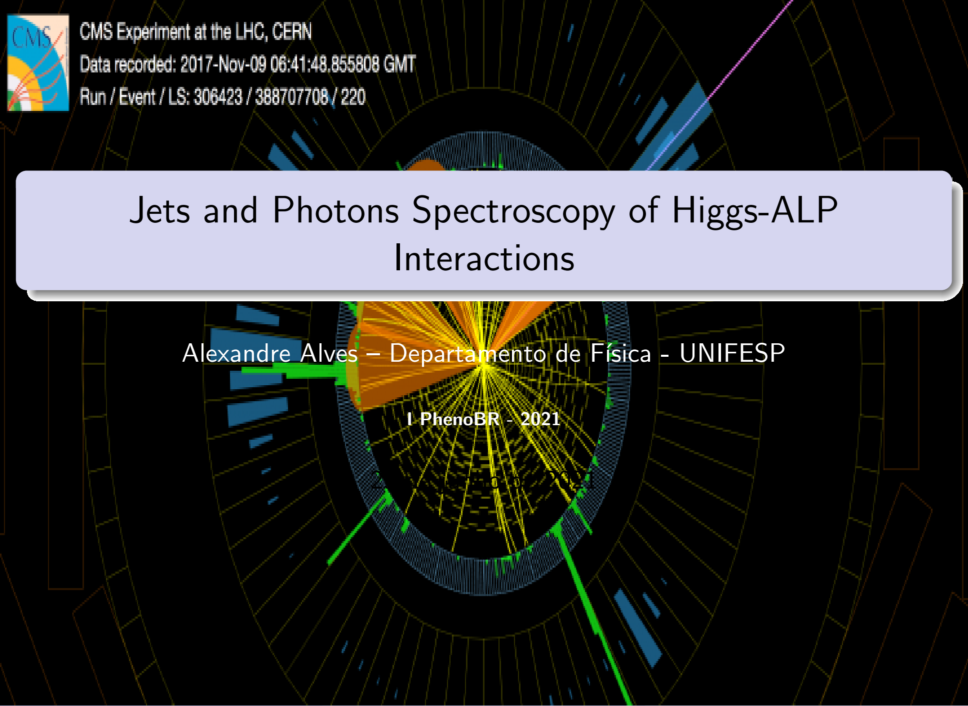


Jets and Photons Spectroscopy of Higgs-ALP Interactions

Alexandre Alves – Departamento de Física - UNIFESP

I PhenoBR - 2021

Outline

- arXiv:2105.01095, with **Alex Dias** and **Diego Lopes** (UFABC), submitted to PLB

Outline

- arXiv:2105.01095, with **Alex Dias** and **Diego Lopes** (UFABC), submitted to PLB
- Motivation
- Analysis/Phenomenology
- Results
- Conclusions and New ideas

ALP-Higgs interactions

ALP-Higgs EFT

ALP-Higgs interactions

ALP-Higgs EFT

- Axion-like particles share properties with axions and appear in many BSM

ALP-Higgs interactions

ALP-Higgs EFT

- Axion-like particles share properties with axions and appear in many BSM
- ALPs are pseudoscalars
- Its pNG nature requires all their interactions to be classically invariant under shifts $a(x) \mapsto a(x) + \alpha$

ALP-Higgs interactions

ALP-Higgs EFT

- Axion-like particles share properties with axions and appear in many BSM
- ALPs are pseudoscalars
- Its pNG nature requires all their interactions to be classically invariant under shifts $a(x) \mapsto a(x) + \alpha$
- Differently, ALPs do not hold a mass-coupling relation like axions $\Rightarrow$ easier to Collider Pheno! 😉

ALP-Higgs interactions

ALP-Higgs EFT

- Axion-like particles share properties with axions and appear in many BSM
- ALPs are pseudoscalars
- Its pNG nature requires all their interactions to be classically invariant under shifts $a(x) \mapsto a(x) + \alpha$
- Differently, ALPs do not hold a mass-coupling relation like axions $\Rightarrow$ easier to Collider Pheno!

$$
\begin{aligned}
\mathcal{L}_{eff}^{ALP} &= \frac{1}{2}\left((\partial_\mu a)(\partial^\mu a) - m_a^2 a\right) \\
&+ \frac{k_{BB}}{\Lambda} a B^{\mu\nu}\tilde{B}_{\mu\nu} + \frac{k_{WW}}{\Lambda} a W_i^{\mu\nu}\tilde{W}^i_{\mu\nu} + \frac{k_{GG}}{\Lambda} a G_a^{\mu\nu}\tilde{G}^a_{\mu\nu} \\
&+ \frac{\sqrt{2} v C_{ha}^{eff}}{\Lambda^2}(\partial_\mu a)(\partial^\mu a) h
\end{aligned}
$$

ALP-Higgs interactions

A new Higgs decay mode

- If $m_a < \frac{m_h}{2}$, $h \to aa$ is possible
- We assume that ALP decays predominatly into photons and gluons

$$\Gamma(h \to aa) = \frac{v^2 |C_{ha}^{eff}|^2}{32\pi\Lambda^4} m_h^3 \left(1 - \frac{2m_a^2}{m_h^2}\right)^2 \sqrt{1 - \frac{4m_a^2}{m_h^2}},$$

$$\Gamma(a \to \gamma\gamma) = \frac{k_{\gamma\gamma}^2}{4\pi\Lambda^2} m_a^3,\ k_{\gamma\gamma} \equiv k_{BB} c_W^2 + k_{WW} s_W^2$$

$$\Gamma(a \to gg) = \frac{8k_{GG}^2}{4\pi\Lambda^2} m_a^3$$

$$\Gamma_a = \Gamma(a \to \gamma\gamma) + \Gamma(a \to gg)$$

ALP-Higgs interactions

A new Higgs decay mode

- If $m_a < \frac{m_h}{2}$, $h \to aa$ is possible
- We assume that ALP decays predominatly into photons and gluons

$$\Gamma(h \to aa) = \frac{v^2 |C_{ha}^{eff}|^2}{32\pi\Lambda^4} m_h^3 \left(1 - \frac{2m_a^2}{m_h^2}\right)^2 \sqrt{1 - \frac{4m_a^2}{m_h^2}},$$

$$\Gamma(a \to \gamma\gamma) = \frac{k_{\gamma\gamma}^2}{4\pi\Lambda^2} m_a^3,\ k_{\gamma\gamma} \equiv k_{BB} c_W^2 + k_{WW} s_W^2$$

$$\Gamma(a \to gg) = \frac{8k_{GG}^2}{4\pi\Lambda^2} m_a^3$$

$$\Gamma_a = \Gamma(a \to \gamma\gamma) + \Gamma(a \to gg)$$

- How to probe this interaction?

ALP-Higgs interactions

A new Higgs decay mode

- If $m_a < \frac{m_h}{2}$, $h \to aa$ is possible
- We assume that ALP decays predominatly into photons and gluons

$$\Gamma(h \to aa) = \frac{v^2 |C_{ha}^{eff}|^2}{32\pi\Lambda^4} m_h^3 \left(1 - \frac{2m_a^2}{m_h^2}\right)^2 \sqrt{1 - \frac{4m_a^2}{m_h^2}},$$

$$\Gamma(a \to \gamma\gamma) = \frac{k_{\gamma\gamma}^2}{4\pi\Lambda^2} m_a^3, \;\; k_{\gamma\gamma} \equiv k_{BB} c_W^2 + k_{WW} s_W^2$$

$$\Gamma(a \to gg) = \frac{8k_{GG}^2}{4\pi\Lambda^2} m_a^3$$

$$\Gamma_a = \Gamma(a \to \gamma\gamma) + \Gamma(a \to gg)$$

- How to probe this interaction? **ALP decays**

ALP-Higgs interactions

ALP decay modes

- Cleaner and easiest channel is the ALP into photons : $a \to \gamma\gamma$

ALP-Higgs interactions

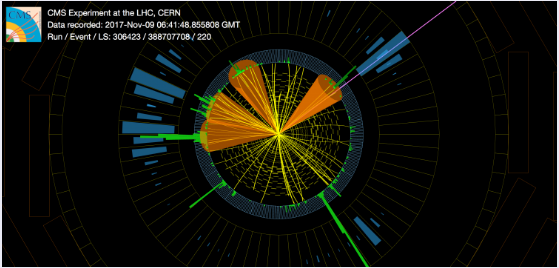
ALP decay modes

- Cleaner and easiest channel is the ALP into photons : $a \to \gamma\gamma$
- $h \to aa \to \gamma\gamma\gamma\gamma$ a gamma-ray burst at the detector!

ALP-Higgs interactions

ALP decay modes

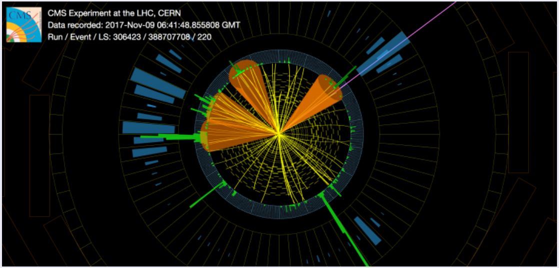
- Cleaner and easiest channel is the ALP into photons : $a \to \gamma\gamma$
- $h \to aa \to \gamma\gamma\gamma\gamma$ a gamma-ray burst at the detector!
- Light enough ALPs such that $\Delta R \sim \frac{4m_a}{m_h} < \delta_{res} \sim 0.04$ lead to colimated photons (and jets) : $m_a \lesssim$ few GeV



ALP-Higgs interactions

ALP decay modes

- Cleaner and easiest channel is the ALP into photons : $a \to \gamma\gamma$
- $h \to aa \to \gamma\gamma\gamma\gamma$ a gamma-ray burst at the detector!
- Light enough ALPs such that $\Delta R \sim \frac{4m_a}{m_h} < \delta_{res} \sim 0.04$ lead to colimated photons (and jets) : $m_a \lesssim$ few GeV

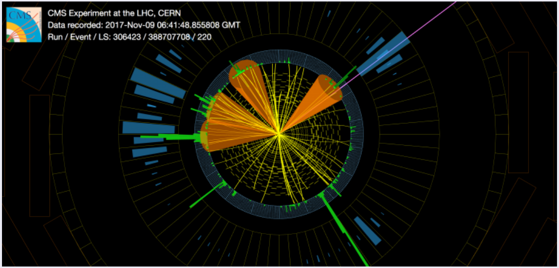


- $pp \to h \to aa \to n\gamma$, n=2,3,4 a many photons signal

ALP-Higgs interactions

ALP decay modes

- Cleaner and easiest channel is the ALP into photons : $a \to \gamma\gamma$
- $h \to aa \to \gamma\gamma\gamma\gamma$ a gamma-ray burst at the detector!
- Light enough ALPs such that $\Delta R \sim \frac{4m_a}{m_h} < \delta_{res} \sim 0.04$ lead to colimated photons (and jets) : $m_a \lesssim$ few GeV

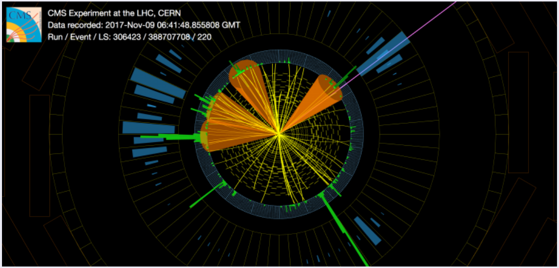


- $pp \to h \to aa \to n\gamma$, n=2,3,4 a many photons signal
- Why not $h \to aa \to n$ jets ???

ALP-Higgs interactions

ALP decay modes

- Cleaner and easiest channel is the ALP into photons : $a \to \gamma\gamma$
- $h \to aa \to \gamma\gamma\gamma\gamma$ a gamma-ray burst at the detector!
- Light enough ALPs such that $\Delta R \sim \frac{4m_a}{m_h} < \delta_{res} \sim 0.04$ lead to colimated photons (and jets) : $m_a \lesssim$ few GeV

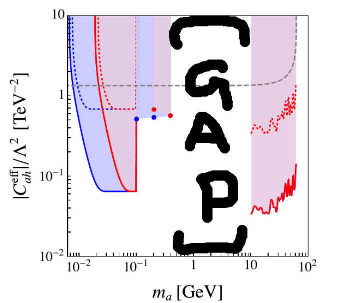


- $pp \to h \to aa \to n\gamma$, n=2,3,4 a many photons signal
- Why not $h \to aa \to n$ jets ???**QCD backgrounds!**

ALP-Higgs interactions

A mass gap

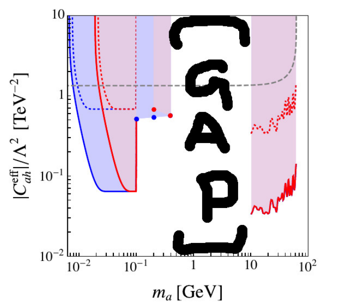
- Bauer/Neubert/Thamm (1708.00443) translate LHC bounds on direct searches for $h \to \gamma\gamma(\gamma)$ (low luminosity)



ALP-Higgs interactions

A mass gap

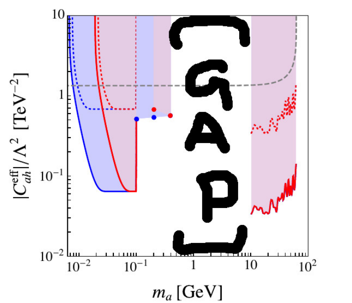
- Bauer/Neubert/Thamm (1708.00443) translate LHC bounds on direct searches for $h \to \gamma\gamma(\gamma)$ (low luminosity)



- $BR(a \to \gamma\gamma)$ plummets when the hadrons channel is open

A mass gap

- Bauer/Neubert/Thamm (1708.00443) translate LHC bounds on direct searches for $h \to \gamma\gamma(\gamma)$ (low luminosity)



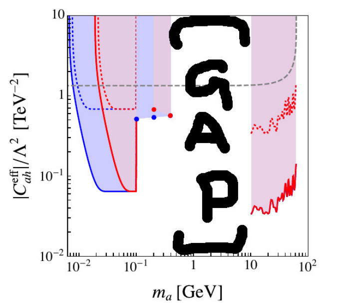
- $BR(a \to \gamma\gamma)$ plummets when the hadrons channel is open
- Moreover, $m_a \sim$ few GeV in the transition regime

unresolved↔resolved

ALP-Higgs interactions

A mass gap

- Bauer/Neubert/Thamm (1708.00443) translate LHC bounds on direct searches for $h \to \gamma\gamma(\gamma)$ (low luminosity)

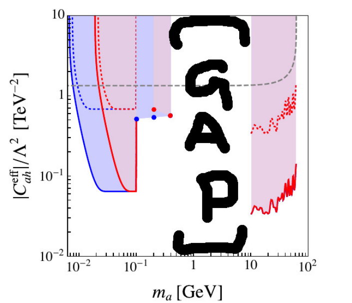


- $BR(a \to \gamma\gamma)$ plummets when the hadrons channel is open
- Moreover, $m_a \sim$ few GeV in the transition regime
  unresolved↔resolved
- Photon efficiency drops

ALP-Higgs interactions

A mass gap

- Bauer/Neubert/Thamm (1708.00443) translate LHC bounds on direct searches for $h \to \gamma\gamma(\gamma)$ (low luminosity)



- $BR(a \to \gamma\gamma)$ plummets when the hadrons channel is open
- Moreover, $m_a \sim$ few GeV in the transition regime unresolved$\leftrightarrow$resolved
- Photon efficiency drops$\Rightarrow$ loose sensitivity 

ALP-Higgs interactions

Our alternative

- Look at the mixed decay channel $h \to aa \to \gamma\gamma + gg$

ALP-Higgs interactions

Our alternative

- Look at the mixed decay channel $h \to aa \to \gamma\gamma + gg$
- A gain factor of $2\frac{1-BR(a\to\gamma\gamma)}{BR(a\to\gamma\gamma)}$

ALP-Higgs interactions

Our alternative

- Look at the mixed decay channel $h \to aa \to \gamma\gamma + gg$
- A gain factor of $2\frac{1-BR(a\to\gamma\gamma)}{BR(a\to\gamma\gamma)}$
- By the way, $h \to j + \gamma$ is prohibited in the SM! 

ALP-Higgs interactions

Our alternative

- Look at the mixed decay channel $h \to aa \to \gamma\gamma + gg$
- A gain factor of $2\frac{1-BR(a\to\gamma\gamma)}{BR(a\to\gamma\gamma)}$
- By the way, $h \to j + \gamma$ is prohibited in the SM!

- Caveat: larger backgrounds than multiphotons channel!
- In special, $\sigma(pp \to jj) \sim 10^{11}$ fb@13 TeV LHC
- Jets contain many things, like $\pi^0 \to \gamma\gamma$

$$P_{j\to\gamma} \sim 10^{-4}$$

We have to tame that beast!

Signal and backgrounds

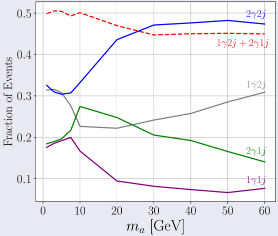
Simulated processes

- $gg \to h \to aa \to j(j) + \gamma(\gamma)$ an inclusive channel with at least a hard photon and a hard jet

Signal and backgrounds

Simulated processes

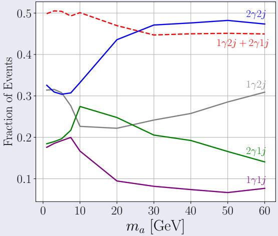
- $gg \to h \to aa \to j(j) + \gamma(\gamma)$ an inclusive channel with at least a hard photon and a hard jet



Signal and backgrounds

Simulated processes

- $gg \to h \to aa \to j(j) + \gamma(\gamma)$ an inclusive channel with at least a hard photon and a hard jet



- **Backgrounds:**
  1. $q\bar{q}, qg \to j + \gamma$ prompt production + 1 extra jet: $j\gamma$ and $jj\gamma$
  2. $pp \to j\gamma\gamma$ + 1 extra jet: $j\gamma\gamma + jj\gamma\gamma$
  3. $pp \to jj$ with $\pi^0 \to \gamma\gamma$, very annoying QCD fakes, it's huge!

Photon isolation criteria are crucial!

Simulations, isolation and basic cuts

Simulation toolkit and basic cuts

- The Fantastic4!
  FeynRules+MadGraph+Pythia+Delphes@13TeV LHC
- Signal@LO with the EFT Higgs-gluon interaction
- Backgrounds@LO plus extra jets with MLM soft/hard jet radiation matching
- Basic cuts

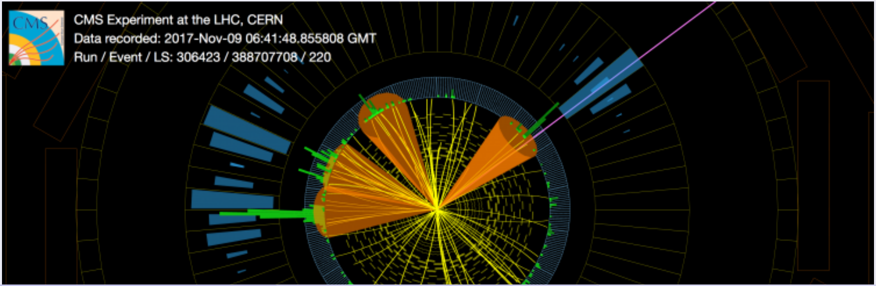
$$
\begin{aligned}
& p_T^j > 30 \text{ GeV}, \; |\eta_j| < 2.4, \\
& p_T^\gamma > 20 \text{ GeV}, \; |\eta_\gamma| < 2.4, \\
& \Delta R_{j\gamma} > 0.4
\end{aligned}
$$

Simulations, isolation and basic cuts

Isolation criteria

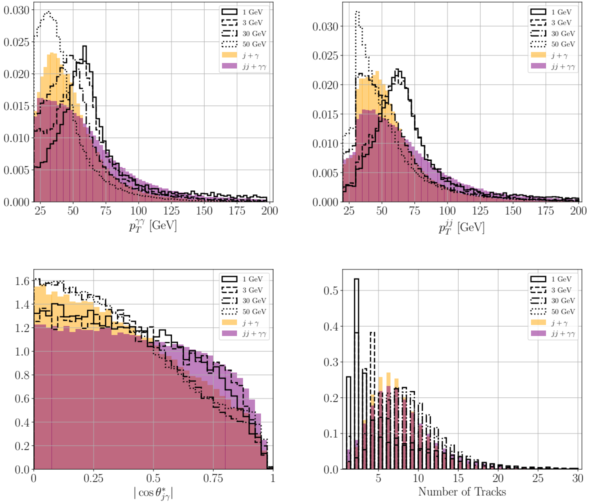
- A photon is considered to be isolated if particles with $p_T > 0.5$ GeV inside a cone of $\Delta R = 0.4$ centered around the photon 3-momentum do not deposit a total fraction of their transverse momentum above 0.05 of the photon p_T.
- Jets are reconstructed using the anti-kt algorithm with a radius parameter of $R = 0.4$ with a minimum transverse momentum of 20 GeV.
- Reject almost all jj fakes but also hurts the signals

...c'est la vie...live and let die...whatever, maybe it works



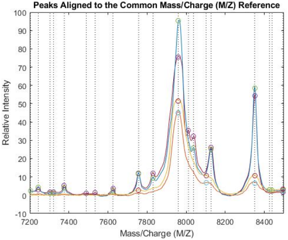
Kinematic Distributions for Rectangular Cuts

- We found a good representation for data



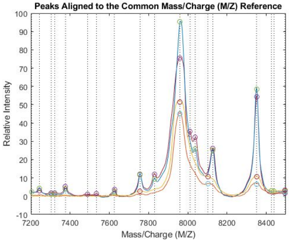
Spectroscopy of Photons and Jets

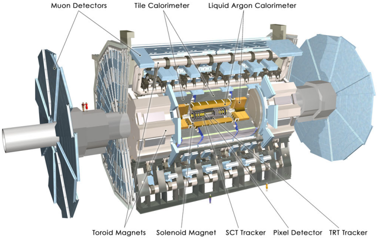
- In mass spectometers, ionized particles are isolated by their mass/charge ratio

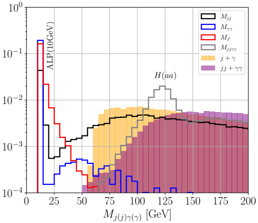


Spectroscopy of Photons and Jets

- In mass spectometers, ionized particles are isolated by their mass/charge ratio



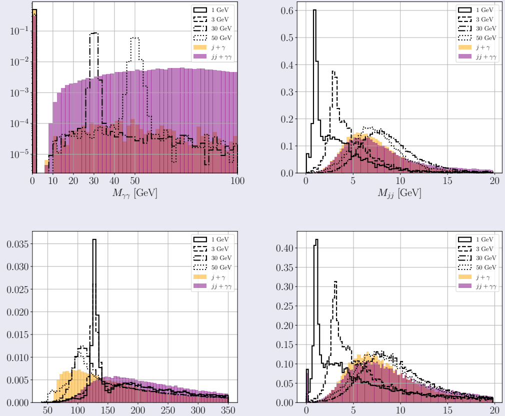




Spectroscopy of Photons and Jets

“Spectral lines”

- Peaks in inv mass distributions resemble spectral lines and make the signal/background separation a lot easier!



ML Event selection

- The peaks move with the ALP mass

ML Event selection

- The peaks move with the ALP mass
- How to go hunting without knowing where's the prey?

ML Event selection

- The peaks move with the ALP mass
- How to go hunting without knowing where's the prey?
- Let a machine look after the resonances...

... and terminate the backgrounds!

Spectroscopy of Photons and Jets

ML Event selection

- Automatically adapt the selection strategy to different ALP masses and optimize the signal significance

$$N_\sigma = \frac{S}{\sqrt{B+(\varepsilon_B B)^2}}, \quad N_{ev} = \sigma \times L \times \varepsilon_{acc} \times \varepsilon_{eff}$$

- We used `Hyperopt` based on Tree Parzen Estimation (TPE) for the search of cuts ⇒ 10 GeV example

$$\begin{aligned}
&0.4 < M_J < 12.4 \text{ GeV},\ 0.9 < M_{jj} < 13.6 \text{ GeV},\\
&1 < M_{\gamma\gamma} < 36 \text{ GeV},\ |M_{jj\gamma\gamma} - m_h| < 9.4 \text{ GeV},\\
&66 < p_T^{\gamma\gamma} < 237.5 \text{ GeV}, 37 < p_T^{jj} < 74 \text{ GeV},\\
&14 < n_{tracks} < 33,\ 0 < |\cos\theta^*_{j\gamma}| < 0.6\ .
\end{aligned}$$

Experimental Constraints

- We need to take experimental constraints into account to look for valid points of the parameters space

1. ALP lifetime – we don't want the ALP to live too much and decay outside the detector!

Experimental Constraints

- We need to take experimental constraints into account to look for valid points of the parameters space

1. ALP lifetime – we don't want the ALP to live too much and decay outside the detector!
2. The Higgs total width – $BR(h \to aa) \lesssim 32\%$ [CMS, arXiv:1901.00174]

Experimental Constraints

- We need to take experimental constraints into account to look for valid points of the parameters space

1. ALP lifetime – we don't want the ALP to live too much and decay outside the detector!
2. The Higgs total width – $BR(h \to aa) \lesssim 32\%$ [CMS, arXiv:1901.00174]
3. Direct search for $h \to jj\gamma\gamma$ [ATLAS, arXiv:1803.11145]

Experimental Constraints

- We need to take experimental constraints into account to look for valid points of the parameters space

1. ALP lifetime – we don't want the ALP to live too much and decay outside the detector!
2. The Higgs total width – $BR(h \to aa) \lesssim 32\%$ [CMS, arXiv:1901.00174]
3. Direct search for $h \to jj\gamma\gamma$ [ATLAS, arXiv:1803.11145]
4. Direct search for $h \to \gamma\gamma\gamma\gamma$ [ATLAS, arXiv:1509.05051]

Experimental Constraints

- We need to take experimental constraints into account to look for valid points of the parameters space

1. ALP lifetime – we don't want the ALP to live too much and decay outside the detector!
2. The Higgs total width – $BR(h \to aa) \lesssim 32\%$ [CMS, arXiv:1901.00174]
3. Direct search for $h \to jj\gamma\gamma$ [ATLAS, arXiv:1803.11145]
4. Direct search for $h \to \gamma\gamma\gamma\gamma$ [ATLAS, arXiv:1509.05051]
5. Photonic Z decays [ATLAS, arXiv:1509.05051]

Scanning the parameters space

- Four basic parameters: k_{GG}/Λ, $k_{\gamma\gamma}/\Lambda$, C_{ah}^{eff}/Λ^2 and m_a

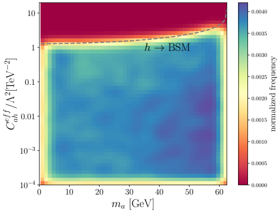
Scanning the parameters space

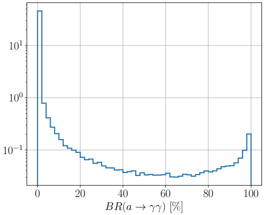
- Four basic parameters: k_{GG}/Λ, $k_{\gamma\gamma}/\Lambda$, C_{ah}^{eff}/Λ^2 and m_a
- Because we are assuming $BR(a \to gg) + BR(a \to \gamma\gamma) = 1$, we can project onto a 3-dim space

Scanning the parameters space

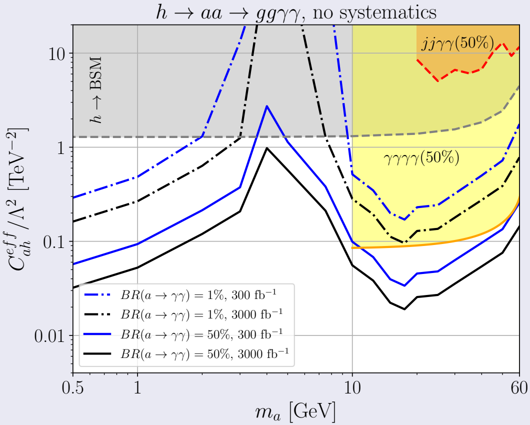
- Four basic parameters: k_{GG}/Λ, $k_{\gamma\gamma}/\Lambda$, C_{ah}^{eff}/Λ^2 and m_a
- Because we are assuming $BR(a \to gg) + BR(a \to \gamma\gamma) = 1$, we can project onto a 3-dim space
- We chose C_{ah}^{eff}/Λ^2, $BR(a \to \gamma\gamma)$ and m_a to present our results after checking its validity by randomly sampling the paremeters

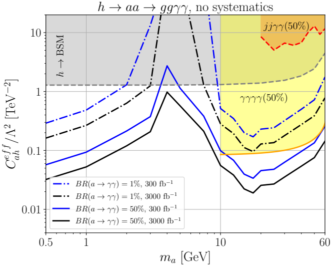
$$\frac{k_{GG}}{\Lambda} \in [10^{-3}, 4\pi]\ \mathrm{TeV}^{-1}, \quad \frac{k_{\gamma\gamma}}{\Lambda} \in [10^{-3}, 4\pi]\mathrm{TeV}^{-1},$$
$$\frac{C_{ah}^{eff}}{\Lambda^2} \in [10^{-4}, 4\pi]\ \mathrm{TeV}^{-2}, m_a \in [0.5, 62.5]\ \mathrm{GeV}.$$

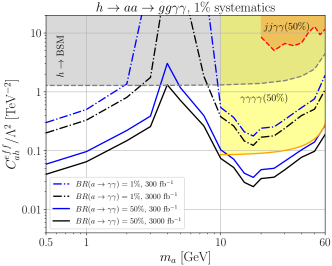


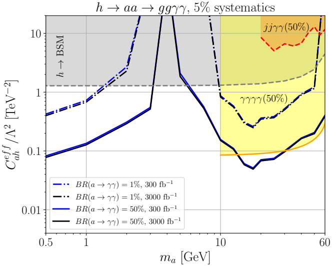


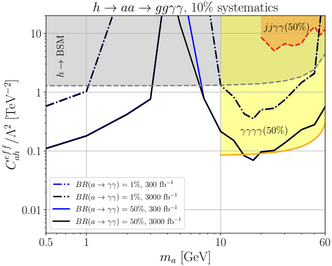
95% CL Exclusion Region@13TeV LHC



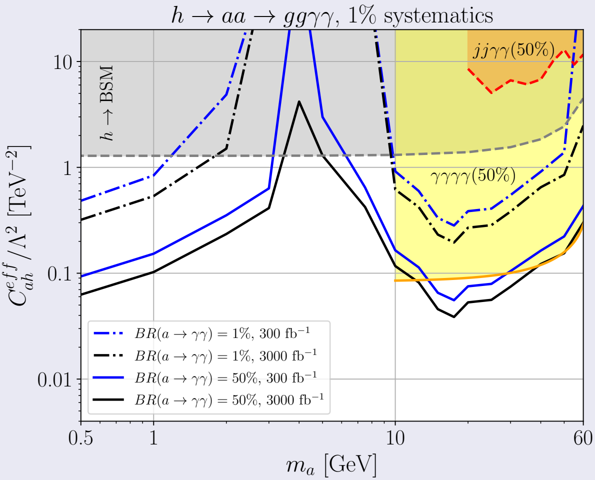

$h \to aa \to gg\gamma\gamma$, no systematics
$h \to$ BSM
$jj\gamma\gamma(50\%)$
$\gamma\gamma\gamma\gamma(50\%)$
C_{ah}^{eff}/Λ^2 [TeV^{-2}]
m_a [GeV]
10
1
0.1
0.01
0.5
1
10
60
$BR(a \to \gamma\gamma) = 1\%$, 300 fb^{-1}
$BR(a \to \gamma\gamma) = 1\%$, 3000 fb^{-1}
$BR(a \to \gamma\gamma) = 50\%$, 300 fb^{-1}
$BR(a \to \gamma\gamma) = 50\%$, 3000 fb^{-1}


$h \to aa \to gg\gamma\gamma$, 1% systematics
$h \to$ BSM
$jj\gamma\gamma(50\%)$
$\gamma\gamma\gamma\gamma(50\%)$
C_{ah}^{eff}/Λ^2 [TeV^{-2}]
m_a [GeV]
10
1
0.1
0.01
0.5
1
10
60
$BR(a \to \gamma\gamma) = 1\%$, 300 fb^{-1}
$BR(a \to \gamma\gamma) = 1\%$, 3000 fb^{-1}
$BR(a \to \gamma\gamma) = 50\%$, 300 fb^{-1}
$BR(a \to \gamma\gamma) = 50\%$, 3000 fb^{-1}

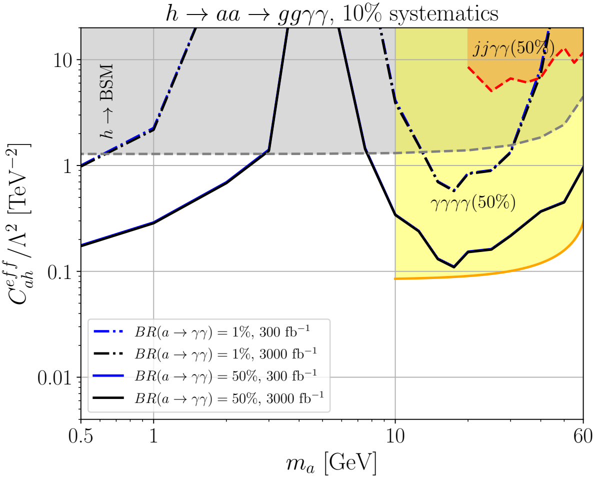

$h \to aa \to gg\gamma\gamma$, 5% systematics
$h \to$ BSM
$jj\gamma\gamma(50\%)$
$\gamma\gamma\gamma\gamma(50\%)$
C_{ah}^{eff}/Λ^2 [TeV^{-2}]
m_a [GeV]
10
1
0.1
0.01
0.5
1
10
60
$BR(a \to \gamma\gamma) = 1\%$, 300 fb^{-1}
$BR(a \to \gamma\gamma) = 1\%$, 3000 fb^{-1}
$BR(a \to \gamma\gamma) = 50\%$, 300 fb^{-1}
$BR(a \to \gamma\gamma) = 50\%$, 3000 fb^{-1}


$h \to aa \to gg\gamma\gamma$, 10% systematics
$h \to$ BSM
$jj\gamma\gamma(50\%)$
$\gamma\gamma\gamma\gamma(50\%)$
C_{ah}^{eff}/Λ^2 [TeV^{-2}]
m_a [GeV]
10
1
0.1
0.01
0.5
1
10
60
$BR(a \to \gamma\gamma) = 1\%$, 300 fb^{-1}
$BR(a \to \gamma\gamma) = 1\%$, 3000 fb^{-1}
$BR(a \to \gamma\gamma) = 50\%$, 300 fb^{-1}
$BR(a \to \gamma\gamma) = 50\%$, 3000 fb^{-1}

Discovery Region@13TeV LHC



Results



$h \to aa \to gg\gamma\gamma$, 10% systematics
C_{ah}^{eff}/Λ^2 [TeV^{-2}]
m_a [GeV]
$h \to$ BSM
$jj\gamma\gamma(50\%)$
$\gamma\gamma\gamma\gamma(50\%)$
$BR(a \to \gamma\gamma) = 1\%$, 300 fb^{-1}
$BR(a \to \gamma\gamma) = 1\%$, 3000 fb^{-1}
$BR(a \to \gamma\gamma) = 50\%$, 300 fb^{-1}
$BR(a \to \gamma\gamma) = 50\%$, 3000 fb^{-1}

Conclusions and New Ideas

- Adopted the inclusive channel $pp \to h \to aa \to j(j) + \gamma(\gamma)$ to probe the Dim-6 Higgs-ALP interaction
- Used ML to adapt cuts and identify resonances : "spectral lines" of photons and jets
- Showed that is possible to probe the mass gap of ALP masses from 0.5 to ~ 10 GeV (and up to ~ 60 GeV)
- New Ideas!
  1. Boosted Higgs : $h \to aa \to$ fat jet
  2. Boosted Higgs + jet images (a mixed hadron+photons image)
  3. Other production channels : VBF, $pp \to Z(W)h$, maybe double Higgs?
  4. ALP decays: invisible, charged leptons, quarks

Obrigado

MUITO OBRIGADO!!!