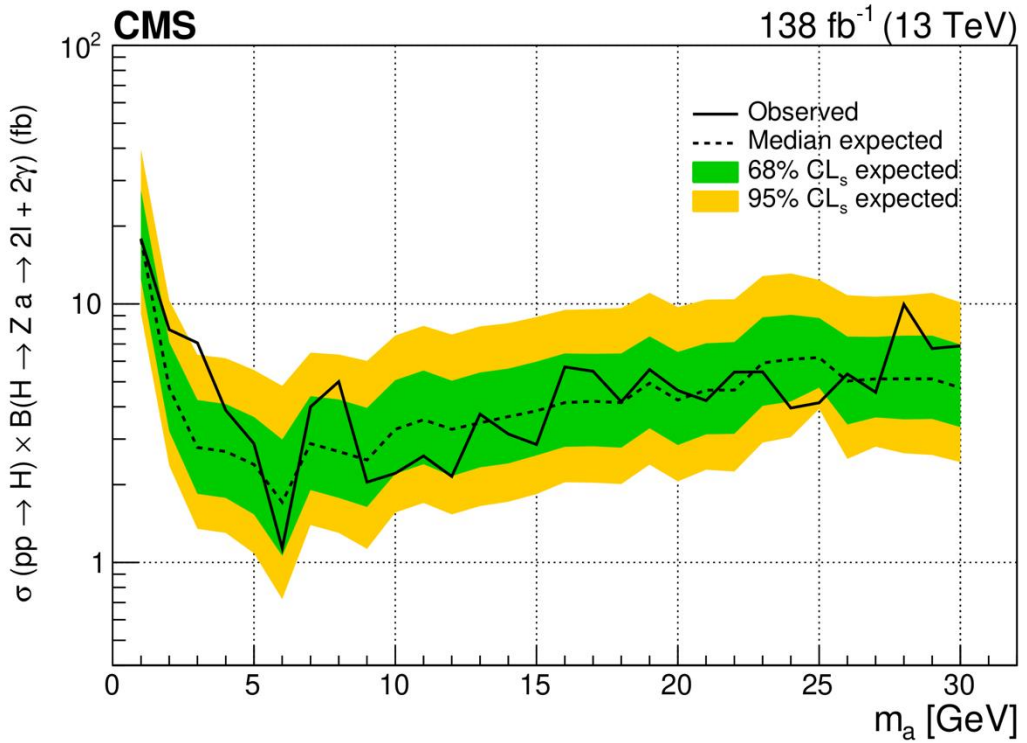
CMS, PLB 860 (2025) 139067

Higgs boson decays H → Za

- Dimension-7 operator c_{Zh}: H → Za with Z → ℓℓ
- **ATLAS** a → γγ, m_a = 0.1–33 GeV, merged and resolved photon categories; a → hadrons, m_a = 0.5–3.5 GeV (PLB 868 (2025) 139671)
- **CMS** a → γγ, m_a = 1–30 GeV: σ×B < 1.1–17.8 fb; largest excess at m_a = 3 GeV, 2.6σ local (1.3σ global)



ATLAS, PLB 850 (2024) 138536

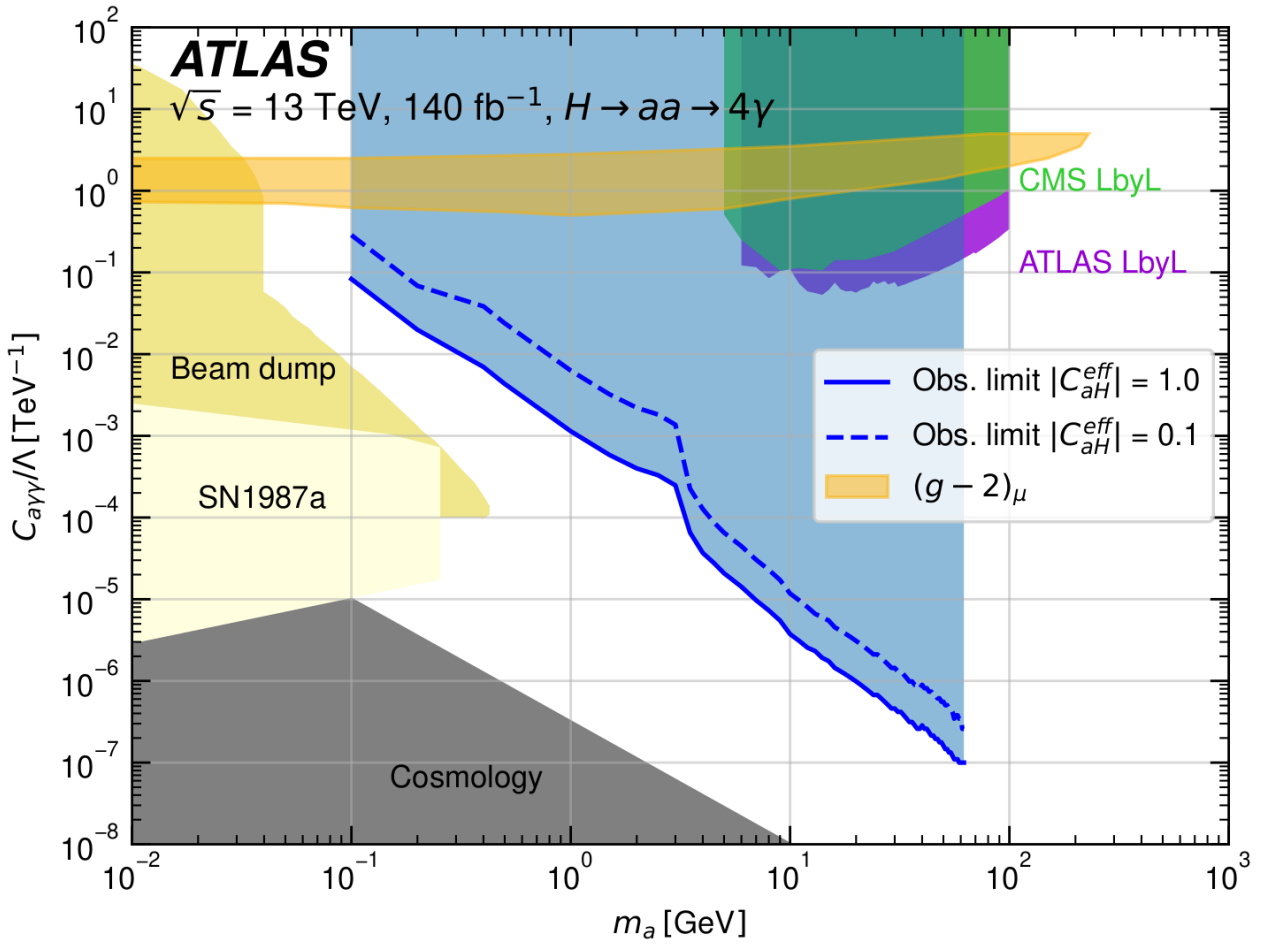


CMS, PLB 852 (2024) 138582

H → aa → 4γ: prompt and long-lived ALPs

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- **ATLAS**, 140 fb^{-1}: m_a = 0.1–62 GeV and $10^{-5} < C_{a\gamma\gamma}/\Lambda < 1$ TeV^{-1}
  - covers collimated photon pairs and significantly displaced vertices
  - motivated by ALP explanations of $(g-2)_\mu$
  - $B(H \to aa \to 4\gamma) < 10^{-5} - 3\times10^{-2}$
- **Long-lived regime:** $\Gamma(a \to \gamma\gamma) \propto (C_{a\gamma\gamma}/\Lambda)^2 m_a^3$, so for small couplings or light ALPs the ALP flies mm – m before decaying → displaced, non-pointing photons that fail standard (prompt) photon selections
- **Long-lived reinterpretation** of H → Za and H → aa → 4γ (ATL-PHYS-PUB-2025-007)
  - H → Za: m_a = 2–33 GeV excluded for $|C_{\gamma\gamma}|/\Lambda$ down to 3×10^{-6} TeV^{-1}
  - H → aa: m_a = 0.01–0.1 GeV excluded for $C_{\gamma\gamma}/\Lambda$ down to 0.1 TeV^{-1}



ATLAS, EPJC 84 (2024) 742

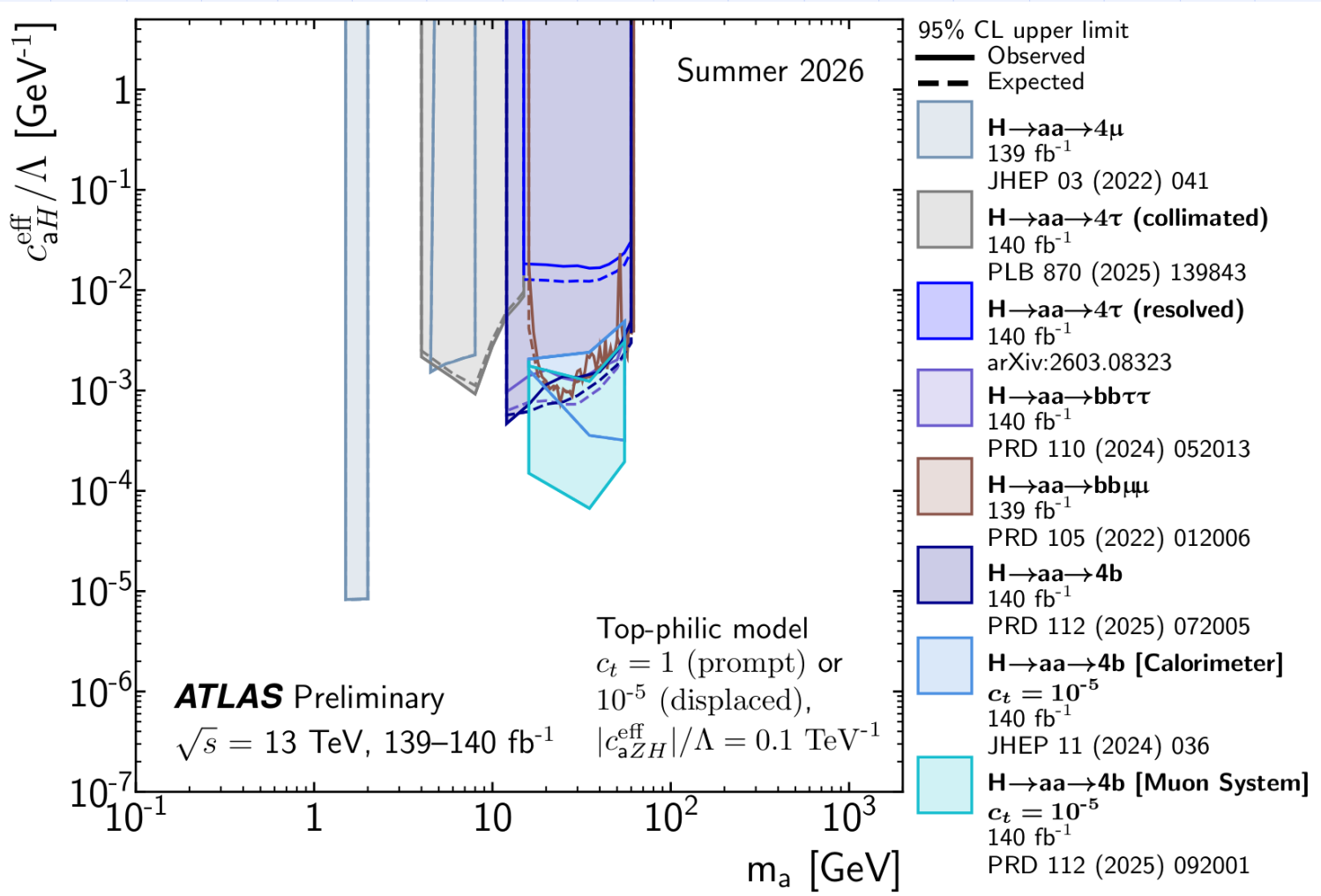
H → aa with fermionic ALP decays: ATLAS

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- Yukawa-like ALP couplings favour a → ττ for $2m_\tau < m_a < 2m_b$ and a → $b\bar{b}$ above; dedicated boosted-object taggers for collimated decays

Final state	m_a (GeV)	95% CL limit
4τ, resolved (2026)	15 – 60	B < 0.06 – 0.23
4τ, boosted	4 – 15	$(\sigma/\sigma_{SM}) \times B$ < 0.03 – 0.10
γγττ	10 – 60	B < 0.2 – 2%
bbττ	12 – 60	B < 2.2 – 3.9%
4b / 6b (ZH)	a_1, a_2 scan	$(\sigma/\sigma_{SM}) \times B$ < 4 – 25% (4b)

arXiv:2603.08323; PLB 870 (2025) 139843; JHEP 03 (2025) 190; PRD 110 (2024) 052013; PRD 112 (2025) 072005

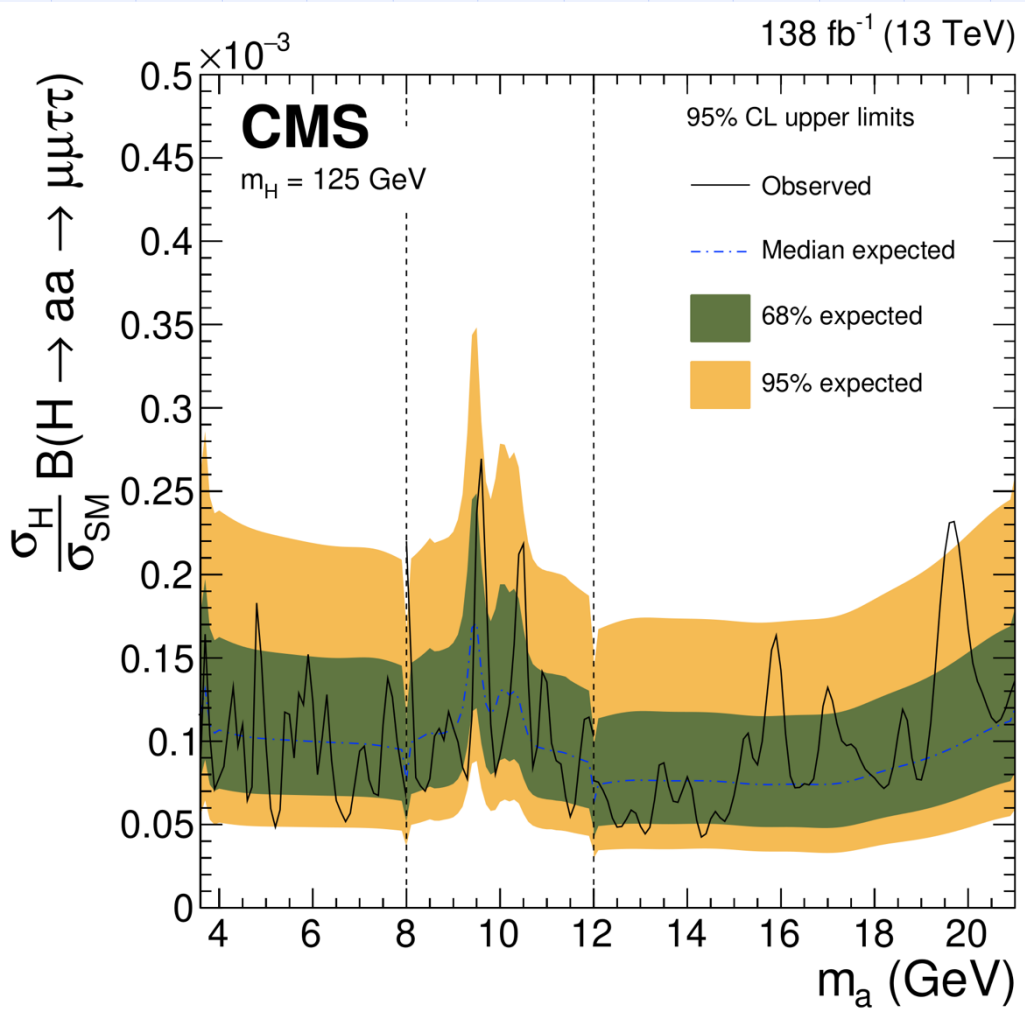


ATL-PHYS-PUB-2026-016

H → aa with leptons, photons and b-quarks: CMS

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- **H → aa → μμττ, boosted** (2026): dedicated ditau reconstruction with a deep neural network; H = h(125) or heavier; $(\sigma/\sigma_{SM})\times B < 5\times10^{-5} – 2.7\times10^{-4}$ for m_a = 3.6–21 GeV
- **H → aa → 4τ and 2μ2τ:** m_a = 4–15 GeV, Yukawa-like couplings
- **H → AA → 4e:** first LHC search, m_A = 10–100 MeV, merged e^+e^- pairs, B sensitivity down to 10^{-5}
- **H → AA → bbγγ** (VH, PAS): m_A = 20–62 GeV, B < 0.06 (WH)
- **H → aa → 4b, μμbb, ττbb** complete the Run-2 programme

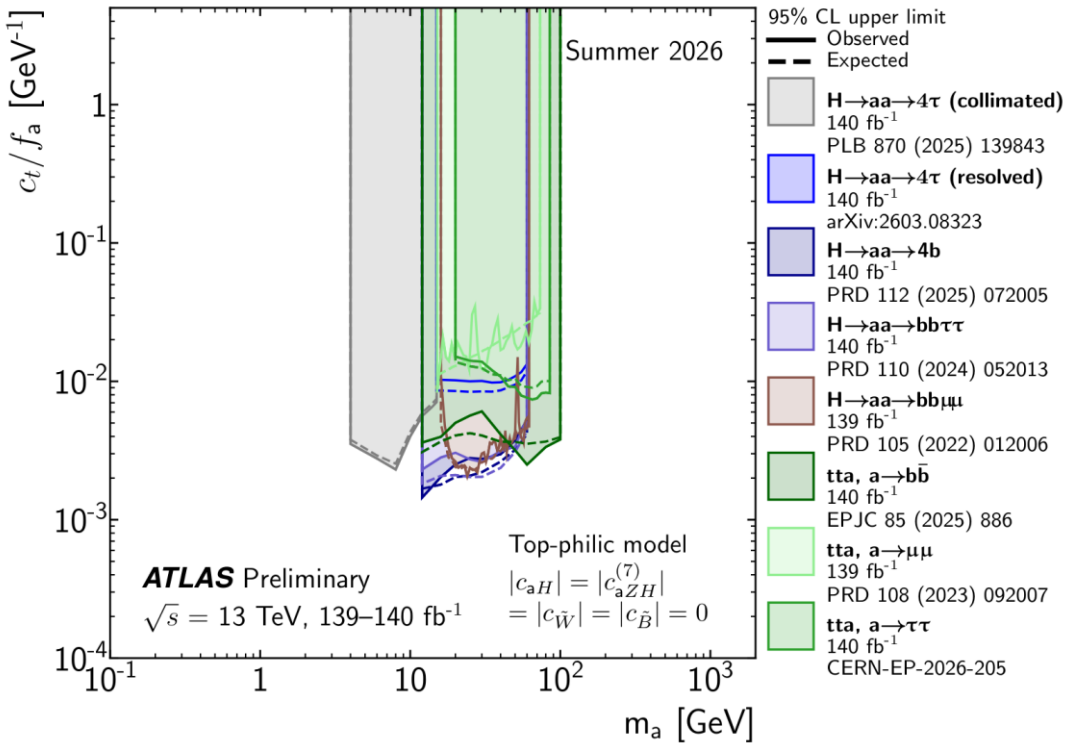


CMS, arXiv:2609.12683

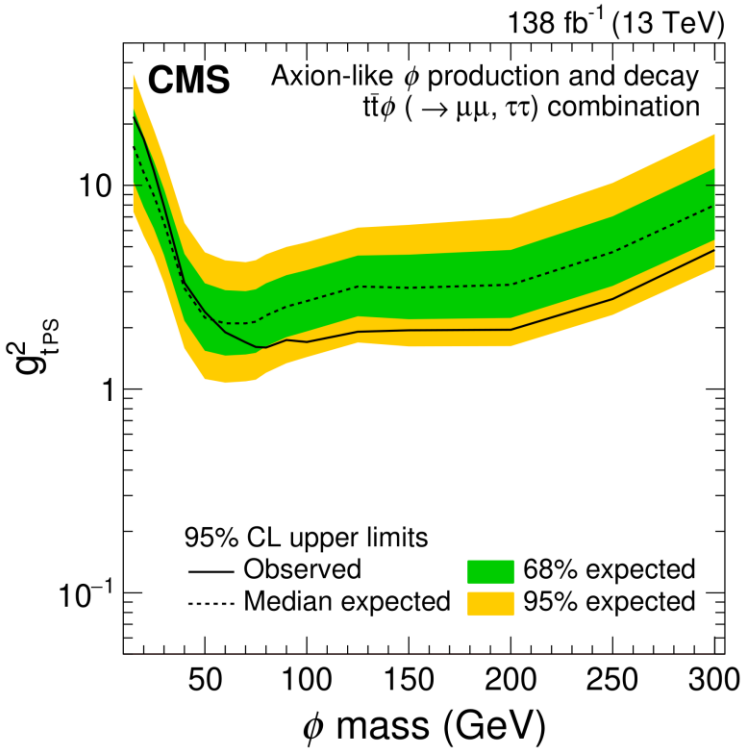
CMS JHEP 04 (2026) 132; PRL 136 (2026) 181807
CMS-PAS-SUS-24-008; CMS JHEP 06 (2024) 097
CMS EPJC 84 (2024) 493

Top-philic ALPs: tt̄a production

- Top-dominated ALP couplings escape light-quark and photon constraints [Blasi et al., JHEP 06 (2024) 077]
- **ATLAS** tt̄a: a → μμ (15–72 GeV, PRD 108 (2023) 092007), a → bb̄ (12–100 GeV, 0.5×y_t excluded for 50–80 GeV, EPJC 85 (2025) 886), a → ττ boosted (20–85 GeV, σ×B < 0.19 fb, arXiv:2607.28484)
- **CMS** tt̄φ, φ → μμ, ττ: limits on the axion-like top coupling g^2_{tPS}



ATL-PHYS-PUB-2026-016

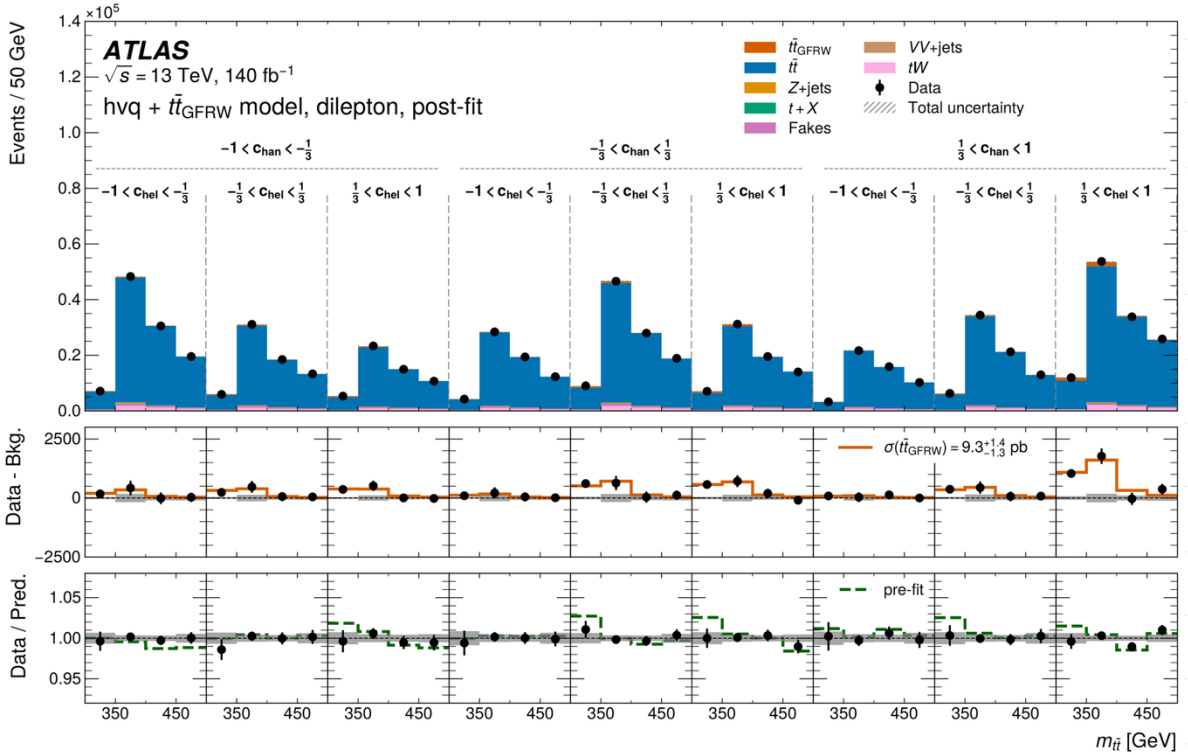


CMS, PRD 110 (2024) 012013

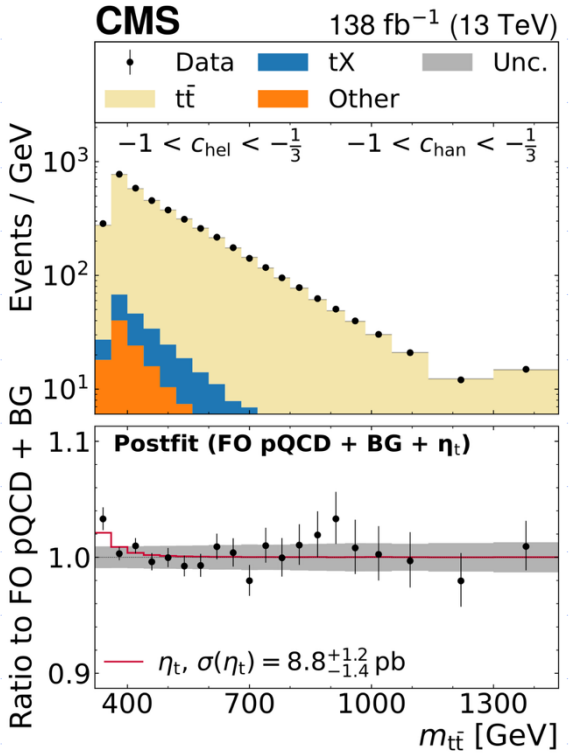
Pseudoscalar excess at the $t\bar{t}$ production threshold

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- Excess near $m_{t\bar{t}} \approx 345$ GeV with spin correlations of a **colour-singlet pseudoscalar** ($^1S_0^{[1]}$), consistent with NRQCD toponium η_t; a heavy A/ALP → $t\bar{t}$ is an alternative
- **CMS** dilepton: > 5σ, $\sigma = 8.8\ ^{+1.2}_{-1.4}$ pb; ℓ+jets: 6.1σ, $\sigma = 5.1 \pm 0.9$ pb (arXiv:2608.19546)
- **ATLAS** dilepton: > 8σ, $\sigma = 9.3\ ^{+1.4}_{-1.3}$ pb; eμ distributions: > 3σ (arXiv:2605.02341)



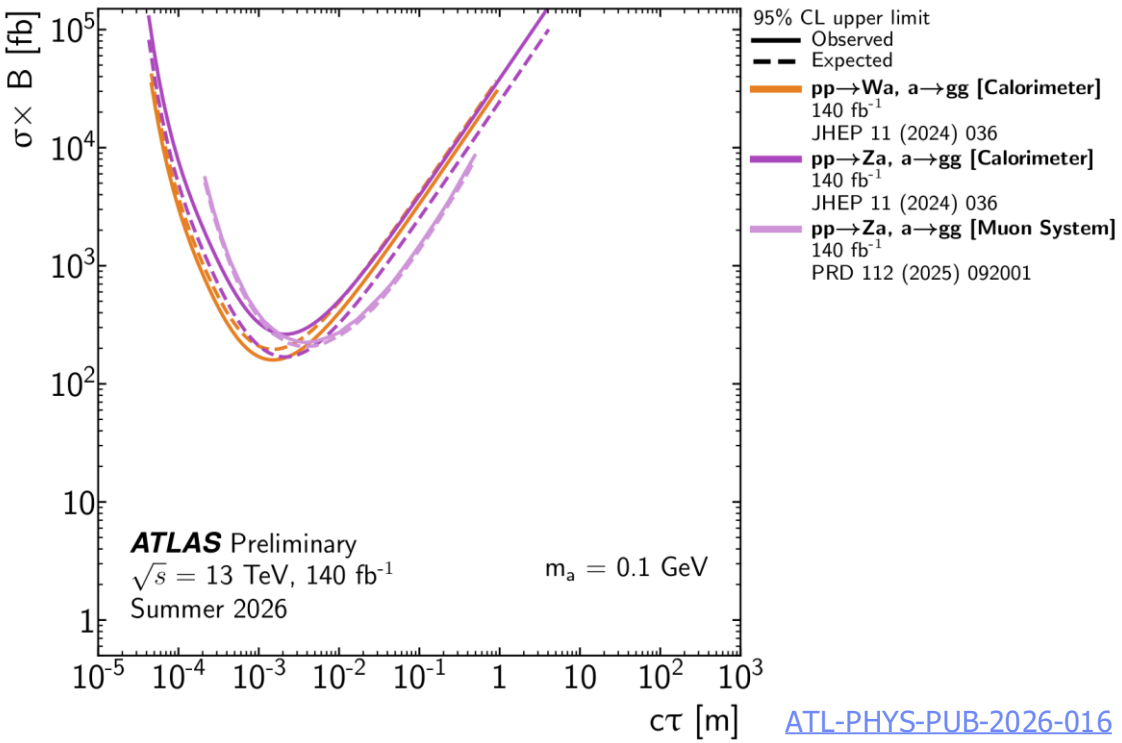
ATLAS, arXiv:2601.11780



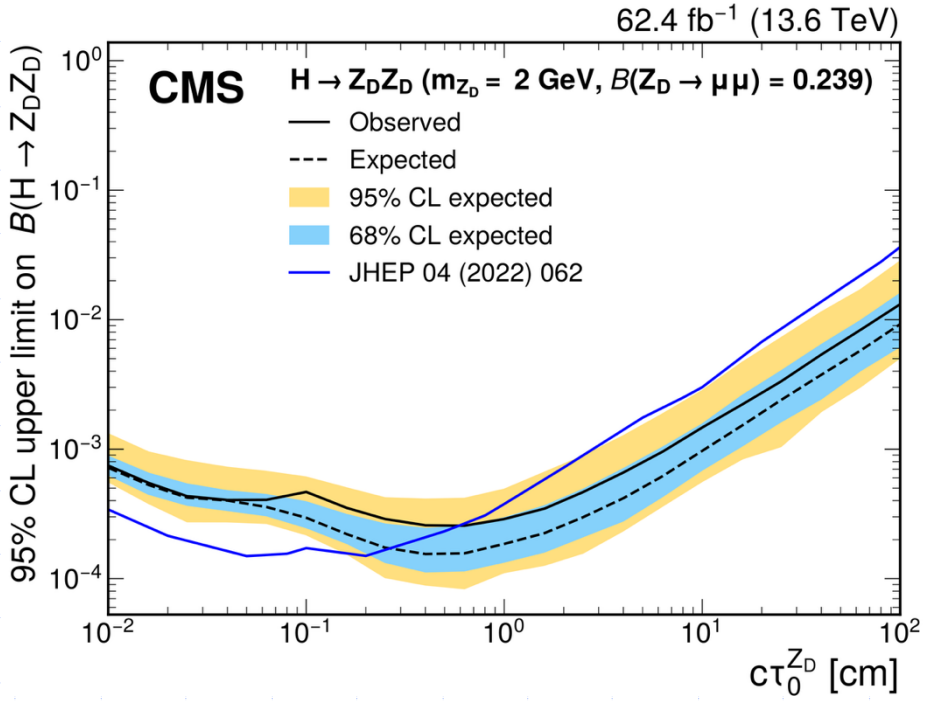
CMS, RPP 88 (2025) 087801

Long-lived ALPs: displaced signatures

- Small couplings or low masses give macroscopic decay lengths: displaced vertices in the inner detector, calorimeter and muon spectrometer
- **ATLAS** PRL 133 (2024) 161803; JHEP 11 (2024) 036; PRD 112 (2025) 092001; recasts of H → Za and H → aa (ATL-PHYS-PUB-2025-007)
- **CMS** long-lived particles → μμ with Run-3 scouting at 13.6 TeV (EXO-24-016); dark-photon benchmark shown



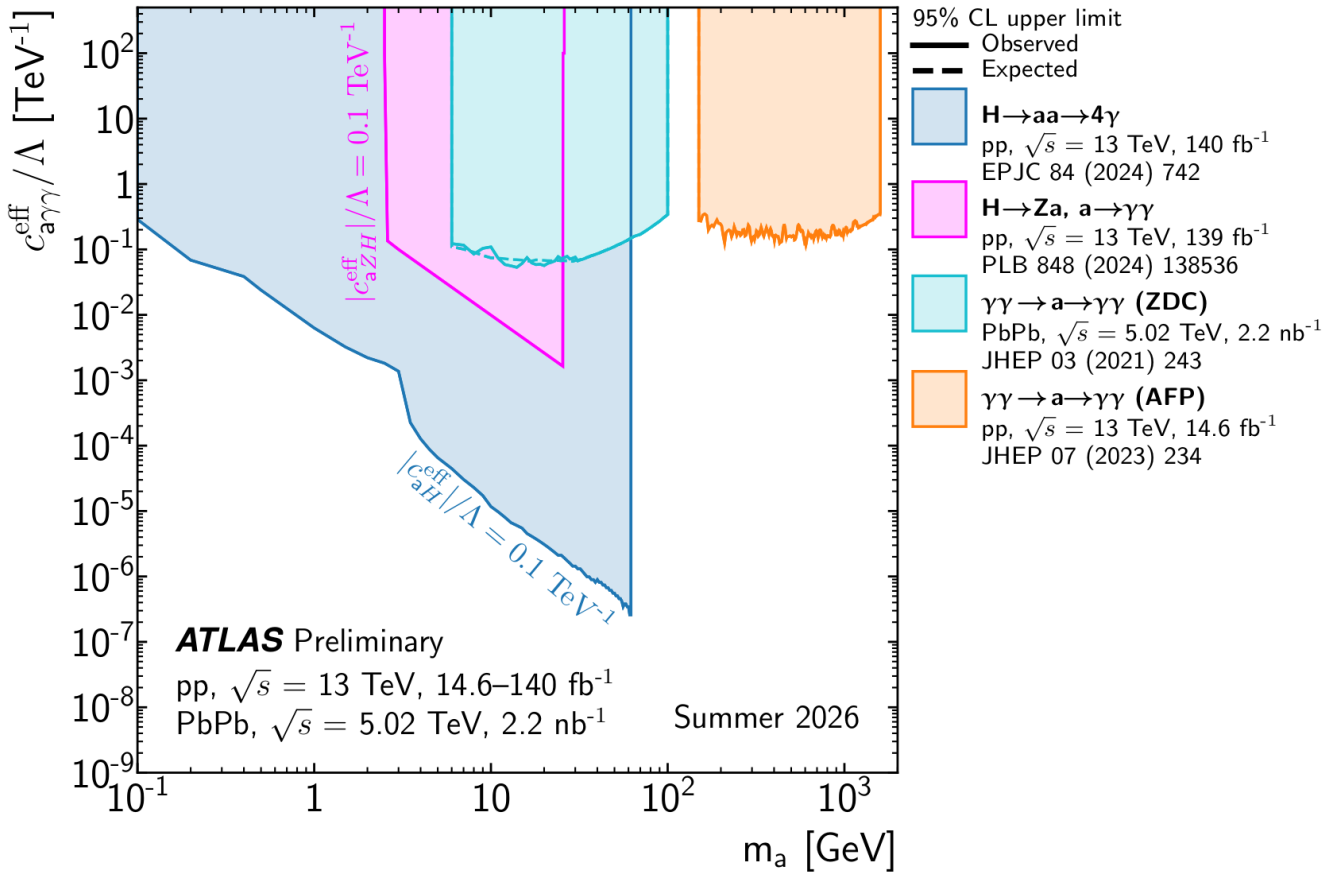
ATL-PHYS-PUB-2026-016

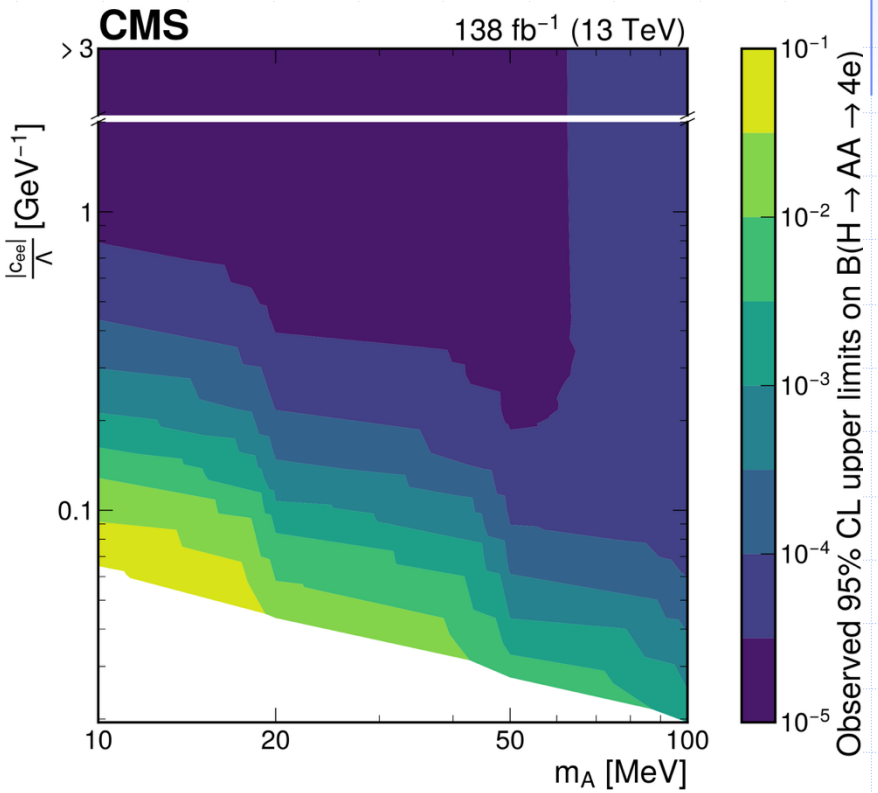


arXiv:2606.25840

ALP limits: from MeV to TeV

- **ATLAS** summary (Summer 2026): combined limits interpreted as effective couplings versus m_a (ATL-PHYS-PUB-2026-016); **CMS** $H \to AA \to 4e$ reaches the lowest ALP masses, 10–100 MeV





CMS, PRL 136 (2026) 181807

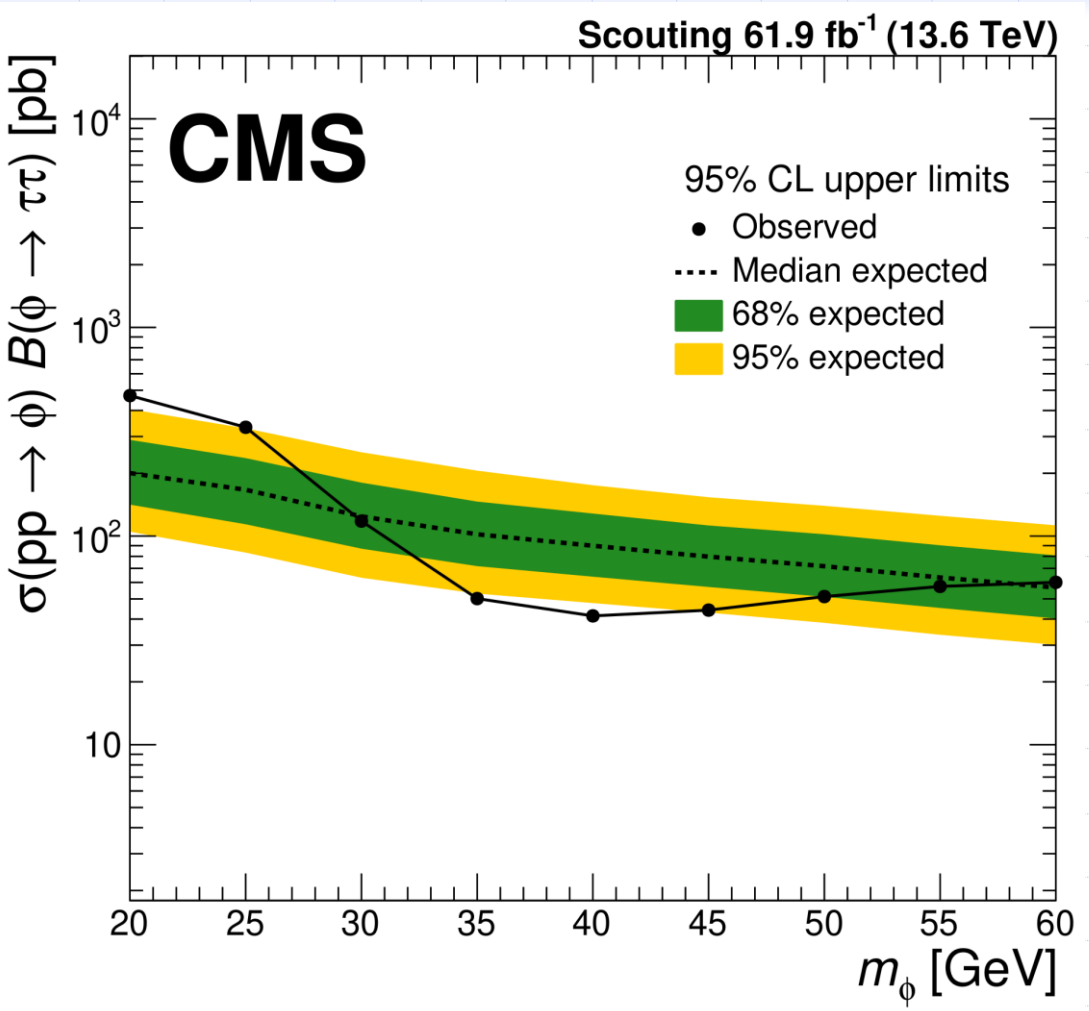
ATL-PHYS-PUB-2026-016

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First Run-3 results and outlook

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- **Run 3** ($\sqrt{s}$ = 13.6 TeV, 2022–2026) with new trigger strategies for soft and displaced objects
  - CMS a → ττ, m = 20–60 GeV, 61.9 fb^{-1}: σ×B < 40–400 pb
  - CMS low-mass dimuon resonances at 13.6 TeV (PAS)
  - CMS long-lived particles → μμ with data scouting
  - ATLAS H → $\gamma\gamma_D$ at 13.6 TeV (dark-sector photons)
- **HL-LHC** (3 ab^{-1} per experiment): ×20 data set, upgraded trackers and timing detectors, forward-proton spectrometers
- Data parking (temporary storage of recorded data) and scouting (simplified reconstruction) for VBF-produced ALPs with m_a = 10 MeV – 10 GeV [arXiv:2609.22570]



CMS, arXiv:2605.25103

CMS-PAS-EXO-25-019; CMS-EXO-24-016
ATLAS HMBS-2024-50

Conclusions

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- ATLAS and CMS cover ALP masses from 10 MeV to above 1 TeV with all couplings of the ALP effective theory
- **Photon coupling:** light-by-light scattering in Pb+Pb and in proton-proton collisions with forward-proton tagging, and boosted diphotons set leading limits for $m_a \approx 5$ GeV – 2 TeV
- **Higgs portal:** $H \to Za$ and $H \to aa$ probed in more than ten final states, $B(H \to aa)$ down to 10^{-5}
- **Top-philic ALPs:** no signal in $t\bar{t}a$ searches up to 100 GeV; the cross-section enhancement at the $t\bar{t}$ threshold seen by ATLAS and CMS is well described by SM toponium (η_t) formation in NRQCD, so no BSM pseudoscalar is required
- **Long-lived ALPs:** displaced-vertex searches and reinterpretations extend reach to very small couplings
- No significant excess in any ALP search; summary plots give a coherent picture in the (m_a, coupling) plane
- Run 3 (scouting, parking, new triggers) and HL-LHC will push to lower masses and weaker couplings

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Supplement

Resources

- ATLAS public results (twiki.cern.ch/twiki/bin/view/AtlasPublic)
- CMS public results (cms-results-search.web.cern.ch)
- ATLAS Summary plots for axion-like particle models, ATL-PHYS-PUB-2026-016 (cds.cern.ch/record/2967223)
- ATLAS Constraints on long-lived ALPs from exotic Higgs decays, ATL-PHYS-PUB-2025-007
- A. Biekötter, K. Mimasu, Axions and axion-like particles: collider searches (arXiv:2508.19358)
- M. Bauer, M. Neubert, A. Thamm, Collider probes of axion-like particles, JHEP 12 (2017) 044
- S. Blasi et al., Top-philic ALP phenomenology at the LHC, JHEP 06 (2024) 077

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Data scouting: recording more events with less information





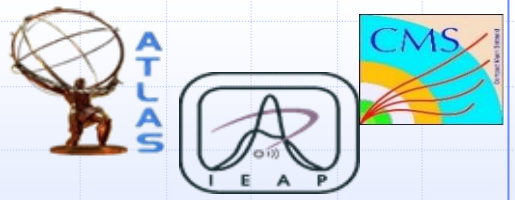


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- LHC: 40 MHz bunch crossings, but only ≈ 1–3 kHz of full events (≈ 1 MB each) can be stored → high trigger thresholds remove the soft decay products of light ALPs
- **Scouting:** store only the physics objects reconstructed in the high-level trigger (jets, muons, photons, vertices; ≈ few kB/event) → ≈ 100× higher rate and much lower thresholds; trade-off: no offline re-reconstruction, reduced precision, well suited for resonance searches
- **Data parking:** store full events at high rate, reconstruct later when computing is available

	Standard trigger	Scouting (CMS) / Trigger-Level Analysis (ATLAS)	Data parking
Event content	full raw data, ≈ 1 MB	HLT physics objects only, ≈ few kB	full raw data
Rate	≈ 1–3 kHz	up to tens of kHz; CMS L1 scouting at 40 MHz	several kHz extra
Reconstruction	prompt, full offline	online (trigger level) only	delayed, full offline
ALP examples	most Run-2 searches	CMS a → ττ and LLP → μμ at 13.6 TeV; ATLAS TLA dijets	VBF ALPs, 10 MeV – 10 GeV (proposal, arXiv:2609.22570)

$t\bar{t}$ threshold enhancement: toponium or pseudoscalar?



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- Near $m_{t\bar{t}} \approx 2m_t$, NRQCD predicts colour-singlet quasi-bound $t\bar{t}$ states; the spin-singlet $^1S_0^{[1]}$ state η_t is a **pseudoscalar** ($J^{PC} = 0^{-+}$), the same quantum numbers as a heavy ALP or 2HDM $A \rightarrow t\bar{t}$
- Spin observables c_{hel}, c_{han} select the spin-singlet configuration; both experiments fit $m_{t\bar{t}}$ in bins of these variables
- Data are well described by adding SM toponium formation to fixed-order pQCD; a BSM pseudoscalar with $m \approx 2m_t$ is not required, but cannot yet be separated by shape alone → line shape, $t\bar{t}$ velocity, Run-3 data

Experiment	Channel	Data	Significance	Excess cross section
CMS	dilepton	138 fb^{-1}	> 5σ	$8.8\ ^{+1.2}_{-1.4}$ pb
CMS	ℓ + jets (2026)	138 fb^{-1}	6.1σ	5.1 ± 0.9 pb
ATLAS	dilepton	140 fb^{-1}	> 8σ	$9.3\ ^{+1.4}_{-1.3}$ pb
ATLAS	eμ differential distributions	140 fb^{-1}	> 3σ	consistent with the dedicated threshold study

CMS Rep. Prog. Phys. 88 (2025) 087801; CMS arXiv:2608.19546; ATLAS arXiv:2601.11780; ATLAS arXiv:2605.02341