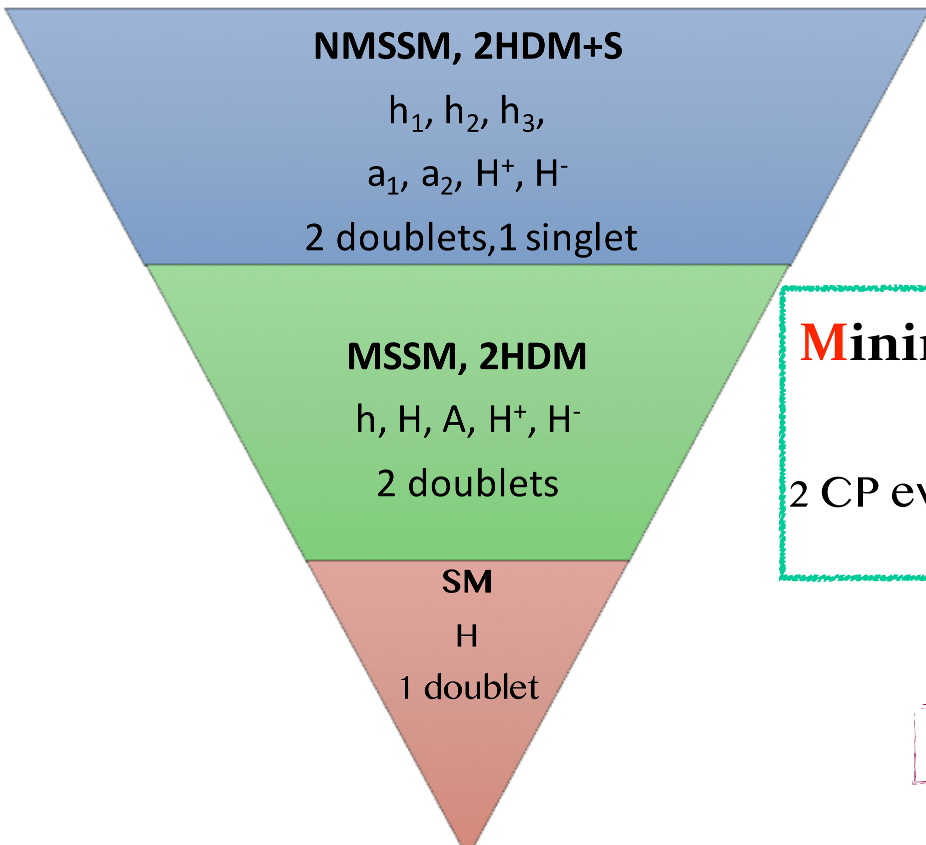
Search for light Higgs bosons with the CMS experiment

Alexis Kalogeropoulos
Princeton University

8-12 April 2019
DIS 2019 - Turin

Extended Higgs sector

- Simplest extensions of the SM : SM +S, 2HDM +s, composite etc
- 2HDM/MSSM : 5 physical Higgs bosons
- NMSSM : 7 physical Higgs bosons
- Composite : h + excited states



Next-to-MSSM

3 CP even h_1, h_2, h_3

2 CP odd a_1, a_2

2 CP charged H^+, H^-

Minimal Supersymmetric Standard Model, 2 Higgs Doublet Model...

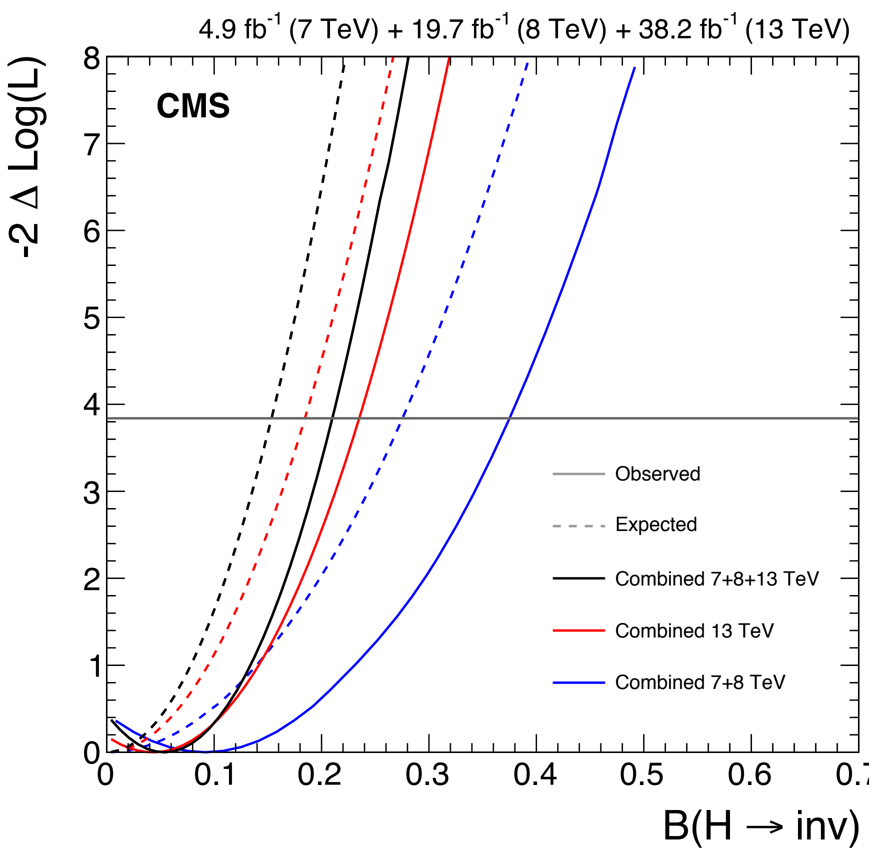
2 CP even (h^0, H^0),1 CP odd (A^0), 2 CP charged $(H^+,H)^-$

Standard Model 1 CP even H

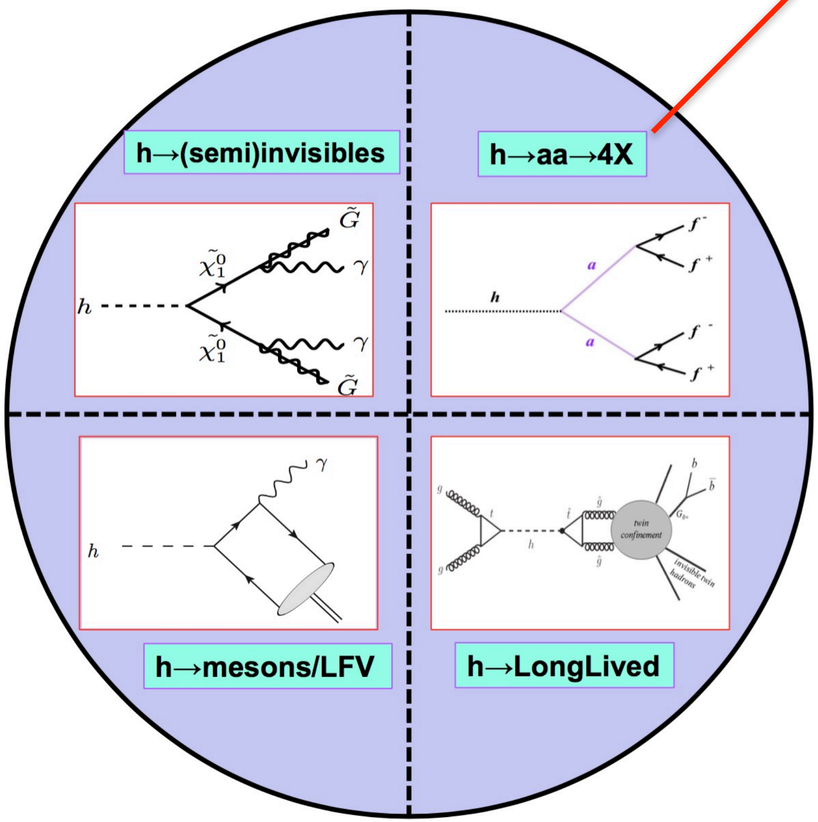
Exotic Higgs decays - *is it even possible ?*

if new physics is allowed to modify the loop-induced couplings

HIG-17-023



this talk



$\mathcal{BR}$ (h → BSM) < 20% @ 95% CL

Exotic Higgs decays - *is it even possible ?*

Exotic Higgs decays assuming $\mathcal{BR}$ (h → BSM) = 10%

arxiV:1312.4992

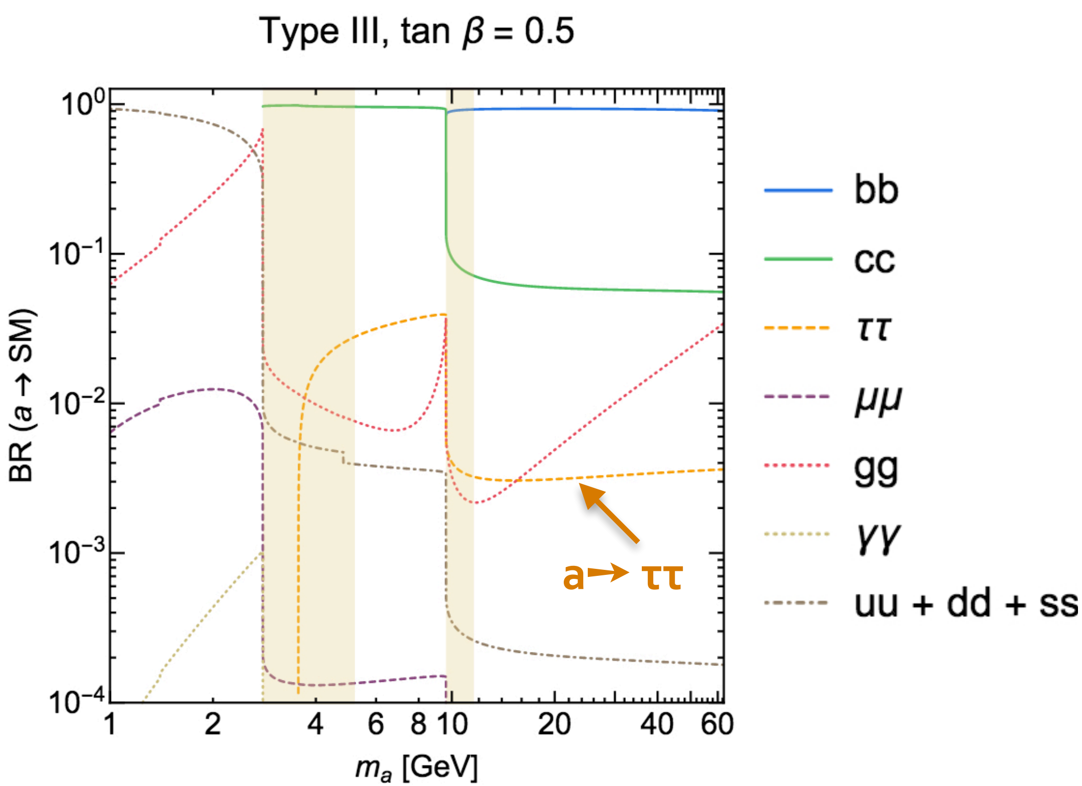
Production	$\sigma_{7\text{ TeV}}$ (pb)	$N_{ev}^{10\%}$, 5 fb^{-1}	$\sigma_{8\text{ TeV}}$ (pb)	$N_{ev}^{10\%}$, 20 fb^{-1}	$\sigma_{14\text{ TeV}}$ (pb)	$N_{ev}^{10\%}$, 300 fb^{-1}
ggF	15.13	7,600	19.27	38,500	49.85	1.5×10^6
VBF	1.22	610	1.58	3,200	4.18	125,000
$hW^\pm$	0.58	290	0.70	1,400	1.5	45,000
$hW^\pm(\ell^\pm\nu)$	$0.58 \cdot 0.21$	62	$0.70 \cdot 0.21$	300	$1.5 \cdot 0.21$	9,600
hZ	0.34	170	0.42	830	0.88	26,500
$hZ(\ell^+\ell^-)$	$0.34 \cdot 0.067$	11	$0.42 \cdot 0.067$	56	$0.88 \cdot 0.067$	1,800
$t\bar{t}h$	0.086	43	0.13	260	0.61	18,300

Still plenty of room for Exotic Higgs!

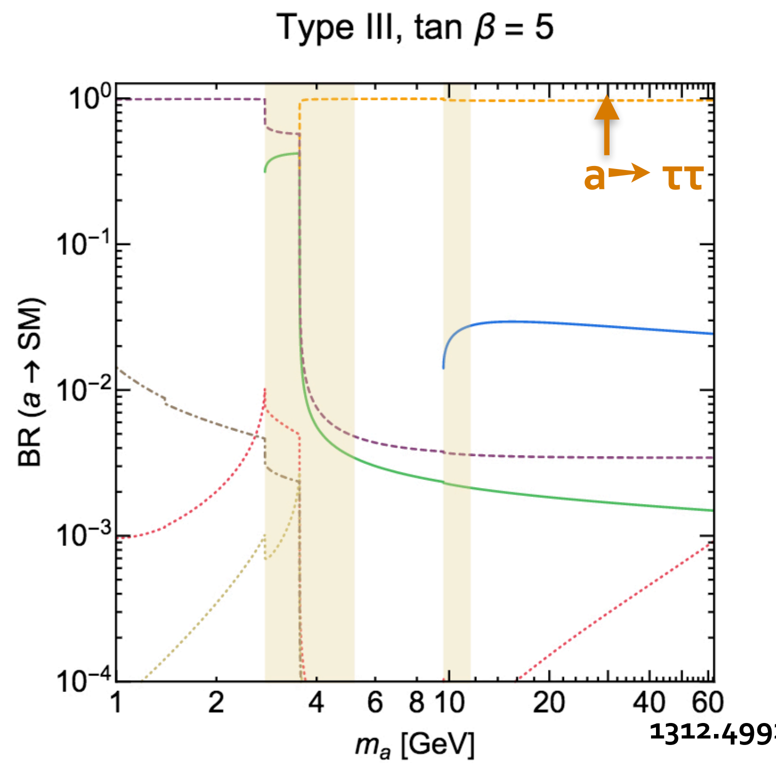
Channel Sensitivity

Sensitivity depends on the channel, model and model parameters

In type-III 2HDM and for tanβ > 1, a_1 boson **decays to leptons are enhanced**, thus a → 2μ2τ becomes more sensitive than a_1 → 2μ2b



$$\mathcal{BR}(a_1 \to \tau\tau) \approx 0.5\%$$
$$\mathcal{BR}(a_1 \to \mu\mu) < 0.01\%$$
$$\mathcal{BR}(a_1 a_1 \to \mu\mu\tau\tau) < 10^{-6}$$
$$\frac{\mathcal{BR}(a_1 a_1 \to \mu\mu\tau\tau)}{\mathcal{BR}(a_1 a_1 \to \mu\mu bb)} \approx 0.005$$



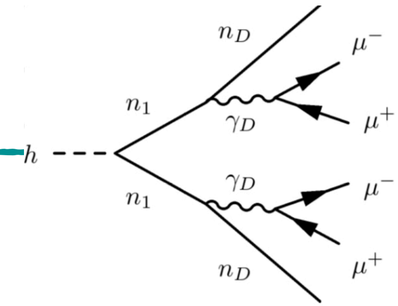
1312.4992

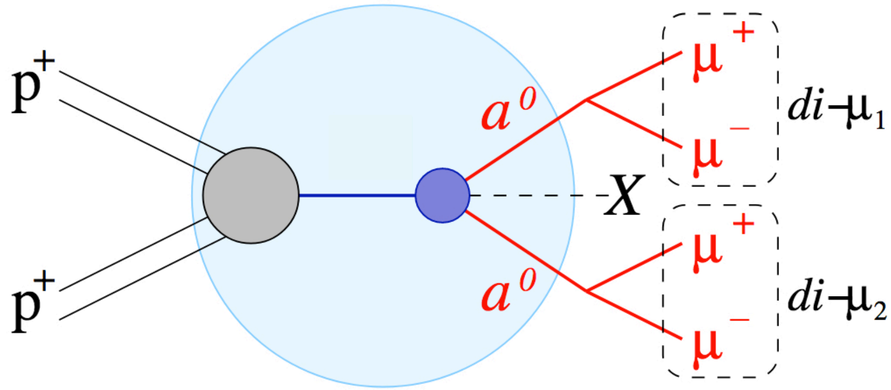
$$\mathcal{BR}(a_1 \to \tau\tau) \approx 97\%$$
$$\mathcal{BR}(a_1 \to \mu\mu) < 0.3\%$$
$$\mathcal{BR}(a_1 a_1 \to \mu\mu\tau\tau) < 10^{-2}$$
$$\frac{\mathcal{BR}(a_1 a_1 \to \mu\mu\tau\tau)}{\mathcal{BR}(a_1 a_1 \to \mu\mu bb)} \approx 40$$

$h \to aa \to 4\mu + X$

HIG-18-003

- Motivated by NMSSM and Dark SUSY models
  - NMSSM: CP even $h_{1,2}$ can decay to a_1: $h_{1,2} \to 2a_1,\ a_1 \to 2\mu$
  - Dark SUSY: h decays to lightest visible neutralino : $h \to 2n_1,\ n_1 \to \gamma_D + n_D$
    - ➡ decays of γ_D give 4μ + X as spectator particles
- Isolated muon-pairs (from same vertex) with $m(_{\mu\mu}) < 9$ GeV





- a_1 : [0.25, 3.55] GeV , γ_D [0.25, 8.5] GeV , $m_{(n1)}$=10 GeV, $m_{(nD)}$ =1 GeV
  - Main backgrounds : $b\bar{b}$, J/ψ, EWK $\to 4\mu$

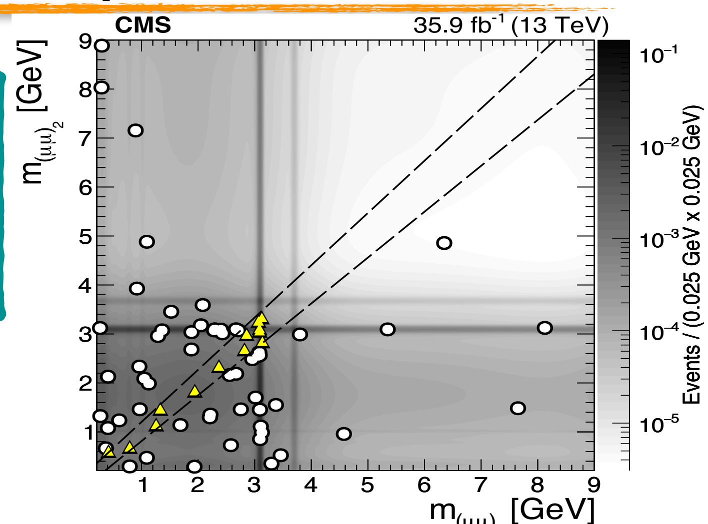
    $b\bar{b}$: estimated from data (1 di-μ pair + 1 “orphan” μ)

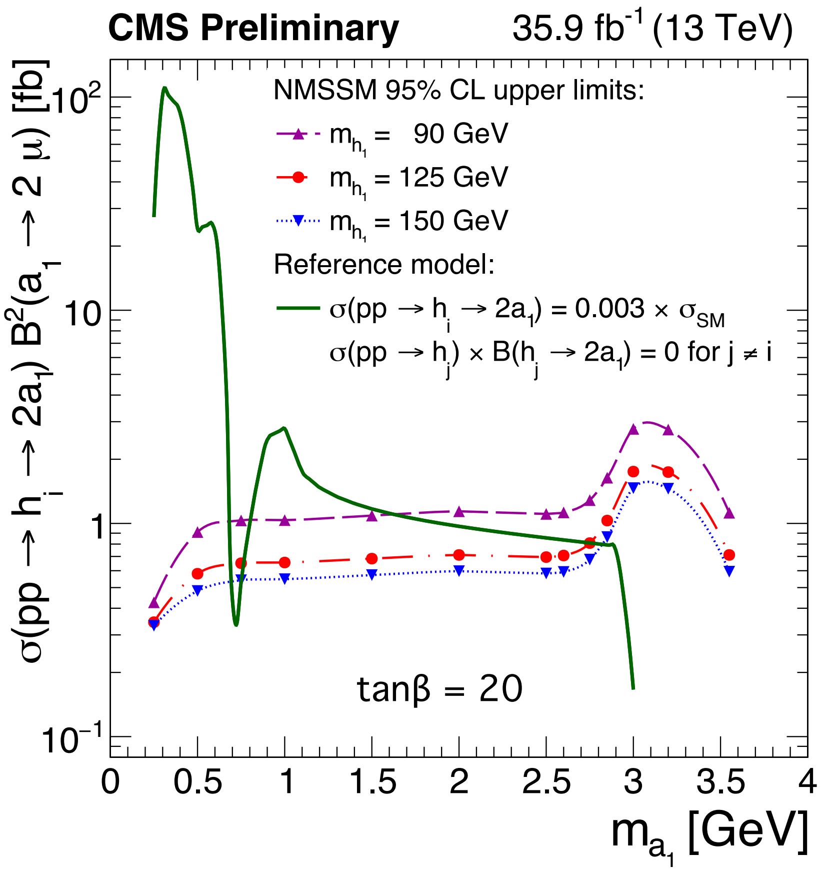
    J/ψ : mainly from SPS/DPS estimated from data and simulation

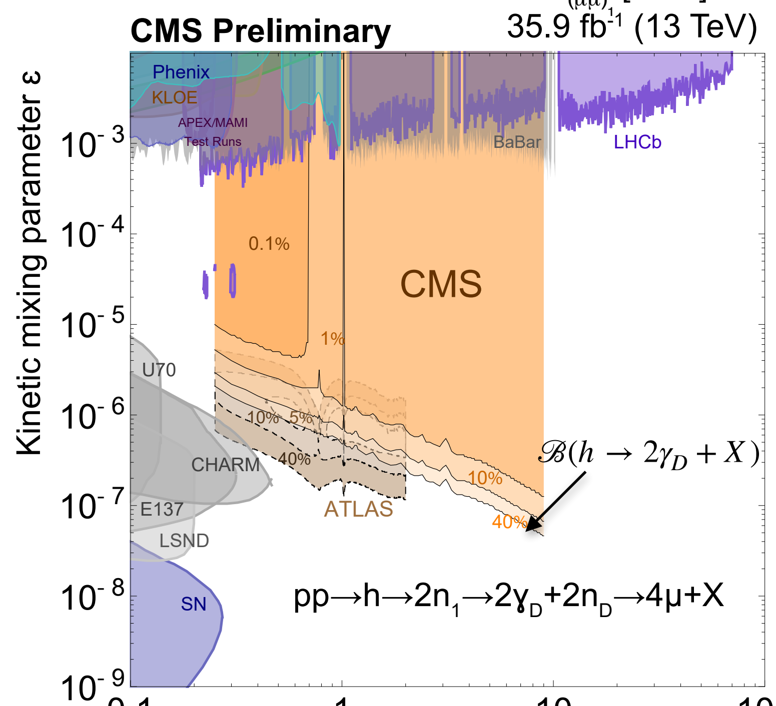
$h \to aa \to 4\mu + X$

HIG-18-003

- ❖ Signal is extracted from the 2D $m(\mu\mu)_1, m(\mu\mu)_2$
- ❖ Leading systematic comes from trigger SF (6%)
- ❖ Results for different h_1/γ_D masses







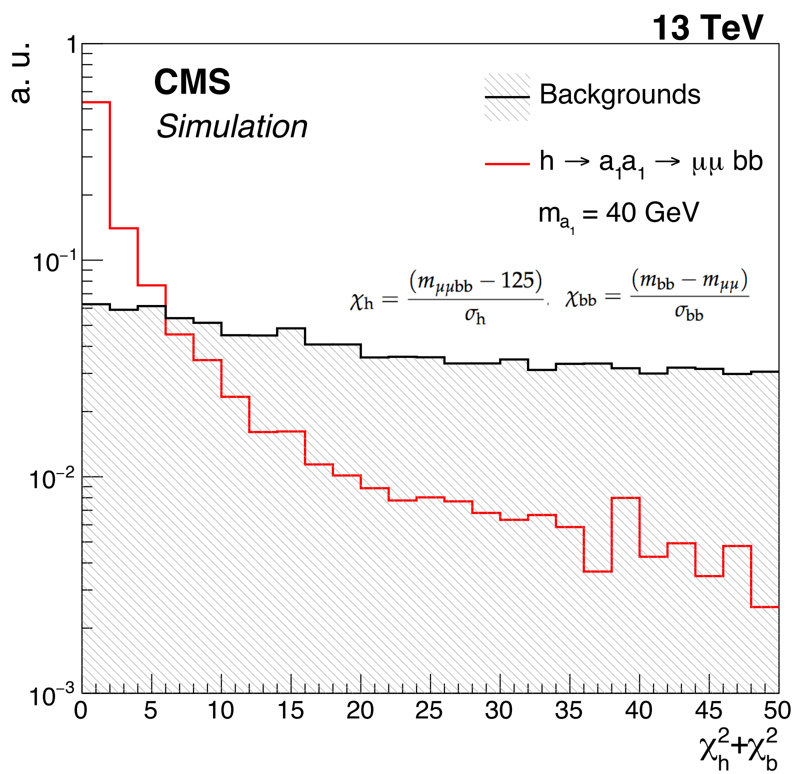
γ_D couples to SM photons via ε. The lifetime, and thus displacement, of the γD depends on $m_{\gamma D}$ and ε

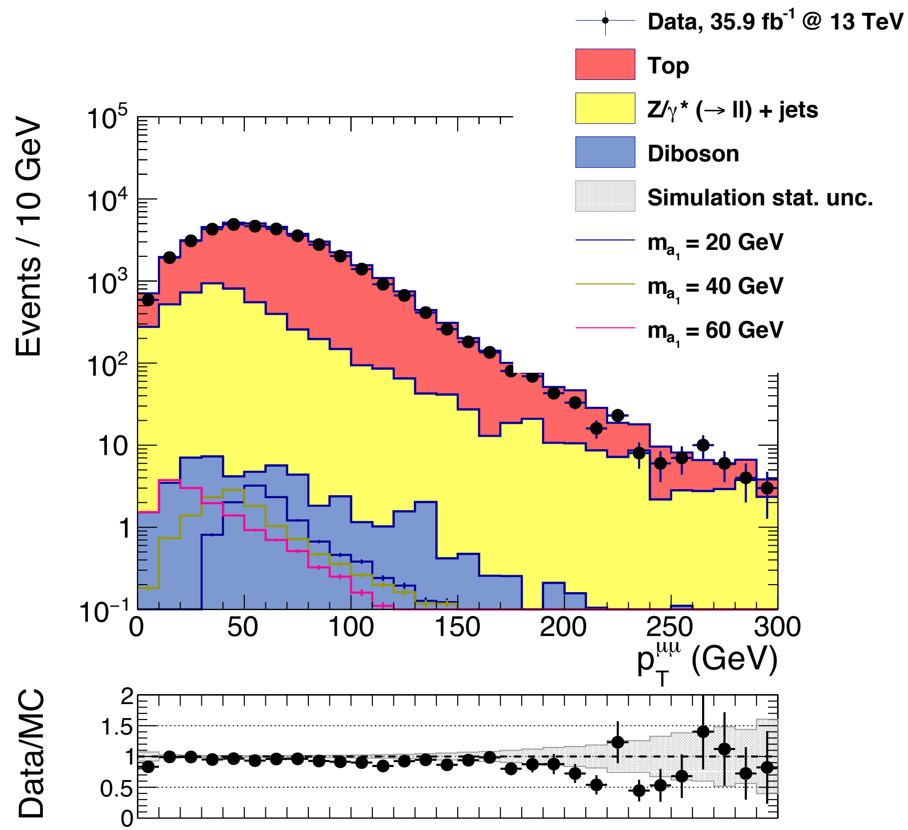
$h \to a_1 a_1 \to 2\mu 2b$

HIG-18-011

- Considering ggF and VBF production for $\mathscr{B}(h \to a_1 a_1) = 10\,\%$
- Probing m(a_1) [20, 62.5] GeV
- Requiring 2 isolated muons, 2 b-jets (Tight + Loose/Medium/Tight) and small MET
- Categorization is based on b-tag discriminators (TT, TM, TT)
- Contamination from ττbb and μμττ is negligible/very small

a χ^2 test is employed to select events

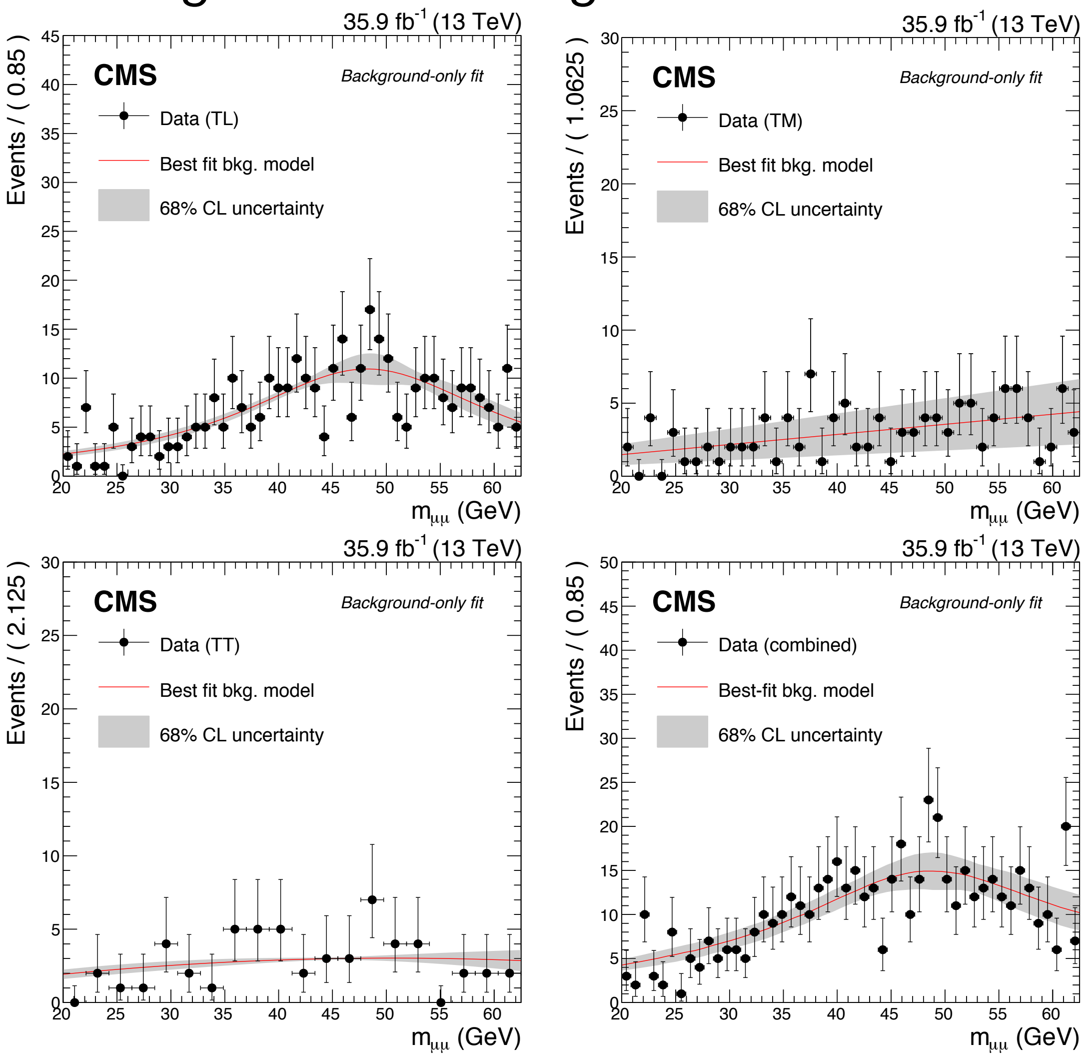




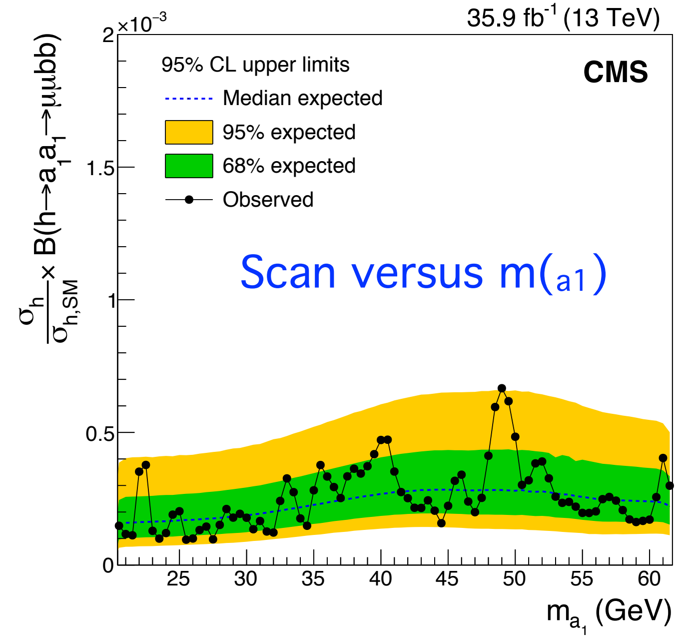
$h \rightarrow a_1 a_1 \rightarrow 2\mu 2b$

HIG-18-011

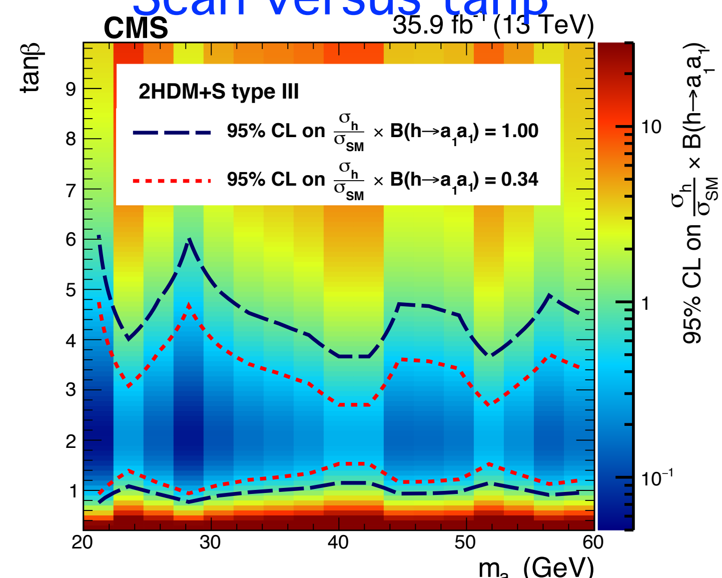
❖ Background modelling with MultiPdf



Best fit to the data for the Tight-Loose category



Scan versus tanβ



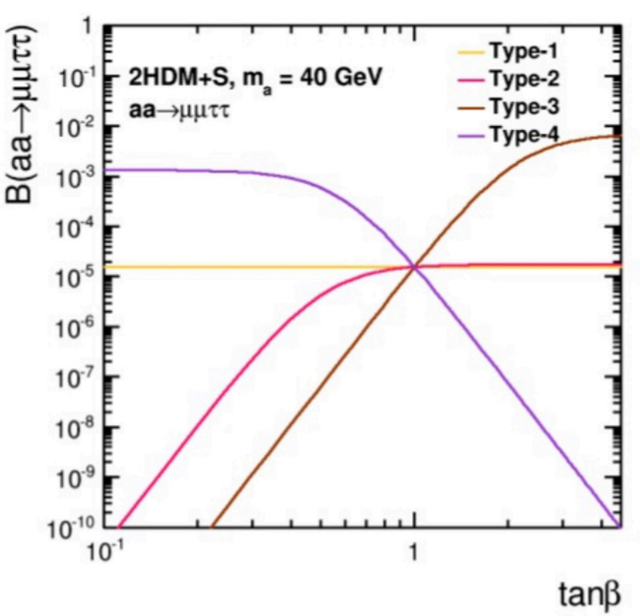
Type-III 2HDM+S when $\mu\mu\tau\tau$ is misidentified as $\mu\mu bb$

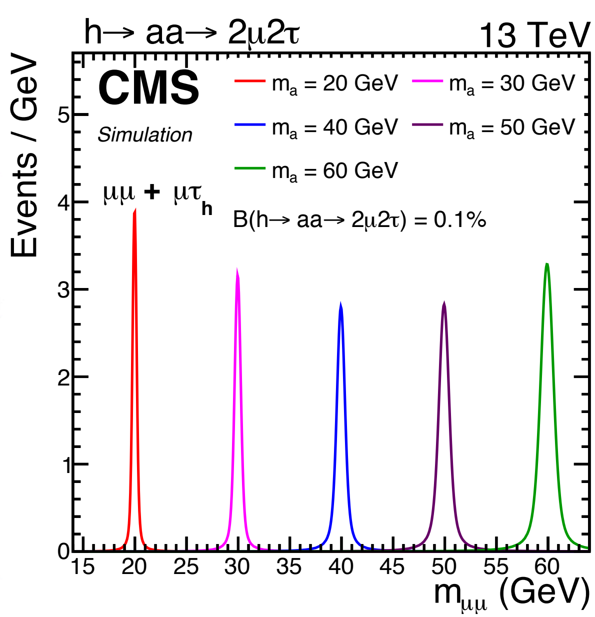
10.1007/JHEP11(2018)018

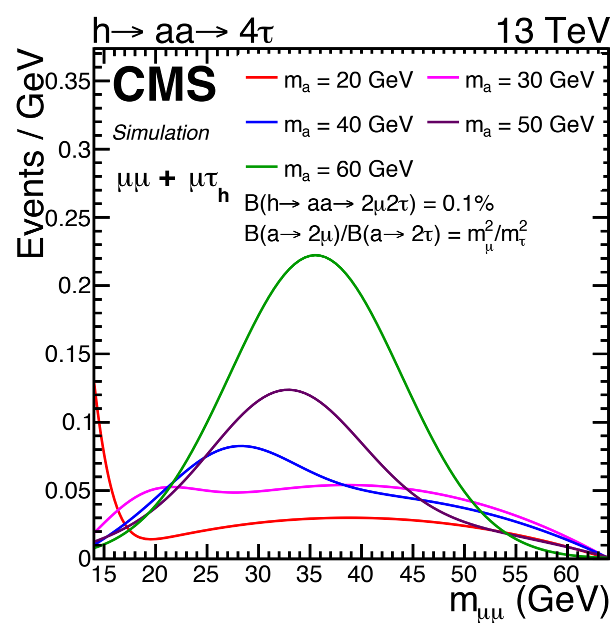
$h \to a_1 a_1 \to 2\mu 2\tau$

HIG-17-029

- Probing $m(a_1)$ [15, 62.5] GeV.
  - ➡ for $m(a_1) < 15$ GeV, no sensitivity due to the boost of the a_1
- $\mu\mu$ + ($e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$) final states, favoured in 2HDM Type III
  - ➡ muons have excellent mass resolution
  - ➡ not considering same-flavour (i.e. ee, μμ) due to high bkg rate
- Signal is extracted from di-muon mass
  - ➡ Shape is different depending on the origin of the μ







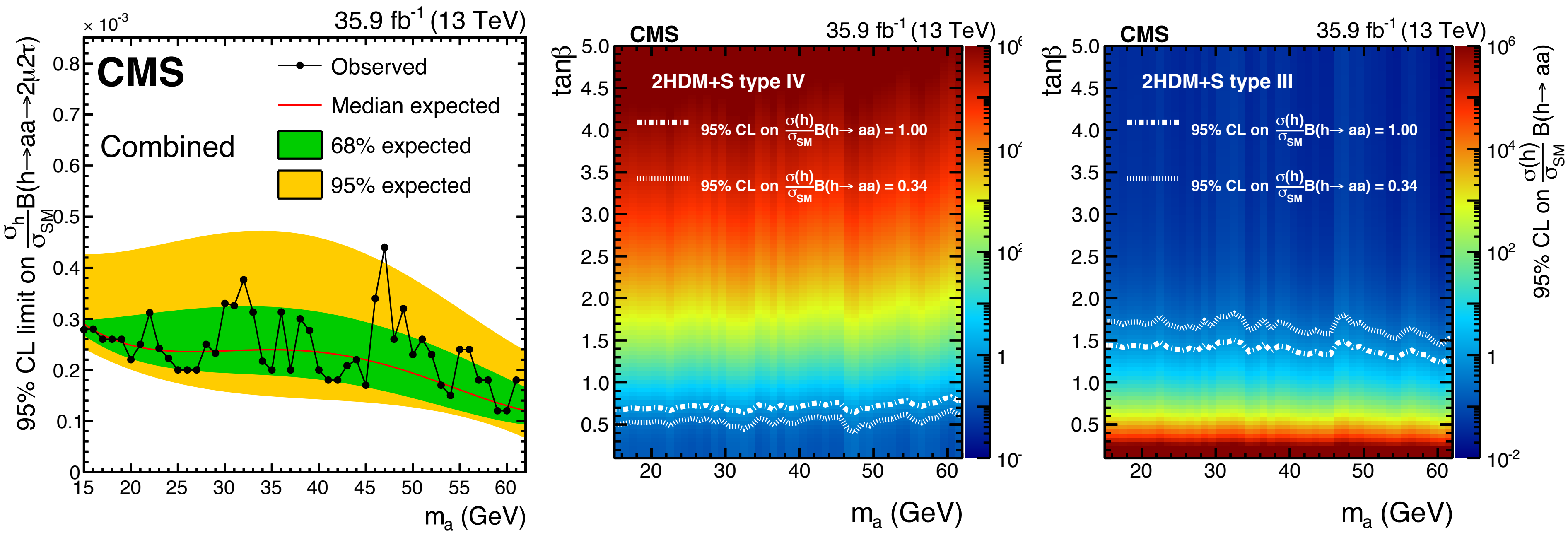
signal is parametrized with Voigt (2μ2τ) / Gaussian+polyn (4τ)

10.1007/JHEP11(2018)018

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

- Backgrounds : ZZ → 4ℓ (irreducible), fake leptons/taus (reducible)
  - ➡ reducible is decreased with b-jet veto
- Reducible comes from jets faking leptons (mostly Z+jets, WZ+jets)
  - ➡ Shape: from data , ZZ enriched w. SS w. relaxed τ_h isolation
  - ➡ Yield: from data with 1 or 2 non-isolated τ weighted with a mis-id probability

Improving previous results by a factor of two



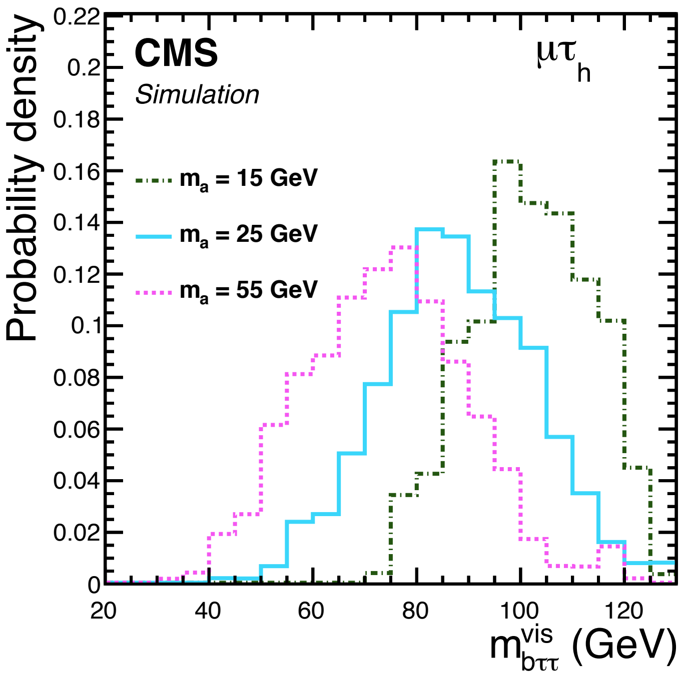
limits as low as ~2 (20)% for Type III (IV)

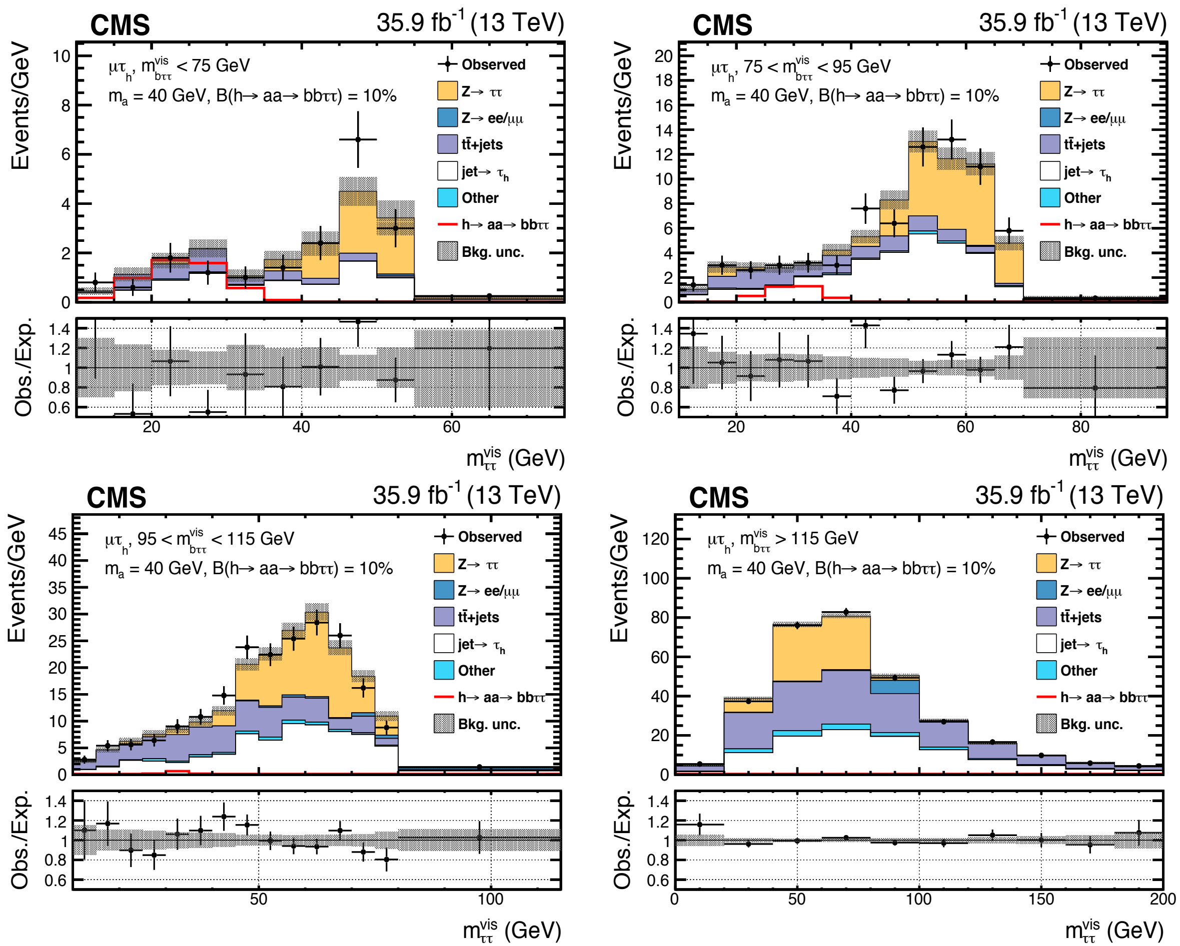
10.1016/j.physletb.2018.08.057

$h \rightarrow a_1 a_1 \rightarrow 2\tau 2b$

HIG-17-024

- Three final states: eμ, $e\tau_h$, $\mu\tau_h$ w. at least 1 b-tagged jet w. p_T > 20 GeV
- Main background is jets faking taus, and it is estimated from data
- Signal is extracted from various di-τ($m^{vis}_{\tau\tau}$) categories (12 in total)



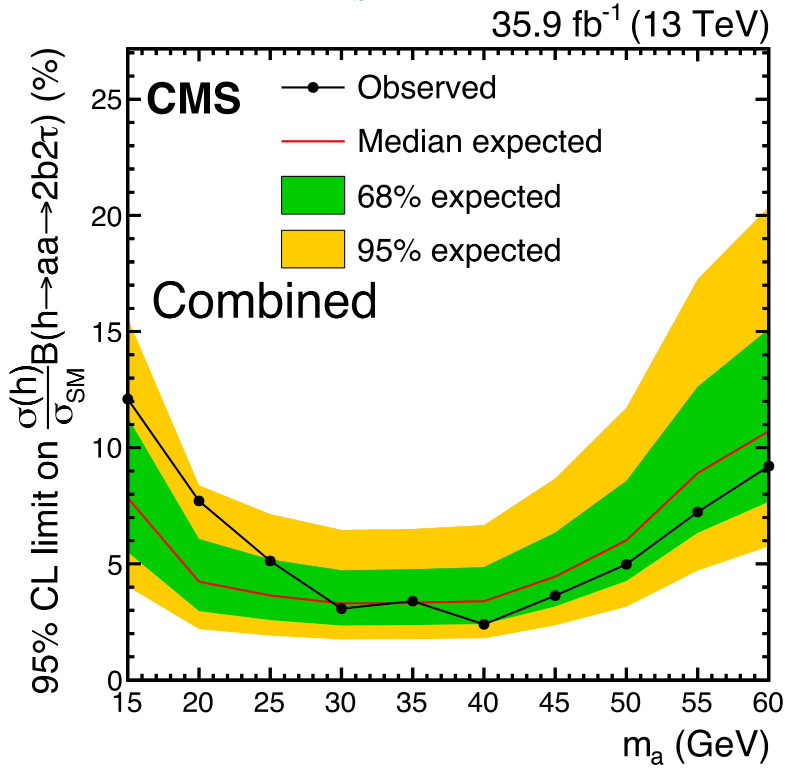


10.1016/j.physletb.2018.08.057

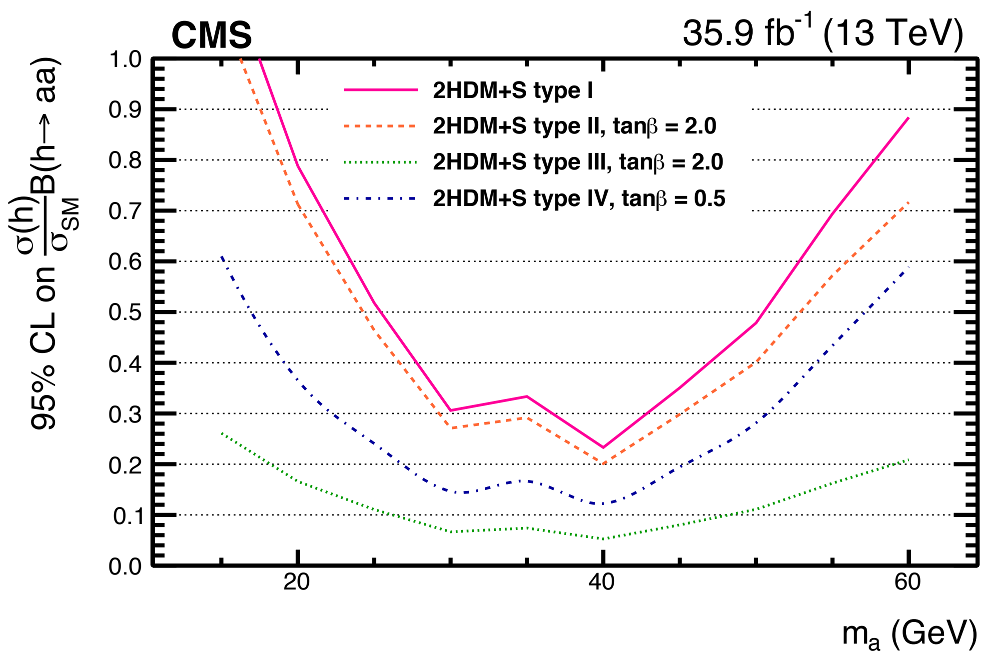
$h \to a_1 a_1 \to 2\tau 2b$

- ❖Reduced sensitivity for m_{a1} < 30 GeV due to low iso eff. of the di-τ system
- ❖Stronger limits on intermediate (low) tanβ in 2HDM+S Type III (IV)

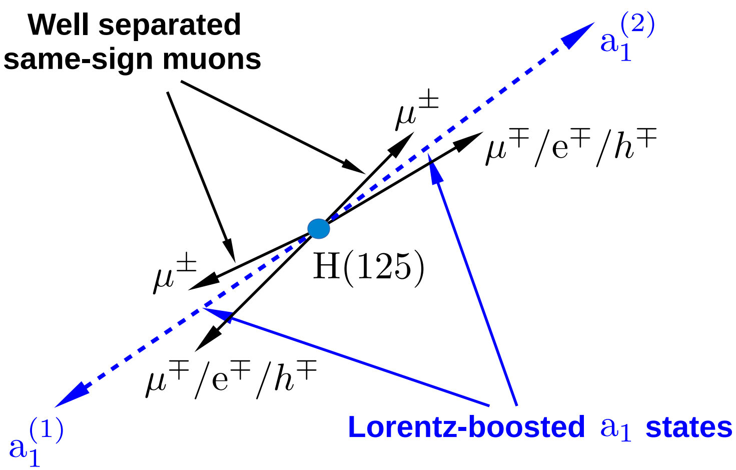
Limits on $\sigma_h/\sigma_{SM} \times BR(h \to aa \to 2\tau 2b$



Limits on $\sigma_h/\sigma_{SM} \times BR(h \to aa)$



$h \rightarrow a_1 a_1 \rightarrow 4\tau$



Given than $m_{H(125)} \gg m_{a_1}$

& H(125) is produced with small p_T

❖ a_1 bosons highly boosted and "back-to-back"

❖ τ-leptons from the same a_1 overlap

➡ thus, hard to reconstruct

➡ use simple objects i.e. μ & tracks

Same-Sign μ with ΔR>2

⇒ Suppress $t\bar{t}$, DY, Wjet

τ decays

For each a_1 decay leg :

➡ $a_1 \rightarrow \tau_{\mu} + \tau_{e/\mu/had,1\text{-}prong}$

➡ Each μ is required to have exactly 1 nearby charged track

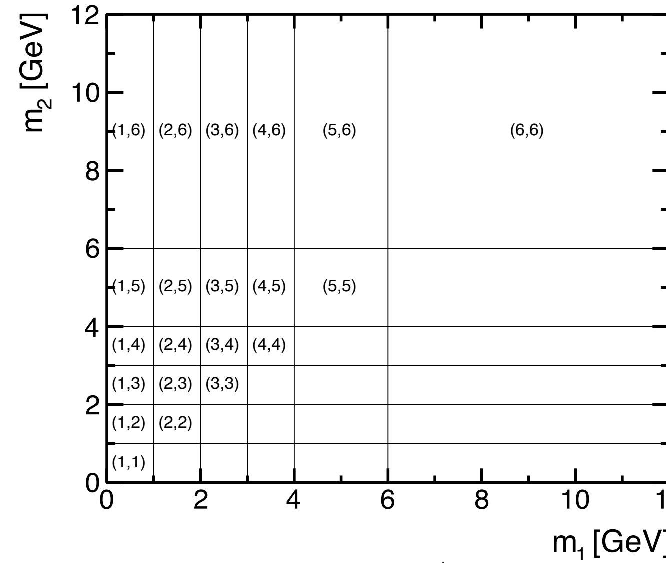
◉ form 2 (μ-trk) pair systems

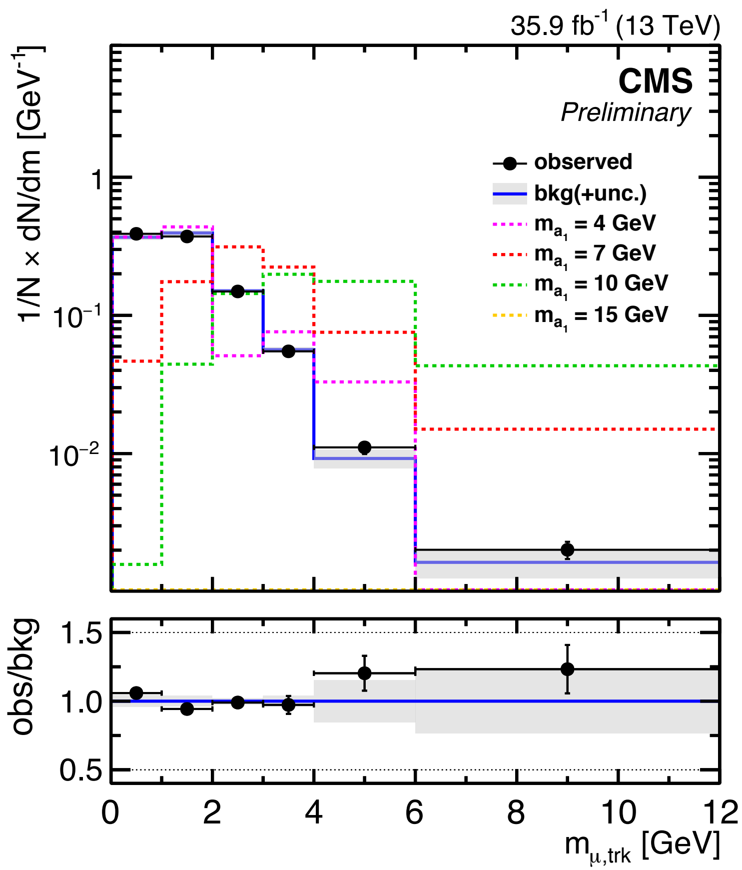
◉ each track w. pT > 2.5 GeV and OS wrt μ

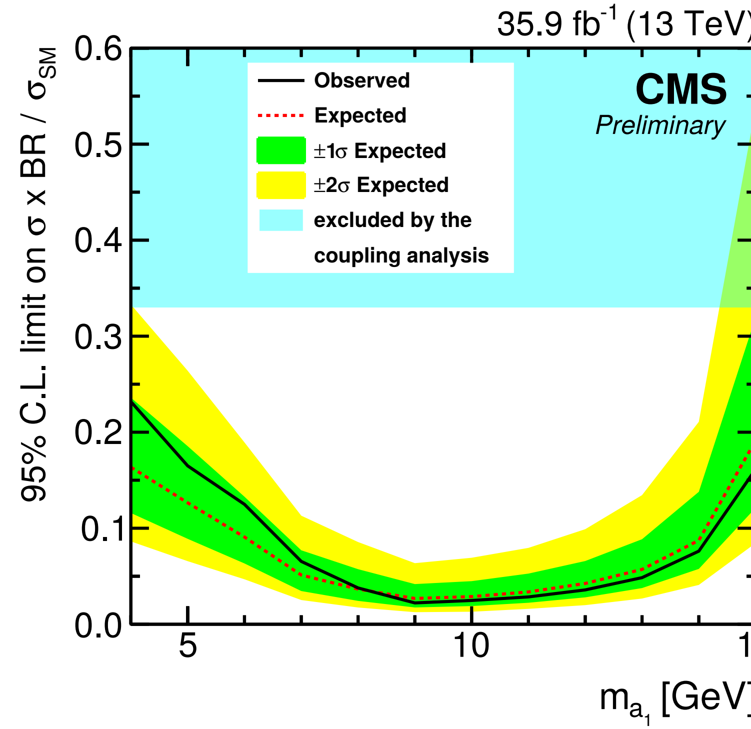
$h \rightarrow a_1 a_1 \rightarrow 4\tau$

HIG-18-006

- Probed mass range a_1 [4, 15] GeV
- Signal extracted from the 2D μ-trk system
- Background is 99% multi-jets
  - ➡ Estimated from sideband region

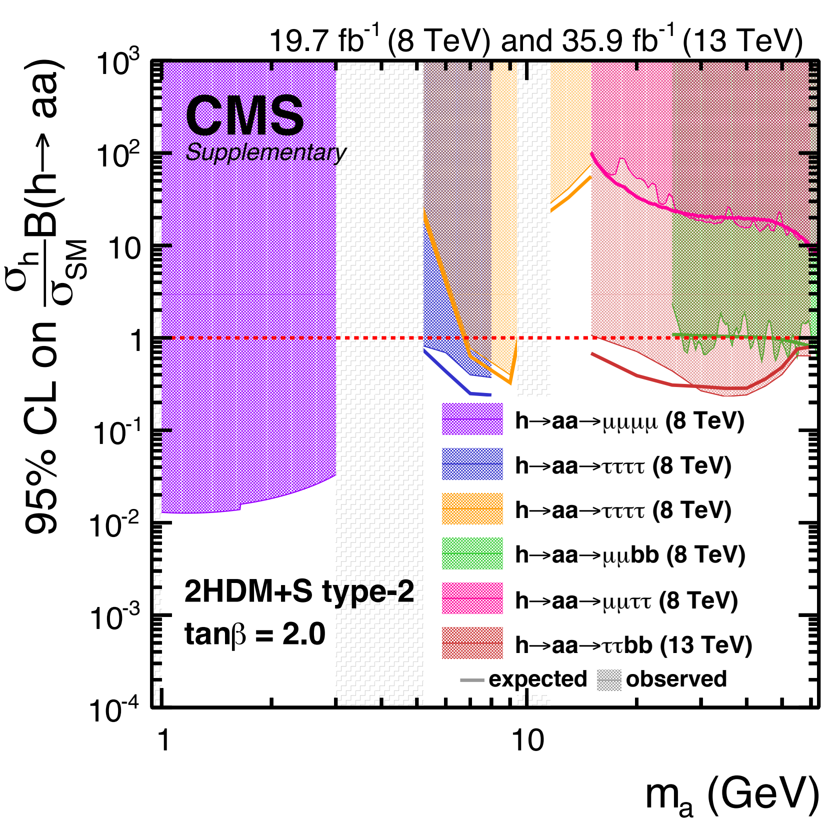


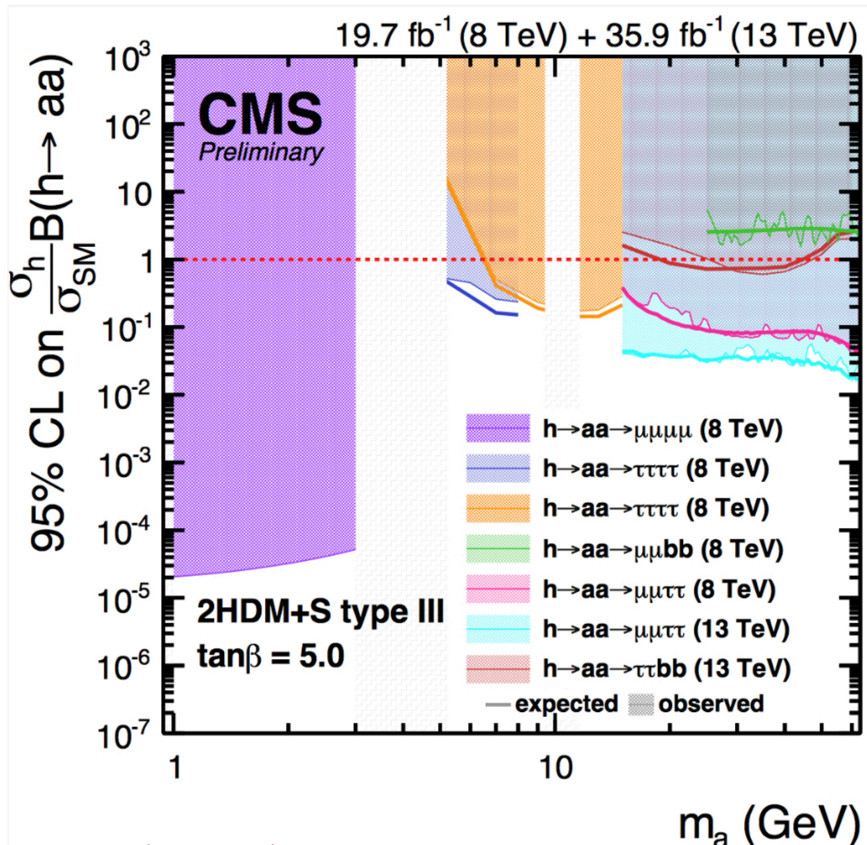




Summary

- Models employing exotic light Higgs decays are still viable
- CMS has in place a rich program covering almost full m_a range
  - $m(a_1) < 15$ GeV favours decays to $4\mu/4\tau$ ($a \rightarrow \tau\tau$, bb)
- Best limits at high masses in general i.e. in type III with large tan β (enhanced couplings to leptons)





Considerable improved results vs Run I

Backup

Exotic Higgs decays - *is it even possible ?*

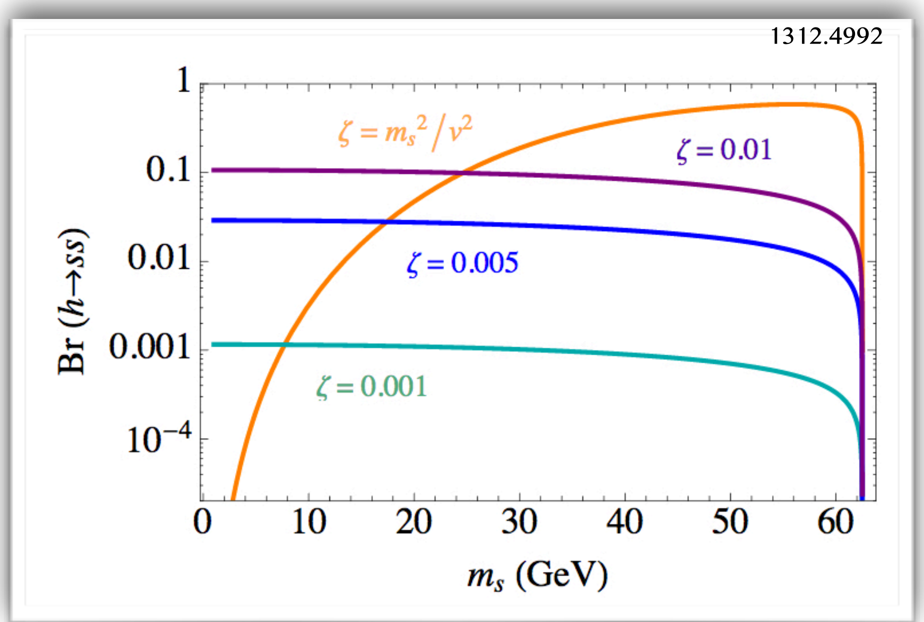
$\Gamma_{H(125)}^{(SM)} \sim 4.1$ MeV or $\Gamma_H/m_h \sim 3.3 \times 10^{-5}$

- That means that even small non-standard couplings to H→BSM can give a sizeable effect ie a non-zero $\mathcal{BR}$ (H →BSM)
- Several BSM models allow for such additional decay modes (Higgs portal, 2HDM, 2HDM+S,NMSSM…)

Example : if a new scalar *s* is coupled :

$$\Delta\mathcal{L} = \frac{\zeta}{2} s^2 |H|^2$$

(common building block in extended Higgs

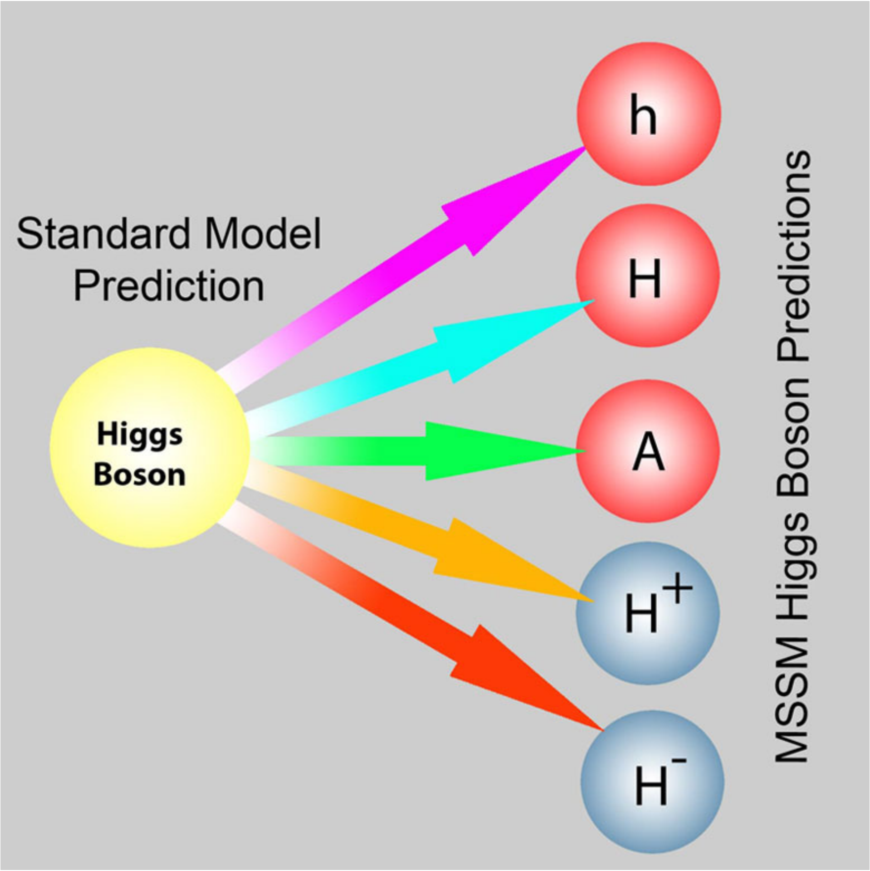


for ζ ~0.01, $\mathcal{BR}$ (H→ BSM) is $\mathcal{O}$(10%) for $m_s < m_H/2$

Higgs Sector in MSSM

Minimal **S**upersymmetric **S**tandard **M**odel

Minimal extension of the SM, introduction 2 Higgs doublets Hu, Hd



5 mass eigenstates :

2 CP even h^0, H^0

1 CP odd A^0

2 CP charged H^+,H^-

Still, MSSM faces some phenomenological flaws, to which Next-to-MSSM can solve

Why going to the NMSSM ?

- **MSSM**

Loop corrections $X_t = m_t (A_t - \mu \cot\beta)$

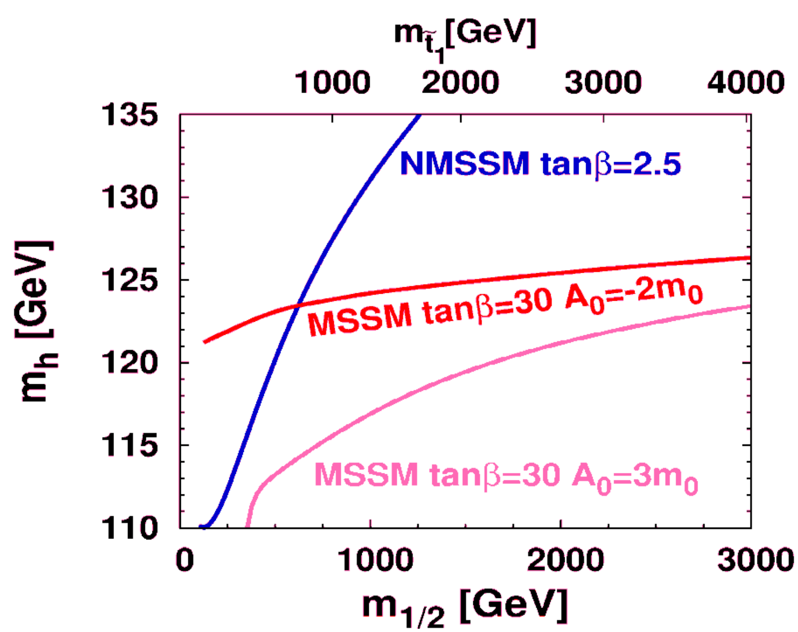
$$\underbrace{m_h^2}_{<(130GeV)^2} \approx \underbrace{m_Z^2 \cos^2 2\beta}_{<m_Z^2} + \frac{3}{(4\pi)^2}\frac{m_t^4}{v^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$

- **NMSSM: Mixing with singlet**

$$m_h^2 \approx \lambda^2 v^2 \sin^2 2\beta + M_Z^2 \cos^2 2\beta + \Delta_{rad} + \Delta_{mix}$$

Ellwanger, arXiv 1108.0157

Increases Higgs mass for large values of λ



Why going to the NMSSM ?

- NMSSM has one additional singlet

MSSM

NMSSM

$$H_1 = S_{1,d} H_d + S_{1,u} H_u + S_{1,s} S$$
$$H_2 = S_{2,d} H_d + S_{2,u} H_u + S_{2,s} S$$
$$H_3 = S_{3,d} H_d + S_{3,u} H_u + S_{3,s} S$$

→

MSSM	NMSSM
2 CP even	3 CP even
1 CP odd	2 CP odd

$$W_{NMSSM} = \lambda \hat{S} \hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3} \hat{S}^3 + \dots$$

- **Pros of NMSSM**
  - ✓ Increase light Higgs mass
  - ✓ Modified couplings to up-/down-type fermions (if $R_{\gamma\gamma} \neq 1$)
  - ✓ Solves μ-Problem (Kim, Nilles Phys. Lett. B 138, 150 (1984))
- **Cons**
  - ✗ **More** free parameters: couplings λ, κ
    trilinear couplings A_κ, A_λ
    mixing parameter $\mu_{eff} = \lambda \langle S \rangle$

(in addition to m_0, $m_{1/2}$, A_0, $\tan\beta$)

Couplings of 2HDM

Couplings of the neutral scalar and pseudoscalar mass eigenstates in the four types of 2HDM

	Couplings	I	II	III (Lepton specific)	IV (Flipped)
	g_{hVV}	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
	$g_{ht\bar{t}}$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
h	$g_{hb\bar{b}}$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
	$g_{h\tau\bar{\tau}}$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
	g_{H^0VV}	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
	$g_{H^0t\bar{t}}$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
H^0	$g_{H^0b\bar{b}}$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
	$g_{H^0\tau\bar{\tau}}$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
	g_{AVV}	0	0	0	0
	$g_{At\bar{t}}$	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
A	$g_{Ab\bar{b}}$	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
	$g_{A\tau\bar{\tau}}$	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

	Type-1	Type-2	Type-3 (lepton-specific)	Type-4 (flipped)
Up-type quarks	Φ_2	Φ_2	Φ_2	Φ_2
Down-type quarks	Φ_2	Φ_1	Φ_2	Φ_1
Charged leptons	Φ_2	Φ_1	Φ_1	Φ_2