Searches for an exotic decay of the Higgs boson to a pair of pseudoscalars in CMS

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On behalf of the CMS collaboration

Motivation

The 125 GeV Higgs boson

$$BR_{BSM} < 34\%$$

Combined ATLAS and CMS coupling analysis for the Run1 Data — JHEP 1608 (2016) 045

2HDM

- One of the simplest possible extensions of the SM
- They play an important role in:
  - **Supersymmetry:** *holomorphy and cancellation of anomalies*
  - **Axion models:** *imposing Peccei and Quinn symmetry only possible if there are two Higgs doublets*
  - **Baryon asymmetry:** *it could contain additional sources of CP violation*

However, 2HDMs are by now strongly constrained from existing data

2HDM+S

- The current constraints can be avoided by:
  - assuming that the 2HDM is in the decoupling limit
    the couplings of h(125) become SM-like or very close to SM-like
  - adding one complex scalar singlet $S = \frac{1}{\sqrt{2}}(S_R + iS_I)$
    it only couples to $H_{1,2}$ and it is allowed to have small mixing with these

Motivation

Light Pseudoscalar (a_1)

- The 2HDM+S contains 7 physical states:

  2 charged (H^+,H^-), 3 CP-even (h_1,h_2,h_3) and 2 CP-odd (a_1,a_2)

  a_1 is the mostly-singlet-like pseudoscalar

- There exist scenarios in which a_1 is lighter than the SM-like Higgs, namely:

$$m_{a_1} < \frac{m_{h(125)}}{2}$$

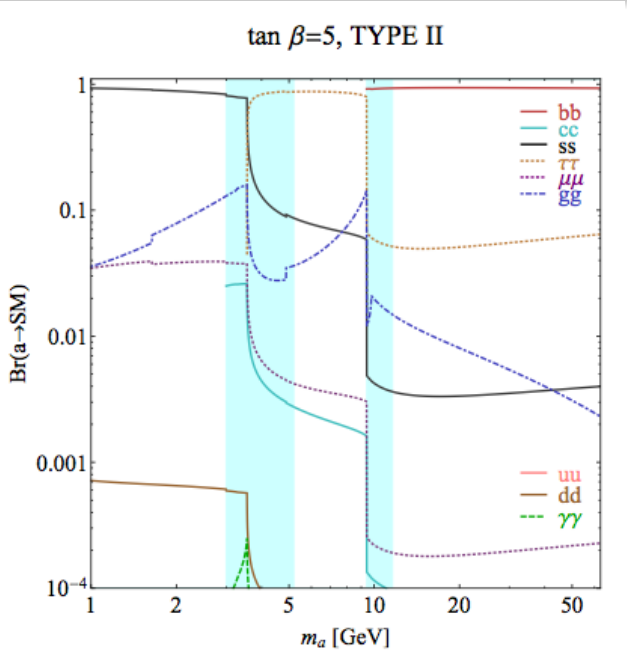
in this case, there are exotic Higgs decays of the form: $h(125) \to a_1 a_1 \to X\overline{X}Y\overline{Y}$

Table: Types of fermion couplings (w/o FCNC)

2HDM	u-type	d-type	lepton
Type-I	H_2	H_2	H_2
Type-II	H_2	H_1	H_1
Type-III	H_2	H_2	H_1
Type-IV	H_2	H_1	H_2

$BR(a_1 \to X\overline{X})$ for Type II

Phys.Rev. D90 (2014) no.7, 075004



CMS Searches

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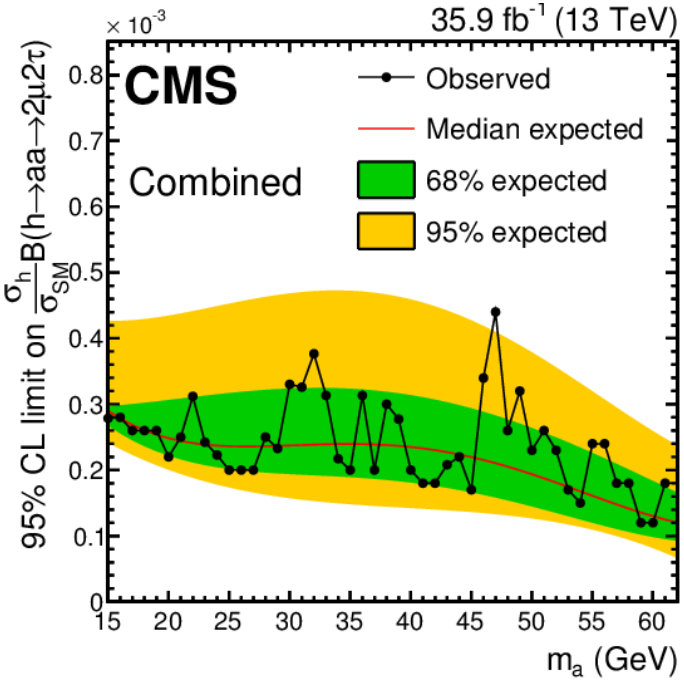
- As m_{a_1} becomes smaller, the mass difference ($m_{h(125)} \gg m_{a_1}$) makes the a_1 bosons highly boosted
- This regime is challenging in terms of particle detection and reconstruction
- One then distinguishes two cases: *Resolved* vs *Boosted* topology

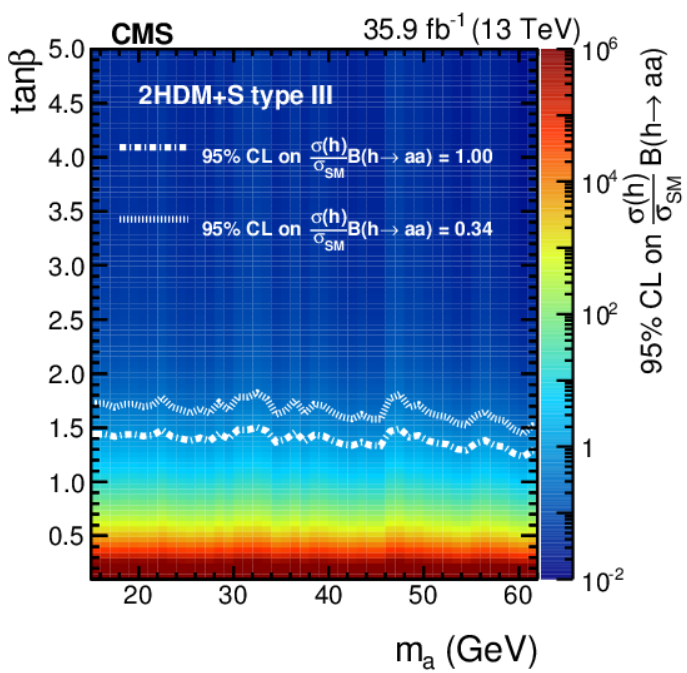
$h(125) \to a_1 a_1$ searches in CMS at 13 TeV

- Resolved Topology
  - $h(125) \to a_1 a_1 \to \tau\tau\mu\mu$
  - $h(125) \to a_1 a_1 \to bb\tau\tau$
  - $h(125) \to a_1 a_1 \to bb\mu\mu$
- Boosted Topology
  - $h(125) \to a_1 a_1 \to \mu\mu\mu\mu$
  - $h(125) \to a_1 a_1 \to \tau\tau\tau\tau$

$h(125) \rightarrow a_1 a_1 \rightarrow \tau\tau\mu\mu$ JHEP 1811 (2018) 018

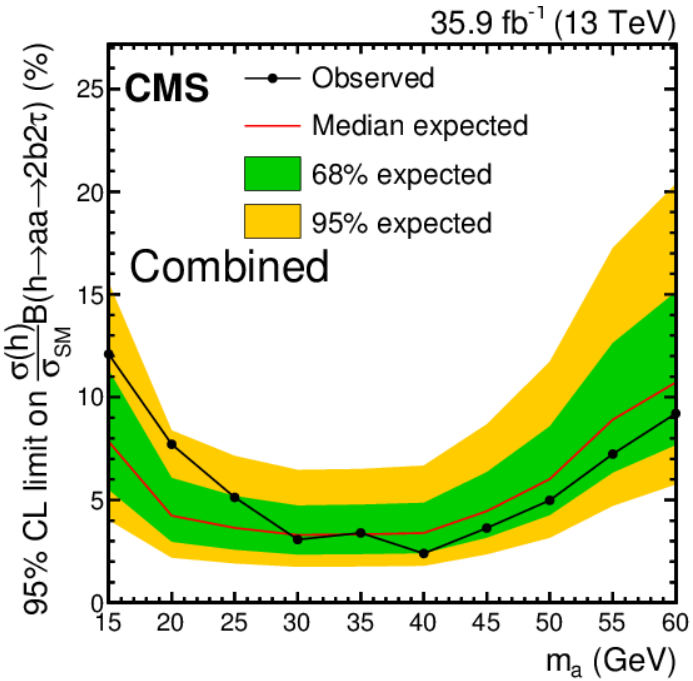
- Mass range probed: $15.0 < m_{a_1} < 62.5$ GeV
- Production modes of h(125) included: **ggH** and **VBF**
- $h(125) \rightarrow a_1 a_1 \rightarrow \tau\tau\tau\tau$ events are also treated as part of the signal
- Four different $\tau\tau$ decay channels: $\mathbf{e\mu}$, $\mathbf{e\tau_h}$, $\boldsymbol{\mu\tau_h}$ and $\boldsymbol{\tau_h\tau_h}$
- Signal extraction: unbinned maximum-likelihood fit to the $m_{\mu\mu}$ distribution
- The background is estimated from data

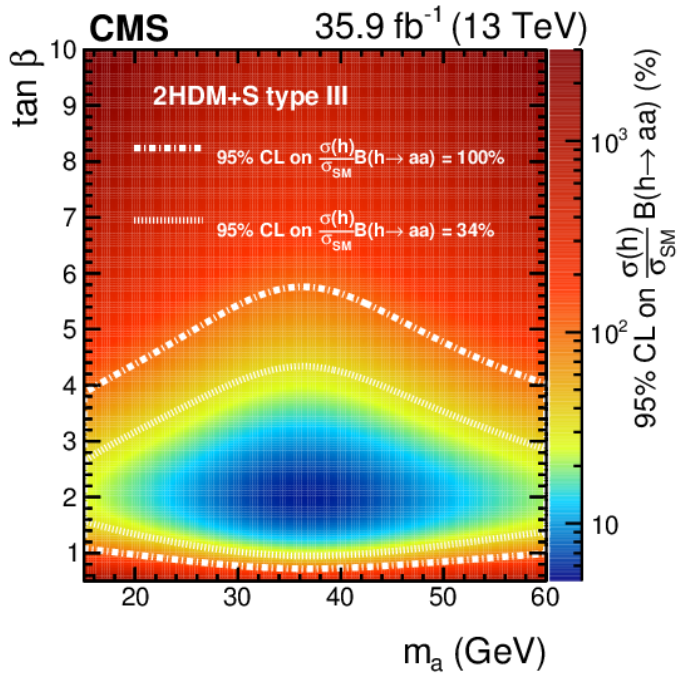




$h(125) \rightarrow a_1 a_1 \rightarrow bb\tau\tau$ Phys.Lett. B785 (2018) 462-488

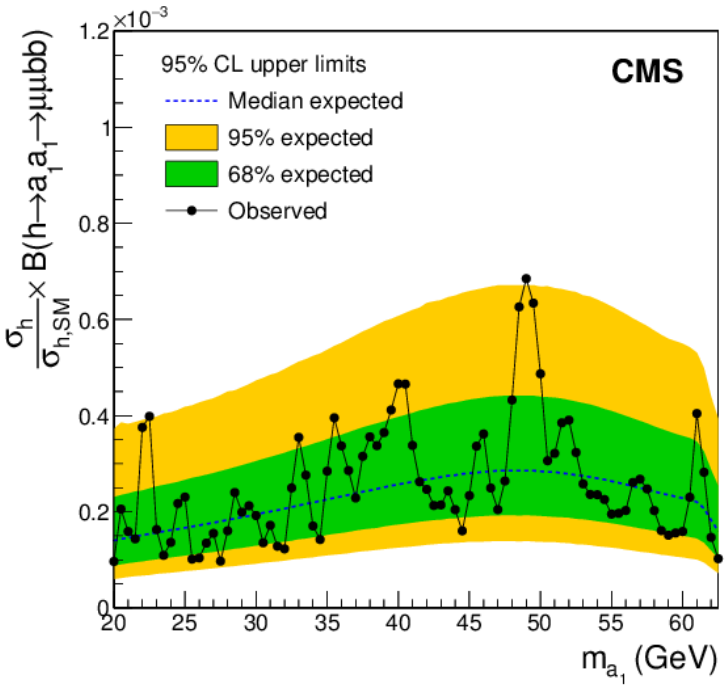
- Mass range probed: $15 < m_{a_1} < 60$ GeV
- Production modes of h(125) included: **ggH**, **VBF** and **VH**
- Three different $\tau\tau$ decay channels: $\mathbf{e\mu}$, $\mathbf{e\tau_h}$ and $\boldsymbol{\mu\tau_h}$
- Categorization (4 cats.) according to 4 kinematic distributions
- Signal extraction: binned maximum-likelihood fit to the $m_{\tau\tau}^{vis}$ distribution
- The backgrounds are estimated from a combination of simulation and data

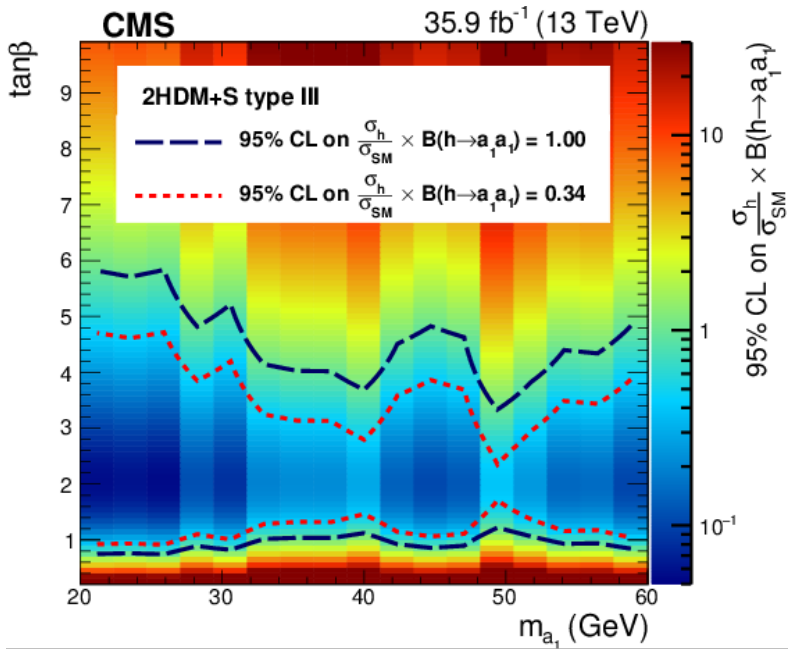




$h(125) \rightarrow a_1 a_1 \rightarrow bb\mu\mu$ Phys.Lett. B795 (2019) 398-423

- Mass range probed: $20.0 < m_{a_1} < 62.5$ GeV
- Production modes of h(125) included: **ggH** and **VBF**
- Categorization (3 cats.) according to the b tagging discriminator value of one of the jets
- Signal extraction: unbinned maximum-likelihood fit to the $m_{\mu\mu}$ distribution
- The background estimation fully relies on data by using the discrete profiling method

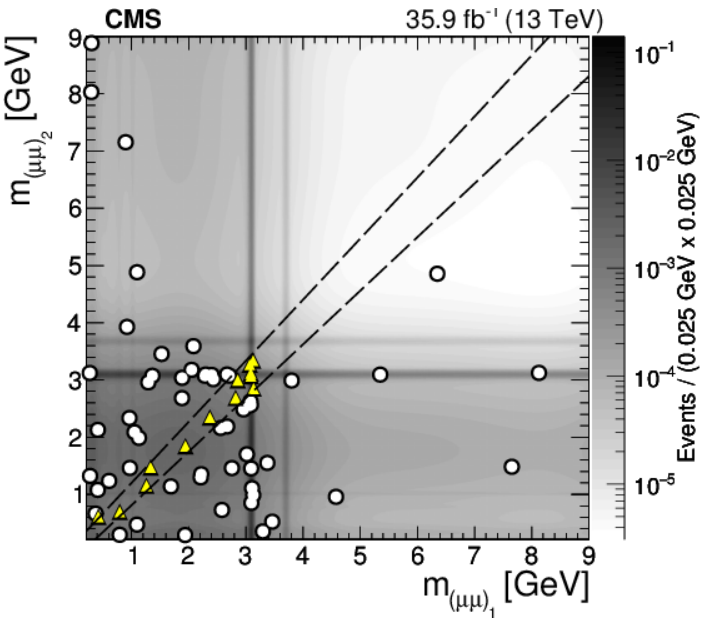


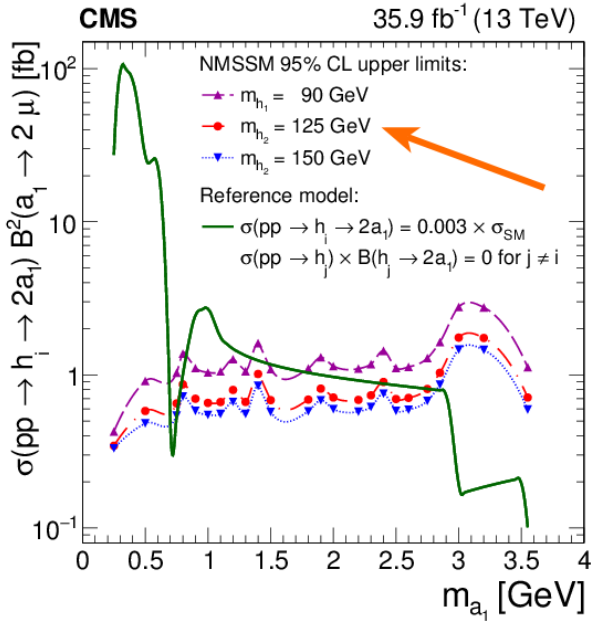


$h(125) \rightarrow a_1 a_1 \rightarrow \mu\mu\mu\mu$ Phys.Lett. B796 (2019) 131-154

- Mass range probed: $0.25 < m_{a_1} < 3.55$ GeV
- Production mode of h(125) included: **ggH**
- Events are selected if they fulfill the relation $m_{(\mu\mu)1} \simeq m_{(\mu\mu)2}$, as shown in the figure
- Signal extraction: unbinned maximum-likelihood fit to the 2D $m_{(\mu\mu)1}$ vs. $m_{(\mu\mu)2}$ distribution
- The estimation of the main background contribution ($b\bar{b}$) is from data

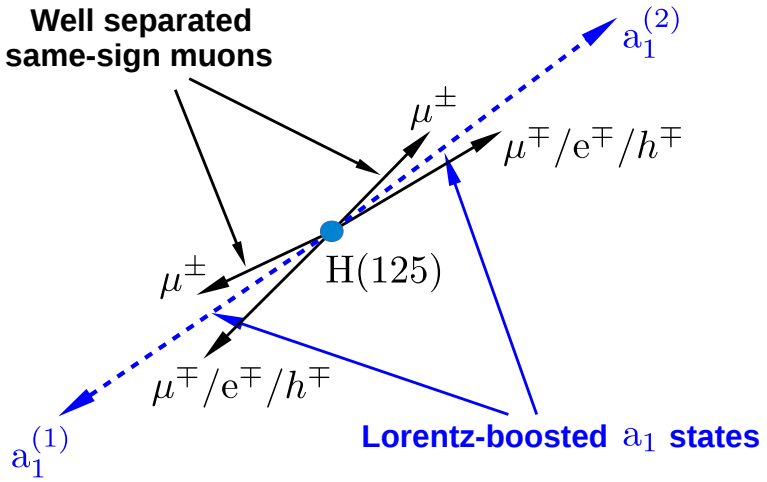
⋆ **Total expected background events:** $9.90 \pm 1.24(stat) \pm 1.84(syst)$ **Observed events:** 13

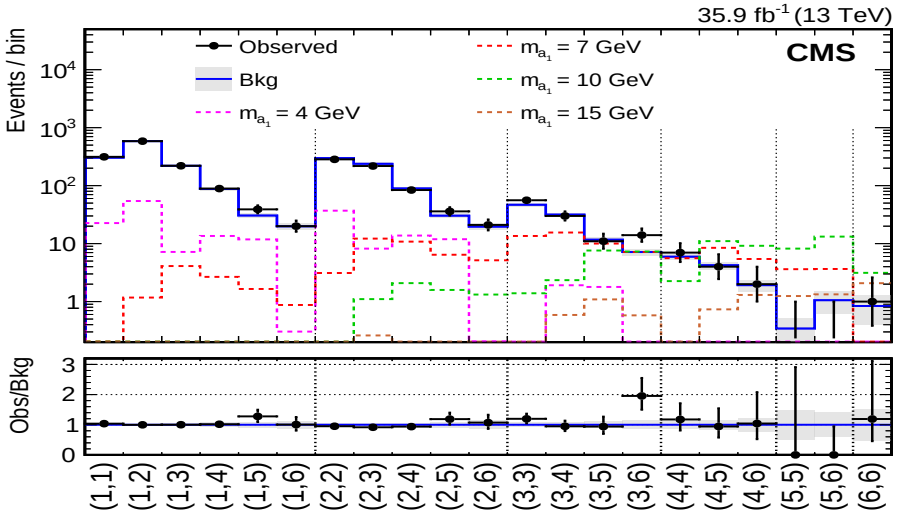


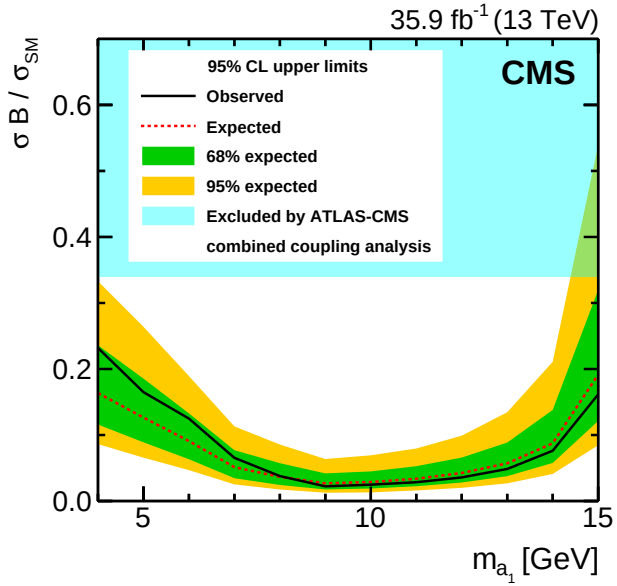


$h(125) \rightarrow a_1 a_1 \rightarrow \tau\tau\tau\tau$ NEW! arXiv:1907.07235

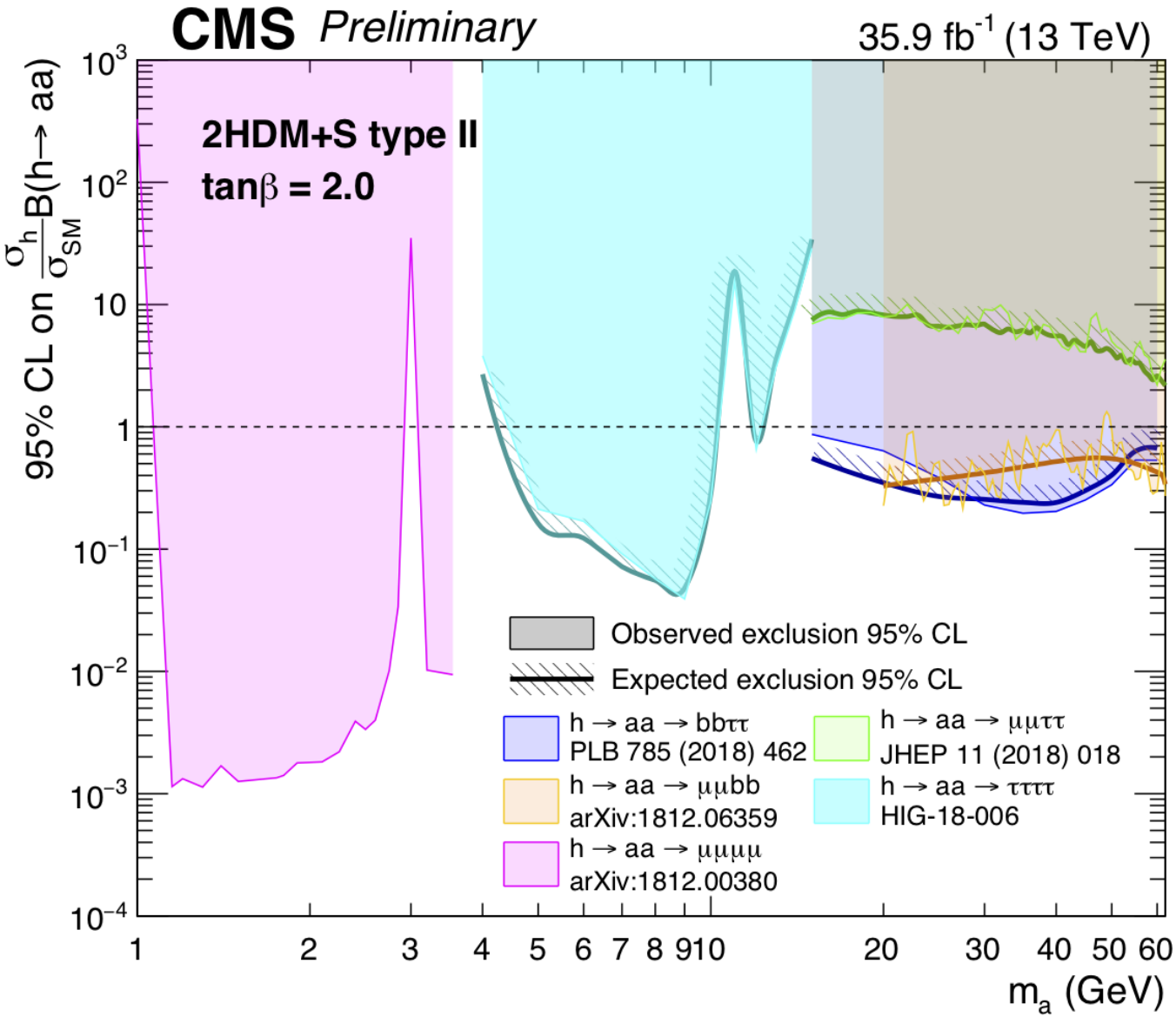
- Mass range probed: $4 < m_{a_1} < 15$ GeV
- Production modes of h(125) included: **ggH**, **VBF**, **VH** and **ttH**
- $h(125) \rightarrow a_1 a_1 \rightarrow \mu\mu\tau\tau$ events are also treated as part of the signal
- Signal extraction: binned maximum-likelihood fit to the 2D $m_{(\mu-trk)1}$ vs. $m_{(\mu-trk)2}$ distribution
- The background modelling is based on data







Summary of the results



Conclusion

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- Many $h(125) \rightarrow a_1 a_1$ searches performed in different decay channels and final states
- The searches cover a large variety of 2HDM+S models
  - Almost all possible low masses of the a_1 boson have been probed, having to deal with different boosted regimes
  - Scenarios comprising all types of fermion coupling have been tested
- No sign of $h(125) \rightarrow a_1 a_1$ decay yet ...
- Limits are becoming more stringent as more data is added
- Other interesting analyses ongoing ...

Conclusion

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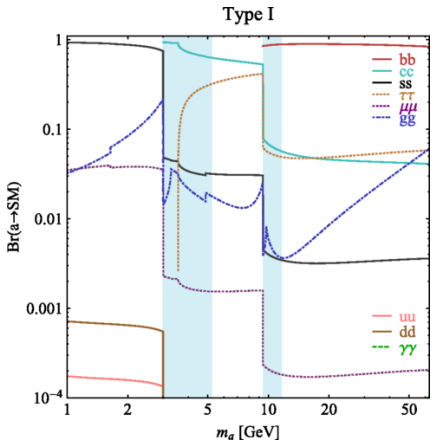
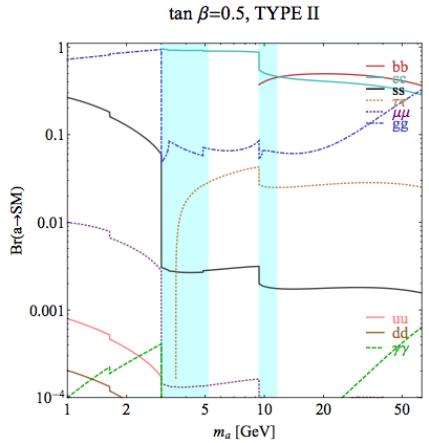
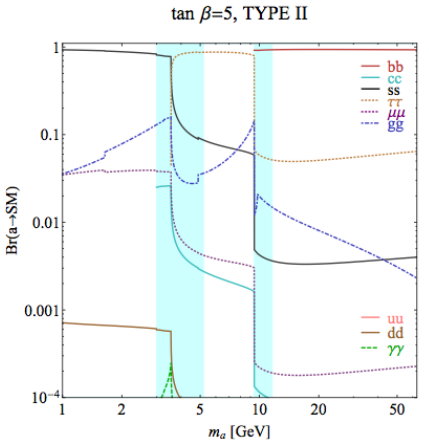
Thanks for your attention!

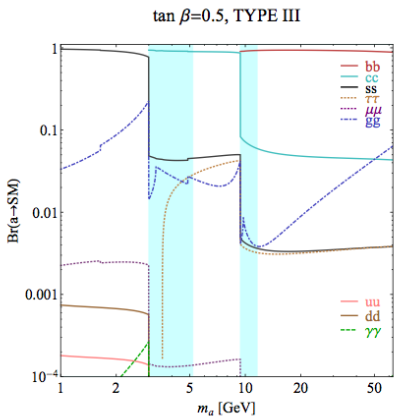
Backup

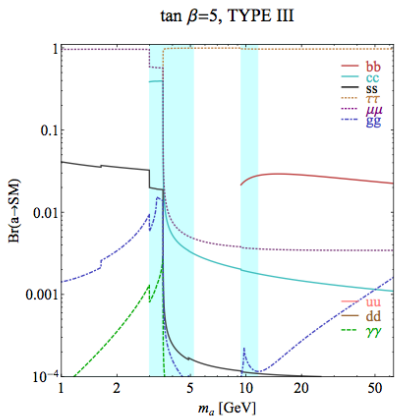
$BR(a_1 \to X\overline{X})$ for types of 2HDM+S models

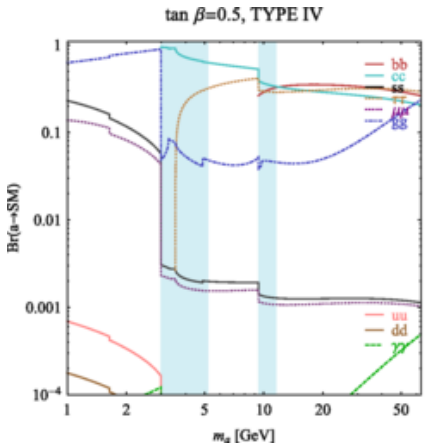


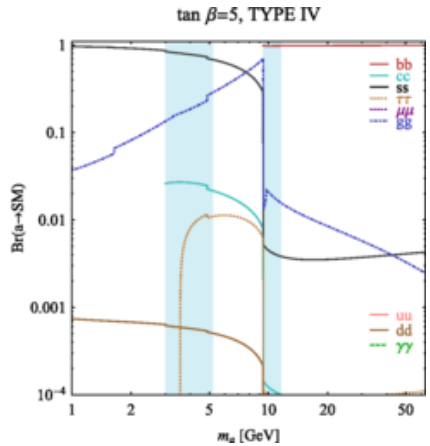




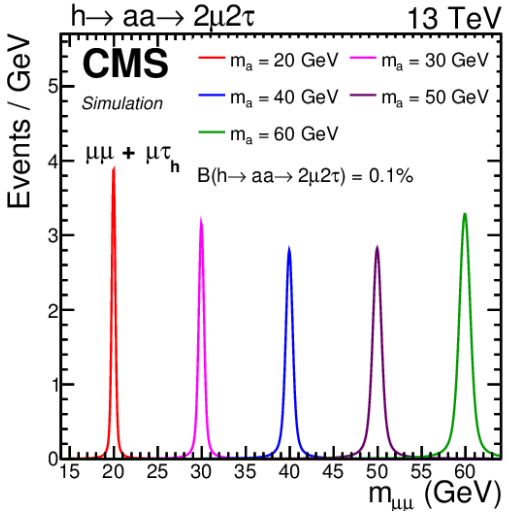


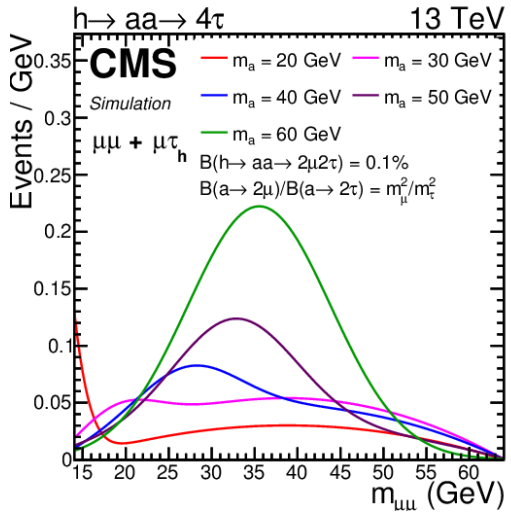


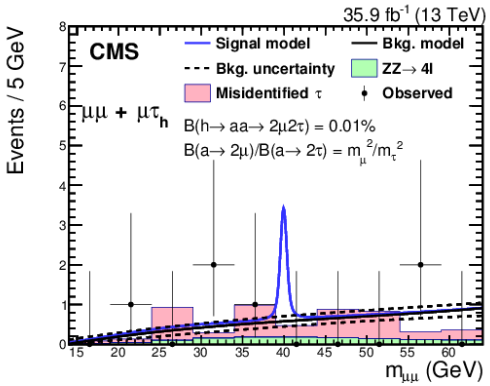


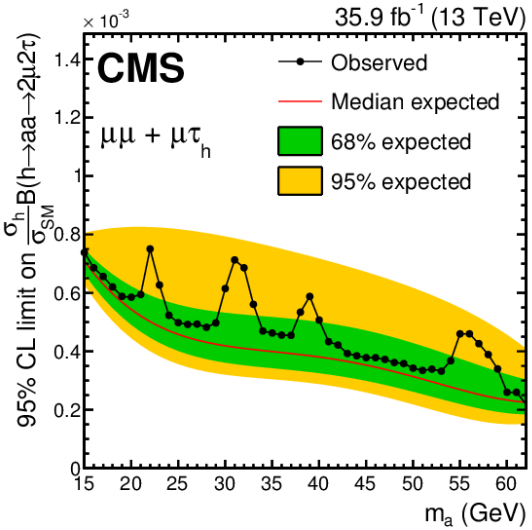


$h(125) \to a_1 a_1 \to \tau\tau\mu\mu$



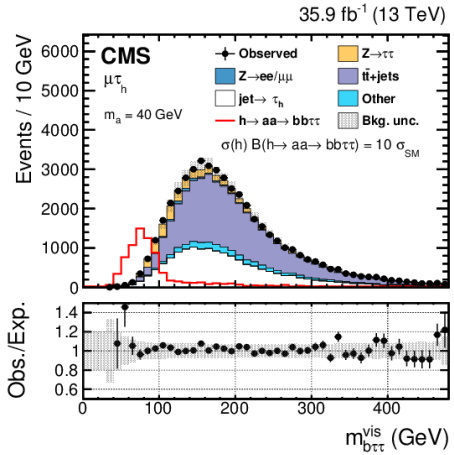


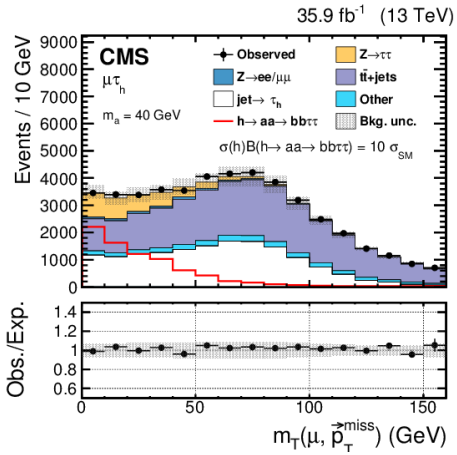


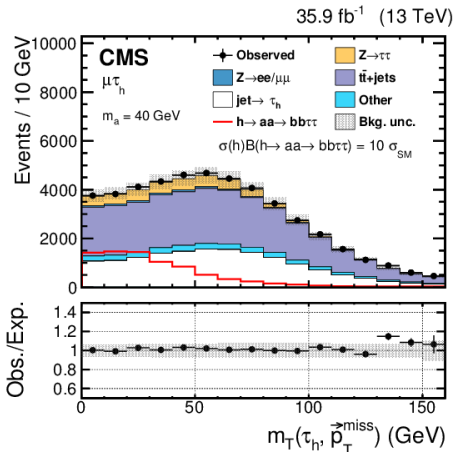


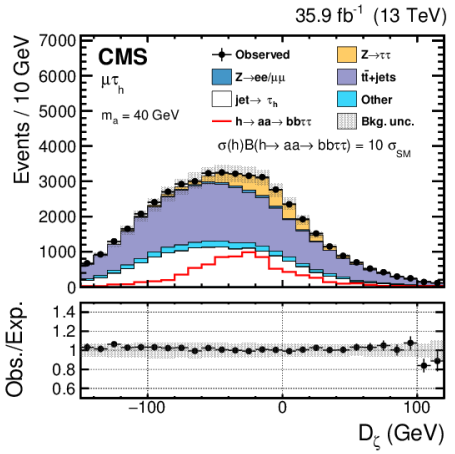
$h(125) \rightarrow a_1 a_1 \rightarrow bb\tau\tau$

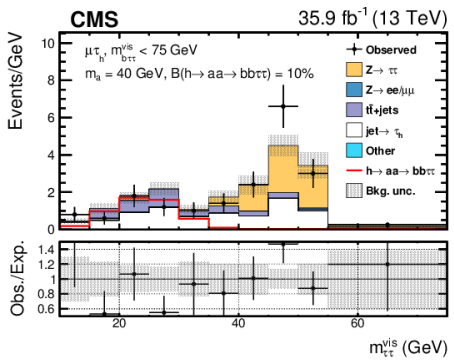
Kinematic distributions used for categorization: $m^{vis}_{b\tau\tau}$, $m_T(e(\mu), \overrightarrow{p}^{miss}_T)$, $m_T(\mu(\tau_h), \overrightarrow{p}^{miss}_T)$, D_ζ [*]

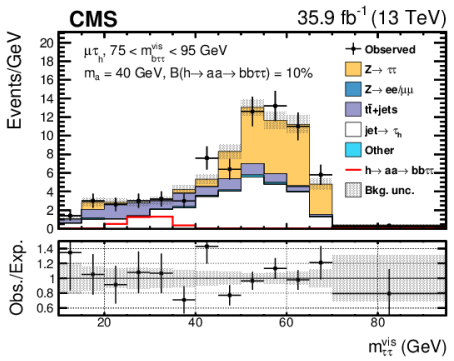


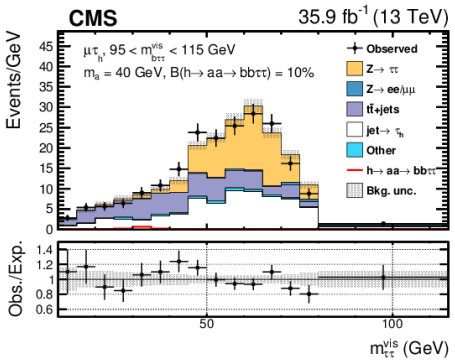


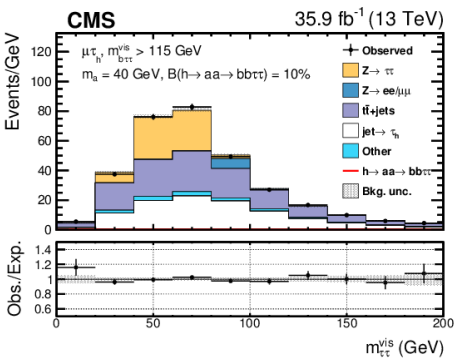












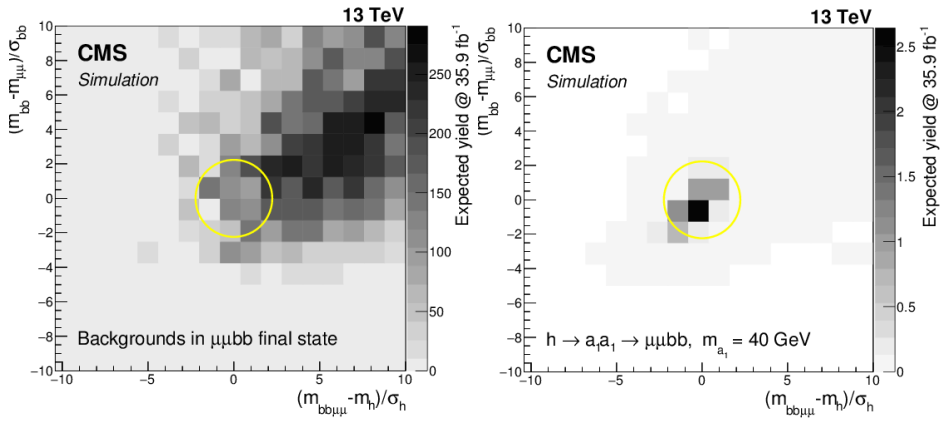
[*] $D_\zeta \equiv \overrightarrow{p}^{miss}_T \cdot \frac{\overrightarrow{\zeta}}{|\overrightarrow{\zeta}|} - 0.85\ (\overrightarrow{p}_{T,1} + \overrightarrow{p}_{T,2}) \cdot \frac{\overrightarrow{\zeta}}{|\overrightarrow{\zeta}|}$

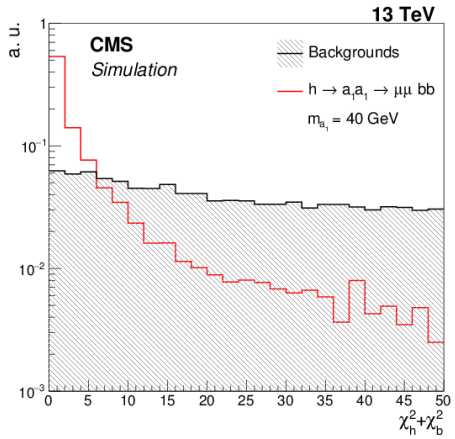
$\overrightarrow{\zeta}$ → bisector of the transverse momenta of the two τ candidates

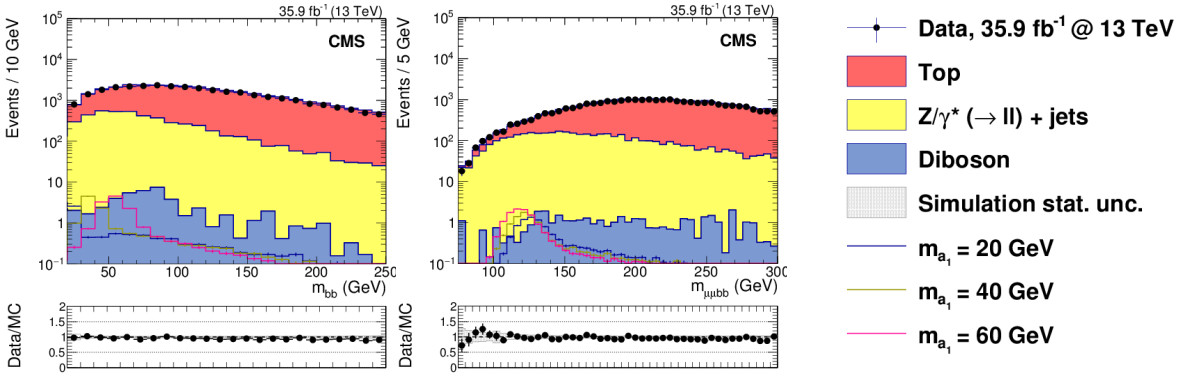
$h(125) \rightarrow a_1 a_1 \rightarrow bb\mu\mu$

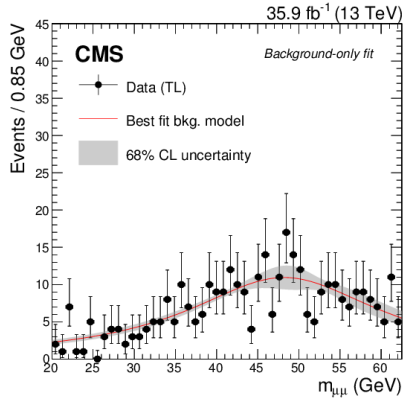
Events selected if they have $\chi^2 < 5$:

$$\chi^2 = \chi^2_{bb} + \chi^2_h \qquad \chi_{bb} = \frac{m_{bb} - m_{\mu\mu}}{\sigma_{bb}} \qquad \chi_h = \frac{m_{\mu\mu bb} - m_h}{\sigma_h}$$









Background model constructed as:

$$f_{2D}(i,j) = C(i,j) \cdot (f_{1D}(i) \cdot f_{1D}(j)) \quad (1)$$