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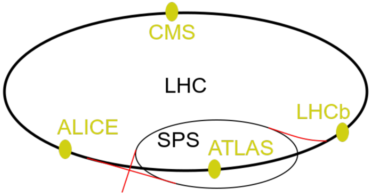
Based on CMS-EXO-24-031, Phys. Rev. Lett. 136, 181807 (2026)

LHC and CMS

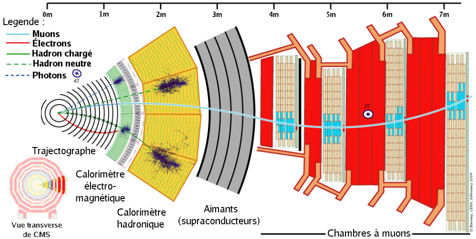
Large Hadron Collider (LHC):

- World's largest and highest-energy collider
- $\sqrt{s} \sim$ 13–14 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

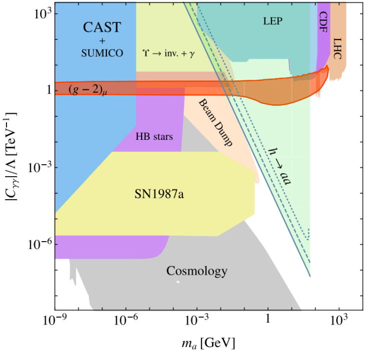


This analysis uses CMS data to search for neutral resonance from Higgs decays

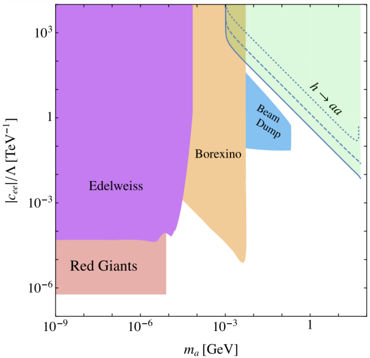
LHC as an ALPs Factory

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)

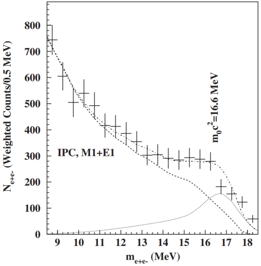


$m_a - \frac{C_{ee}}{\Lambda}$ Parameter Space (Green Region: LHC Run2)

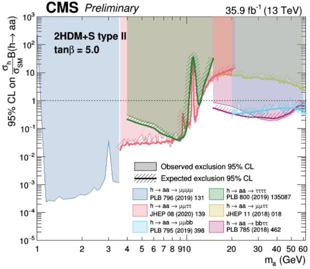
The LHC can search for ALPs across a large parameter space

Previous Research

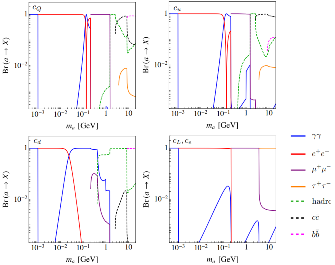
Phys.Rev.Lett.116,042501



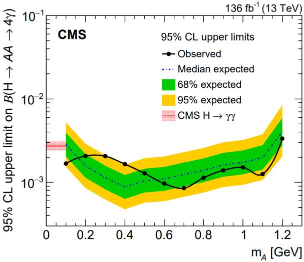
arXiv:2204.03053



J.High Energy Phys.09(2022)056



Phys.Rev.Lett.131,101801



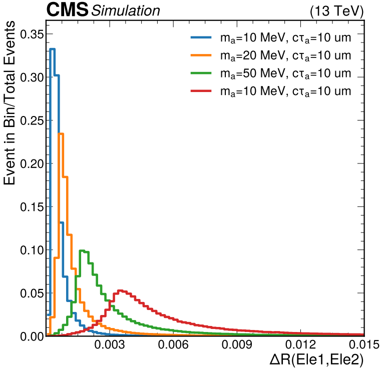
- ATOMKI anomaly suggests a 17 MeV resonance
- In CMS, tens of MeV ALPs still untouched
- Tens of MeV ALPs mainly decay to e^+e^- or $\gamma\gamma$
- Hard to search Tens of MeV ALPs by γ decay

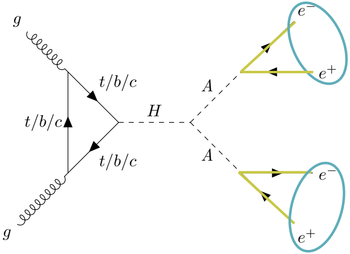
No CMS search yet for Higgs decays to ALPs with tens of MeV mass
The electron channel is important for probing such decays

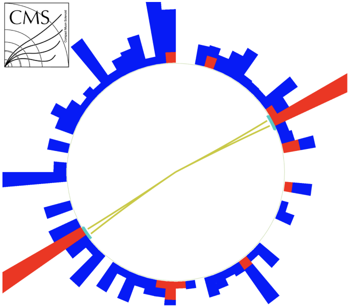
Signal Samples

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

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





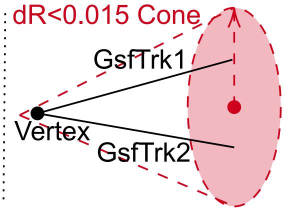


H→AA→4e Event Display

Signal Signature

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

Select Merged Electron Pairs to Reconstruct Higgs Candidate Mass

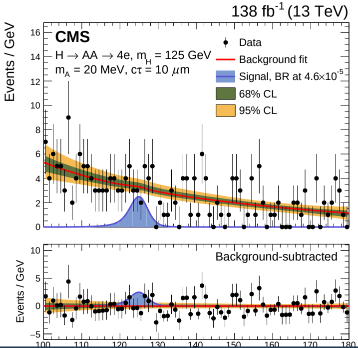


1. Merged Electron Pair Reconstruction (Eff$\sim$ 35%)

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

2. Merge Electron Pair Identification (Eff$\sim$ 60%)

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



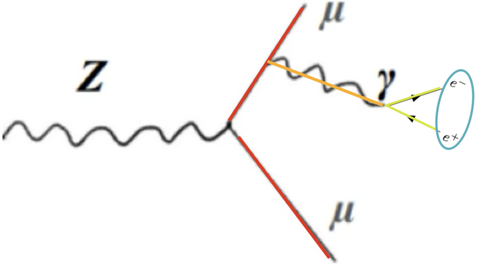
3. Reconstruct m_H from top-2 p_T selected MEPs

Signal efficiency after all three selection steps: $\sim$5%

Merged Electron Pair ID Efficiency Calibration

Tag and Probe Method to Calibrate

- Process: $Z \to \mu\mu\gamma$
- Tag: Muon pair $\to$ 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

- $\mathrm{SF} = \epsilon^{Data}/\epsilon^{MC}$
- 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

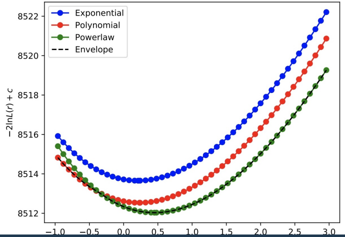
Resonance Modeling

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

- Function: DCB + Gaussian or 5-Gaussian

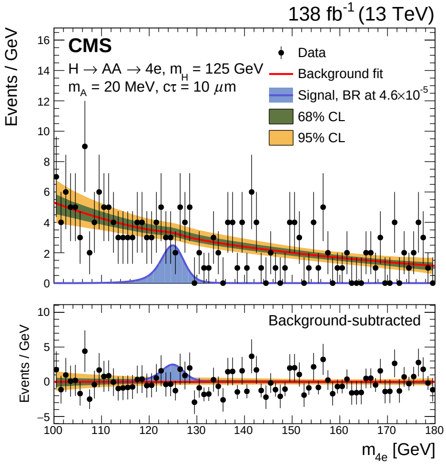
Non-Resonance Modeling

- Build model with data in sideband
- Function: bern, exp, pow, lau
- Envelope Method: link



S+B Post-fit Plot

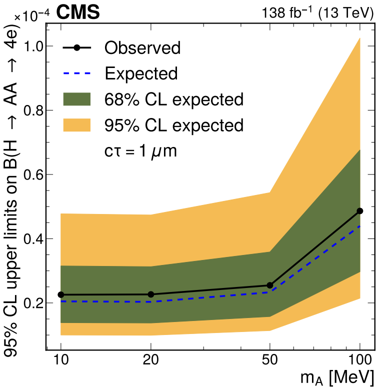
- 20MeV 10um ALP as signal hypothesis



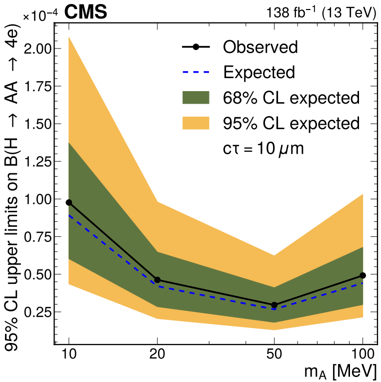
1D Limit Figures

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

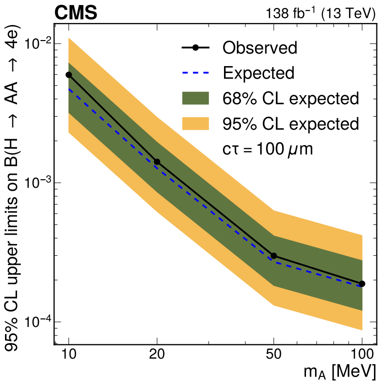
- First CMS Limits on tens of MeV ALPs
- Observed limits within the 1σ band of the background-only expectation



Limits of 1um ALPs



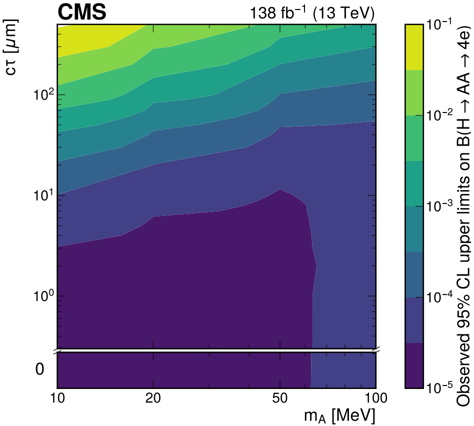
Limits of 10um ALPs



Limits of 100um ALPs

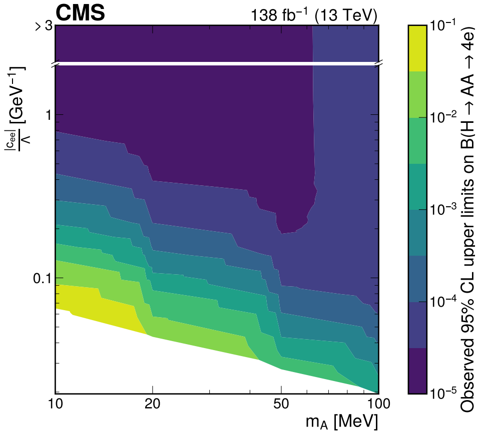
Results Interpretation

$m_A - c\tau$ Contour



$$\frac{C_{ee}}{\Lambda} = \sqrt{\frac{8\pi}{\tau\, m_e^2\, m_A} \cdot \frac{1}{\sqrt{1 - \frac{4\, m_e^2}{m_A^2}}}}$$

$m_A - \frac{C_{ee}}{\Lambda}$ Contour



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

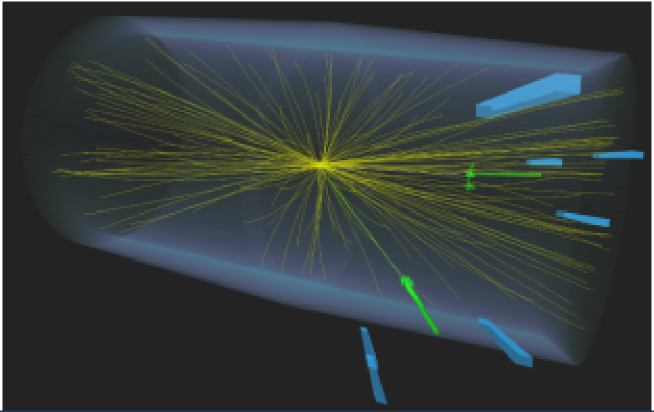
Summary

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:

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

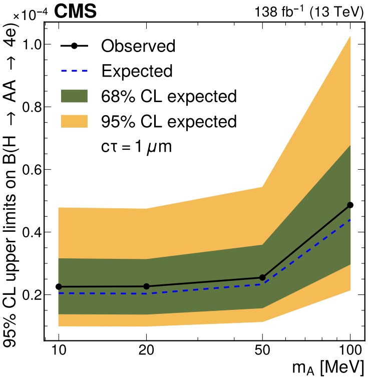
- In massless electron limit ($E \approx Pc$, $\beta \approx 1$):

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

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

H→AA→4e(This Analysis)

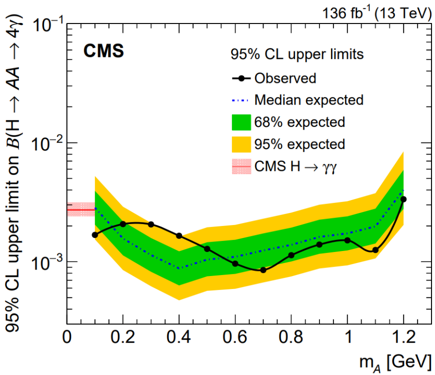
- ALPs mass: 10MeV-100MeV
- Limits: BR($H \to AA \to 4e$) at 10^{-5} scale



Limit of 1um ALPs

H→AA→ 4γ(Phys.Rev.Lett.131,101801)

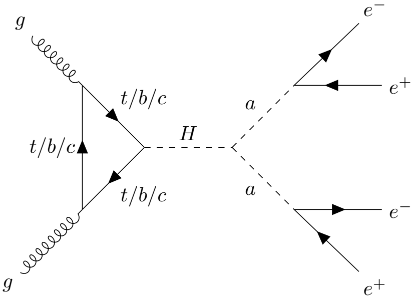
- ALPs mass: 100MeV-1200MeV
- Limits: BR($H \to AA \to 4\gamma$) at 10^{-3} scale



Limit of prompt ALPs

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

$ggH \to AA \to 4e$



1.ALP Fly Distance

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

2.Electron Pair Open Angle

- $\Delta R(ele1, ele2) \approx \frac{2}{\gamma \sin\theta} \sim 10^{-3}$ (backup p13)
- CMS Tracker Resolution Limit: $\Delta R \sim 10^{-3}$

Motivation

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

Chanllenge

- $\Delta R(ele1, ele2) \sim 10^{-3}$→Merged into a single ECAL Cluster →Merged Electron Pair(MEP)
- Merged Electron Pair: 1 Cluster + 2 Tracks → Similar to conversion photon

BDT Training (Toolkit:XGBoost)

- Variables:

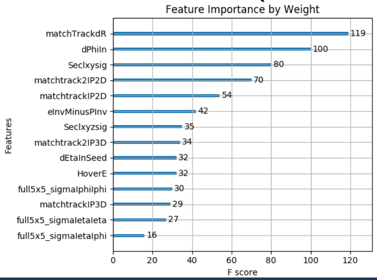
full5x5_sigmaletaleta	full5x5_sigmalphilphi	full5x5_sigmaletalphi	dEtaInSeed	dPhiIn	HoverE
1/E-1/P	ImpactParameter2D(x2)	ImpactParameter3D(x2)	dR(Tk1,Tk2)	VertexLxySig	VertexLxyzSig

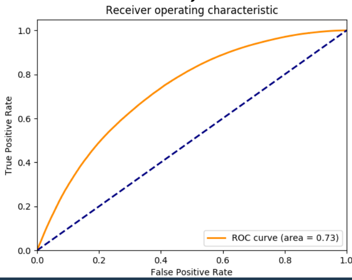
- Samples: Training:Testing = 4:1

Samples	DY→ee	Diphton Jets	GJet > 40GeV	H→AA→4e($c\tau$ < 30um)
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)





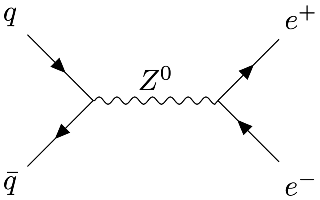
Trigger Choice

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

2016UL	2017UL	2018UL
HLT_DoubleEle33_CaloIdL_MW HLT_DoubleEle33_CaloIdL_GsfTrkIdVL HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_DZ	HLT_DoubleEle33_CaloIdL_MW HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL	HLT_DoubleEle25_CaloIdL_MW HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL

Tag and Probe Method to Calibrate Trigger Efficiency

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



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