


# Searches for exotic decays of the Higgs boson into light scalars/pseudoscalars at the CMS experiment

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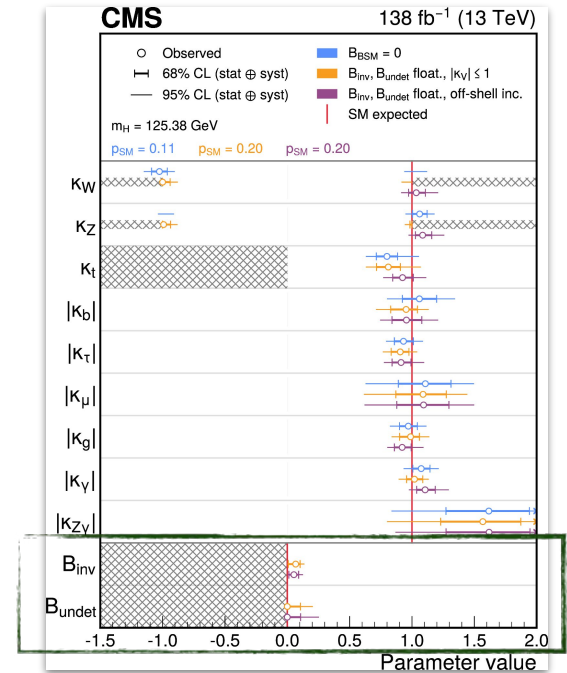
*On behalf of the CMS Collaboration*

 Φαινó 2026  
The 2026 Phenomenology Symposium  
University of Pittsburgh  
May 11-13, 2026



# Why search for exotic Higgs decays?

- The Higgs boson discovered in 2012 is so far consistent with Standard Model (SM) predictions
- Current Higgs coupling measurements still allow sizable branching fractions to beyond-the-Standard-Model (BSM) decays (~10–20% at 95% CL)
- In SM only 1 higgs doublet ( $\Phi_1$ )
  - After electroweak symmetry breaking : **1 neutral, CP even Higgs boson**
- Many well-motivated BSM scenarios predict extended Higgs sectors
- Exotic Higgs decays provide a powerful probe of hidden or weakly coupled sectors



[arXiv:2602.18611](https://arxiv.org/abs/2602.18611)

# Extended Higgs sector beyond the SM

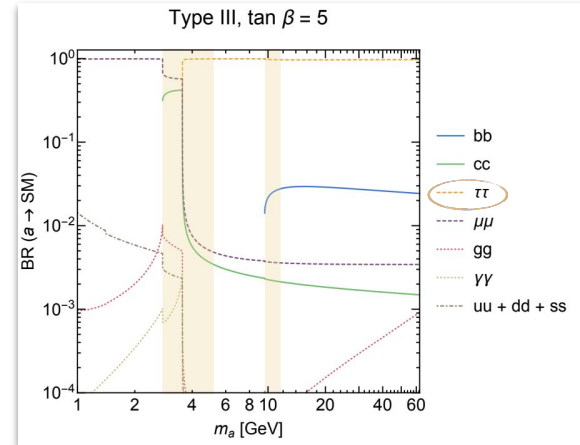
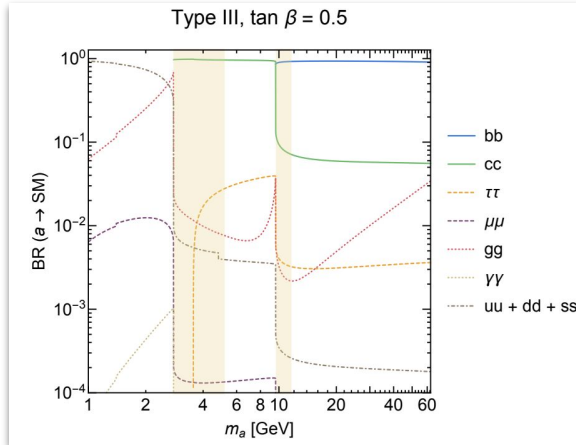
- Extended Higgs sector models predict additional scalar and pseudoscalar Higgs bosons
  - Heavy neutral Higgs bosons with masses above 125 GeV are also possible
- Two Real Singlet Model (TRSM)** extends the SM scalar sector by two real scalar singlets
  - $H \rightarrow \phi_1 \phi_2 \rightarrow \text{SM fermions}$
- Two Higgs Doublet Model (2HDM)** adds a second higgs doublet ( $\Phi_2$ ) to the SM higgs doublet ( $\Phi_1$ )
  - Neutral scalar ( $h, H$ ), Pseudoscalar ( $A$ ), Charged Higgs ( $H^\pm$ )
  - Type II : minimal supersymmetry model (MSSM)
- Extend 2HDM to add additional singlet field: (2HDM + S)**
  - Neutral scalar ( $h_1, h_2, h_3$ ), Pseudoscalar ( $a_1, a_2$ ), Charged Higgs ( $H^\pm$ )
  - Type II is the next to minimal supersymmetry model (NMSSM)
  - $H \rightarrow aa \rightarrow \text{SM fermions}$

	<i>u</i> -type	<i>d</i> -type	Leptons
Type I	$\Phi_2$	$\Phi_2$	$\Phi_2$
Type II	$\Phi_2$	$\Phi_1$	$\Phi_1$
Type III (lepton-specific)	$\Phi_2$	$\Phi_2$	$\Phi_1$
Type IV (flipped)	$\Phi_2$	$\Phi_1$	$\Phi_2$

# Extended Higgs sector beyond the SM

- Branching of “a” boson to SM particles depends on:
  - mass of the “a” boson
  - type of model
  - model parameters  $\tan\beta$  (ratio of vacuum expectation values for  $\Phi_1$  and  $\Phi_2$ )
- Type III - enhanced couplings to leptons especially at high  $\tan\beta$
- Searches have been performed in several final states

[10.1103/PhysRevD.90.075004](https://arxiv.org/abs/10.1103/PhysRevD.90.075004)



# Today's Focus

- This talk presents three recent CMS analyses targeting asymmetric scalar decays / boosted low-mass pseudoscalars / heavy Higgs interpretations
- Using  $138 \text{ fb}^{-1}$  CMS Run 2 (2016-2018) data at  $\sqrt{s} = 13 \text{ TeV}$



Search for a light pseudoscalar Higgs boson in boosted  $\mu\mu\tau\tau$  final states

$H \rightarrow aa \rightarrow \mu\mu\tau\tau$  [CMS PAS SUS-23-005](#)



Search for light pseudoscalar boson pairs in boosted  $4\tau$  and  $2\mu 2\tau$  final states

$H \rightarrow a_1 a_1 \rightarrow 4\tau, 2\mu 2\tau$  [10.1007/JHEP04\(2026\)132](#)

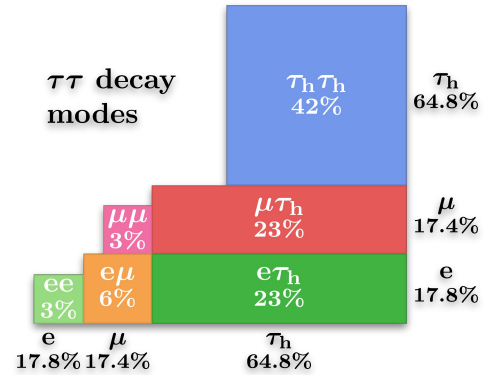
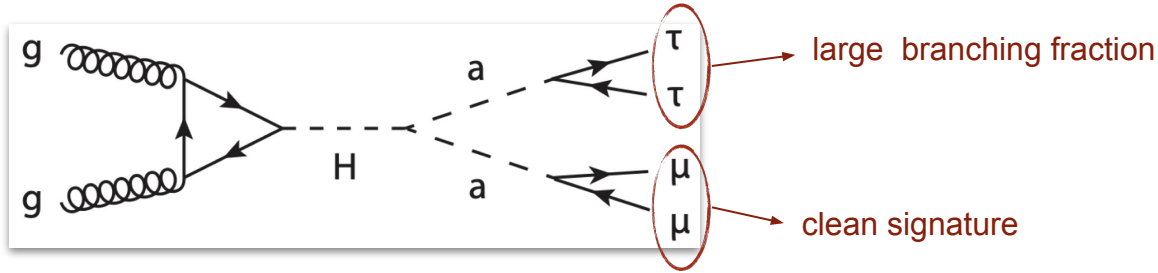


Search for Higgs boson decays into two neutral scalars with unequal masses

$H \rightarrow \phi_1 \phi_2 \rightarrow 2\tau 2b, 2\tau 4b$  [CMS PAS NPS-25-003](#)

# H $\rightarrow$ aa $\rightarrow$ $\mu\mu\tau\tau$ - Motivation

CMS PAS SUS-23-005



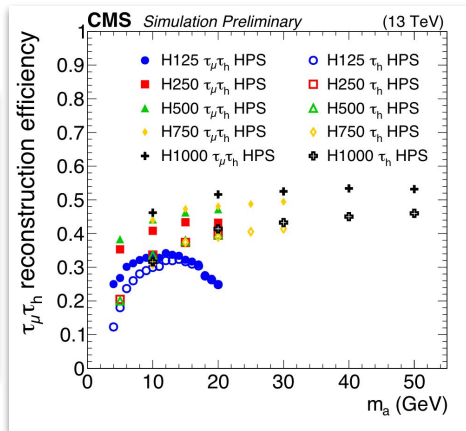
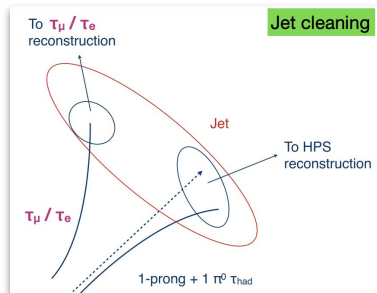
- Higgs production mechanisms: ggF (dominate), VBF
- **125 GeV Higgs boson and heavier Higgs** (Motivated in 2HDM+S)
- Final states include:
  - Full-leptonic di-tau decay:  $H \rightarrow aa \rightarrow \mu\mu e e$
  - Semi-leptonic di-tau decay:  $H \rightarrow aa \rightarrow \mu\mu\mu\tau_h, \mu\mu e\tau_h$
  - Full-hadronic di-tau decay:  $H \rightarrow aa \rightarrow \mu\mu\tau_h\tau_h$
- Both 1-prong and 3-prongs  $\tau_h$  decays are considered
- Boosted di-tau topology

$m_H$ (GeV)	$m_a$ search range (GeV)	Generated $m_a$ [step size] (GeV)
125	3.6–21	3.6, 4–21 [1]
250	3.6–25	5–20 [5]
500	3.6–30	5–20 [5]
750	3.6–35	10–30 [5]
1000	3.6–50	10–50 [10]

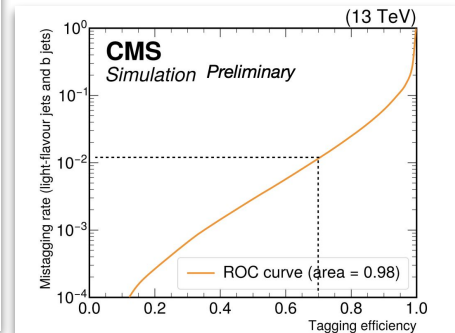
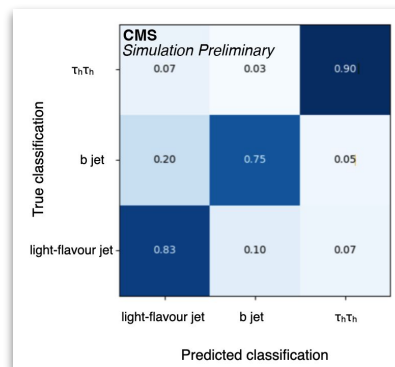
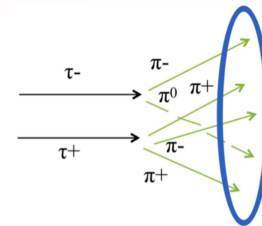
# H $\rightarrow$ aa $\rightarrow$ $\mu\mu\tau\tau$ - Reconstruction of boosted $\tau_\mu\tau_h$ , $\tau_e\tau_h$ & $\tau_h\tau_h$

CMS PAS SUS-23-005

- **Modified Hadron-plus-strips (HPS) Algorithm** developed for reconstruction of  $\tau_\mu\tau_h$  and  $\tau_e\tau_h$
- Jets are cleaned by removing  $\mu/e$  momentum.
- Send lepton-subtracted jets to HPS to reconstruct  $\tau_h$
- Re-define  $\tau_h$  isolation and keep  $\tau_h(p_T > 10 \text{ GeV})$
- Signal efficiency is significantly improved



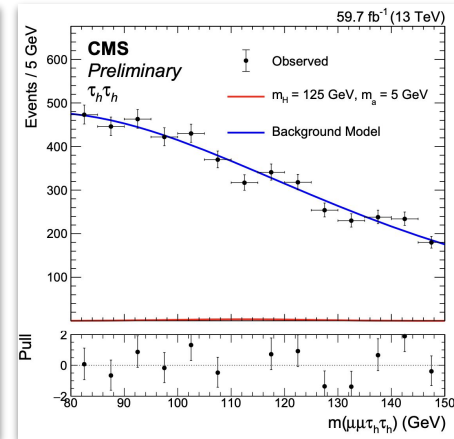
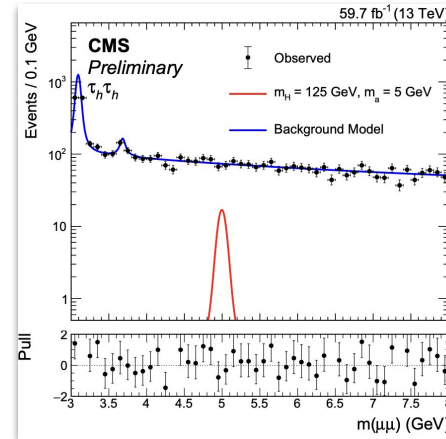
- Overlapping  $\tau_h\tau_h$  decays
- standard  $\tau_h$  reconstruction inefficient
- **DEEPDITAU**: DNN-based AK4 jet tagger for  $\tau_h\tau_h$  identification
- Trained on simulated signal and background samples (QCD, tt, light/b jets)
- Working points optimized using ROC curves



# H $\rightarrow$ aa $\rightarrow$ $\mu\mu\tau\tau$ - Analysis Strategy

[CMS PAS SUS-23-005](#)

- Background modeled using a data-driven approach with signal and sideband regions
- Control regions used to constrain resonance background modeling
- 2D un-binned likelihood fit:  $m_{\text{vis}}(\mu\mu\tau\tau)$  vs.  $m(\mu\mu)$
- $m(\mu\mu)$  is split into following regions:
  - 3 - 8 GeV: low mass
  - 8 - 12 GeV: intermediate mass
  - 12 - 30 GeV: high mass
  - 30 - 50 GeV: high mass extension for H1000
- Different  $m_{\text{vis}}(\mu\mu\tau\tau)$  ranges are applied for different final states to optimize modeling

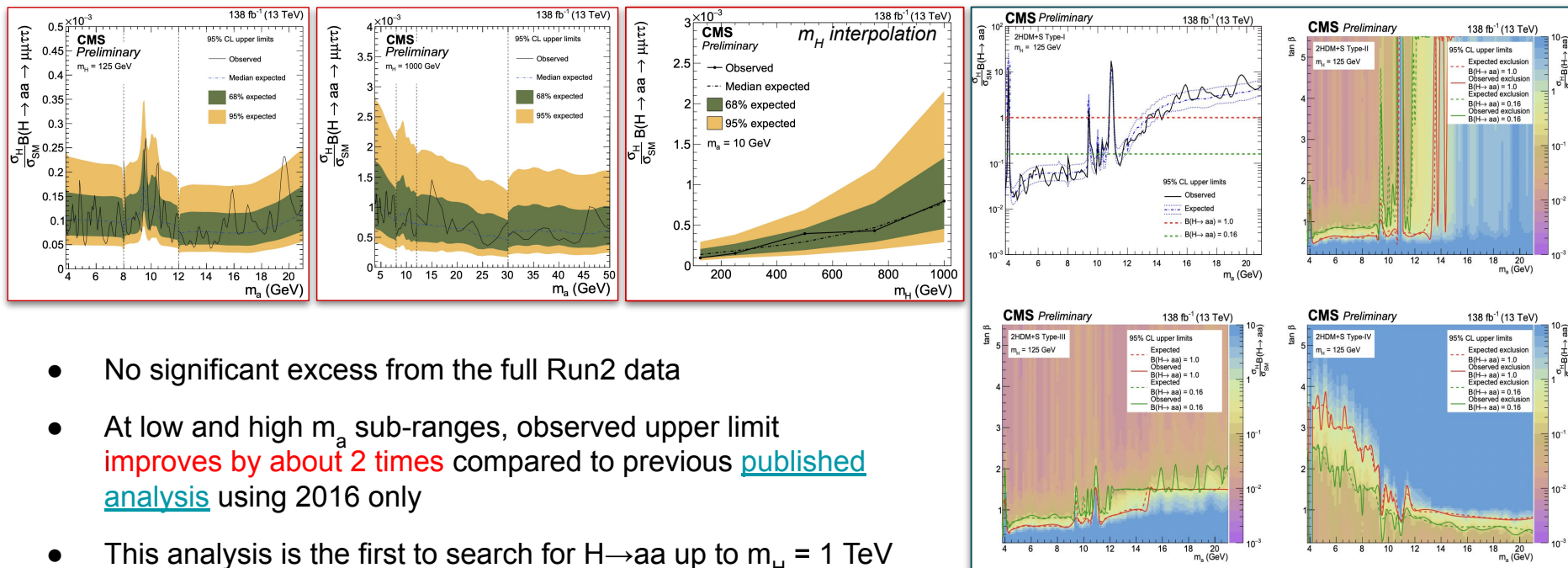


“low mass” region

Projections of the post-fit two-dimensional background PDFs and observed data

# H → aa → μμττ - Results

CMS PAS SUS-23-005

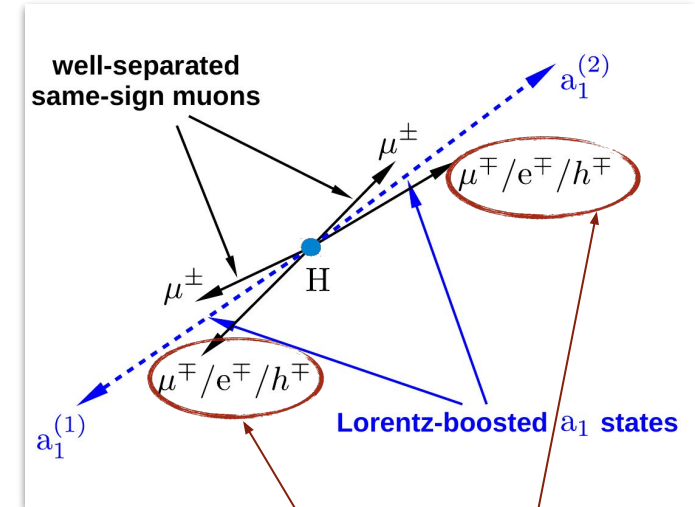


- No significant excess from the full Run2 data
- At low and high m<sub>a</sub> sub-ranges, observed upper limit **improves by about 2 times** compared to previous [published analysis](#) using 2016 only
- This analysis is the first to search for H → aa up to m<sub>H</sub> = 1 TeV
- **Type-II & Type-III interpretations:** strongest constraint from 3.6 GeV to 9 GeV at tan β > 2

# $H \rightarrow a_1 a_1 \rightarrow 4\tau, 2\mu 2\tau$ - Motivation

[10.1007/JHEP04\(2026\)132](#)

- Analysis targets  $H(125) \rightarrow a_1 a_1$  decay, with  $a_1 \rightarrow \tau_\mu \tau_{1\text{-prong}}$
- Search for low-mass pseudoscalars:  $m_{a_1} = 4\text{-}15$  GeV
- Motivated from extended Higgs sector models: 2HDM+S / NMSSM
- Highly boosted  $a_1$  bosons:
  - collimated decay products
  - Non-isolated leptons in final states
- $H \rightarrow a_1 a_1 \rightarrow \mu\mu\tau\tau_{1\text{-prong}}$  also included due to similar topology

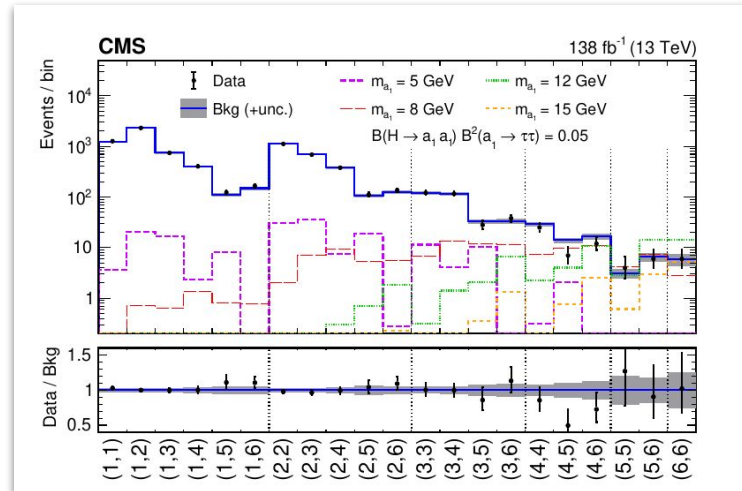


Identified as tracks close to muons

# $H \rightarrow a_1 a_1 \rightarrow 4\tau, 2\mu 2\tau$ - Analysis Strategy

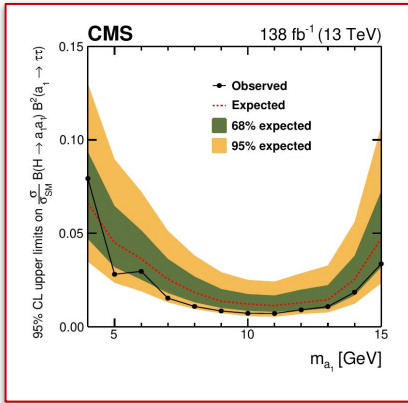
[10.1007/JHEP04\(2026\)132](https://arxiv.org/abs/10.1007/JHEP04(2026)132)

- Select same-sign muons with large angular separation
- Require muons to be accompanied by only one oppositely charged nearby track
- Reconstruct invariant mass of the two muon-track systems,  $m_1$  and  $m_2$
- Extract signal using 2D ( $m_1, m_2$ ) distribution

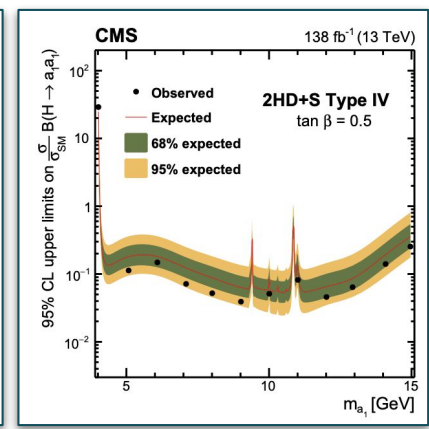
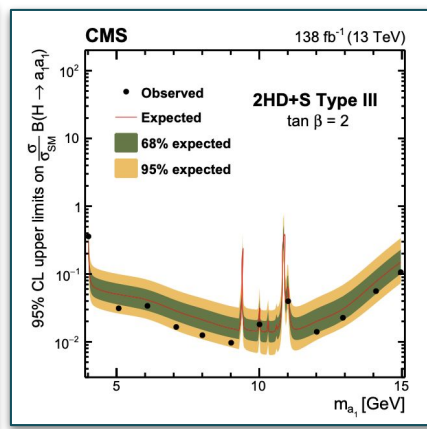
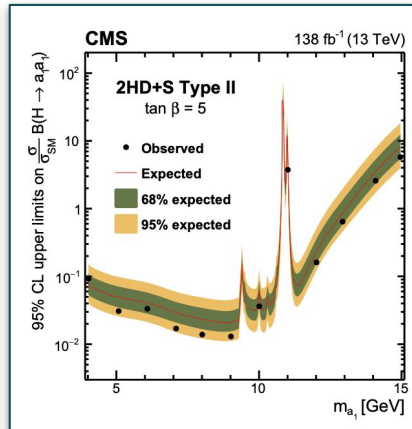
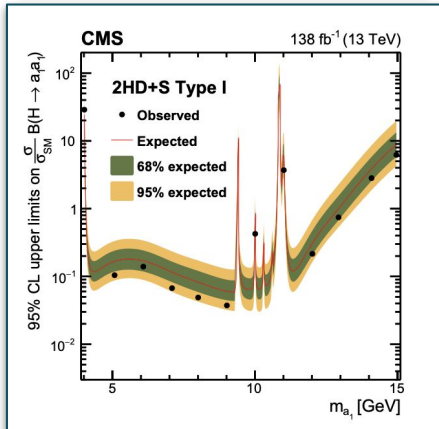


# $H \rightarrow a_1 a_1 \rightarrow 4\tau, 2\mu 2\tau$ - Results

[10.1007/JHEP04\(2026\)132](https://arxiv.org/abs/10.1007/JHEP04(2026)132)



- **2-4x better observed limits** compared to the previously published [results](#)
- Results interpreted in 2HD+S models
  - Sharp features arise from mixing with quarkonium state
- **Type II**: strong constraints obtained for mass up to 9 GeV
- **Type III**: strongest sensitivity obtained across all mass points



# H $\rightarrow$ $\phi_1\phi_2 \rightarrow 2\tau 2b$ , $2\tau 4b$ - Motivation

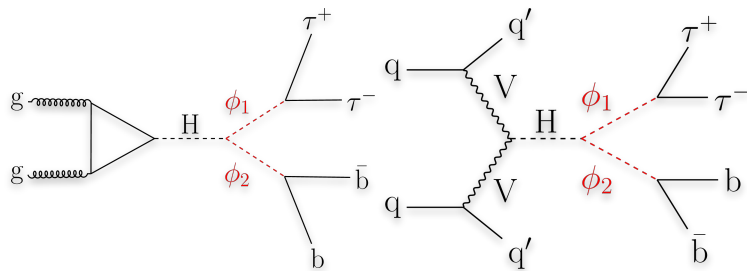
- First CMS search for asymmetric exotic decays :  $H(125) \rightarrow \phi_1\phi_2$  ( $m_{\phi_1} \neq m_{\phi_2}$ )
- Motivated by extended scalar sector models: TRSM
- Two scenarios considered:

## Non-cascade

$$H \rightarrow \phi_1\phi_2 \rightarrow 2\tau 2b$$

$$m_{\phi_1}: (15, 20, 30, 40, 50) \text{ GeV}$$

$$m_{\phi_2}: 20 - 80 \text{ GeV}$$



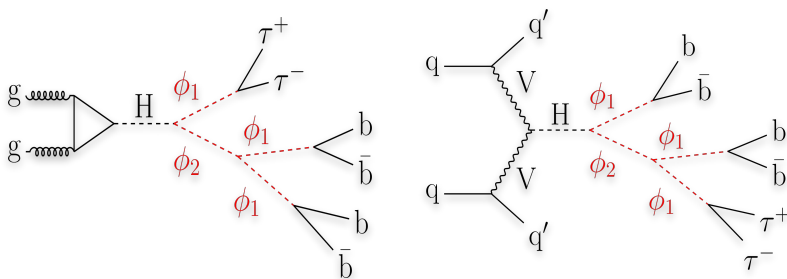
## Cascade

$$\phi_2 \rightarrow \phi_1\phi_1 \text{ for } m_{\phi_2} > 2 m_{\phi_1}$$

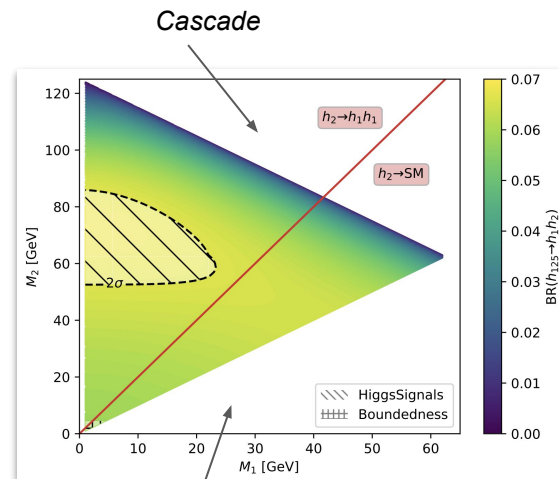
$$H \rightarrow \phi_1\phi_2 \rightarrow 3\phi_1 \rightarrow 2\tau 4b$$

$$m_{\phi_1}: (15, 20, 30) \text{ GeV}$$

$$m_{\phi_2}: 30 - 110 \text{ GeV}$$



Benchmark Plane BP1 for 13TeV LHC Signal Rate

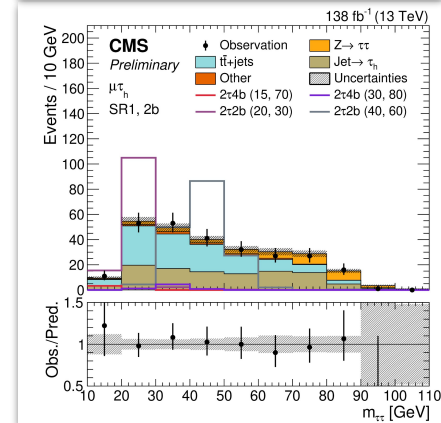
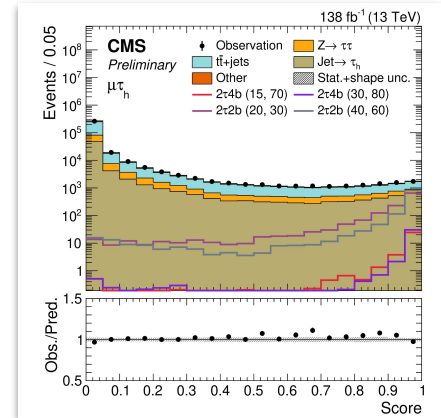


Non-cascade

# H $\rightarrow$ $\phi_1\phi_2 \rightarrow 2\tau 2b$ , $2\tau 4b$ - Analysis Strategy

CMS PAS NPS-25-003

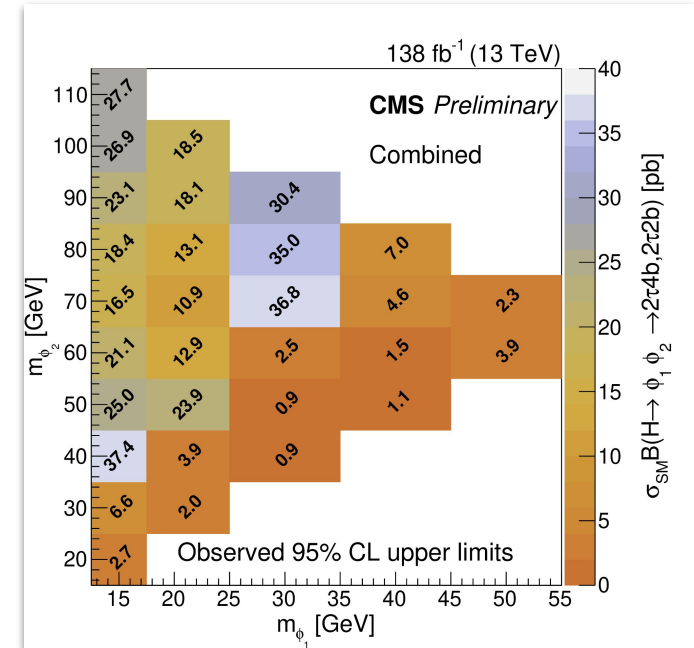
- Events categorized by:
  - $\tau$  decay mode:  $\mu\tau_h$ ,  $e\tau_h$ ,  $e\mu$
  - b-jet multiplicity
- 6 dedicated Boosted Decision Trees (BDT) trained to target the asymmetric signal topology
- 17 signal regions defined depending on the BDT discriminator score
- Majority of backgrounds estimated from data:
  - Irreducible  $Z \rightarrow \tau\tau$  estimated via embedded samples
  - Fake tau & QCD derived from dedicated control regions
- Final signal extraction performed using the reconstructed  $m_{\tau\tau}$  distribution
  - $m_{\tau\tau}$  reconstructed with the [SVFit algorithm](#)



# H $\rightarrow$ $\phi_1\phi_2 \rightarrow 2\tau 2b$ , $2\tau 4b$ - Results

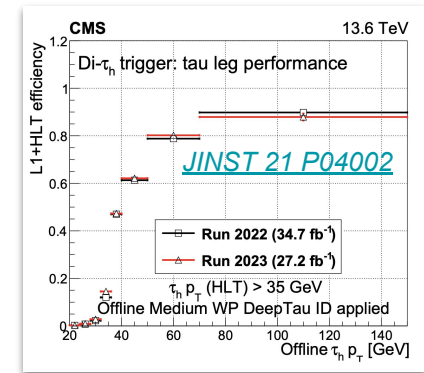
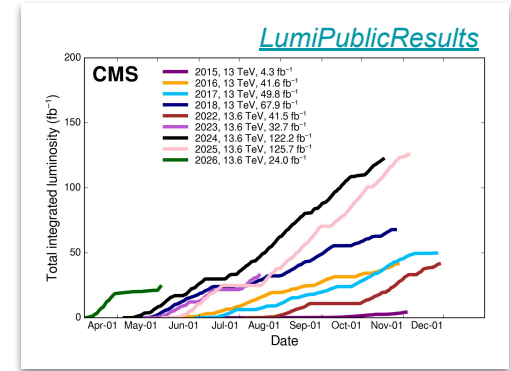
[CMS PAS NPS-25-003](#)

- No significant deviation from the SM expectation observed
- **First CMS limits on H decays to asymmetric scalar pairs**
- Upper limits set on  $\sigma_{\text{SM}} \times \text{B}(H \rightarrow \phi_1\phi_2 \rightarrow 2\tau 4b / 2\tau 2b)$
- Best sensitivity achieved for non-cascade mass hypotheses (30,40) GeV
  - limits on the branching fraction reaching  $\sim 1\%$
- **Provides complementary coverage beyond conventional H $\rightarrow$ aa searches**



# Summary and Outlook

- ? The 125 GeV Higgs boson may be part of an extended Higgs sector
- ✓ Three complementary CMS searches for exotic Higgs decays presented
- ✓ Dedicated techniques developed for boosted and collimated final states
- ✓ No significant excess over the SM expectation observed (yet)
- ✓ Exciting times ahead of us with LHC Run 3 data
  - New  $\tau_h$  based triggers deployed
  - Increasingly sophisticated ML techniques will continue to unlock challenging final states
- ✓ Exotic Higgs decays remain a promising portal to BSM physics



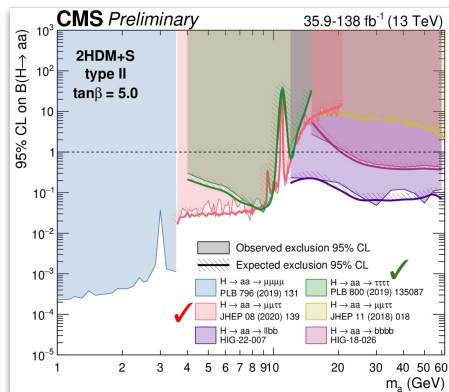
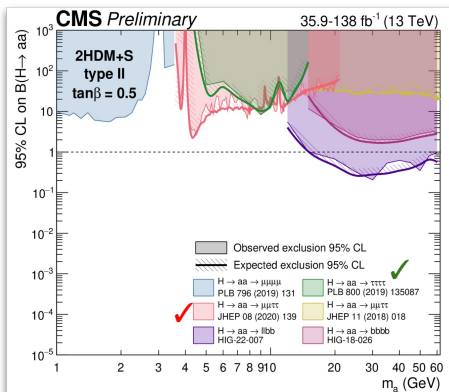
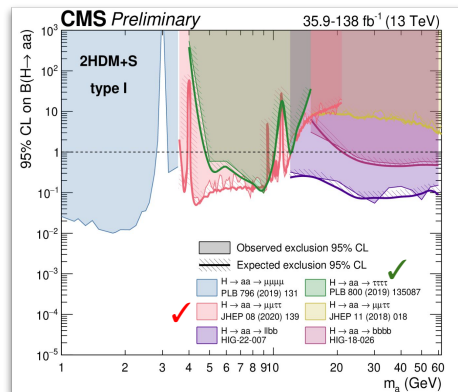
A stylized, high-contrast illustration in shades of brown, tan, and black. It depicts a boat with a large, draped net. On the left, a large eye is painted on the hull. Several figures are visible: one standing on the deck, and others in the water. A large, winged figure is prominent in the upper right. The background is dark with some abstract shapes.

**The search for exotic decays continues...  
Onward to the Run 3 frontier.**

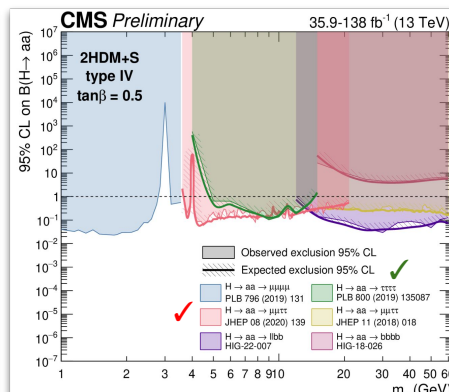
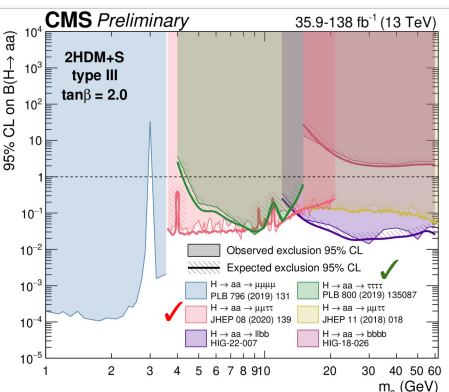
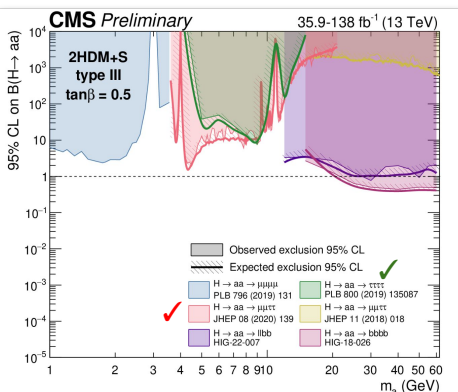
*Thank you!*

Backup

# Summary of 2HDM+S searches at 13 TeV (Run 2)



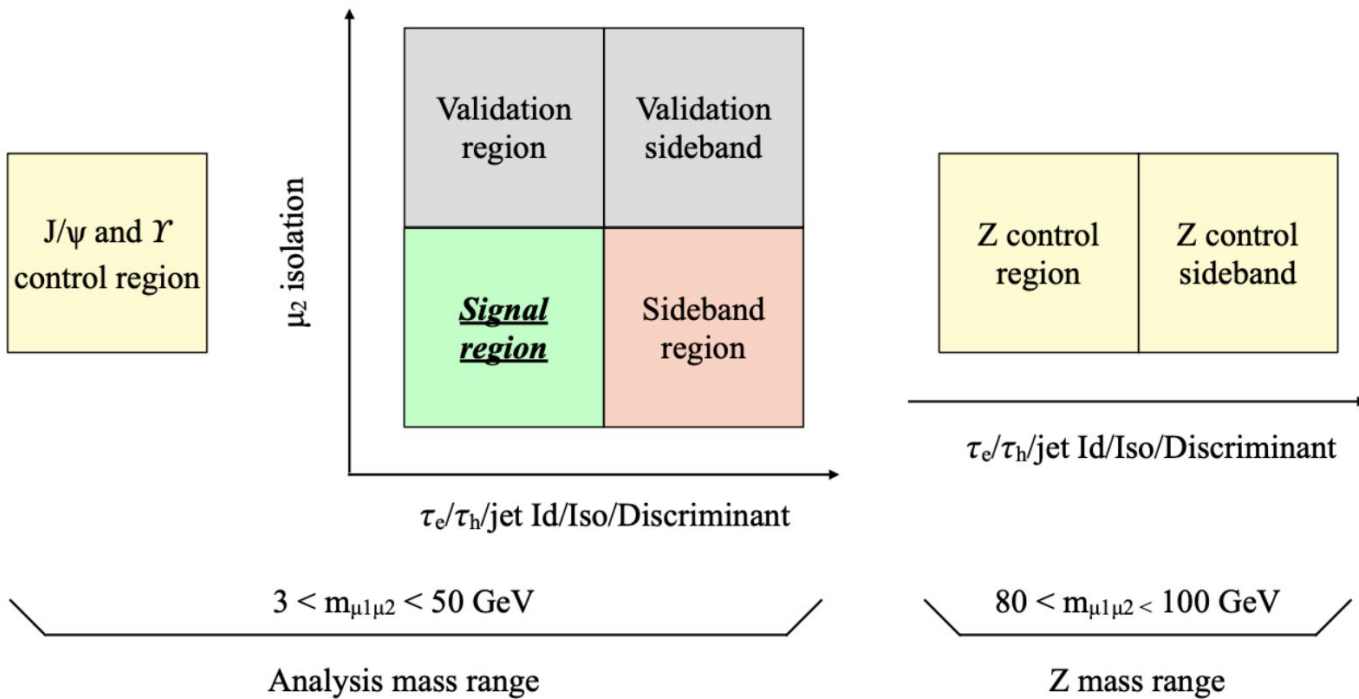
- Complementary final states probe different regions of 2HD+S parameter space



- Enhanced leptonic couplings in Type III improve sensitivity of  $\tau\tau$ - and  $\mu\mu$ -based searches

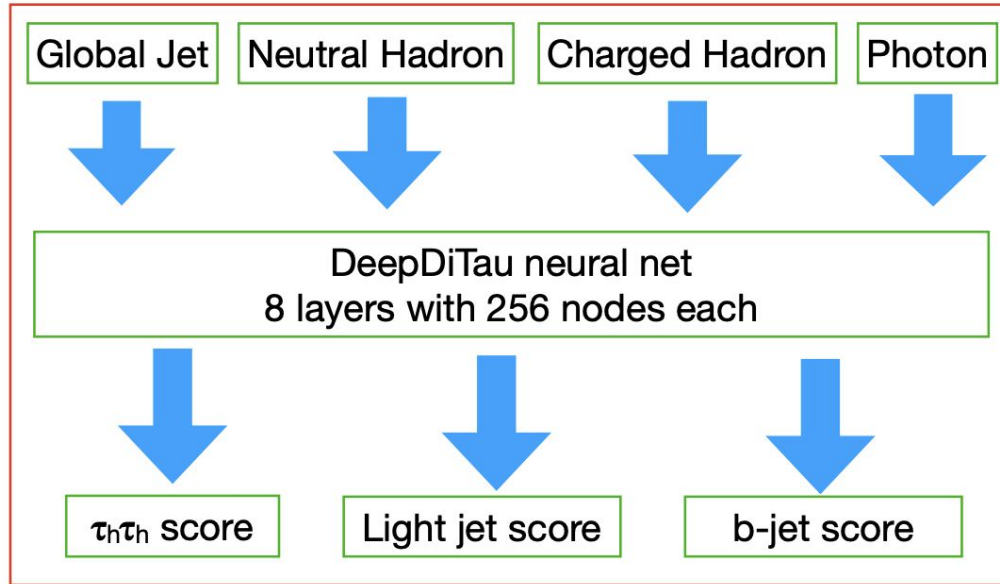
**H**  $\rightarrow$  **aa**  $\rightarrow$   **$\mu\mu\tau\tau$**

[CMS PAS SUS-23-005](#)



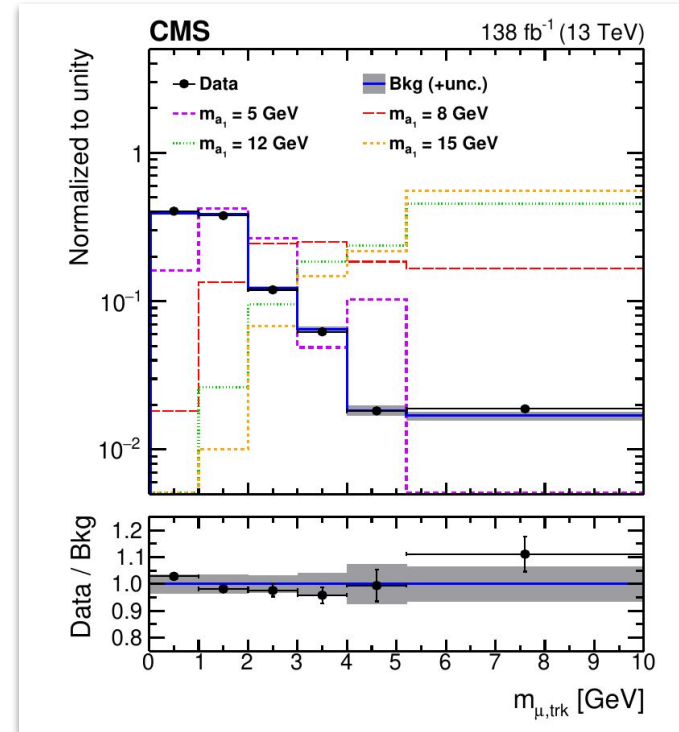
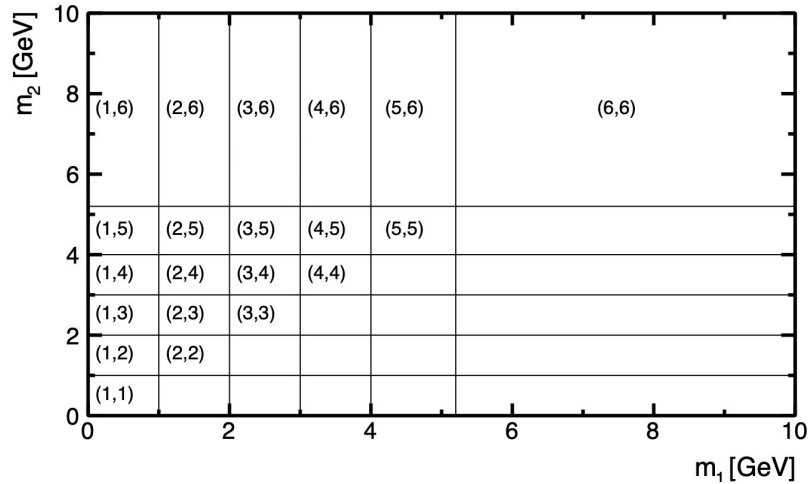
# $H \rightarrow aa \rightarrow \mu\mu\tau\tau$ - Reconstruction of boosted $\tau_h\tau_h$

[CMS PAS SUS-23-0005](#)



# $H \rightarrow a_1 a_1 \rightarrow 4\tau, 2\mu 2\tau$ - Analysis Strategy

[10.1007/JHEP04\(2026\)132](https://arxiv.org/abs/10.1007/JHEP04(2026)132)



# H $\rightarrow$ $\phi_1\phi_2 \rightarrow 2\tau 2b, 2\tau 4b$

Definitions of signal and control regions using BDT discriminator score.

	SR1	SR2	SR3	SR4	CR
$\mu\tau_{h'}$ , 1b	[0.99, 1]	[0.98, 0.99]	[0.95, 0.98]	[0.80,0.95]	[0,0.80]
$\mu\tau_{h'}$ , 2b	[0.99, 1]	[0.84, 0.99]	—	—	[0,0.80]
$e\tau_{h'}$ , 1b	[0.99, 1]	[0.98, 0.99]	[0.95, 0.98]	[0.80,0.95]	[0,0.80]
$e\tau_{h'}$ , 2b	[0.99, 1]	[0.80, 0.99]	—	—	[0,0.80]
$e\mu$ , 1b	[0.99, 1]	[0.97, 0.99]	[0.90, 0.97]	—	[0,0.80]
$e\mu$ , 2b	[0.99, 1]	[0.90, 0.99]	—	—	[0,0.80]

**Table 1** Overview of the benchmark scenarios: The second column denotes the Higgs mass eigenstate that we identify with the observed Higgs boson,  $h_{125}$ , the third column names the targeted decay mode of the resonantly produced Higgs state, and the fourth column lists possible relevant successive decays of the resulting Higgs states

Benchmark scenario	$h_{125}$ candidate	Target signature	Possible successive decays
<b>BP1</b>	$h_3$	$h_{125} \rightarrow h_1 h_2$	$h_2 \rightarrow h_1 h_1$ if $M_2 > 2M_1$
<b>BP2</b>	$h_2$	$h_3 \rightarrow h_1 h_{125}$	—
<b>BP3</b>	$h_1$	$h_3 \rightarrow h_{125} h_2$	$h_2 \rightarrow h_{125} h_{125}$ if $M_2 > 250$ GeV
<b>BP4</b>	$h_3$	$h_2 \rightarrow h_1 h_1$	—
<b>BP5</b>	$h_2$	$h_3 \rightarrow h_1 h_1$	—
<b>BP6</b>	$h_1$	$h_3 \rightarrow h_2 h_2$	$h_2 \rightarrow h_{125} h_{125}$ if $M_2 > 250$ GeV

## TRSM BPs