



Search for light pseudoscalar bosons, pair-produced in Higgs boson decays in the four-electron final state in proton-proton collisions at $\sqrt{s} = 13$ TeV

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Based on CMS-EXO-24-031, Phys. Rev. Lett. 136, 181807 (2026)

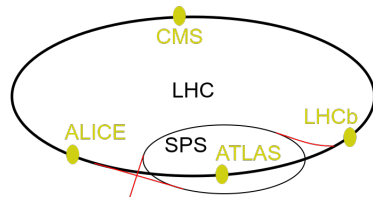
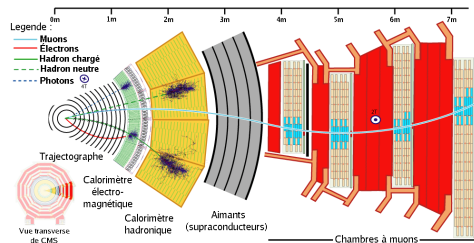
LHC and CMS

Large Hadron Collider (LHC):

- World's largest and highest-energy collider
- $\sqrt{s} \sim 13\text{--}14$ TeV
- 27 km circumference, ~ 100 m underground
- Detectors: ATLAS, ALICE, LHCb, CMS

Compact Muon Solenoid (CMS):

- General-purpose detector at LHC
- Size: 28.7 m long, 15.0 m diameter
- Features: 3.8T field, Precise tracker, Muon system
- Achievements: Higgs discovery, BSM searches

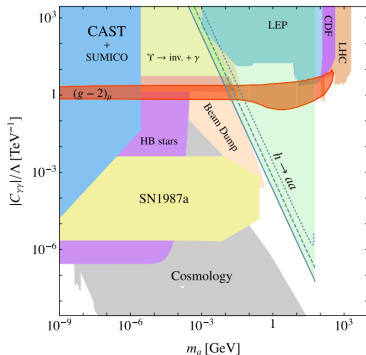


This analysis uses CMS data to search for neutral resonance from Higgs decays

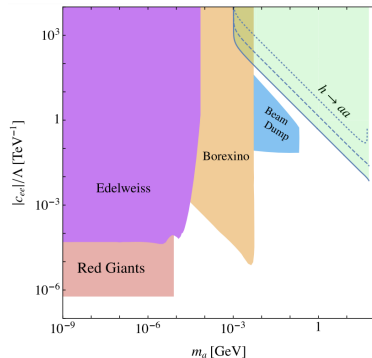
LHC as an ALPs Factory

Axion-Like Particles (ALPs) Introduction (Reference: [PRL.119,031802 \(2017\)](#))

- Pseudoscalar neutral particles from well-motivated extensions of the standard model
- Motivations: strong CP problem, hidden sectors, global symmetry breaking...
- ALPs can be search by different experiments:



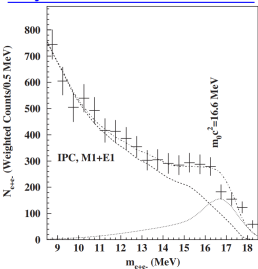
$m_a - \frac{C_{\gamma\gamma}}{\Lambda}$ Parameter Space (Green Region: LHC Run2)



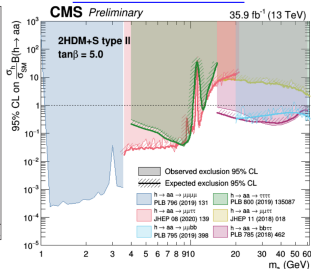
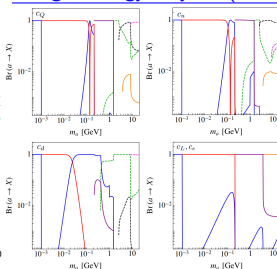
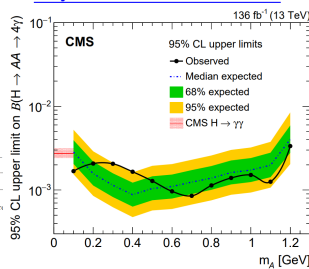
$m_a - \frac{C_{ee}}{\Lambda}$ Parameter Space (Green Region: LHC Run2)

The LHC can search for ALPs across a large parameter space

Previous Research

[Phys.Rev.Lett.116,042501](#)

- ATOMKI anomaly suggests a 17 MeV resonance
- In CMS, tens of MeV ALPs still untouched
- Tens of MeV ALPs mainly decay to e^+e^- or $\gamma\gamma$
- Hard to search Tens of MeV ALPs by γ decay

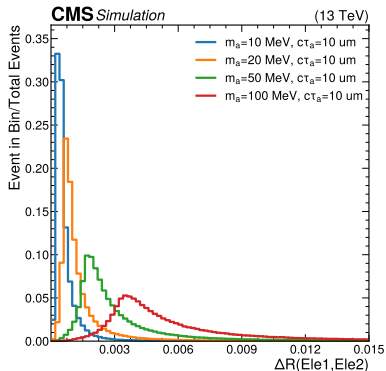
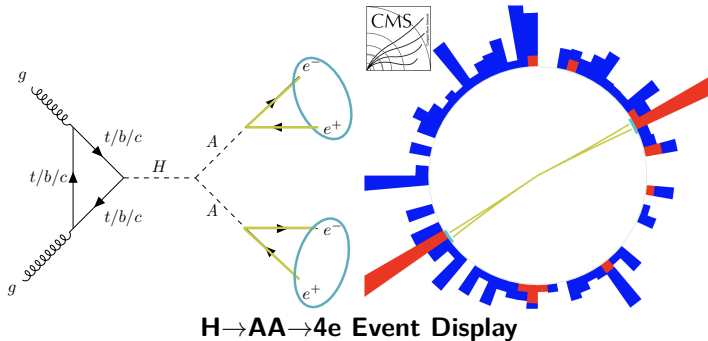
[arXiv:2204.03053](#)[J.High Energy Phys.09\(2022\)056](#)[Phys.Rev.Lett.131,101801](#)

No CMS search yet for Higgs decays to ALPs with tens of MeV mass
The electron channel is important for probing such decays

Signal Samples

$H \rightarrow AA \rightarrow 4e$ Sample Setting

- Run-2UL (138 fb^{-1} , $\sqrt{S}=13\text{TeV}$)
- Higgs production: Gluon fusion
- m_A : 10, 20, 50, 100 MeV
- $c\tau$: 0, 1, 3, 10, 30, 100, 500 μm



Signal Signature

- Tracks of electron pair resolved, but ECAL cluster merged
- Merged ECAL cluster Energy $\approx$ GenALP Energy
- Almost all electron pairs' $\Delta R < 0.015$

Select Merged Electron Pairs to Reconstruct Higgs Candidate Mass

1. Merged Electron Pair Reconstruction (Eff ~ 35%)

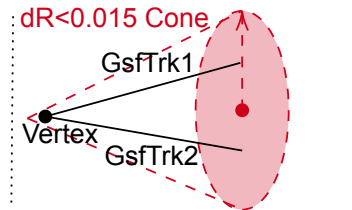
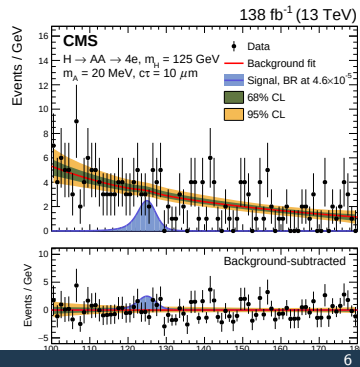
- $N_{\text{miss hits}}^{\text{trk}} < 2$, $p_T^{\text{trk}} > 5$ GeV, $p_T^{\text{SC}} > 25$ GeV
- 2 trks: $\Delta R(\text{SC}, \text{trk}) < 0.015$, $\frac{|p_T^{\text{SC}} - \text{Sum}(p_T^{\text{trk}})|}{p_T^{\text{SC}}} < 0.7$
- Vertex(2 trks): $\chi^2 < 5$

2. Merge Electron Pair Identification (Eff ~ 60%)

- a. Iso Variables (Trk, ECAL, HCAL) Cuts on MEP
- b. Boosted Decision Tree (BDT) Selection on MEP

3. Reconstruct m_H from top-2 p_T selected MEPs

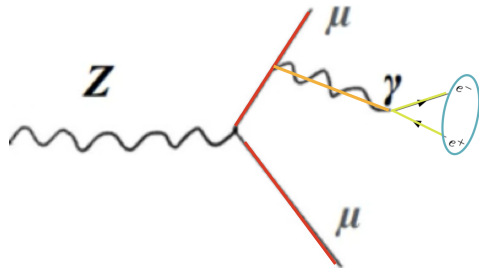
Signal efficiency after all three selection steps: ~5%



Merged Electron Pair ID Efficiency Calibration

Tag and Probe Method to Calibrate

- Process: $Z \rightarrow \mu\mu\gamma$
- Tag: **Muon pair** $\rightarrow$ providing pure phase space
- Probe: Converted **FSR photon** reconstructed as **MEP**
- Pass Criteria: The **MEP** pass the ID requirements
- Efficiency = N_{pass}/N_{probe}



Calibration Scale Factors

- $SF = \epsilon^{Data} / \epsilon^{MC}$
- Uncertainties: Statistical(Below table) + 10%(Systematic) + 5%(Kinematics)

Era	2016preVFP	2016postVFP	2017	2018
SFs	1.28 ± 0.40	1.10 ± 0.26	0.99 ± 0.14	1.04 ± 0.15

Calibration yields Scale Factors close to 1, verifying the MEP ID

Final Fits

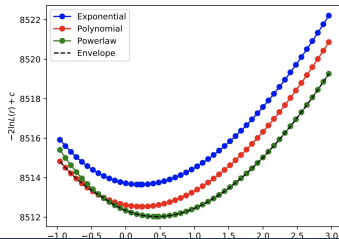
Resonance Modeling

Sample	$\sigma(\text{ggH}) \times \text{BR}/\text{fb}$	Efficiency	Expected Yields
$\text{ggH} \rightarrow \text{AA} \rightarrow 4\text{e}$	0.5(Nominal)	$\sim 5\%$	$69 \times \text{Efficiency}$
$\text{ggH} \rightarrow \gamma\gamma$	110	4.4×10^{-5}	0.67
$\text{ggH} \rightarrow \text{ee}\gamma$	3.93	5.4×10^{-4}	0.29

- Function: DCB + Gaussian or 5-Gaussian

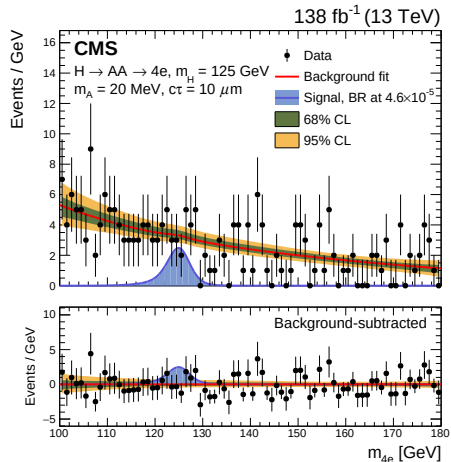
Non-Resonance Modeling

- Build model with data in sideband
- Function: bern, exp, pow, lau
- Envelope Method: [link](#)



S+B Post-fit Plot

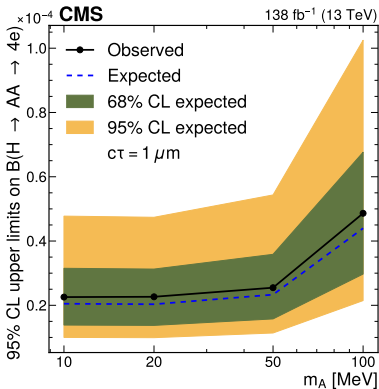
- 20MeV 10um ALP as signal hypothesis



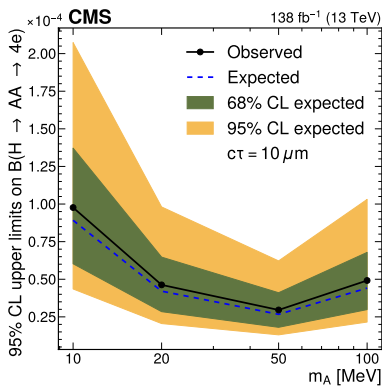
1D Limit Figures

95% CL Upper Limit on Branch Ratio $H \rightarrow AA \rightarrow 4e$

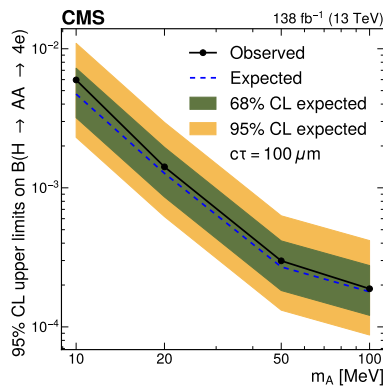
- First CMS Limits on tens of MeV ALPs
- Observed limits within the 1σ band of the background-only expectation



Limits of 1um ALPs

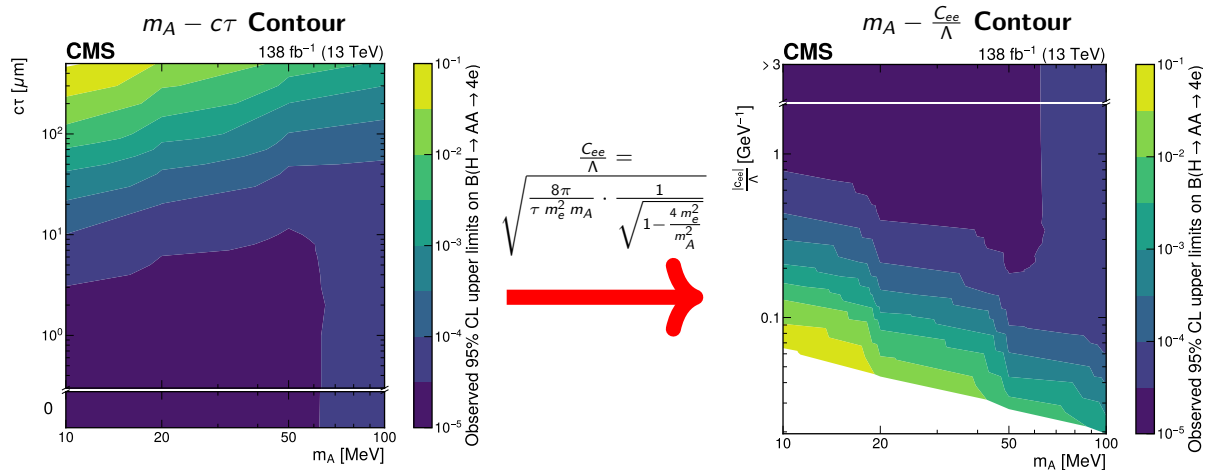


Limits of 10um ALPs



Limits of 100um ALPs

Results Interpretation



First CMS exclusion of tens-of-MeV ALPs with limits as low as 10^{-5}

Summary

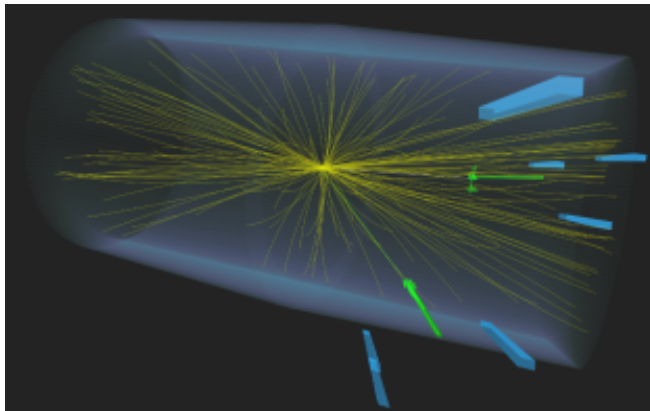
Analysis Summary

- First CMS search for ALPs with masses in the tens of MeV range
- Developed a novel MEP ID for this analysis and derived the ID SF and uncertainty using $Z \rightarrow \mu\mu\gamma$
- No significant excess observed and 95% CL upper limits on $B(H \rightarrow AA \rightarrow 4e)$ at the 10^{-5} scale

Related Documentation:

- Published in *Physical Review Letters*:
[Phys. Rev. Lett. 136, 181807 \(2026\)](#)
- Featured in an official CMS news report:
[CMS Physics Briefing](#)

Thank you for your attention!



BackUps

Opening Angle of Electrons from ALP Decay

- In ALP rest frame: equal and opposite momenta, satisfy:

$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ im_a c^2 \end{bmatrix} = \begin{bmatrix} p \cos \theta c \\ p \sin \theta \cos \varphi c \\ p \sin \theta \sin \varphi c \\ im_{dau1} c^2 \end{bmatrix} + \begin{bmatrix} -p \cos \theta c \\ -p \sin \theta \cos \varphi c \\ -p \sin \theta \sin \varphi c \\ im_{dau2} c^2 \end{bmatrix}$$

- Transform momenta of daughter particles to laboratory frame:

$$p_{dau1} = \begin{bmatrix} \gamma(p \cos \theta + \beta E/c)c \\ p \sin \theta \cos \varphi c \\ p \sin \theta \sin \varphi c \\ i\gamma(P \cos \theta \beta c + E) \end{bmatrix} \quad p_{dau2} = \begin{bmatrix} \gamma(-p \cos \theta + \beta E/c)c \\ -p \sin \theta \cos \varphi c \\ -p \sin \theta \sin \varphi c \\ i\gamma(-P \cos \theta \beta c + E) \end{bmatrix}$$

- Opening angles of decay electrons:

$$\tan \phi = \frac{\sin \theta}{\gamma(\cos \theta + \beta E/Pc)} \quad \tan \phi' = \frac{-\sin \theta}{\gamma(-\cos \theta + \beta E/Pc)}$$

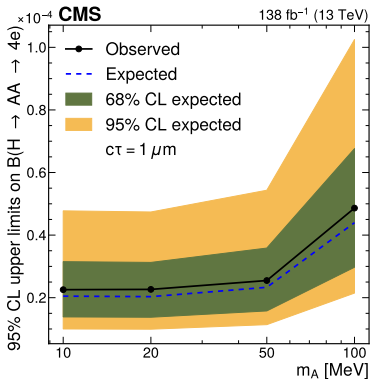
- In massless electron limit ($E \approx Pc$, $\beta \approx 1$):

$$\tan \phi + \tan \phi' \approx \frac{\sin \theta}{\gamma(1 + \cos \theta)} + \frac{\sin \theta}{\gamma(1 - \cos \theta)} = \frac{2}{\gamma \sin \theta}$$

Compare Results with $H \rightarrow AA \rightarrow 4\gamma$

$H \rightarrow AA \rightarrow 4e$ (This Analysis)

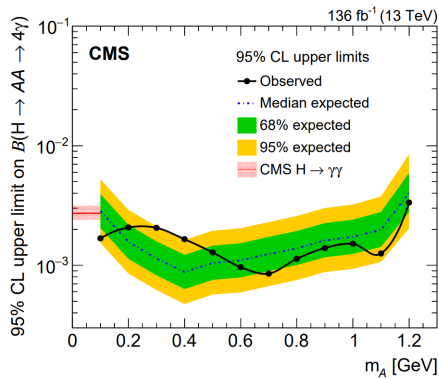
- ALPs mass: 10 MeV-100 MeV
- Limits: $\text{BR}(H \rightarrow AA \rightarrow 4e)$ at 10^{-5} scale



Limit of 1 μm ALPs

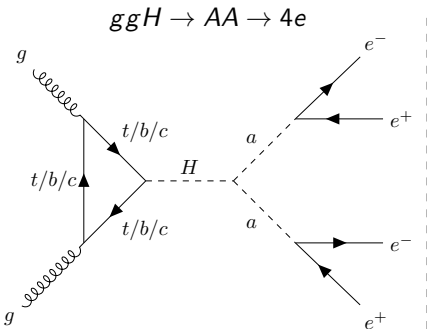
$H \rightarrow AA \rightarrow 4\gamma$ ([Phys.Rev.Lett.131,101801](#))

- ALPs mass: 100 MeV-1200 MeV
- Limits: $\text{BR}(H \rightarrow AA \rightarrow 4\gamma)$ at 10^{-3} scale



Limit of prompt ALPs

Search for Tens of MeV ALPs by $H \rightarrow AA \rightarrow 4e$



1. ALP Fly Distance

- $\Gamma(a \rightarrow \ell^+ \ell^-) = \frac{m_a m_\ell^2}{8\pi \Lambda^2} c_{\ell\ell}^2 \sqrt{1 - \frac{4m_\ell^2}{m_a^2}}$ ([PRL.119,031802\(2017\)](#))
- $\beta\gamma c\tau_a \approx 0.3 \text{ cm}$ ($m_a = 20 \text{ MeV}$, $\frac{C_{ee}}{\Lambda} = 1 \text{ GeV}^{-1}$)

2. Electron Pair Open Angle

- $\Delta R(e\ell_1, e\ell_2) \approx \frac{2}{\gamma \sin \theta} \sim 10^{-3}$ (backup p13)
- CMS Tracker Resolution Limit: $\Delta R \sim 10^{-3}$

Motivation

- Tens of MeV ALPs could decay within tracker ($\beta\gamma c\tau_a \approx 0.3 \text{ cm}$)
- The tracks of electron pair decay from ALPs could be resolved

Challenge

- $\Delta R(e\ell_1, e\ell_2) \sim 10^{-3} \rightarrow$ Merged into a single ECAL Cluster $\rightarrow$ Merged Electron Pair (MEP)
- Merged Electron Pair: 1 Cluster + 2 Tracks $\rightarrow$ Similar to conversion photon

BDT Model

BDT Training (Toolkit: [XGBoost](#))

- Variables:

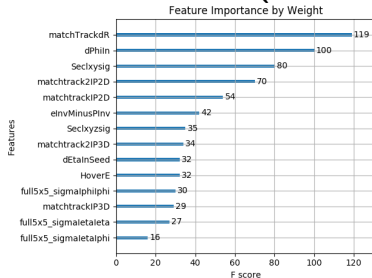
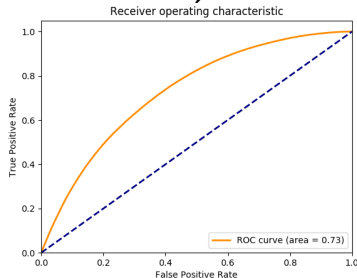
full5x5_sigmaletaleta	full5x5_sigmalphilphi	full5x5_sigmaletalphi	dEtaInSeed	dPhiIn	HoverE
1/E-1/P	ImpactParameter2D(x2)	ImpactParameter3D(x2)	dR(Tk1,Tk2)	VertexLxySig	VertexLxyzSig

- Samples: Training:Testing = 4:1

Samples	DY→ee	Diphton Jets	GJet > 40GeV	H→AA→4e($C_T < 30\mu\text{m}$)
Type	Electron Bkg	Conversion Bkg	Conversion + QCD Bkg	Signal

- WP: Chosen in the $S/\sqrt{B}$ -optimal region, with 70% signal efficiency

Training Results of BDT Model (Show 2017UL Barrel)



Trigger Choice and Trigger Efficiency Calibration

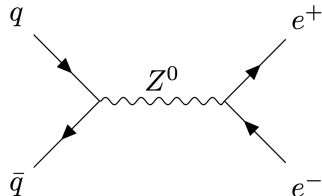
Trigger Choice

- Isolation cuts and BDT model are independent of the trigger choice
- Triggers from the EGM recommend list ([EgHLTRunIISummary](#)) yield over 95% trigger efficiency
- Trigger Eff = $\frac{\text{Number of Events Passing Event Selection and Trigger}}{\text{Number of Events Passing Event Selection}}$

2016UL	2017UL	2018UL
HLT_DoubleEle33_CaloldL_MW	HLT_DoubleEle33_CaloldL_MW	HLT_DoubleEle25_CaloldL_MW
HLT_DoubleEle33_CaloldL_GsfTrkIdVL	HLT_Ele23_Ele12_CaloldL_TrackIdL_IsoVL	HLT_Ele23_Ele12_CaloldL_TrackIdL_IsoVL
HLT_Ele23_Ele12_CaloldL_TrackIdL_IsoVL_DZ		

Tag and Probe Method to Calibrate Trigger Efficiency

- Process: $Z \rightarrow ee$; One ele as tag
- Probe: Other ele reconstructed as MEP and pass ID
- Pass Criteria: The MEP also matches to a trigger object
- **Results:** Calibration SFs close to 1 with 0.2% uncertainty



Compare Results vs. PRL.119,031802(2017):

