Search for Tens of MeV Neutral Resonance from Higgs decay

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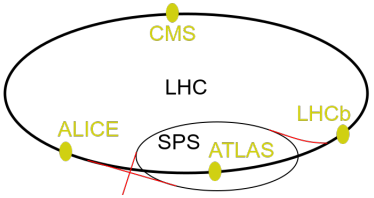
LHC and CMS

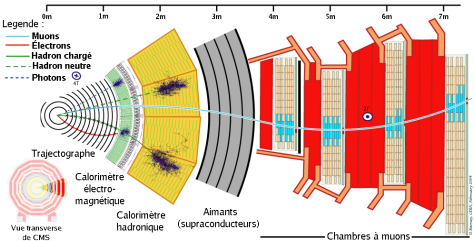
Large Hadron Collider (LHC):

- World's largest and highest-energy collider
- $\sqrt{s} \sim$ 13–14 TeV
- 27 km circumference, $\sim$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
- Achievements: Higgs discovery, BSM searches
- Features: 3.8T field, Precise tracker, Muon system

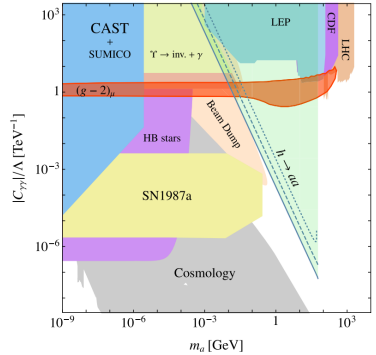


This analysis uses CMS data to search for neutral resonance from Higgs decays

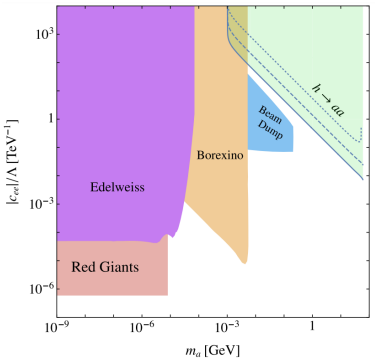
LHC as an ALPs Factory

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)**

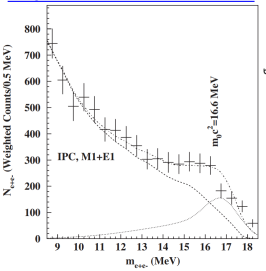


$m_a - \frac{C_{ee}}{\Lambda}$ **Parameter Space (Green Region: LHC Run2)**

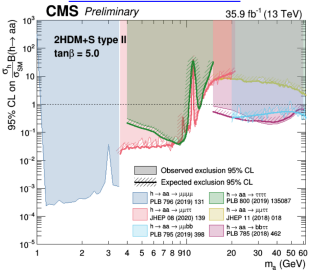
The LHC can search for ALPs across a large parameter space

Previous Research

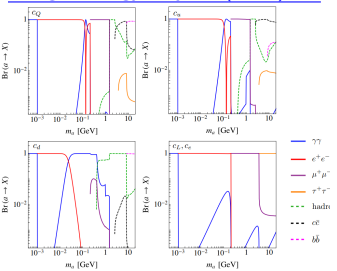
Phys.Rev.Lett.116,042501



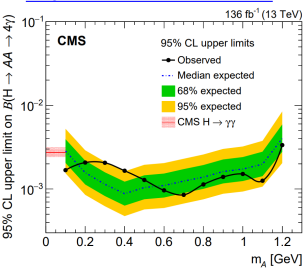
arXiv:2204.03053



J.High Energy Phys.09(2022)056



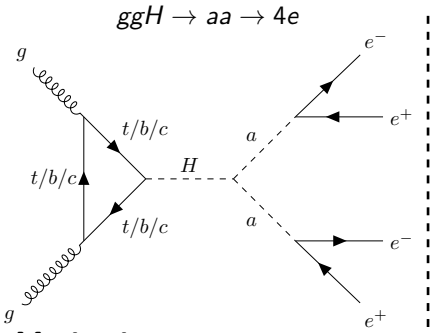
Phys.Rev.Lett.131,101801



- 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

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



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 p15)
- 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

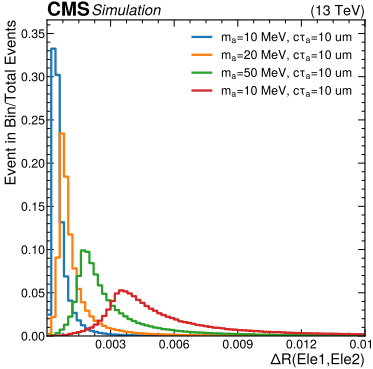
Chanllenge

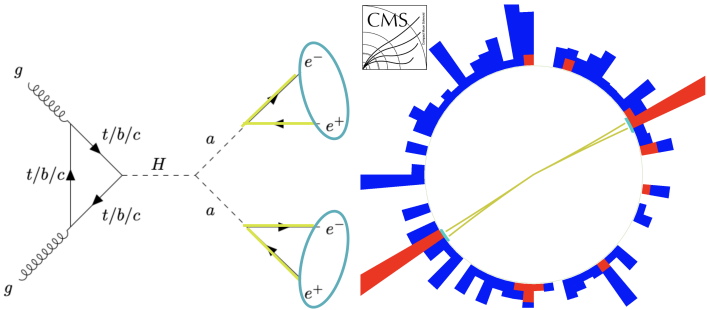
- $\Delta R(ele1, ele2) \sim 10^{-3}$→Merged into a single ECAL Cluster →Merged Electron Pair(MEP)
- Merged Electron Pair: 1 Cluster + 2 Tracks → Similar to conversion photon

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, 100MeV
- $c\tau_a$: 1, 3, 10, 30, 100, 500um





H→aa→4e Event Display

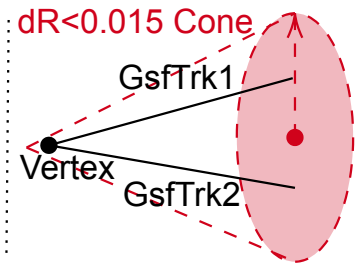
Signal Signature

- 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%)

- Trks'missing inner hits <2 and p_T^{Trk}>5GeV; $p_T^{Cluster}$ > 25GeV
- 2 Trks satisfy $\Delta R(Cluster, Trk)$<0.015 & $\frac{|\vec{p_T}^{\,\mathrm{Tk1}}+\vec{p_T}^{\,\mathrm{Tk2}}-\vec{p_T}^{\,\mathrm{Cl.}}|}{p_T^{\mathrm{Cl.}}}$<70%
- Reconstruct vertex by 2 Trks & Vertex $\chi^2 < 5$



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.Higgs Candidate Mass Reconstruction

- Reconstruct Higgs candidate mass from events with 2 highest-p_T selected MEPs

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

BDT Model

BDT Training (Toolkit:XGBoost)

- Variables:

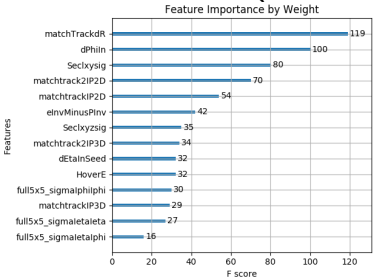
full5x5_sigmaletaleta	full5x5_sigmalphilphi	full5x5_sigmaletalphi	dEtaInSeed	dPhiIn	HoverE
1/E-1/P	ImpactParameter2D(x2)	ImpactParameter3D(x2)	dR(Tk1,Tk2)	VertexLxySig	VertexLxyzSig

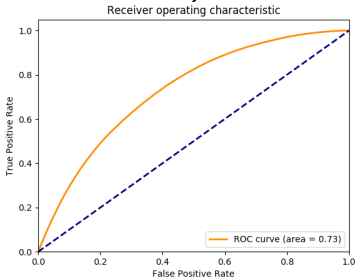
- Samples: Training:Testing = 4:1

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

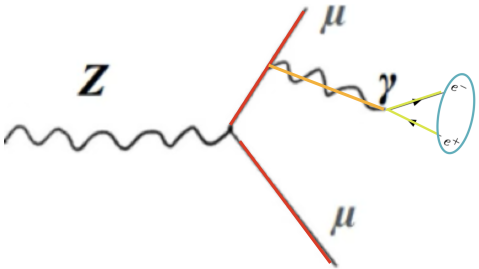




Merged Electron Pair ID Efficiency Calibration

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

- 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

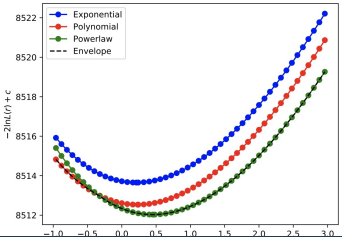
Resonance Modeling

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

- Function: DCB + Gaussian or 5-Gaussian

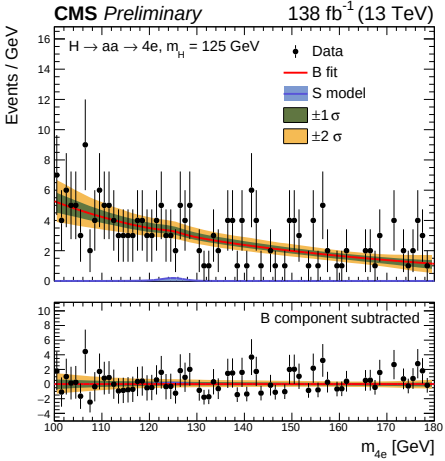
Non-Resonance Modeling

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



S+B Post-fit Plot

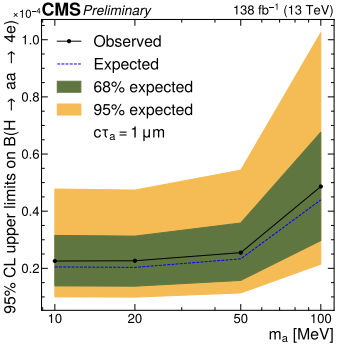
- 20MeV 10um ALP as signal hypothesis



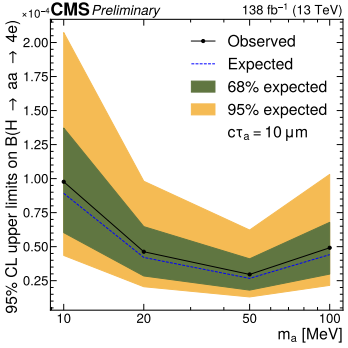
1D Limit Figures

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

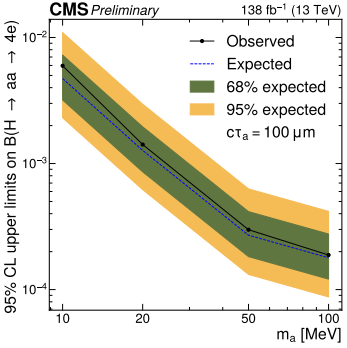
- First CMS Limits on tens of MeV ALPs
- Observed limits within the 1σ band of the background-only expectation



Limits of 1um ALPs

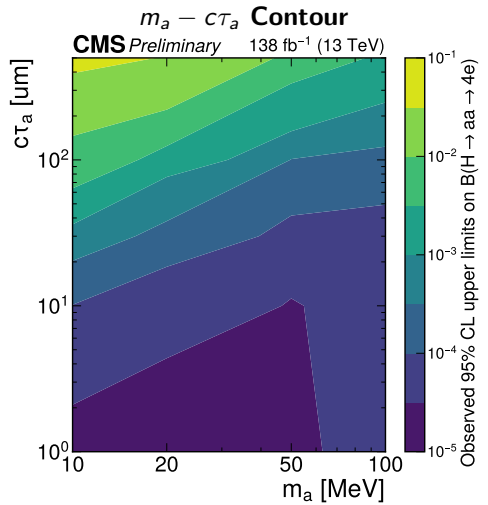


Limits of 10um ALPs

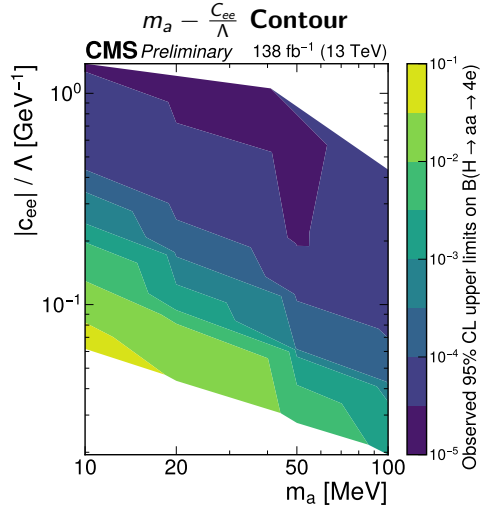


Limits of 100um ALPs

Results Interpretation



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

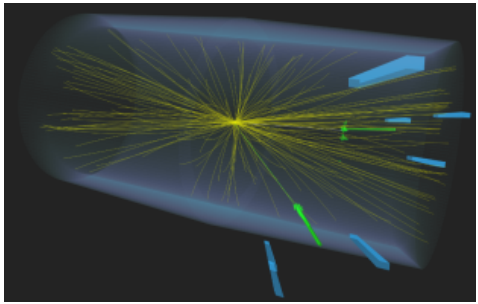


First CMS exclusion of tens-of-MeV ALPs with limits as low as 10^{-5}

Summary: Search for Tens of MeV Neutral Resonance from Higgs decay

Analysis Summary

- First CMS search for ALPs with masses in the tens of MeV range
- Tracks resolved at $\Delta R \sim 0.001$ level, enabling MEP selection
- Developed a novel MEP ID for this analysis and derived the ID SF and uncertainty using $Z \to \mu\mu\gamma$
- No significant excess observed and 95% CL upper limits on $B(H \to aa \to 4e)$ at the 10^{-5} scale



Related Documentation:

- Physics Analysis Summary: EXO-24-031
- Physics Brifing: link

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:

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

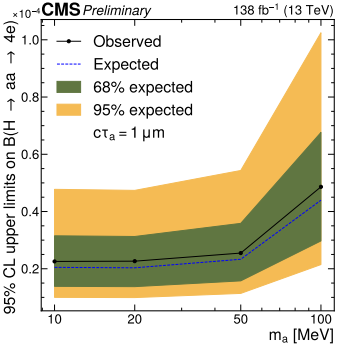
- In massless electron limit ($E \approx Pc$, $\beta \approx 1$):

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

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

H→aa→4e(This Analysis)

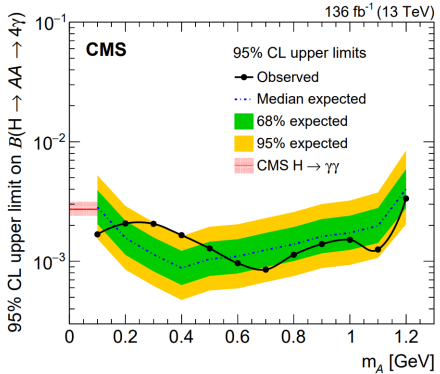
- ALPs mass: 10MeV-100MeV
- Limits: BR($H \to aa \to 4e$) at 10^{-5} scale



Limit of 1um ALPs

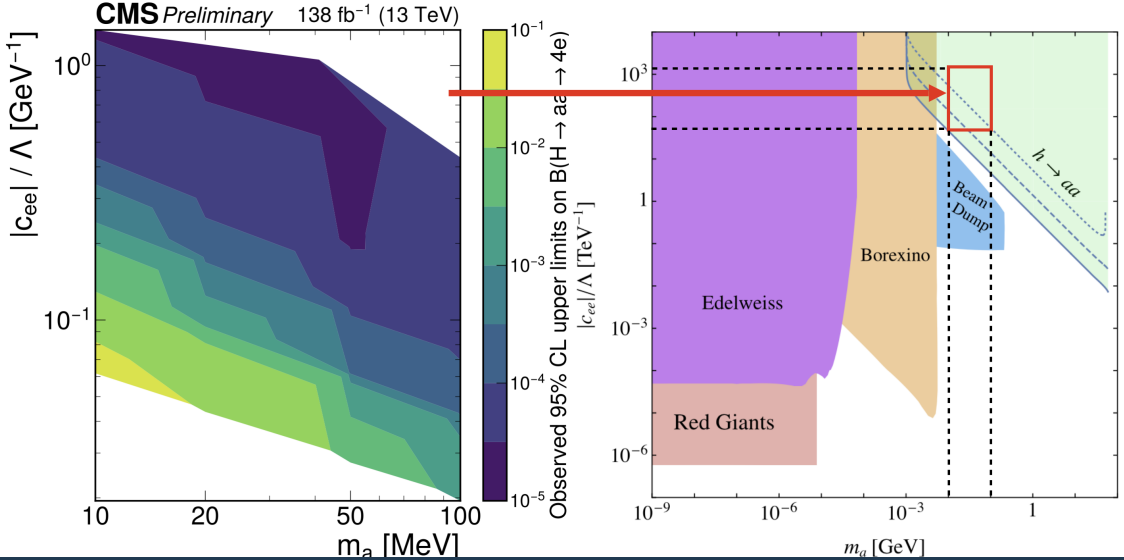
H→aa→ 4γ(Phys.Rev.Lett.131,101801)

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



Limit of prompt ALPs

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



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_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