YSF: Search for a pair of (pseudo)scalars in decays of the Higgs boson at CMS

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on behalf of the CMS Collaboration

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Introduction

- Assuming the SM production for the Higgs boson, $B(H\to BSM) < 16\%$ at 95% CL [1]

- Possibility of light (pseudo)scalar states in several well-motivated models

  - 2HDM+S
    - Extension of 2HDM by addition of a complex singlet, $S_R + iS_I$
    - Higgs sector composed of 7 physical states:
      - 2 charged bosons ($H^{\pm}$), 3 scalars ($h_{1,2,3}$), 2 pseudoscalars ($a_{1,2}$)

![Graph showing branching ratios of a singlet-like pseudoscalar in the 2HDM+S for Type II Yukawa couplings. Decays to quarkonia likely invalidate our simple calculations in the shaded regions.]

![Graph showing branching ratios of a singlet-like pseudoscalar in the 2HDM+S for Type III Yukawa couplings. Decays to quarkonia likely invalidate our simple calculations in the shaded regions.]

H→aa searches within CMS

CMS Run 2 Analyses

Boosted

h → aa → γγγγ
CMS-PAS-HIG-21-016

h → aa → μμμμ

h → aa → μμττ
JHEP 08 (2020) 039

h → aa → ττττ

Resolved

h → aa → γγγγ
CMS-PAS-HIG-21-008

h → aa → μμττ
JHEP 11 (2018) 018

h → aa → μμbb
CMS-PAS-HIG-21-021

h → aa → ττbb

h → aa → bbbb
**CMS Run 2 Analyses**

- **Boosted**
  - $h \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma$
    - CMS-PAS-HIG-21-016
  - $h \rightarrow aa \rightarrow \mu\mu\mu\mu$
  - $h \rightarrow aa \rightarrow \mu\mu\tau\tau$
    - JHEP 08 (2020) 139
  - $h \rightarrow aa \rightarrow \tau\tau\tau\tau$
  - $h \rightarrow aa \rightarrow bbb\bar{b}$
    - CMS-PAS-HIG-21-021

- **Resolved**
  - $h \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma$
    - CMS-PAS-HIG-21-003
  - $h \rightarrow aa \rightarrow \mu\mu\mu\mu$
    - JHEP 11 (2018) 018
  - $h \rightarrow aa \rightarrow \mu\mu\tau\tau$
    - CMS-PAS-HIG-21-021
  - $h \rightarrow aa \rightarrow \tau\taubb$

**NEW! Talk by Siddhesh**

**Focus of this talk**
$H \rightarrow aa \rightarrow 4\gamma$ (boosted)

CMS-PAS-HIG-21-016
**H → aa → 4γ (boosted)**

- **B(a→γγ) enhanced below** $m_a < 2m_\mu$

- However diphoton invariant mass measurement extremely challenging in this $a$ mass regime
  - Smaller $m_a$ → larger Lorentz boost
    - $\gamma_L = E_a/m_a$

- $γγ$ part of the same super-cluster

- First CMS analysis of $H → aa → 4γ$ for merged photons ($0.1 < m_a < 1.2$ GeV)
  - Complements parallel CMS search in resolved regime
  - First direct probe of mass spectrum of merged photons thanks to novel end-to-end $m_{γγ}$ regression technique
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**CMS-PAS-HIG-21-016**

**Merged reco $Γ$s**
H→aa→4γ (boosted)

- Photons selected using a diphoton trigger, selection requirements imposed
- Only barrel photons used to reduce tracker material effects
- Cluster shape constraints relaxed, isolation constraints increased to compensate
- CNN technique used to reconstruct and measure the mass of merged photon system in CMS ECAL  
  arXiv:2204.12313, Talk by Shilpi
**H→aa→4γ (boosted)**

- Background: H→γγ, non-resonant QCD dijet and γ+jet production

- Using MC simulation for H→γγ and data-driven templates for non-resonant background
Results

- No excess of events above expected background

- Upper limits on $B(H\rightarrow a a \rightarrow 4\gamma)$ set at 95% CL
  - Observed limits: $(0.9 - 3.3) \times 10^{-3}$
  - First direct probe of the invariant mass of merged $a\rightarrow\gamma\gamma$ candidates

Figure 3: Observed (black solid curve with points) and median expected (blue dashed curve) 95% CL upper limits on $B(H\rightarrow A A \rightarrow 4\gamma)$ as a function of $m_A$. The 68 and 95% CIs around the expected limits are shown by the green and yellow bands, respectively. The upper limit from a previous CMS measurement [1] of $B(H\rightarrow gg)$ is shown in red, where the width of the red band represents the uncertainty in the measurement. It is accurate for $m_A \ll 0.1$ GeV where the acceptance is comparable to that for the CMS SM $H\rightarrow gg$ selection criteria and increases approximately twofold toward $m_A = 1.0$ GeV as the relative acceptance diverges.
\( H \rightarrow a a \rightarrow \mu \mu b b \)
Very attractive channel for discovering $H\rightarrow aa$ decays

- $a\rightarrow \mu\mu$: two muons are easily detectable and have a very precise mass resolution
- $a\rightarrow bb$: large BR in many parts of the parameter space

Analysis performed using full CMS Run 2 data

$m_a$ ranges from 15 to 62.5 GeV - lower bound set in order to ignore intermediate states with quarkonia

Gluon-gluon fusion and vector boson fusion mechanisms considered for Higgs boson production
Two muons (di-muon trigger) and two b-jets selected

To further suppress background, $\chi^2_{tot}$ defined

$$\chi^2_{tot} = \chi^2_{bb} + \chi^2_H$$

$$\chi_{bb} = \frac{m_{bb} - m_{\mu\mu}}{\sigma_{bb}} \quad \chi_H = \frac{m_{\mu\mu bb} - 125}{\sigma_H}$$

$\chi_{bb}$ and $\chi_H$ correlated $\rightarrow$ Decorrelated and new variable $\chi^2_d$ defined

$$\chi^2_d = \chi^2_{H,d} + \chi^2_{bb,d}$$

Events with $\chi^2_d < 1.5$ selected
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\( H \rightarrow aa \rightarrow \mu \mu bb \)

- **Signal model**
  
  - Constructed from simulation
  
  - Modeled as Voigt Profile + Crystal Ball function
  
  - All parameters, except resolutions, found independent of \( m_a \)

- **Background model**
  
  - Fully data driven method
  
  - Background modeling and estimation with the envelope method
  
  - Different types of polynomials checked on data in SR for different categories
**H → aa → μμbb**

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• Results

• Upper limits on $\mathcal{B}(H\rightarrow aa\rightarrow\mu\mu bb)$ set at 95% CLs, for mass range 15 to 62.5 GeV,
  
  • Observed: $(0.17 - 3.3) \times 10^{-4}$

• Significant improvement as compared to previous published CMS result with partial Run 2 data

• Latest ATLAS measurement:
  
  • Observed: $(0.22 - 4) \times 10^{-4}$
Summary

- Rich set of $H \rightarrow aa$ searches being pursued by CMS
  - Extensive range of masses of the (pseudo)scalar boson covered, from very boosted to non-boosted topologies
  - Many channels investigated using 2016 data and a few full Run 2 results already completed. Several more results in the pipeline!
  - First CMS results for $H \rightarrow aa \rightarrow 4\gamma$ with merged photons now available!
  - Improved sensitivities achieved for $H \rightarrow aa \rightarrow \mu\mu bb$
- No significant excess or deviation yet
- Vast parameter phase-space still to be probed
Backup
H→aa→4\gamma (boosted)

![Simulation results for the decay chain H→aa→4\gamma (boosted)](image)

- CMS Simulation, \( m_A = 0.1 \) GeV
- CMS Simulation, \( m_A = 1.0 \) GeV

| \( \Delta\eta(\gamma_1,\gamma_2)_{\text{gen}} \) [crystal units] |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| \( \Delta\phi(\gamma_1,\gamma_2)_{\text{gen}} \) [crystal units] |
| 0.00 | 0.00 | 0.00 | 0.00 |
| 0.01 | 0.00 | 0.00 | 0.00 |
| 0.98 | 0.01 | 0.00 | 0.00 |

- Normalized units / bin
- Crystal \( \eta \) index
- Crystal \( \phi \) index
- Energy [GeV]
\( H \rightarrow aa \rightarrow \mu \mu b b \)

- To decorrelate \( \chi_{bb} \) and \( \chi_H \), the two quantities evaluated in a new basis

\[
\begin{pmatrix}
\chi_H \\
\chi_{bb}
\end{pmatrix}_d = \begin{pmatrix}
a \\
\frac{b}{\sqrt{\lambda_1}} \\
-\frac{b}{\sqrt{\lambda_2}} \\
\frac{a}{\sqrt{\lambda_2}}
\end{pmatrix} \begin{pmatrix}
\chi_H \\
\chi_{bb}
\end{pmatrix}_c
\]

\( \lambda_1, \lambda_2 \rightarrow \text{eigen values} \)
\( \begin{pmatrix}
a \\
b
\end{pmatrix} \rightarrow \text{eigen vector} \)

of the correlation matrix

\[
\chi^2_d = \chi^2_{H,d} + \chi^2_{bb,d}
\]
• Events further classified on the basis of properties of the b-jets

<table>
<thead>
<tr>
<th>Categories for selected events</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low $p_T$</td>
<td>at least one b-jet with $p_T &lt; 20$ GeV</td>
</tr>
<tr>
<td>VBF</td>
<td>two additional jets with $p_T &gt; 30$ GeV, $</td>
</tr>
<tr>
<td>TL</td>
<td>looser b-jet passes L but fails M</td>
</tr>
<tr>
<td>TM</td>
<td>looser b-jet passes M but fails T</td>
</tr>
<tr>
<td>TT</td>
<td>looser b-jet passes T</td>
</tr>
</tbody>
</table>

T: Tight  M: Medium  L: Loose