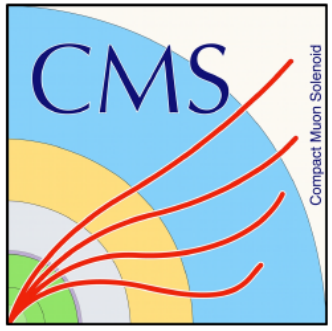
Search for a pair of pseudoscalars in decays of the Higgs boson in CMS

Sandra Consuegra Rodríguez (DESY) on behalf of the CMS collaboration

Workshop on Connecting Insights in Fundamental Physics: Standard Model and Beyond, Corfu, 06.09.2019

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES



Motivation:

- Discovery of the Higgs boson lead to extensive measurements to probe its consistency with Standard Model (SM) predictions
- Branching fraction of 34% into exotic decay modes still allowed by existing data [JHEP 1608 (2016) 045] (Run I combined ATLAS and CMS analysis)
- Exotic Higgs decays → natural signature of very broad class of beyond the SM theories

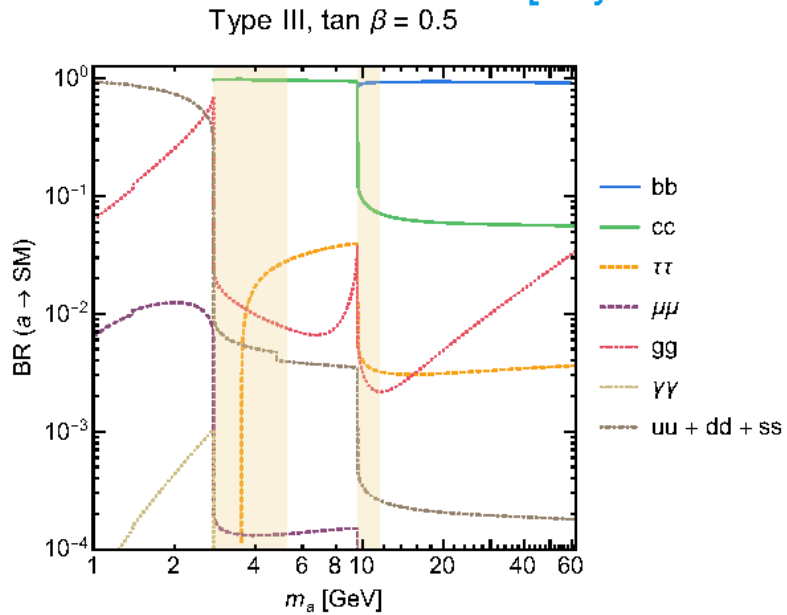
2HDM Models:
(already strongly constrained by existing data)

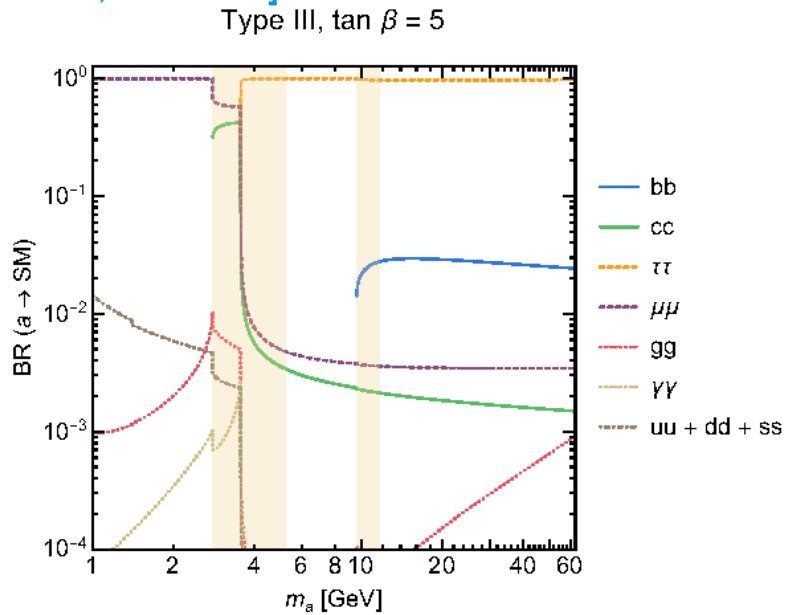
2HDM+S Models:

three CP-even ($h_{1,2,3}$), two CP-odd ($a_{1,2}$), and two charged Higgs states (H^+, H^-)

Constrains set for the 2DHM models avoided

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





Motivation:

- CMS → Dedicated searches with Run I and a fraction of Run II already done and others currently ongoing

This talk: Assessment of the status of exotic Higgs decays searches to a pair of light pseudoscalars at CMS after LHC Run II, with emphasis on high luminosity projections

- **Overview of the Run-2 analyses:**

Fully leptonic analysis:

$h \to a_1 a_1 \to 4\tau$

$h \to a_1 a_1 \to 2\mu 2\tau$

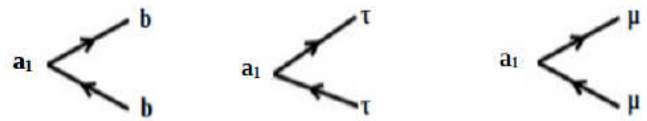
$h \to a_1 a_1 \to 4\mu$

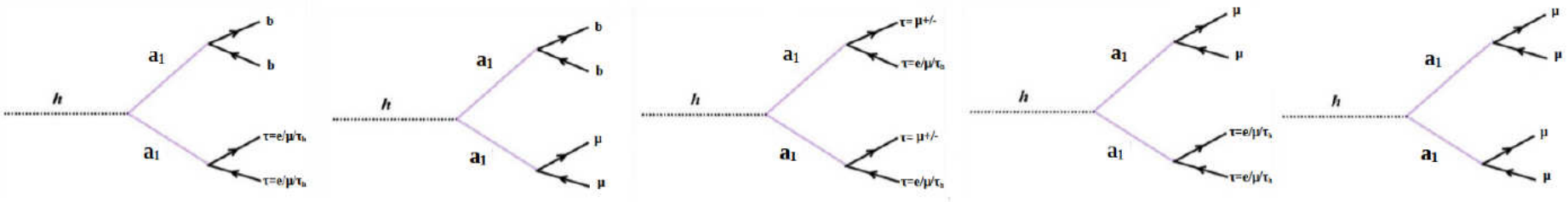
- (complementary mass range probed)

$h \to a_1 a_1 \to 2b2\tau$

$h \to a_1 a_1 \to 2\mu 2b$

- same mass range probed (cleaner signature in $a \to \mu\mu$ leg vs. higher BR of $a \to \tau\tau$ leg)

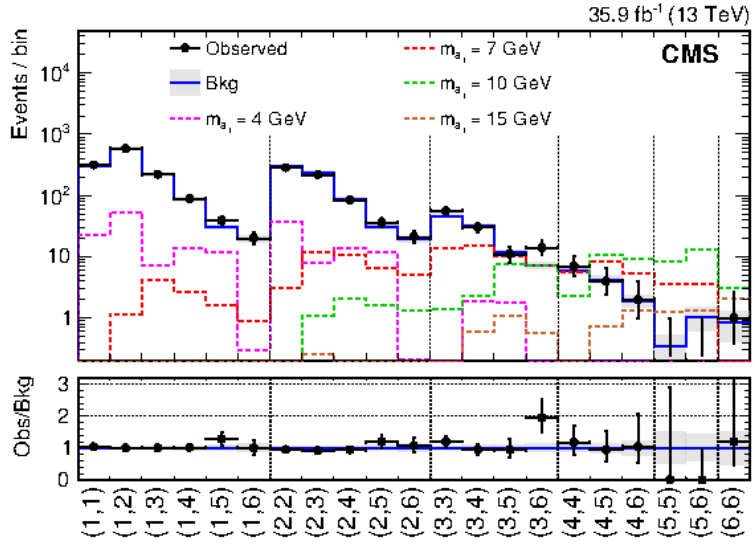


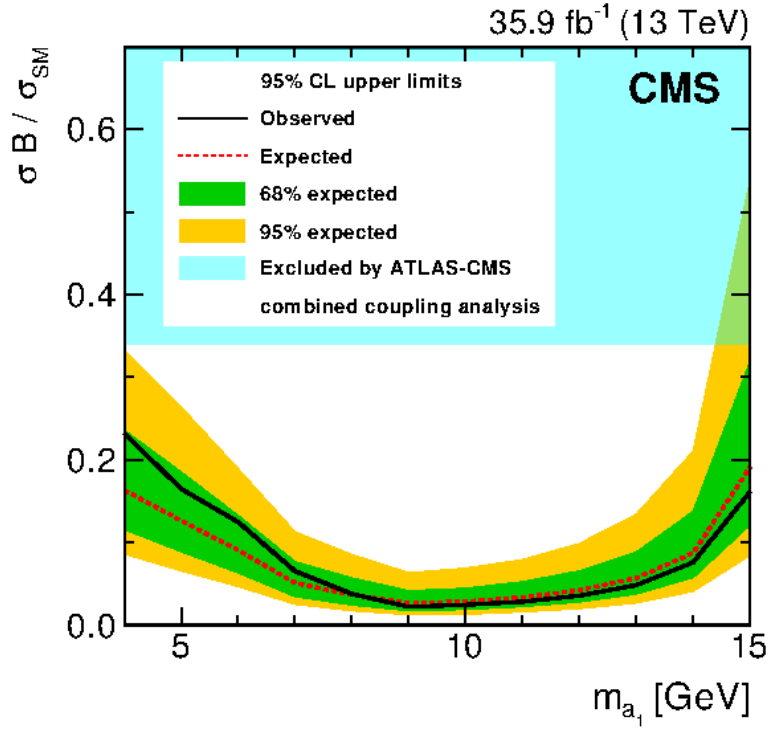


$h \to a_1 a_1 \to 4\tau$ [NEW]

[arXiv:1907.07235v1] (Submitted to Phys. Lett. B)

- Branching fraction:
  - For Type-III 2HDM+S models enhanced $a_1 \to \tau\tau$ decay rate for tan$\beta > 1$
- Event selection: two muon-track pairs
- m_{a_1} region probed: 4 GeV $< m_{a_1} <$ 15 GeV
- Events from h$\to a_1 a_1 \to 2\mu 2\tau$ can also enter the signal region (treated as a part of the signal)
- Main background: QCD-multijet events
- Final discriminant: binned maximum-likelihood fit to the 2D (m_1, m_2) distribution





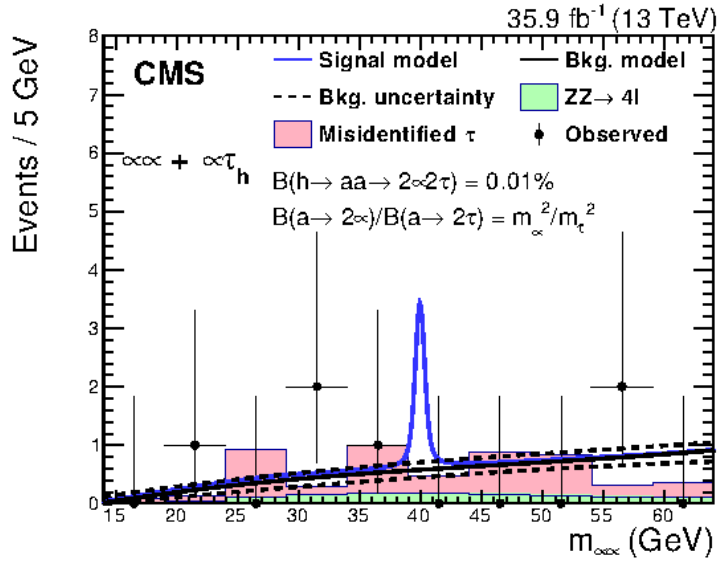
$h \to a_1 a_1 \to 2\mu 2\tau$

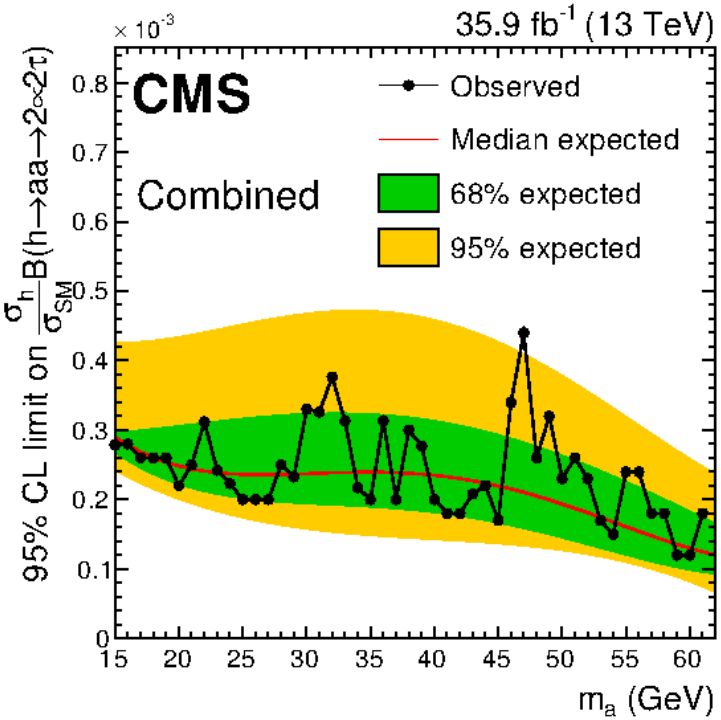
[JHEP 1811 (2018) 018]

- Branching fraction:

$$\frac{\Gamma(a\to\mu\mu)}{\Gamma(a\to\tau\tau)} = \frac{m_\mu^2\sqrt{(1-\frac{2m_\mu}{m_a})^2}}{m_\tau^2\sqrt{(1-\frac{2m_\tau}{m_a})^2}}$$

- Event selection: opposite-sign(OS) pair of isolated muons and OS pair of isolated τ candidates
- m_{a_1} region probed: 15 GeV $< m_{a_1} <$ 62.5 GeV
- Events from h$\to a_1 a_1 \to 4\tau$ can also enter the signal region (treated as a part of the signal)
- Main background: jets misidentified as τ leptons
- Final discriminant: unbinned maximum-likelihood fit to the $m_{\mu\mu}$ invariant mass distribution

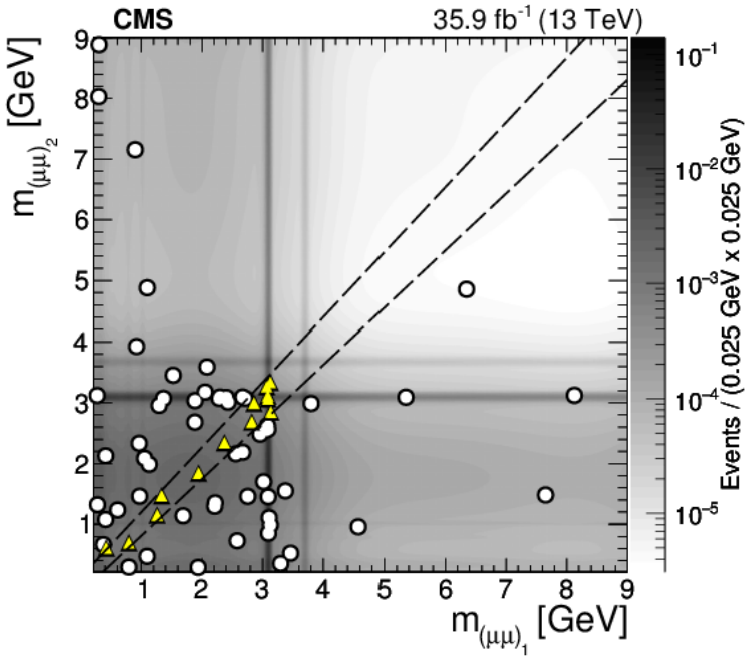


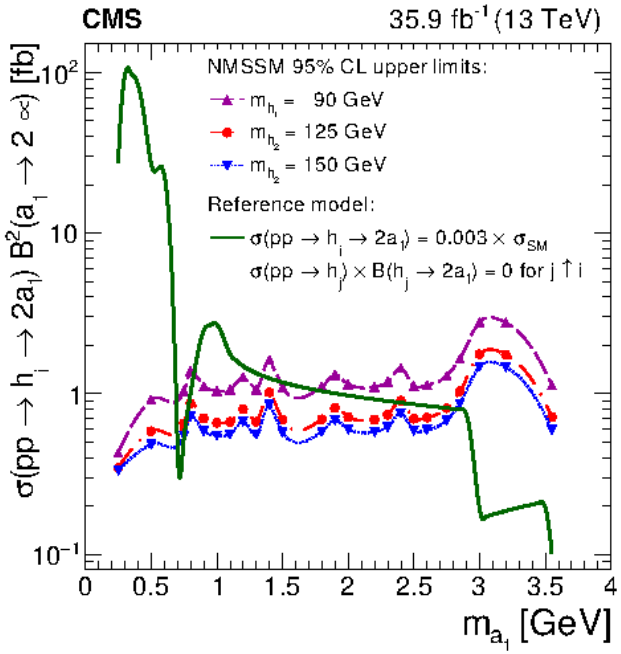


$h \to a_1 a_1 \to 4\mu$

[Phys.Lett. B796 (2019)]

- Event selection: exactly 2 dimuons
- Dimuon masses consistent with each other to within 5 times detector resolution
- m_{a_1} region probed: 0.25 GeV $< m_{a_1} <$ 3.55 GeV (lowest mass range probed)
- Main background: b quark pair production (in general very small background contribution in signal region)
- Final discriminant: unbinned maximum-likelihood fit to the 2D $(m_{(\mu\mu)_1}, m_{(\mu\mu)_2})$ distribution

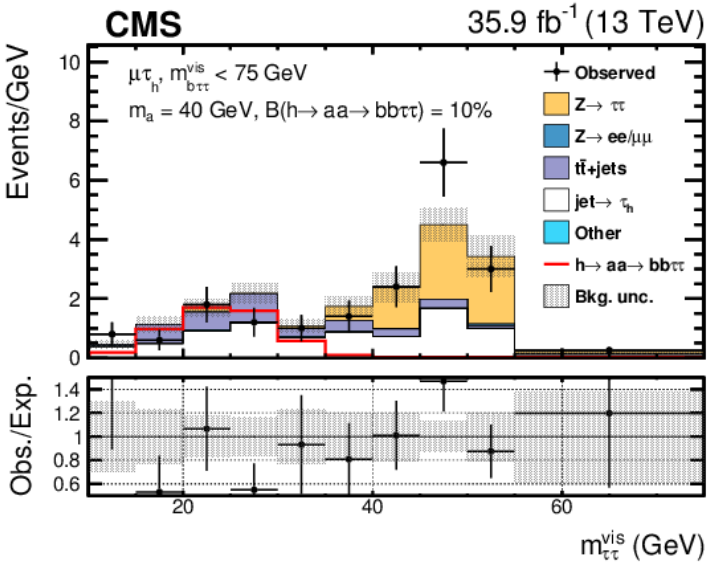


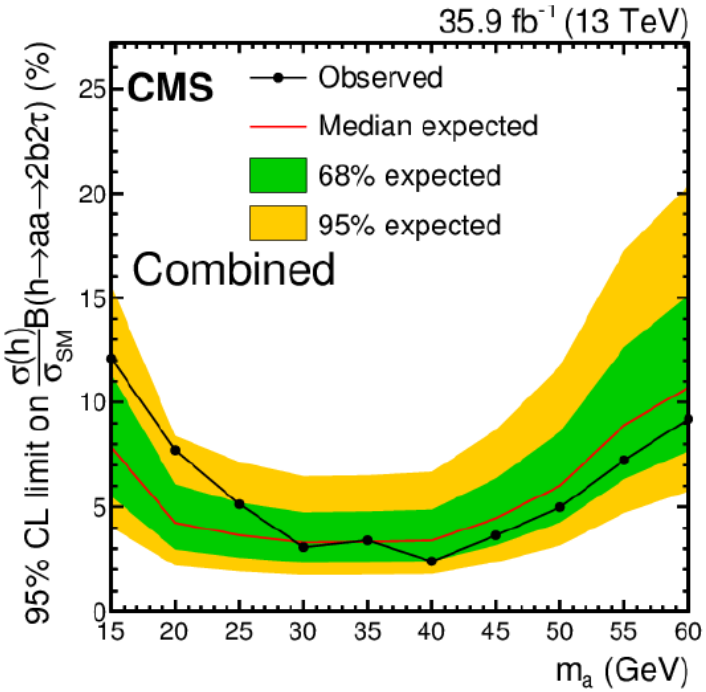


$h \to a_1 a_1 \to 2b2\tau$

[Phys.Lett. B785 (2018) 462]

- Branching fraction:
  - Above 10% in Type-II 2HDM+S models and $\tan\beta > 1$
  - Up to about 50% in Type-III 2HDM+S models with $\tan\beta \approx 2$
- Event selection: Three different $\tau\tau$ final states: eμ, eτ_h, and $\mu\tau_h$, with at least one b-tagged jet
- m_{a_1} region probed: 15 GeV $< m_{a_1} <$ 60 GeV
- Main background: $t\bar{t}$ and Z $\to \tau\tau$ production
- Final discriminant: binned maximum likelihood fit to the $m_{\tau\tau}^{vis}$ distribution

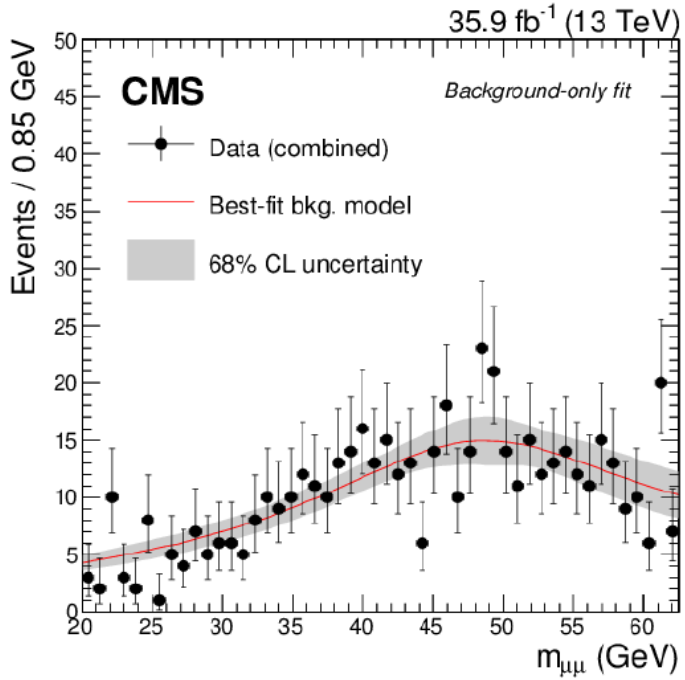


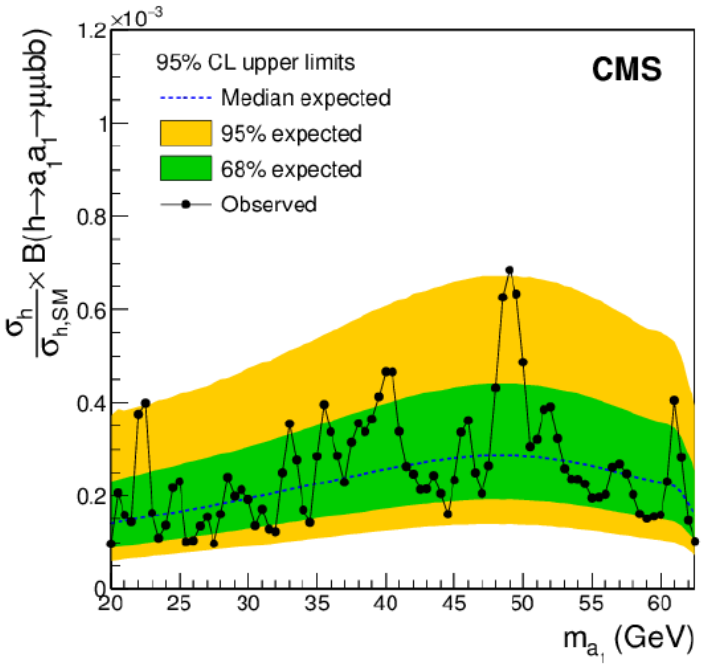


$h \to a_1 a_1 \to 2\mu 2b$

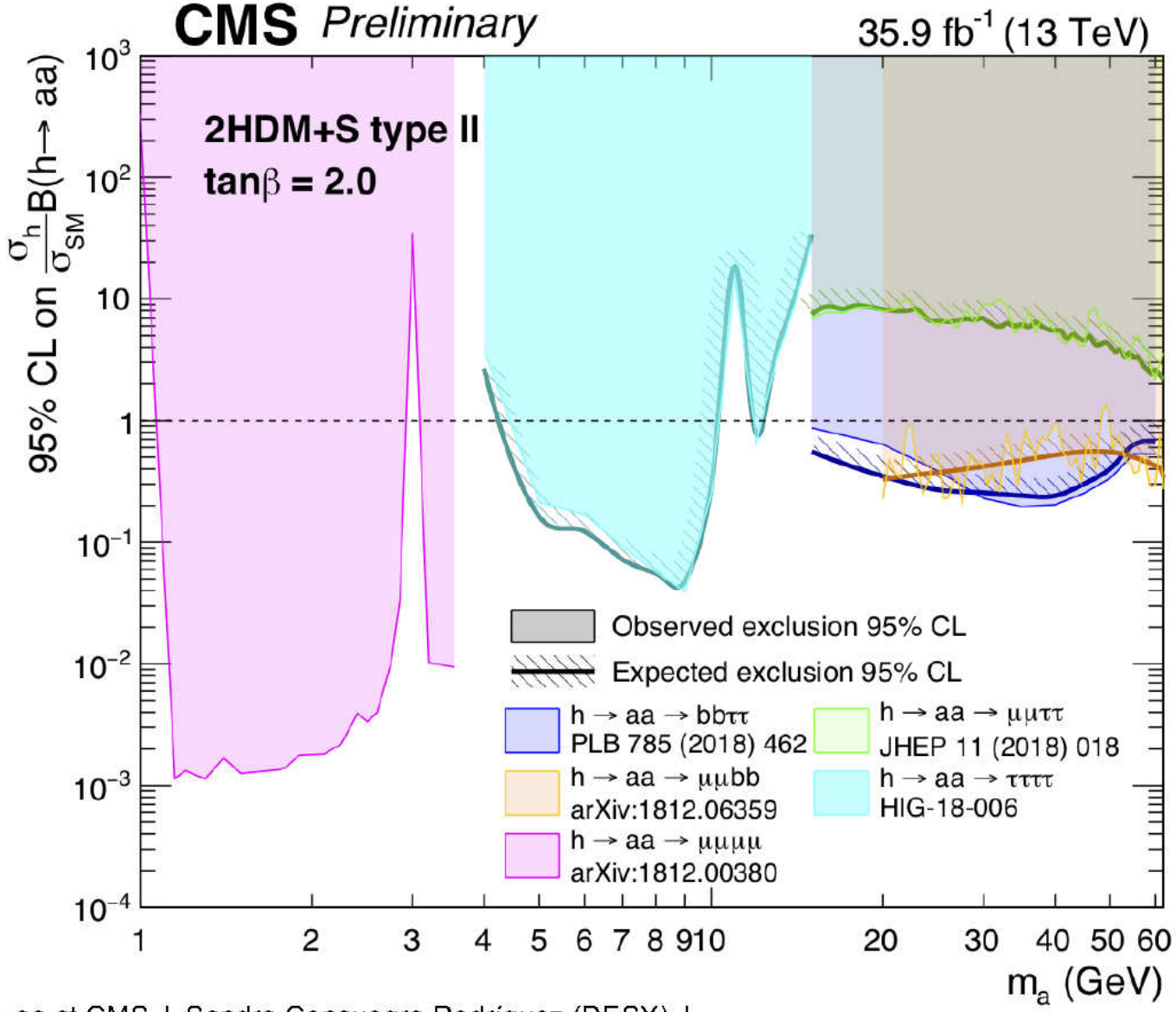
[Phys.Lett. B795 (2019)]

- **Branching fraction:**
  - For $tan\beta = 2$, $ma_1 = 30$ GeV in Type-III 2HDM+S models: $2 \cdot B(a_1 \to bb) \cdot B(a_1 \to \mu^+\mu^-) = 1.7{\times}10^{-3}$
- **Event selection:** at least 2 b jets and 2 opposite sign muons
- **m_{a_1} region probed:** 20 GeV $< m_{a_1} <$ 62.5 GeV
- **Background:** Modeled with a set of analytical functions, using the discrete profiling method
- **Final discriminant:** unbinned maximum-likelihood fit to the $m_{\mu\mu}$ invariant mass distribution





Summary of $h(125) \rightarrow aa$ searches at 13 TeV at CMS:



Higgs Exotic Decays to light pseudoscalars at the HL-LHC

[CMS-PAS-FTR-18-035]

> CMS detector will be substantially upgraded

> **2 scenarios for treatment of systematic uncertainties at the HL-LHC:**

> "Run 2 systematic uncertainties" scenario:

- All experimental and theoretical systematic uncertainties:

  -unchanged with respect to Run 2 analyses reference

  -kept constant with integrated luminosity

- allows for comparisons with current analyses

> "YR18 systematics uncertainties" scenario:

- Theoretical uncertainties reduced by a factor of two with respect to Run 2 analyses reference

- Experimental systematic uncertainties scale with square root of integrated luminosity until reaching a defined lower limit

- more realistic given the expected conditions for the HL-LHC

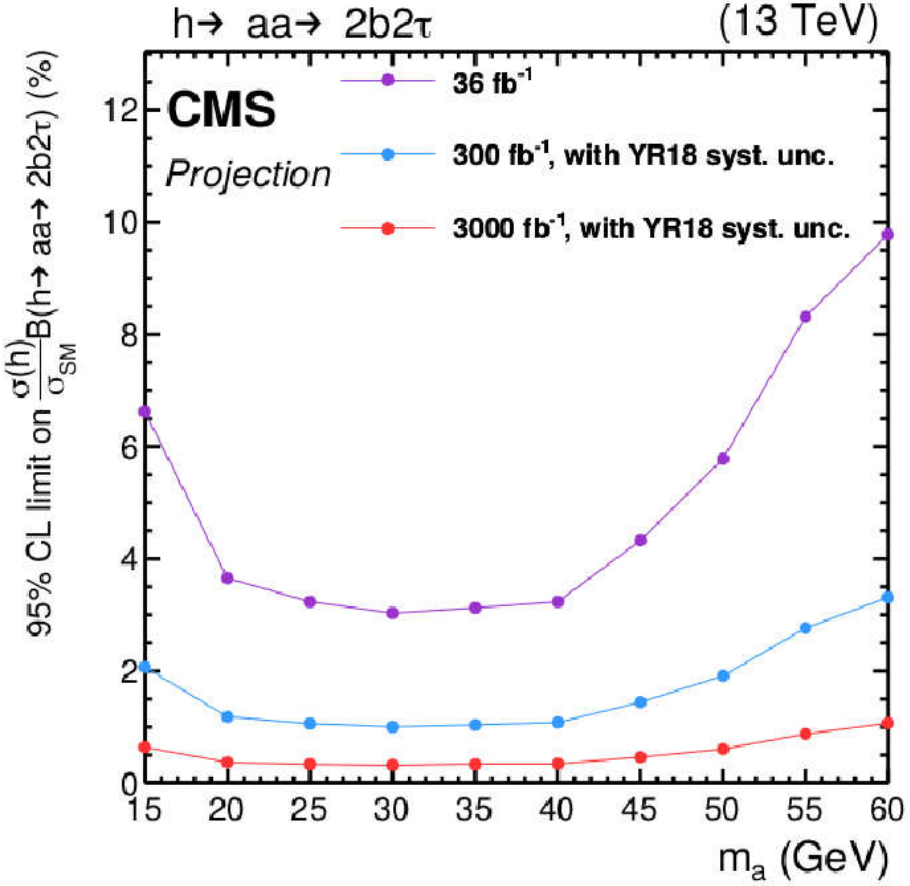
- All uncertainties related to limited number of simulated events neglected

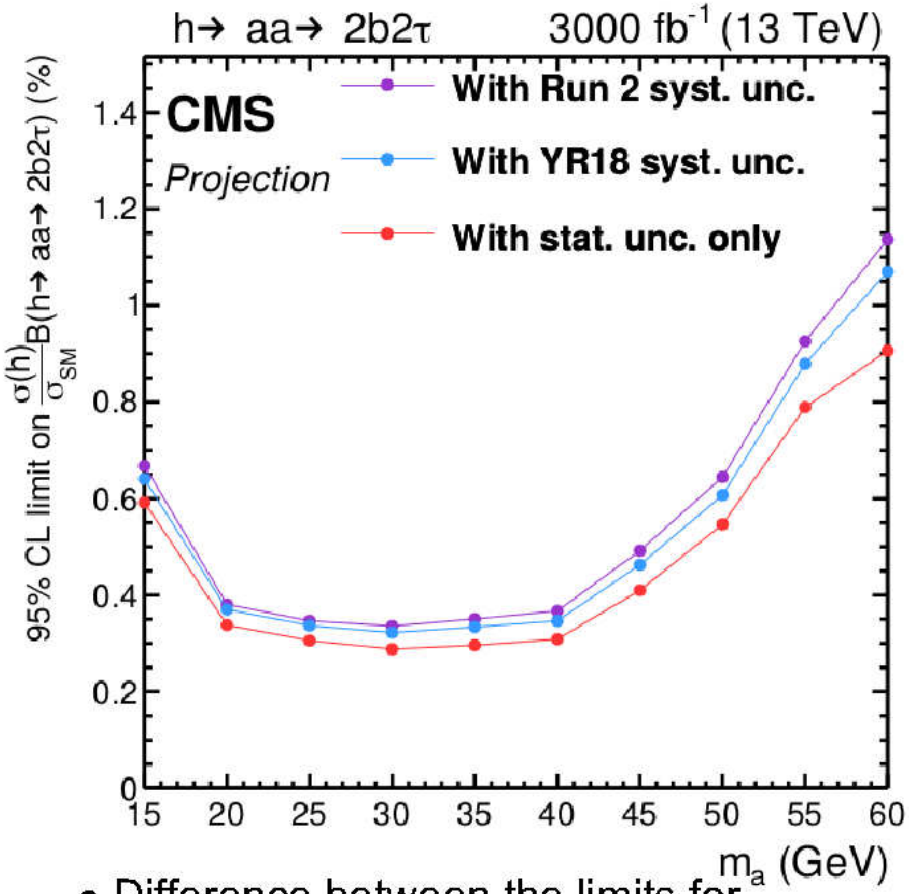
- Intrinsic statistical uncertainty in the measurement reduced by a factor $\frac{1}{\sqrt[2]{R_L}}$

(R_L: projection of integrated luminosity divided by that of reference Run 2 analysis)

Projections of $h \to a_1 a_1 \to 2b2\tau$ for the HL-LHC

[CMS-PAS-FTR-18-035]



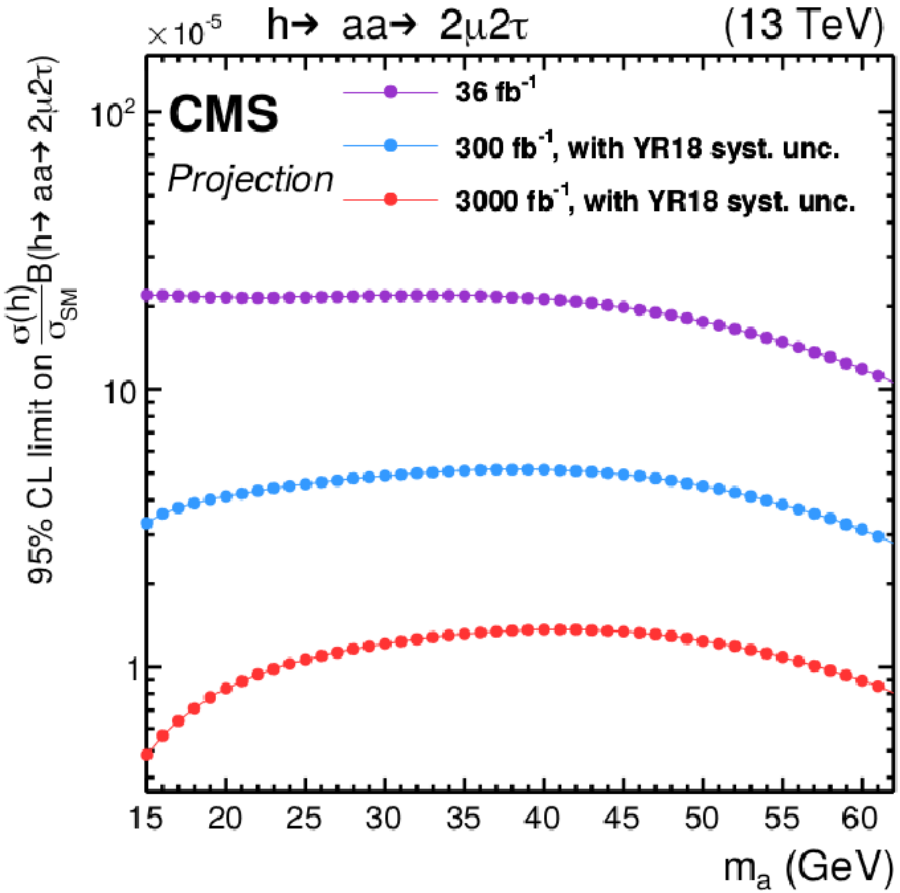


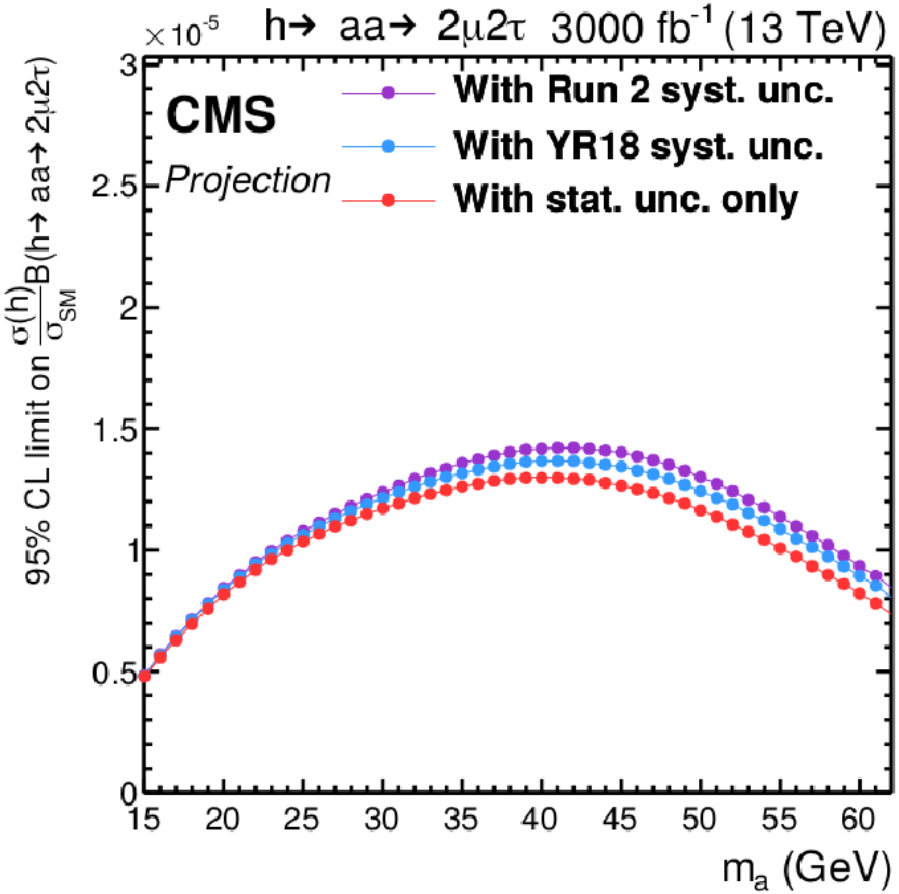
- Limits improve proportionally to square root of integrated luminosity

- Difference between the limits for systematic uncertainties Run 2 and YR18 scenarios, of the order of 5%
- Limits become another 5% better if all systematic uncertainties are neglected

Projections of $h \to a_1 a_1 \to 2\mu 2\tau$ for the HL-LHC

[CMS-PAS-FTR-18-035]





- low m_{a_1}: Limits scale inverse-proportionally to the luminosity
- high m_{a_1}: Limits improve proportionally to square root of integrated luminosity

- Difference between the limits for systematic uncertainties Run 2 and YR18 scenarios up to 5%, and largest at high m_{a_1}

Conclusion:

- Exotic decays of the Higgs boson to a pair of light pseudoscalars represent an interesting opportunity to discover new physics
- **Large number of $h(125) \rightarrow aa$ searches, exploiting exciting physics potential of the LHC, have been done**
- No significant excess observed
- Searches interpreted in the context of 2HDM+S models
- Projections of recent searches for integrated luminosities of up to 3000 fb^{-1}, achievable at the High-Luminosity LHC, show foreseen improvement on sensitivity

New results with full Run II dataset also on the way and exciting perspectives for HL-LHC

Thank you!

Contact

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Backup

> Additional material

HL-LHC projections:

[CMS-PAS-FTR-18-035]

> Sources of systematic uncertainties for which limiting values are applied in the "YR18 systematic uncertainties" scenario

Source	Component	Run 2 unc.	Projection minimum unc.
Muon ID		1–2%	0.5%
Electron ID		1–2%	0.5%
Photon ID		0.5–2%	0.25–1%
Hadronic τ ID		6%	Same as Run 2
Jet energy scale	Absolute	0.5%	0.1–0.2%
	Relative	0.1–3%	0.1–0.5%
	Pileup	0–2%	Same as Run 2
	Method and sample	0.5–5%	No limit
	Jet flavour	1.5%	0.75%
	Time stability	0.2%	No limit
Jet energy resolution		Varies with p_T and η	Half of Run 2
$\vec{p}_T^{\,miss}$ scale		Varies with analysis selection	Half of Run 2
b-tagging	b-/c-jets (syst.)	Varies with p_T and η	Same as Run 2
	light mis-tag (syst.)	Varies with p_T and η	Same as Run 2
	b-/c-jets (stat.)	Varies with p_T and η	No limit
	light mis-tag (stat.)	Varies with p_T and η	No limit
Integrated luminosity		2.5%	1%
Reducible bkg. ($h \to aa \to 2\mu 2\tau$)		20–40%	4–8%

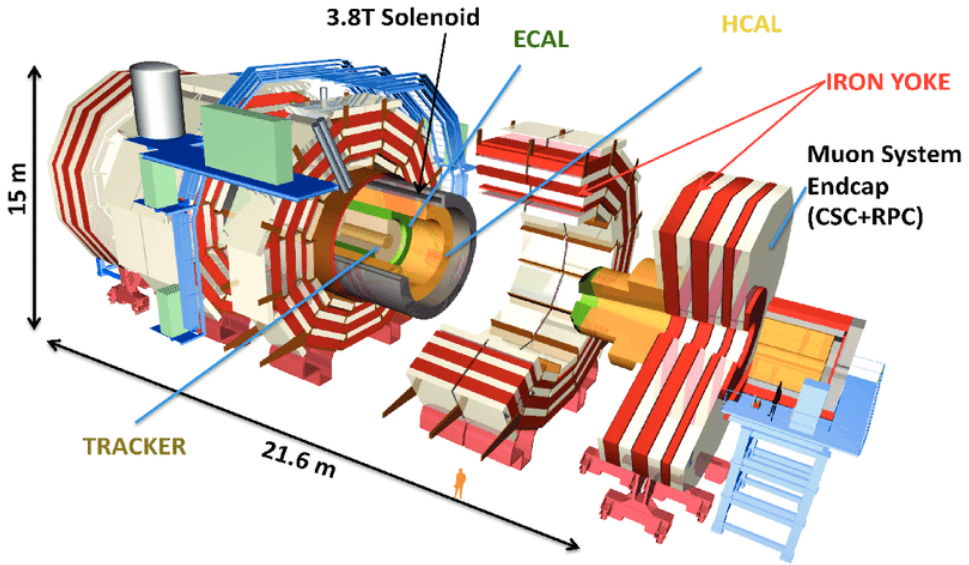
CMS HL-LHC Upgrades

- CMS detector will be substantially upgraded → fully exploit physics potential offered by increase in luminosity at HL-LHC

- Trigger/HLT/DAQ
  - Increase of L1 rate
  - Reduce HLT rate

- Muon system
  - Upgrade of cathode strip chambers (CSC), resistive plate chambers (RPC) and drift tubes (DT) electronics
  - Extend geometrical coverage up to $|\eta| = 2.8$ with improved RPC and gas electron multiplier (GEM) technologies

- high PU mitigation with addition of a new timing detector for minimum ionizing particles (MTD) → capability for 4-dimensional reconstruction of interaction vertices



CMS HL-LHC Upgrades

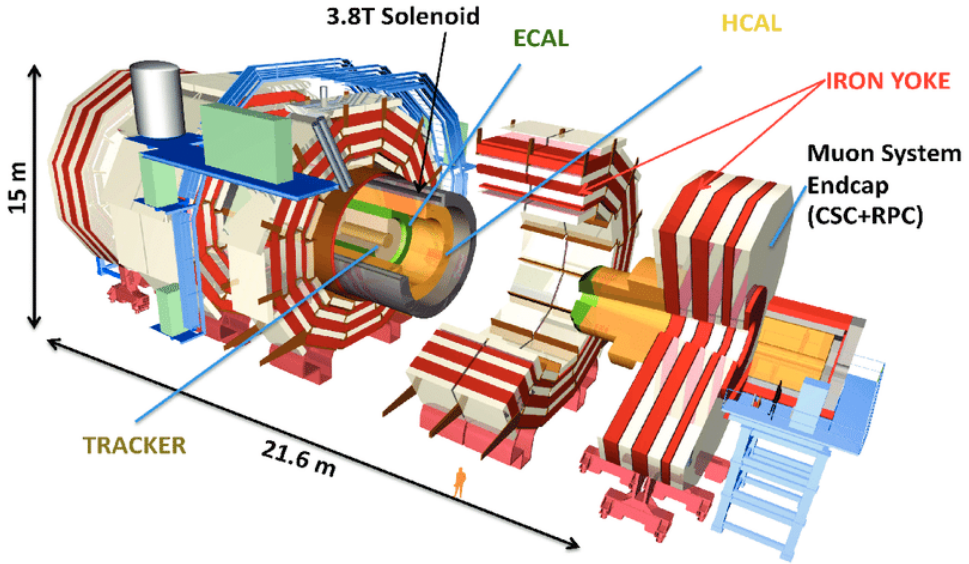
> Tracker

Entire pixel and strip tracker detector replaced to:

- Reduce material budget in the tracking volume
- Improve radiation hardness
- Extend geometrical coverage → efficient tracking up to $|\eta| = 4$

> Endcap calorimeters:

- Upgrade of front-end electronics → exploit information from single crystals at L1 trigger level
- 160 MHz sampling → high precision timing capability for photons
- New combined sampling calorimeter (HGCal) → highly-segmented spatial information and high-precision timing information



Motivation:

- Categorizing 2HDM+S Models:

Model	2HDM I	2HDM II	2HDM III	2HDM IV
u	Φ_2	Φ_2	Φ_2	Φ_2
d	Φ_2	Φ_1	Φ_2	Φ_1
e	Φ_2	Φ_1	Φ_1	Φ_2

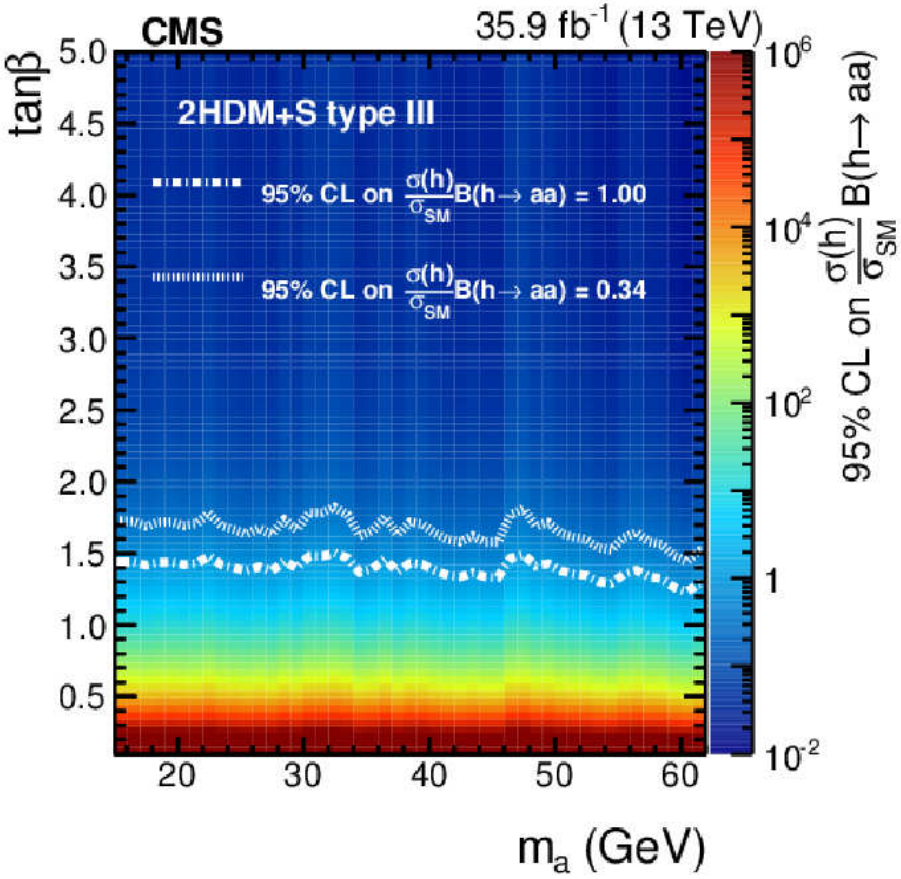
[Phys.Rev. D90 (2014) no.7, 075004]

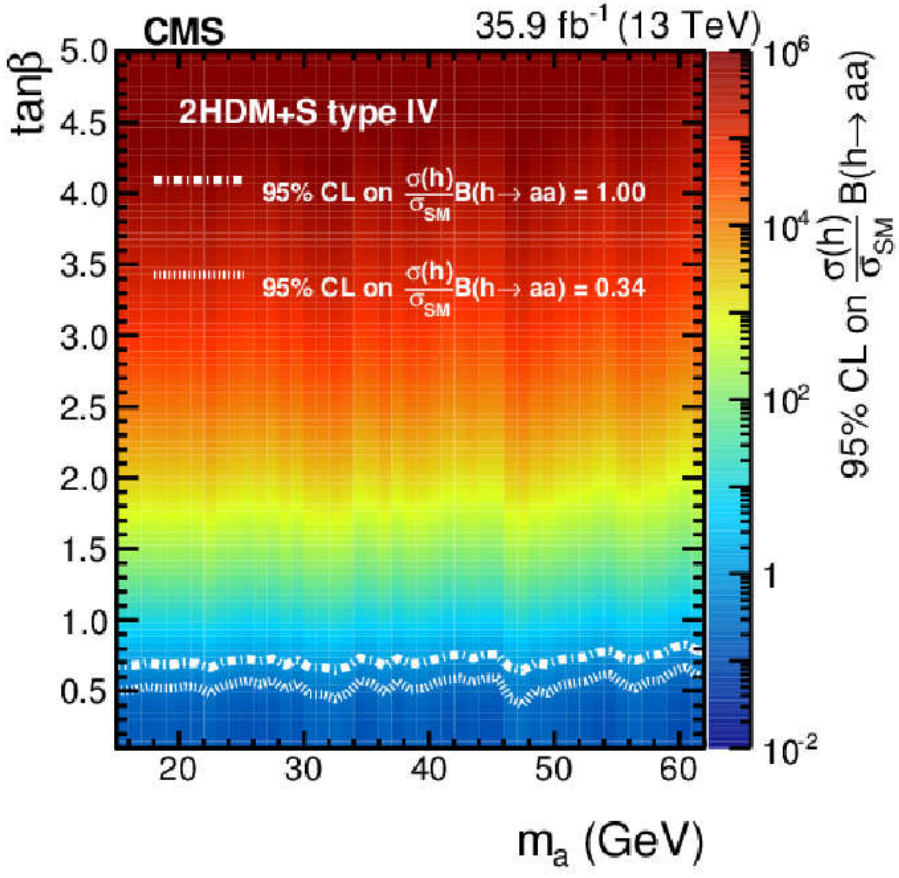
- Branching ratios only independent of tanβ for Type-I

Observed limits on $B(h \to a_1 a_1)$ in the plane of $(m_{a_1}, tan\beta)$ for 2HDM+S models

$h \to a_1 a_1 \to 2\mu 2\tau$

[JHEP 1811 (2018) 018]

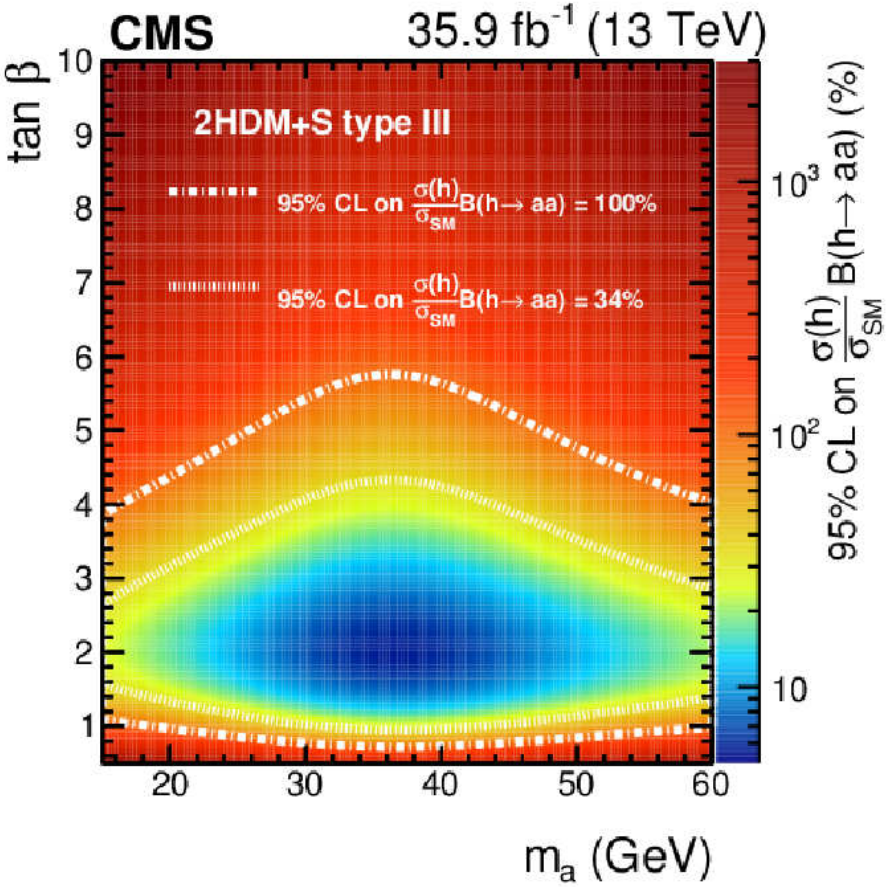


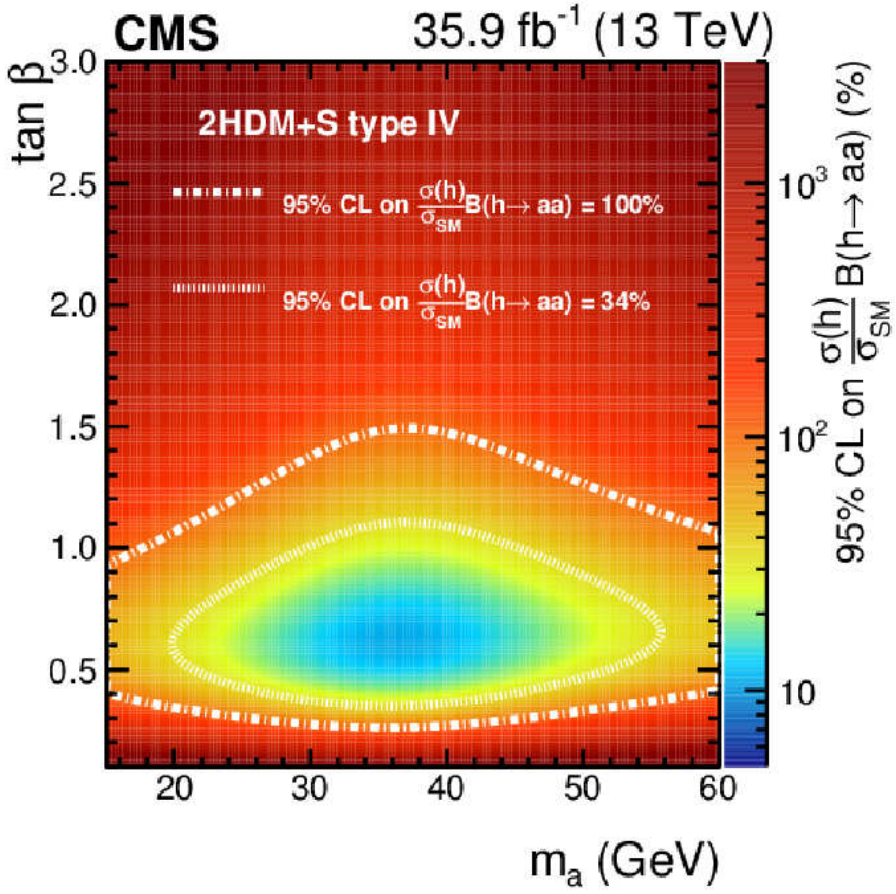


Observed limits on $B(h \to a_1 a_1)$ in the plane of $(m_{a_1}, tan\beta)$ for 2HDM+S models

$h \to a_1 a_1 \to 2b2\tau$

[Phys.Lett. B785 (2018) 462]





Observed limits on $B(h \to a_1 a_1)$ in the plane of $(m_{a_1}, tan\beta)$ for 2HDM+S models

$h \to a_1 a_1 \to 2\mu 2b$

[Phys.Lett. B795 (2019)]