Searches for axion-like-particles (ALPs) in Higgs boson decays in ATLAS

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ATLAS EXPERIMENT

ICHEP 2024 | Prague

Introduction to axion-like particles (ALPs)

ALPs are **pseudoscalar particles** that appear in many well-motivated extensions of the SM, such as:

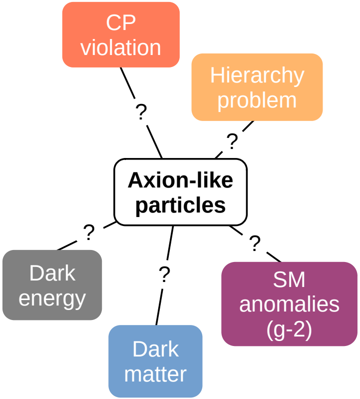
Supersymmetry (e.g. NMSSM)
Axion models
Dark/extended Higgs sectors ...

They are pseudo-NG bosons generated by the **spontaneous breaking** of an approximate global symmetry, and can naturally be **light** w.r.t. the EW scale.

In general, **ALP phenomenology** is studied using broader models, e.g.:

2HDM+S [1]
ALP EFT [2]

which can be later reinterpreted.



[1] Phys. Rev. D 90 (2014) 075004
[2] JHEP 12 (2017) 044

ALP searches in ATLAS

There is a rich program in ATLAS for the study of light spin-0 resonances in different production modes and decay channels:

Previously published analyses

- $tta, a \to \mu\mu$
- $gg \to X \to \gamma\gamma$
- $H \to bb + E_T^{miss}$
- $H \to aa \to bb\mu\mu$
- $H \to Za \to \ell\ell(gg/ss)$

} 139 fb^{-1}@ 13 TeV

- $H \to XX/ZX \to 4\ell$
- $H \to aa \to \gamma\gamma gg$
- $H \to aa \to 4b$

} 36 fb^{-1}@ 13 TeV

- $H \to aa \to 4\gamma$
- $H \to aa \to \mu\mu\tau\tau$

} 20 fb^{-1}@ 8 TeV

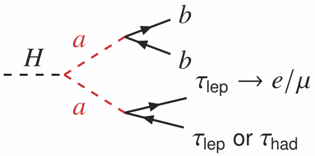
New analysis ⇒ covered in this talk

- $H \to aa \to bb\tau\tau$
- $H \to aa \to 4\gamma$
- $H \to Za \to \ell\ell\gamma\gamma$

} 139 fb^{-1}@ 13 TeV

arXiv:2407.01335 | Submitted to: Phys. Rev. D.
[3] ATL-PHYS-PUB-2022-042

$H \rightarrow aa \rightarrow bb\tau\tau$



- Search for the decay of a **SM Higgs** boson into **two light light pseudoscalars**.
- $\boldsymbol{m_a}$ **from 12 to 60 GeV.**
- **Main backgrounds**: τ_{had}-fakes, e/μ-fakes, tt+jets and Z+jets.

$a \rightarrow bb$

Boosted for low m_a ($a \rightarrow B$)

Resolved for high m_a ($a \rightarrow bb$)

$a \rightarrow \tau\tau$

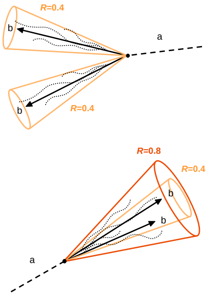
3 channels: $\boldsymbol{e\tau_{\text{had}}}$, $\boldsymbol{\mu\tau_{\text{had}}}$, $\boldsymbol{e\mu}$ (~50% of τ decays)

***b*-jets** refer to a jet originating from a single b-hadron.

– They have a radius $\boldsymbol{R = 0.4}$.

***B*-jets** are a boosted bb pair that can not be reconstructed as 2 b-jets.

– They are identified by a dedicated tagger (DeXTer) [3] using low-level tracks and secondary vertices up to $\boldsymbol{R = 0.8}$.



$H \to aa \to bb\tau\tau$

Event selection

- $e/\mu/e\mu$ triggers with low p_T threshold.
- b-jet $p_T > 15$ GeV
- B-jet $p_T > 20$ GeV
- 9 categories $\Rightarrow$

$(e\mu, 1B)$	$(e\mu, 1b)$	$(e\mu, 2b)$
$(\mu\tau_{had}, 1B)$	$(\mu\tau_{had}, 1b)$	$(\mu\tau_{had}, 2b)$
$(e\tau_{had}, 1B)$	$(e\tau_{had}, 1b)$	$(e\tau_{had}, 2b)$

Background modelling

***Z*+jets** and ***tt*+jets** MC is corrected using a data-driven reweighting.

Non-prompt (fake) rates for $e/\mu/\tau_{had}$ are estimated in same-sign regions.

Analysis strategy

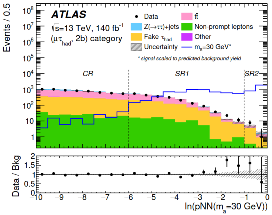
$m_{a\to\tau\tau}$ can not be reconstructed due to ν in τ_{lep}.

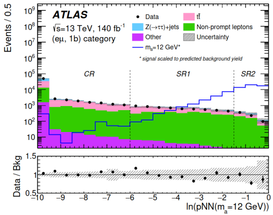
Missing mass calculator (MMC)

$\Rightarrow$ maximum likelihood estimate of the ν 4-momenta.

$\Rightarrow$ most probable value of $m_H = m_{MMC}(bb\tau\tau)$, etc.

SvsB discrimation via **m_a-parametrised NN**.



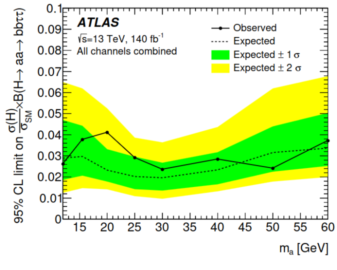


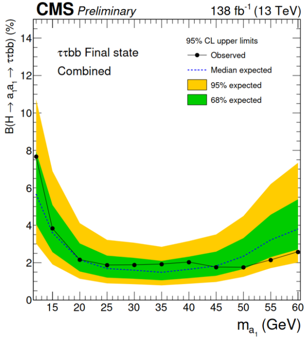
$H \rightarrow aa \rightarrow bb\tau\tau$

Upper limits on BR($H \rightarrow aa \rightarrow bb\tau\tau$)

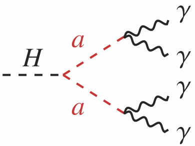
Improved limit at low m_a w.r.t. previous studies thanks to new techniques targetting the boosted $a \rightarrow bb$ decays.

CMS result: `Eur. Phys. J. C 84 (2024) 493`





$H \to aa \to 4\gamma$

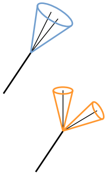


- Search for the decay of a **SM Higgs** boson into **two light pseudoscalars**.
- m_a **from 0.1 to 62 GeV**.
- **Main backgrounds**: di-γ and non-resonant multi-jet.

ALP decays

$m_a < 3.5$ GeV ⟹ boosted $a \to \gamma\gamma$

$m_a \geq 3.5$ GeV ⟹ resolved $a \to \gamma\gamma$



ALP lifetime

$$\frac{1}{\tau} \propto m_a^3 \left|\frac{C_{\gamma\gamma}}{\Lambda}\right|^2, \Lambda = 1 \text{ TeV}$$

$C_{\gamma\gamma} \geq 0.1$ ⟹ promptly decaying ALP

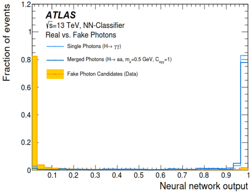
$10^{-5} \geq C_{\gamma\gamma} \geq 0.1$ ⟹ long-lived ALP

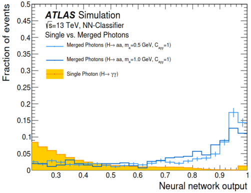
$C_{\gamma\gamma} < 10^{-5}$ ⟹ decay outside of the detector

$H \rightarrow aa \rightarrow 4\gamma$

Boosted $\gamma\gamma$ reconstructed as one **merged** γ.

- NN1 to separate merged γ from 'fake γ' (jets).
- NN2 to separate merged γ from single γ.





Resolved $\gamma\gamma$ reconstructed using stardard identification criteria (ECal energy deposits and energy leakage into HCal).

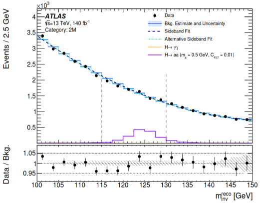
Event selection and analysis strategy

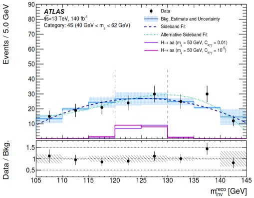
- Di-γ trigger.
- $E_T^{\gamma} \geq 15$ GeV.
- Merged SRs $\Longrightarrow$ 2M, 1M1S, 2S.
- Resolved SRs $\Longrightarrow$ 3S, 4S.

Additionally, selection based on:

- m_a^{reco} = best $a \rightarrow \gamma\gamma$ pairing (NN for 3S and 4S)
- $m_{\text{inv}}^{\text{reco}}$ = invariant mass of all γ candidates $\approx m_H$

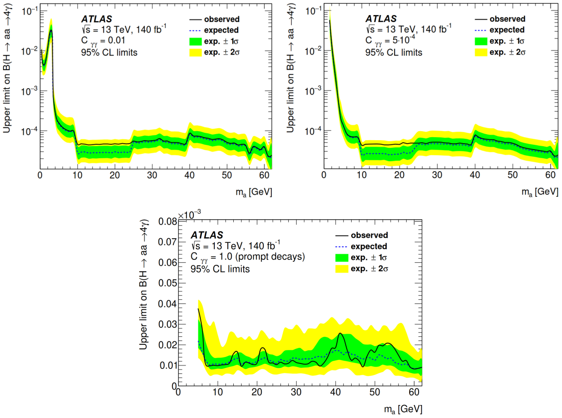
$m_{\text{inv}}^{\text{reco}}$ sidebands used for background estimation.





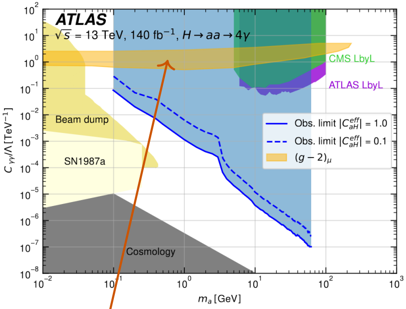
$H \to aa \to 4\gamma$

Upper limits on BR($H \to aa \to 4\gamma$)



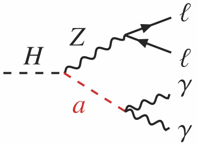
Exclusion limits in the ALP EFT

Limits on $C_{\gamma\gamma}$ for different values of C_{aH}.



$(g-2)_\mu$ anomaly preferred parameter space

$H \to Za \to \ell\ell\gamma\gamma$



- Search for the decay of a **SM Higgs** boson into a Z **boson + light pseudoscalar**.
- m_a **from 0.1 to 33 GeV**
- **Main backgrounds**: $Z\gamma$ and Z+jets.

ALP lifetime & mass

Prompt ALP decays ($L_{xy} \leq 33$ mm).

$m_a < 2$ GeV $\Rightarrow$ merged $a \to \gamma\gamma$

$m_a \geq 2$ GeV $\Rightarrow$ resolved $a \to \gamma\gamma$

Event selection

- Lepton triggers to select $Z \to \ell\ell$
- $p_T^{\ell 1} > 27$ GeV and $p_T^{\ell 2} > 20$ GeV
- $\Delta R_{\ell\ell} > 0.2$
- $|m_{\ell\ell} - m_Z| < 10$ GeV
- $p_T^{\ell\ell} > 10$ GeV

+ Resolved regime

- At least 2 γ with $p_T^{\gamma} > 10$ GeV and $\Delta R_{\gamma\gamma} < 1.5$
- $0.96 < X < 1.2$ with $X = \frac{\Delta R_{\gamma\gamma} p_T^{\gamma\gamma}}{2 m_{\gamma\gamma}}$
- Best di-γ pair with X closest to 1
- $|m_{Z\gamma\gamma} - m_H| < 15$ GeV

+ Merged regime

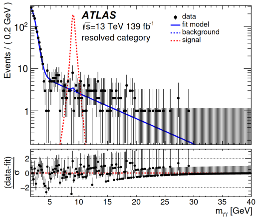
- One merged γ with $p_T^{\gamma} > 20$ GeV
- $|m_{Z\gamma} - m_H| < 10$ GeV
- Fake jet veto

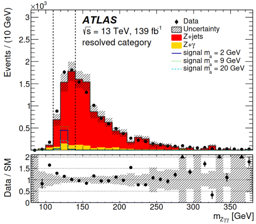
$H \to Za \to \ell\ell\gamma\gamma$

Resolved regime

Data-driven background estimation using an analytic model, calculated in a control region with $|m_{Z\gamma\gamma} - m_H| > 15$ GeV.

Binned maximum likelihood fit to $m_{\gamma\gamma}$.

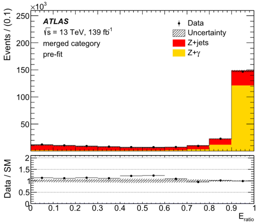


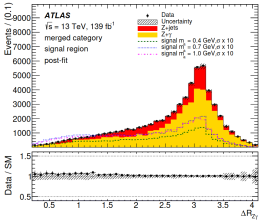


Merged regime

MC simulation for background with data-driven corrections estimated in a control region with $|m_{Z\gamma} - m_H| > 10$ GeV.

Binned maximum likelihood fit to $\Delta R_{Z\gamma}$ in the SR and E_{ratio} in the sidebands.



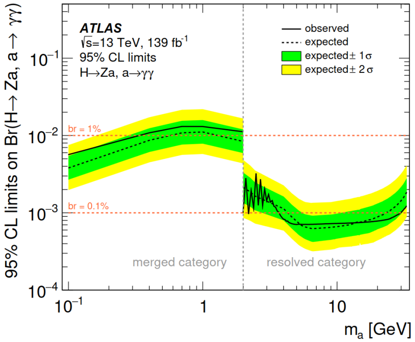


$H \to Za \to \ell\ell\gamma\gamma$

Upper limits on BR($H \to Za, a \to \gamma\gamma$)

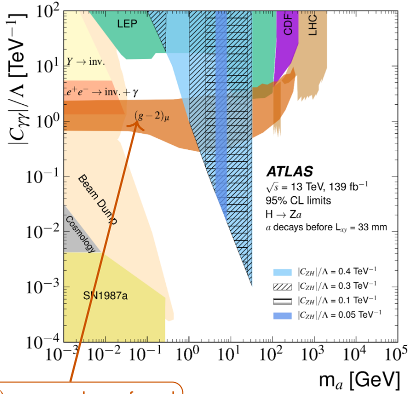
BR above ~2% excluded for $m_a < 2$ GeV.

BR above ~0.1% excluded for $m_a > 2$ GeV.



Exclusion limits in the ALP EFT

Limits on $C_{\gamma\gamma}$ for different values of C_{ZH}.



$(g-2)_\mu$ anomaly preferred parameter space

Summary

- ALPs appear in many different BSM models, and could be used to explain phenomena such as EW baryogenesis, dark matter or the $g-2$ anomalies.
- Light ALPs with $m_a < m_H$ are easily reachable at LHC energy, and can be studied in many different production modes and decay channels.
- Today, 4 recently published ALP searches have been presented:

  $H \to aa \to bb\tau\tau$

  $H \to aa \to 4\gamma$

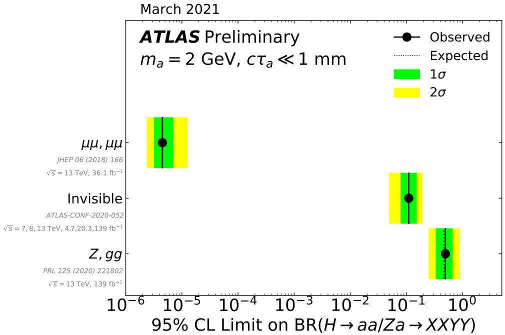
  $H \to Za \to \ell\ell\gamma\gamma$
- This is only the tip of the iceberg

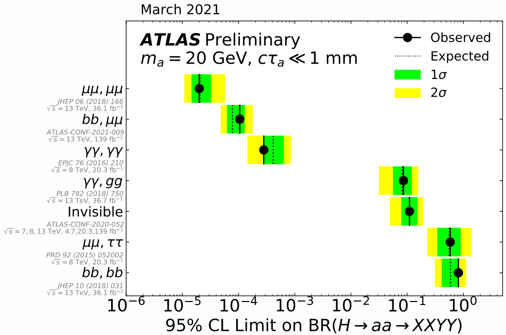
  $\Longrightarrow$ Lots of other analyses already published, and many more to come!


Thank you for your attention
Source: Webb Telescope

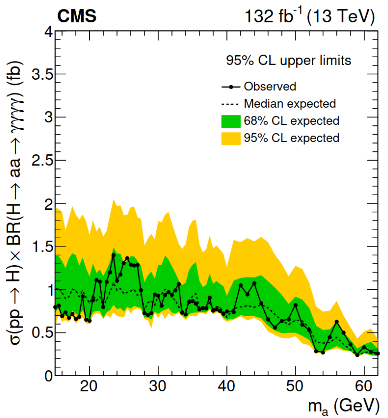
BACKUP

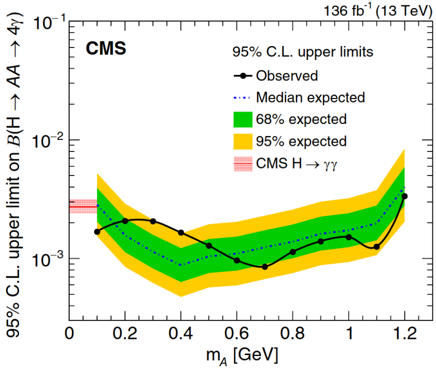
Summary plots from $H \rightarrow aa$ and $H \rightarrow Za$ searches





CMS $H \to aa \to 4\gamma$

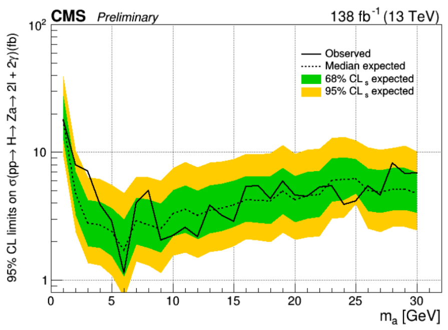


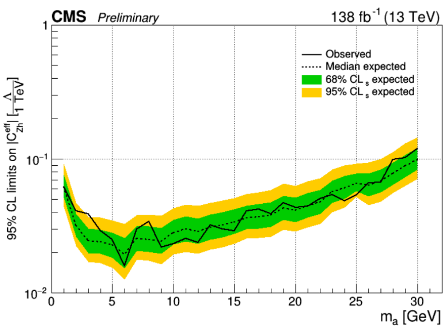


JHEP 07 (2023) 148

Phys. Rev. Lett. 131 (2023) 101801

CMS $H \to Za \to \ell\ell\gamma\gamma$

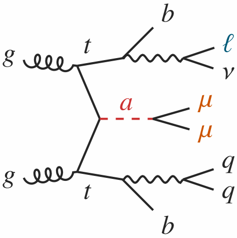


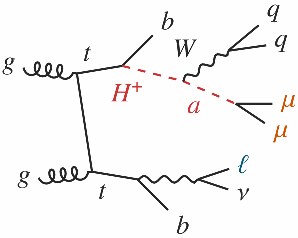


CMS-PAS-HIG-22-003

ALPs in other production modes

tta, $a \rightarrow \mu\mu$





Event selection

- 2 channels: $e\mu\mu$ and $\mu\mu\mu$.
  $\mu\mu = \mu^-\mu^+$ with $\min(|m_a - m_{\mu^-\mu^+}|)$.
- $p_T^{e \text{ or } \mu} > 27$ GeV.
- $p_T^{\mu} > 15$ GeV.
- $12 < m_{\mu\mu} < 77$ GeV.
- $m_{\mu\mu} < 77$ GeV OR $m_{\mu\mu} > 107$ GeV.

- Search for a **light pseudoscalar** produced in association **with a tt pair** $\Longrightarrow$ trigger on ℓ from t-decay.
- **m_a between 15 and 72 GeV**, **m_{H^+} between 120 and 160 GeV**.
- **$a \rightarrow \mu\mu$ decay** = good resolution and background rejection.
- **Main backgrounds**: di-ℓ tt+jets with μ-fakes and ttZ.

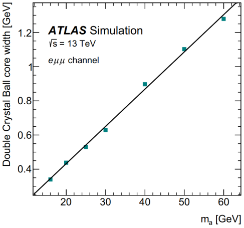
Phys. Rev. D 108 (2023) 092007

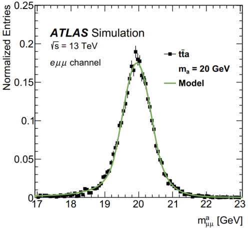
$tta,\ a \to \mu\mu$

Signal modelling

$m_{\mu\mu}$ modelled using a double-sided crystal ball function.

Calculated separately for $e\mu\mu$ and $\mu\mu\mu$ and the tta and H^{+} signals.



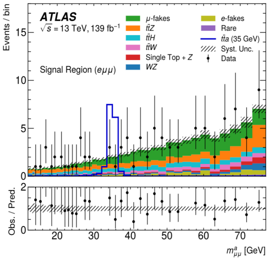


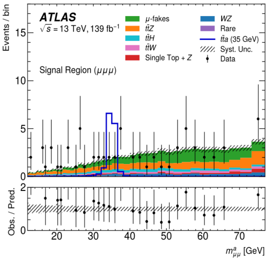
Background modelling

Backgrounds with **prompt** leptons are estimated using **MC simulation**.

– ttZ, ttH, ttW, tZ, di-boson,...

Backgrounds with **non-prompt** leptons are dominated by di-ℓ tt + 1 μ-fake $\Longrightarrow$ **estimated from data**.



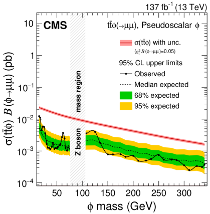


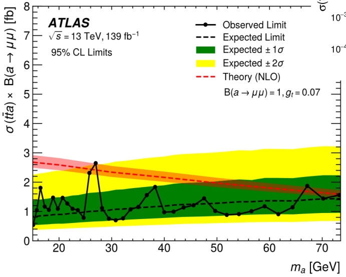
$tta, a \rightarrow \mu\mu$

Upper limits on $\sigma(tta) \times \mathrm{BR}(a \rightarrow \mu\mu)$

Improved limit at low m_a w.r.t. previous studies.

CMS result: JHEP 03 (2020) 51





Upper limits on H^+ production

CMS result: Phys. Rev. D 123 (2019) 131802