Πανεπιστήμιο Κύπρου
Τμήμα Φυσικής

Search for the exotic decays of the Higgs boson

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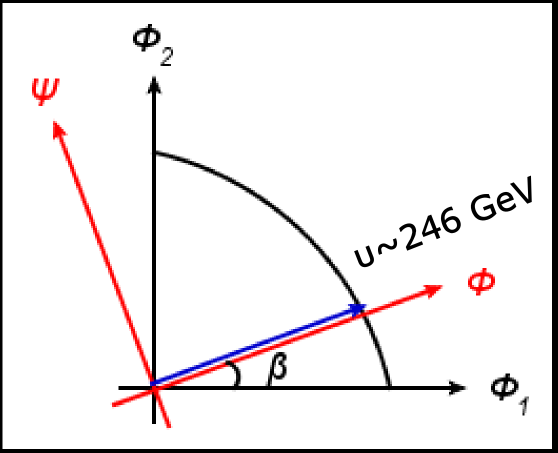
Two Higgs Doublet Models (2HDM)

- We consider a model with an $SU(2)_L$
- Two doublets - ϕ_1 and ϕ_2

$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \Phi \\ \Psi \end{pmatrix}$$

$\tan\beta = \upsilon_2/\upsilon_1$ $\quad \upsilon_1^2 + \upsilon_2^2 = \upsilon^2$

υ_i vacuum expectation values (vev) of the neutral component.



Goldstone bosons (**NG) boson**

Charged Higgs

$$\Phi = \begin{bmatrix} G^+ \\ \frac{1}{\sqrt{2}}(h_1' + v + iG^0) \end{bmatrix} \qquad \Psi = \begin{bmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h_2' + iA) \end{bmatrix}$$

CP-even Higgs

CP-odd Higgs

$$\begin{pmatrix} h_1' \\ h_2' \end{pmatrix} \begin{pmatrix} \cos(\beta-\alpha) & \sin(\beta-\alpha) \\ -\sin(\beta-\alpha) & \cos(\beta-\alpha) \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

SM-like Higgs with 125 GeV

Two Higgs Doublet Models (2HDM)

- The 2HDM Lagrangian for Φ_i

$$L = \sum_i \left| D_\mu \Phi_i \right|^2 - V(\Phi_1, \Phi_2) + L_{yuk}$$

Kinetic term for the two Higgs doublets

The 2HDM potential

Yukawa interaction between Φ_i and the SM fermions

$$\begin{aligned} V(\Phi_1, \Phi_2) \;=\; & m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 - (m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}) + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 \\ & + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \frac{1}{2}\lambda_5 [(\Phi_1^\dagger \Phi_2)^2 + \text{h.c.}] \,. \end{aligned}$$

After EW symmetry breaking, the physical scalar spectrum of five states:

1) Two CP-even Higges h, H with $m_h < m_H$, can be SM-like
2) CP-odd scalar A
3) Charge scalar pair $H^\pm$

Three of these are absorbed by and given mass to the $W^\pm$ and Z boson

Interpretation with 2HDM

Parameters in the **physical basis** : m_h=125 GeV in our case

$$m_h,\ m_H,\ m_A,\ m_{H\pm},\ \tan\beta,\ \sin(\beta-\alpha),\ v,\ m_{12}^2$$

Mass of bosons

The ratio of Vacuum expectation values.

The mixing angle between cp-even boson

Potential parameter

4 types of 2HDM : different ways to couple ϕ_1 and ϕ_2 to fermions

	Type I	Type II	Flipped (Type Y)	Lepton Specific (Type X)
Up-type quark	ϕ_2	ϕ_2	ϕ_2	ϕ_2
Down-type quark	ϕ_2	ϕ_1	ϕ_1	ϕ_2
Leptons	ϕ_2	ϕ_1	ϕ_2	ϕ_1

- **Type I**: All quarks and leptons couple to only one scalar doublet ϕ_2 .
- **Type 2: MSSM-like, d_R and e_R couple to** ϕ_1, u_R to ϕ_2
- **Type 3 (lepton specifiec)**: all quarks couple to ϕ_2, leptons couple to ϕ_1
- **Type 04 (flipped)**: with u_R, e_R coupling to ϕ_2 and d_R to ϕ_1

2HDM + S

- Add to the 2HDM one complex scalar singlet S, which has a small mixing with Φ_1 and Φ_2.
- This leads to two additional singlet states (CP-even scalar *s* and CP-odd *α*) which inherit interactions to the SM fermions from their mixing with the Higgs doublets.
- The general 2HDM+S model generates a large variety of Higgs decay phenomenology

$$h \to \alpha\alpha \to X\bar{X}Y\bar{Y},\ h \to ss \to X\bar{X}Y\bar{Y},\ and\ \ h \to \alpha Z \to X\bar{X}Y\bar{Y}$$

- Four types of 2HDM+S forbid flavor changing neutral currents (FCNC) at tree level.
  - **Type 1**: all SM particles couple to the first doublet.
  - **Type 2:** leptons and down-type quarks couple to the second doublet, whereas up-type quarks couple to the first doublet. The next-to-minimal supersymmetric model (NMSSM) is a particular case of 2HDM+S that brings a solution to the *μ* problem.
  - **Type 3**: leptons couple to the second doublet, and quarks to the first one.
  - **Type 04**: down-type quarks couple to the second doublet while leptons and up-type quarks couple to the first doublet.

Channels investigated

Dimitra Tsiakkouri

$$h(125) \rightarrow \alpha\alpha \rightarrow b\bar{b}\tau^+\tau^- \begin{cases} b\bar{b} + e\tau_h, b\bar{b} + \mu\tau_h, b\bar{b} + e\mu \\ b\bar{b} + \tau_h\tau_h, b\bar{b} + \mu\mu, b\bar{b} + ee \end{cases}$$

low signal acceptance due to trigger threshold (at least p_T >40 GeV offline for each τ_h)

are discarded due to small branching fraction

Eleni Irodotou

$$h(125) \rightarrow \alpha\alpha \rightarrow \tau^+\tau^-\mu^+\mu^- \begin{cases} \mu\mu + e\mu, \mu\mu + e\tau_h, \mu\mu + \mu\tau_h, \mu\mu + \tau_h\tau_h \\ \mu\mu + ee, \mu\mu + \mu\mu \end{cases}$$

Are not considered, small BR and large irreducible background

Channels investigated

Aimilios Ioannou

$$A \rightarrow Zh \rightarrow \ell^+\ell^- b\bar{b} \begin{cases} ee b\bar{b}, \mu\mu b\bar{b} \\ e\mu b\bar{b}, \nu\nu b\bar{b} \end{cases}$$

Ioannis Vasilas

$$A \rightarrow Zh \rightarrow \ell^+\ell^- \tau^+\tau^- \begin{cases} ee\tau_h\tau_h, eee\mu, eee\tau_h, ee\mu\tau_h \\ \mu\mu\tau_h\tau_h, \mu\mu e\mu, \mu\mu e\tau_h, \mu\mu\mu\tau_h \\ \mu\mu\mu\mu, eeee \end{cases}$$

Are not considered, small BR and large irreducible background

Channels investigated

$$h \rightarrow \alpha\alpha \rightarrow \tau^+\tau^-\tau^+\tau^- \begin{cases} e^-e^+\mu^-\mu^+, e^-e^+\tau_h\tau_h, \mu^-\mu^+\tau_h\tau_h \\ eeee, \mu\mu\mu\mu, \tau_h\tau_h\tau_h\tau_h \end{cases}$$

$$h \rightarrow \alpha\alpha \rightarrow b\bar{b}\mu^+\mu^-$$

Decay Mode	Branching ratio (%)	
$\tau^- \rightarrow \mu^-\bar{\nu}_\mu\nu_\tau$	17.41	
$\tau^- \rightarrow e^-\bar{\nu}_e\nu_\tau$	17.83	
$\tau^- \rightarrow l^-\bar{\nu}_e\nu_\tau$	35.24	
$\tau^- \rightarrow \pi^-\nu_\tau$	11.53	47.01
$\tau^- \rightarrow \pi^-\pi^0\nu_\tau$	25.95	
$\tau^- \rightarrow \pi^-\pi^0\pi^0\nu_\tau$	9.53	
$\tau^- \rightarrow \pi^-\pi^+\pi^-\pi^0\nu_\tau$	4.80	14.6
$\tau^- \rightarrow \pi^-\pi^+\pi^-\nu_\tau$	9.80	
Other modes with hadrons	3.15	
All hadronic modes	64.76	

The benchmark points

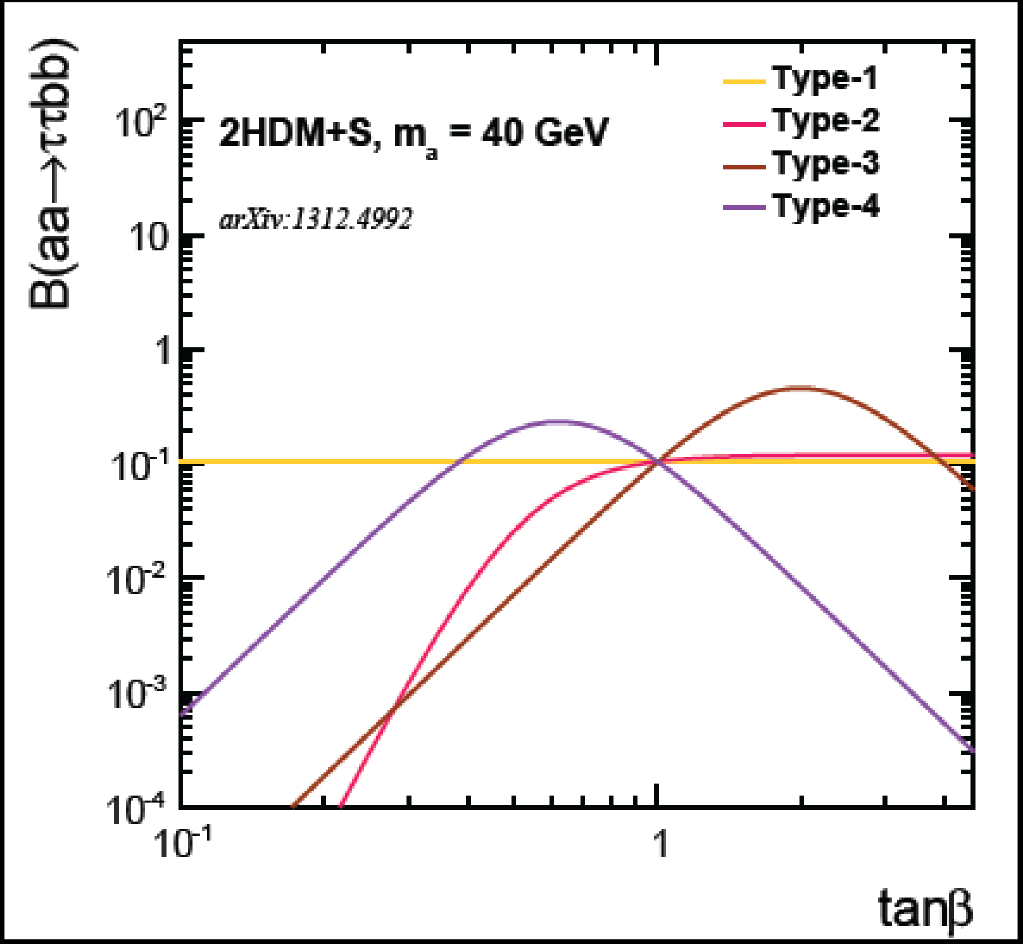
$$h \to \alpha\alpha \to b\bar{b}\tau^+\tau^-$$

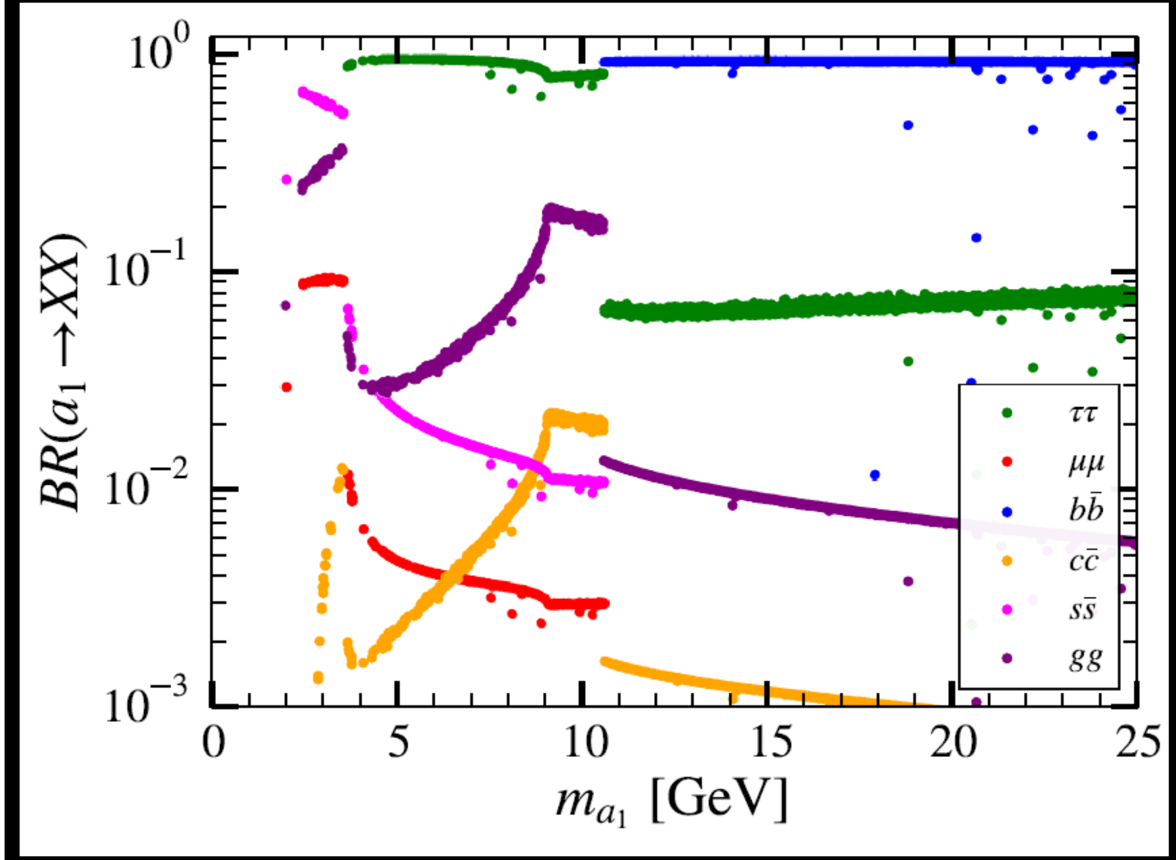
final state with good sensitivity because of the large branching fractions to τ and b quarks in most models.

$$Br(a \to \tau^+\tau^-) = 6\%$$

$$Br\left(a \to b\bar{b}\right) = 94\%$$

$2m_b < m_\alpha < m_{h/2}$





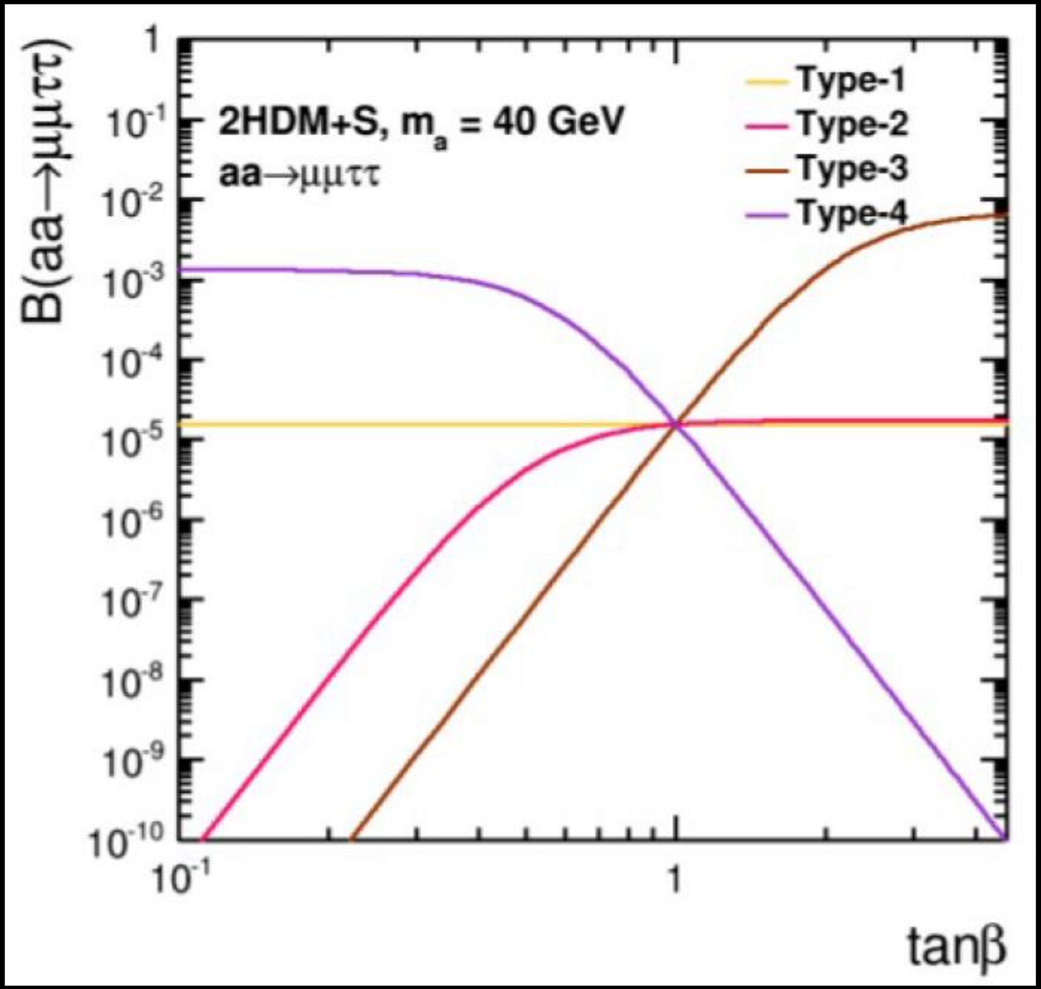
The benchmark points

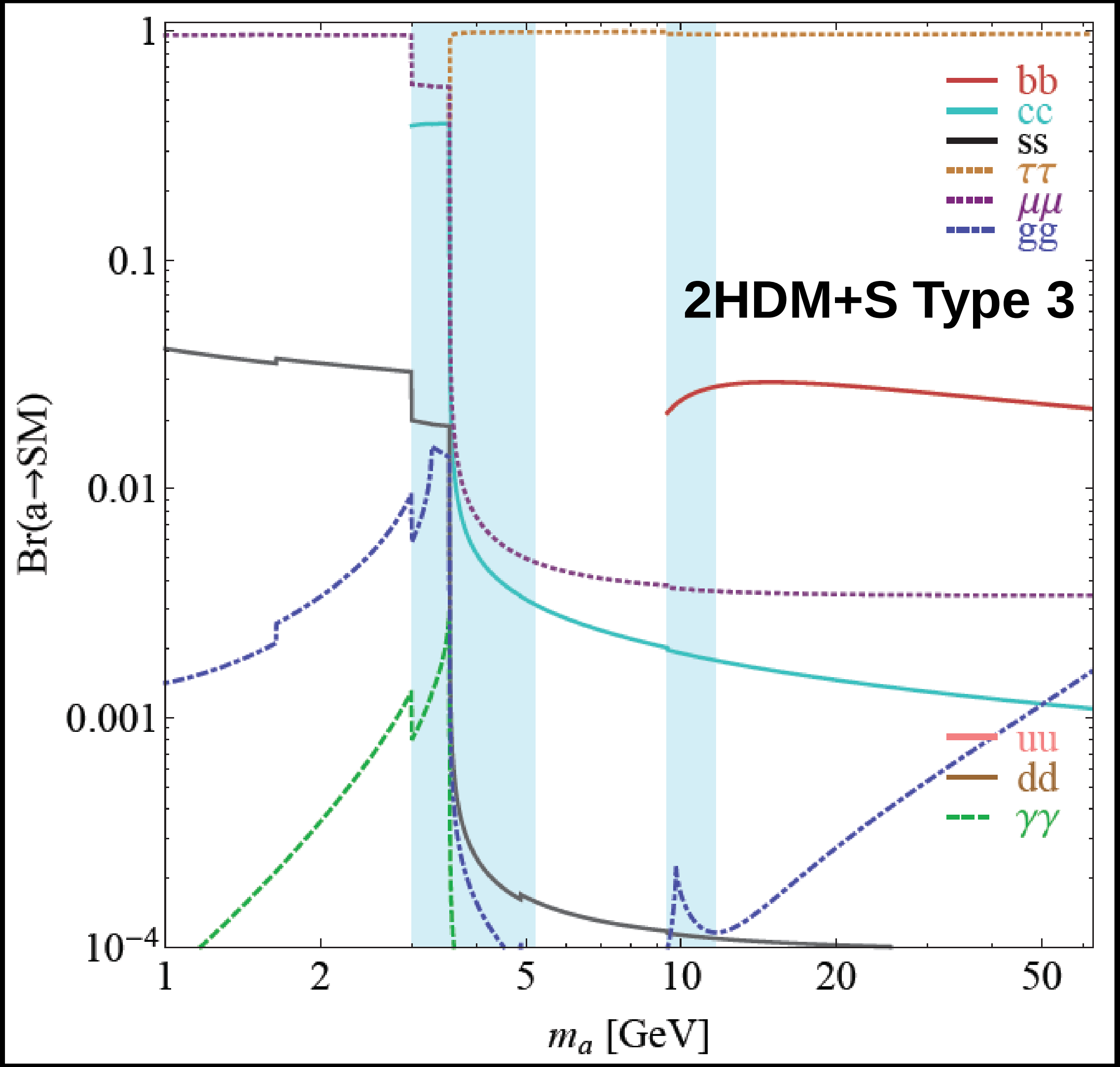
$h \to \alpha\alpha \to \mu^+\mu^-\tau^+\tau^-$

$(2m_\tau < m_\alpha < m_{h/2})$

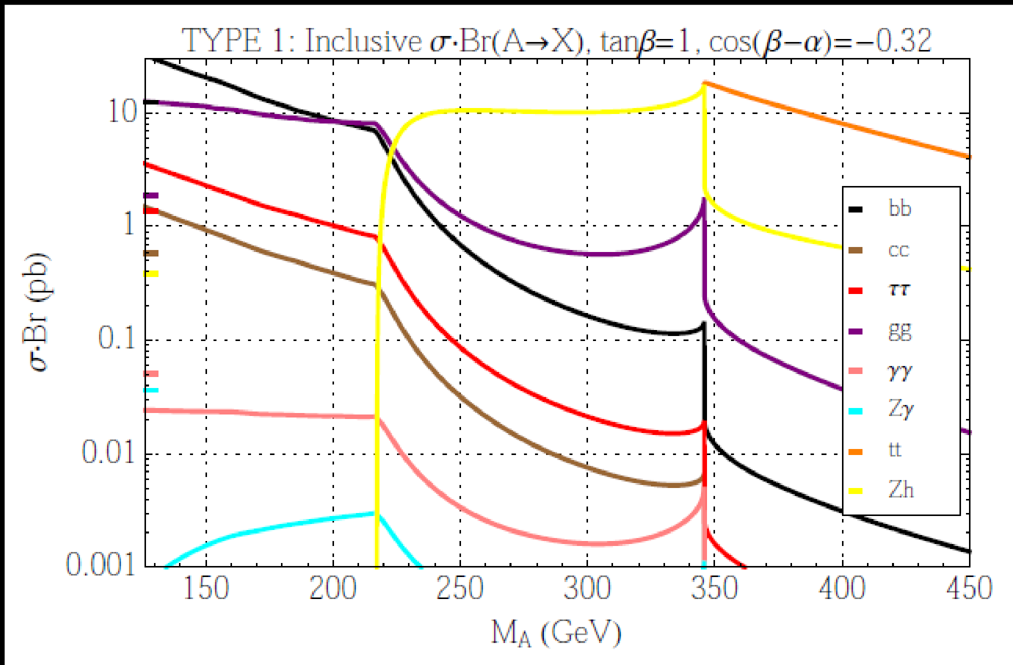
$Br(\alpha \to \tau^+\tau^-) \simeq 100\%$

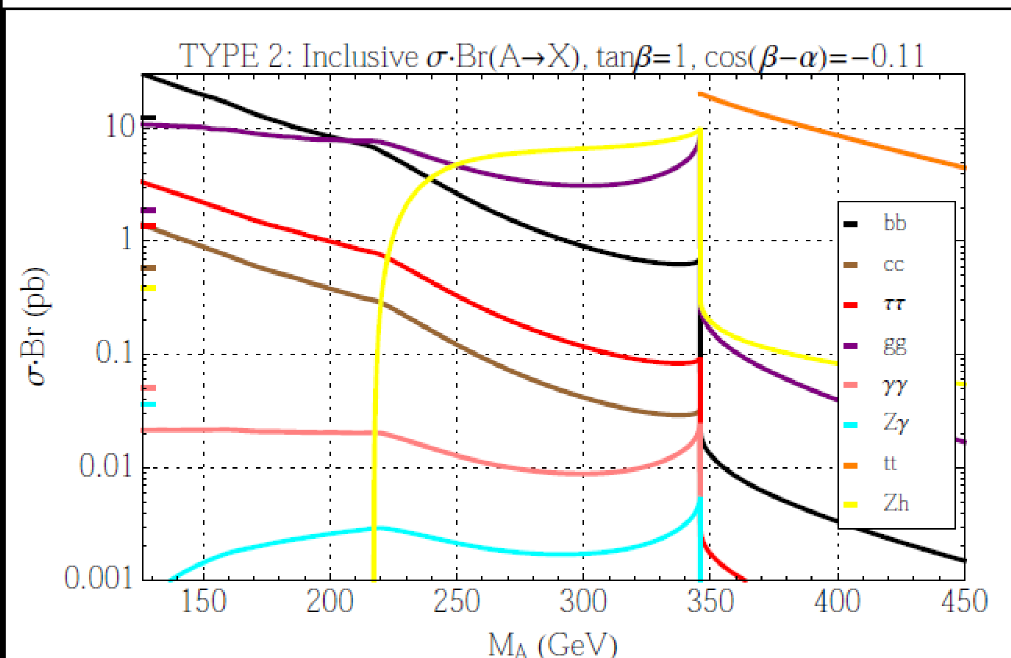
$Br(\alpha \to \mu^+\mu^-) = 0.35\%$





$A \to Zh \to \ell^+\ell^- b\bar{b}$

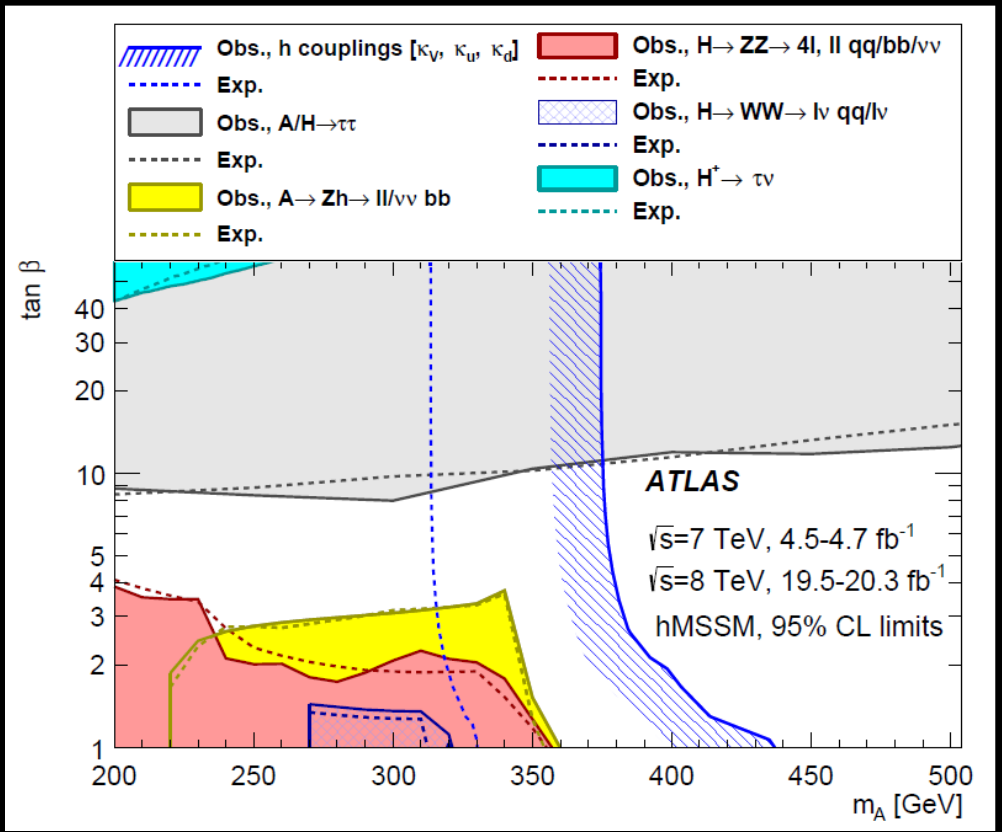




The benchmark points

m_h	m_H	m_A	$m_{H^\pm}$	$\sin(\beta-\alpha)$	$\tan\beta$	m_{12}
125 GeV	300 GeV	300 GeV	400 GeV	0.6	2	100 GeV

$Br(A \to Zh) = 98.4\%$ $\quad Br(h \to b\bar{b}) = 69.9\%$

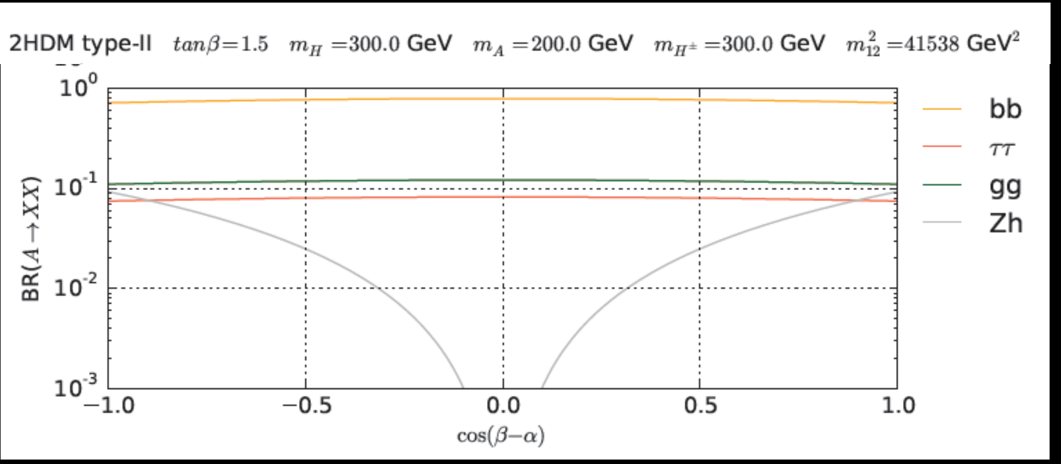


The ATLAS collaboration reported a small deviation on the search channel $A \to Zh$: an excess, relative to background expectations, of 0.1-0.3 pb for $\sigma(A \to Zh)BR(h \to b\bar{b})$, for a potential pseudoscalar mass of about 440 GeV.

The benchmark points

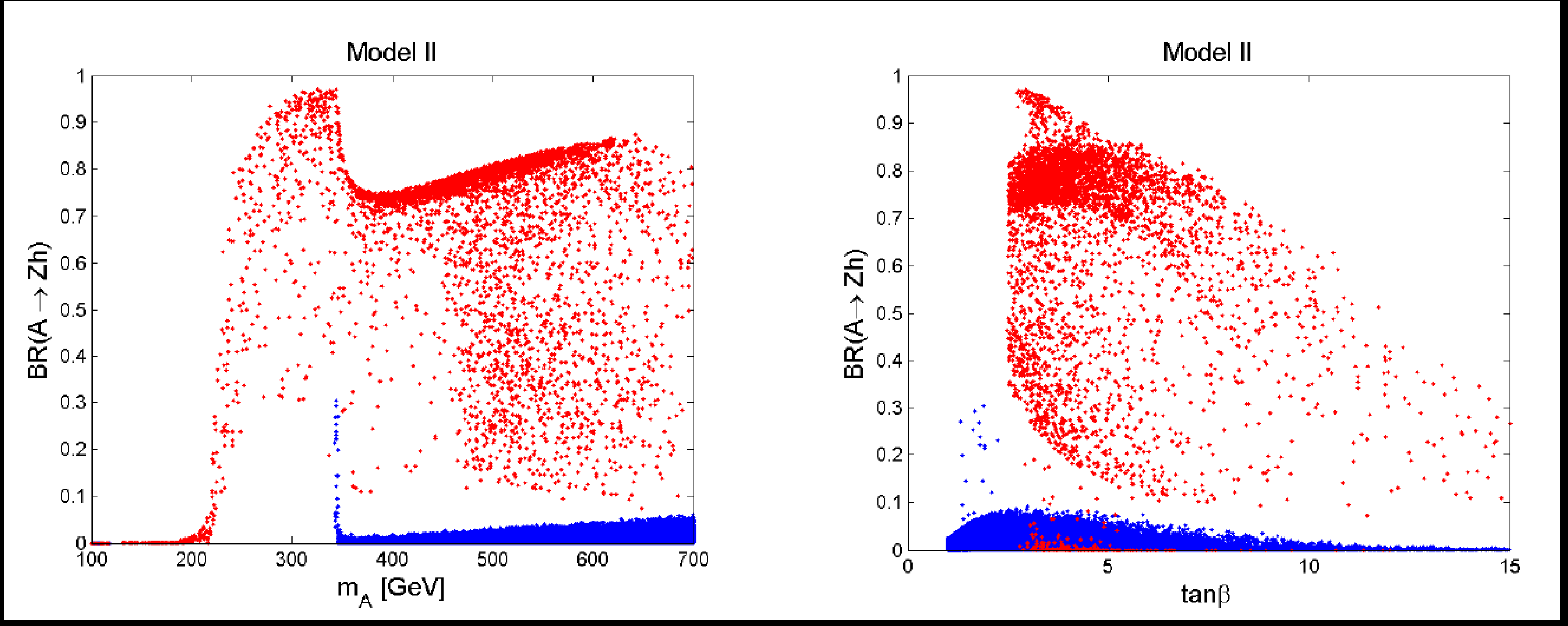
$$A \to Zh \to \ell^+\ell^-\tau^+\tau^-$$

m_h	m_H	m_A	$m_{H^\pm}$	$\sin(\beta-\alpha)$	$\tan\beta$	m_{12}
125 GeV	300 GeV	300 GeV	400 GeV	0.6	2	100 GeV



$$Br(A \to Zh) = 98.4\%$$

$$Br(h \to \tau^+\tau^-) = 6.8\%$$

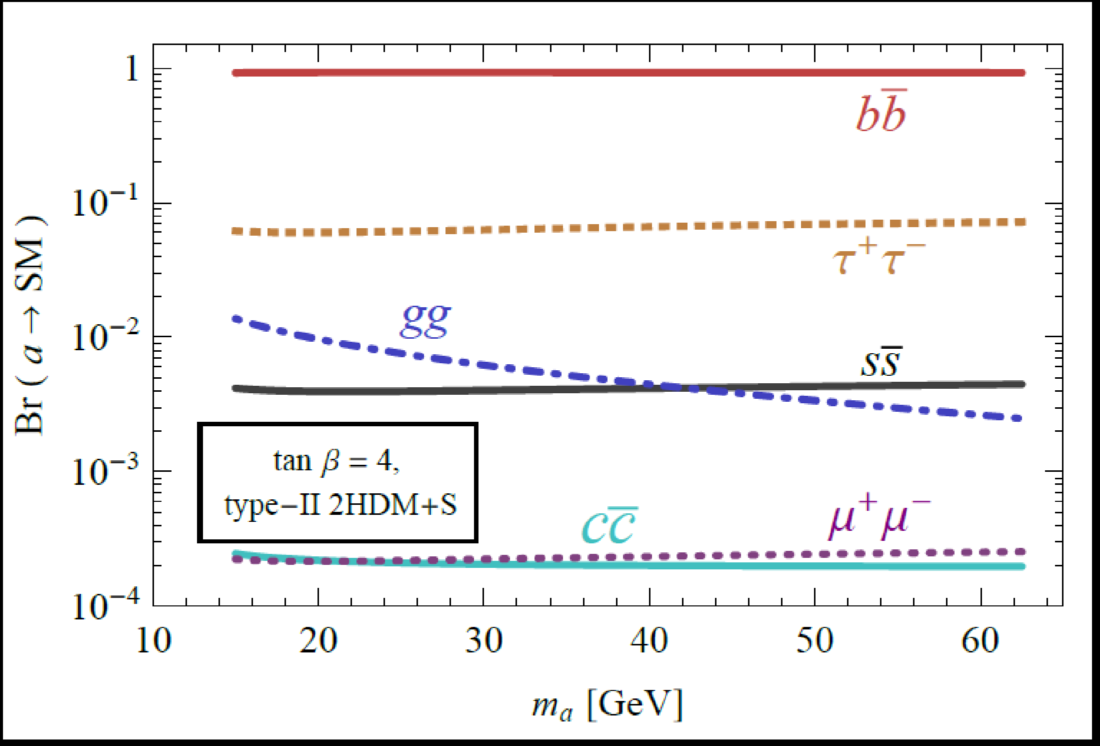


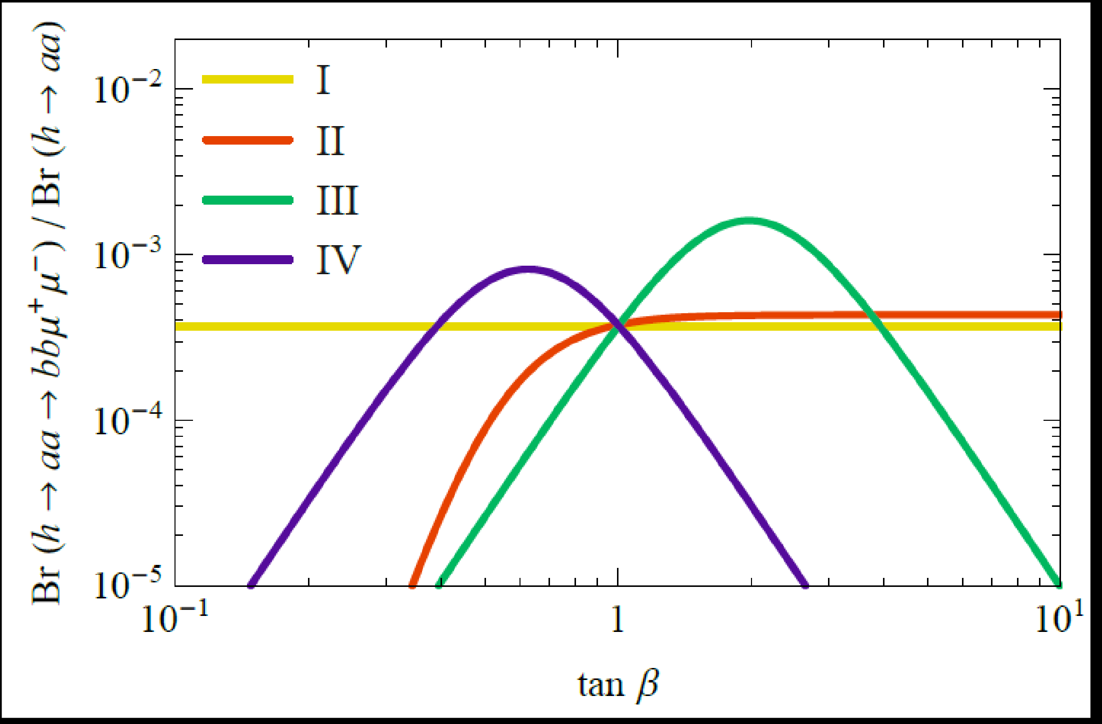
The benchmark points

$$h \to \alpha\alpha \to b\bar{b}\mu^+\mu^-$$

In 2HDM+S Type 3 the branching fractions of the $h \to \alpha\alpha$ channel is 10 % with $tan\,\beta = 2$.

$$2 \times Br\left(\alpha \to b\bar{b}\right) Br\left(\alpha \to \mu^+\mu^-\right) = 1.7 \times 10^{-3}$$





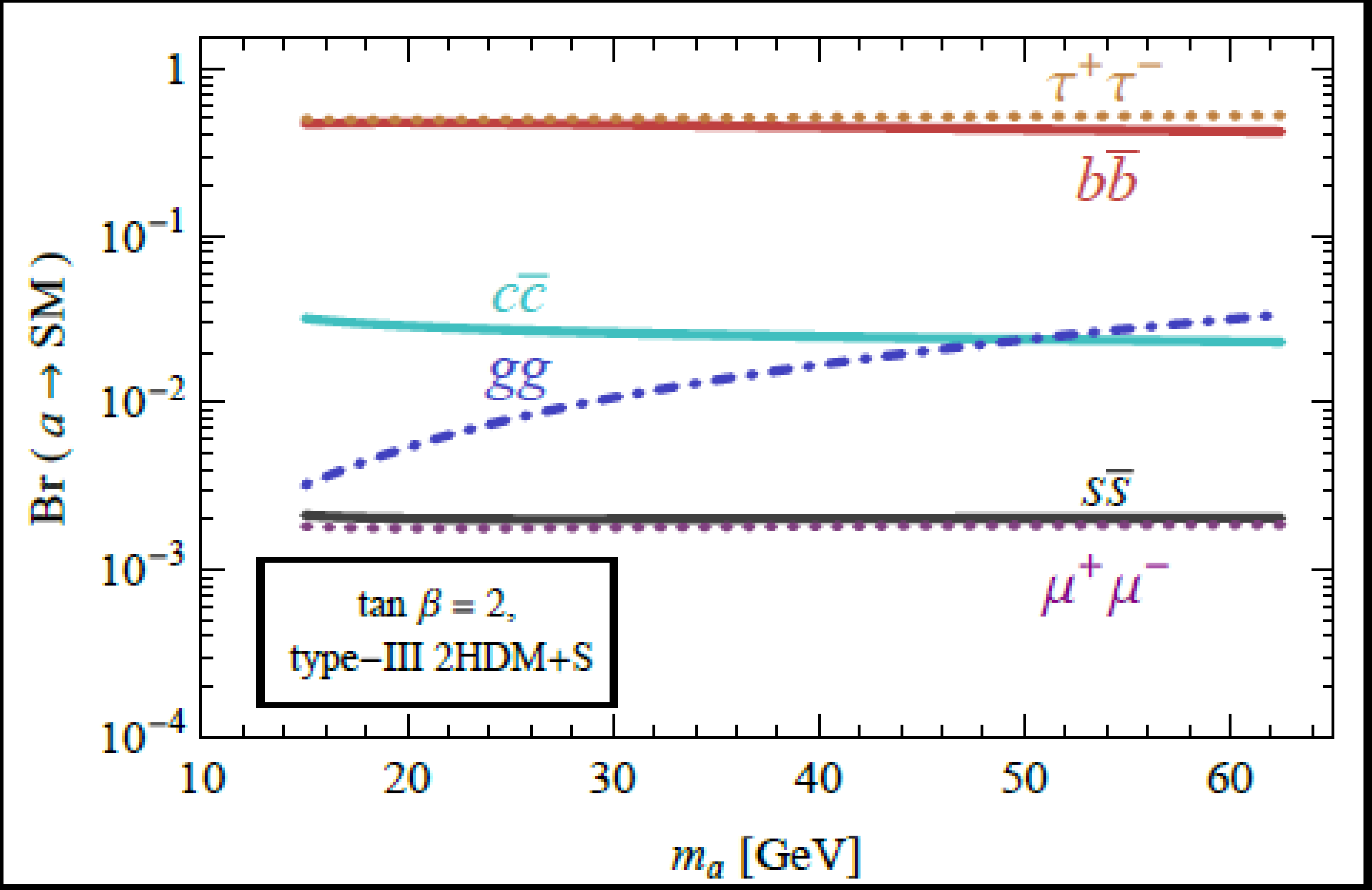
The benchmark points

$$h \rightarrow \alpha\alpha \rightarrow \tau^+\tau^-\tau^+\tau^-$$

The branching ratios to lepton pairs are in proportion

$\tau^+\tau^- : \mu^+\mu^- : e^+e^- \simeq 1 : 3.5\times 10^{-3} : 8\times 10^{-8}$

$m_\alpha = [2m_\tau, m_{h/2}]$



2HDM+S Type 3

Background Processes

$$h \to aa \to 4\tau,\ h \to aa \to 2\tau 2\mu$$

- ***ZZjj* and *WZjj* production:** The production of two vector bosons in association with two jets is the main background processes for this channel.
- ***tt(bar)* production:** Two leptons or hadrons and neutrino that produce missing momentum can originate from the decays of the two *W* bosons. The third lepton/hadron and an additional neutrino can be produced in the decay of a bottom quark (for the case of 4 taus).
- ***Ztt(bar)* and *Wtt(bar)* production:** In these processes an additional vector boson is produced, in association with a top quark pair.
- ***Zbb(bar)* and *Wbb(bar)* production**: One or two leptons can originate from the decays of the vector bosons. One or even two leptons can then be produced in the *b-quark* decays.
- **QCD:**. Potential background is caused by events containing misidentified leptons or leptons from *b* meson decays.

Background Processes

$h \to aa \to 2\tau 2\mu,\ h \to aa \to 2b2\mu$

- **Drell–Yan production of $Z \to \tau^+\tau^-$** : In the e τ_h channel, $Z \to \tau^+\tau^-$ production is also an important source of background because of the 2–3% probability for electrons to be misidentified as electron is misidentified as τ_h.
- **W + jets samples:** *W* boson decays leptonically and a jet is misidentified as τ_h
- **ttbar + Single top:** is one of the main backgrounds in the eμ channel.
- $WZ^* / \gamma^* (\to \tau^+\tau^-) b\bar{b}$ **:** has the $b\bar{b}$ pairs from a virtual gluon splitting, the $\tau^+\tau^-$ pair from an intermediate Z^* / γ^* and the charged lepton plus missing energy from *W* boson.
- Diboson production (WW, ZZ, and WZ):
- Reducible background arises from jets misidentified as *b-quarks*, or as hadronically decaying taus.

Background Processes

$$A \rightarrow Zh \rightarrow \ell^+\ell^- b\bar{b}$$

- **Z + jets:** The production of single Z/*g* bosons in association with one or more partons or gluons in the final state is topologically similar to the searched signal.
- **W + jets**: The leptonic decay of a W boson can be an irreducible background in the single-lepton channel, or in the zero-lepton channel in the case the charged lepton escapes undetected or fails the lepton identification requirements.
- $t\bar{t}$: These events always contain two energetic b-jets and two W bosons which may decay to high p_T, isolated leptons.
- **single-top:**
- **Diboson (**W W, W Z, Z Z**)**: the production of two vector bosons in the SM is a rare process, with a similar kinematics to that of the signal. Furthermore, the boost of the bosons could be large.
- **multijet (QCD)**: despite its enormous cross section at LHC, the probability to produce final states with prompt, isolated leptons or large missing transverse momentum is very low.

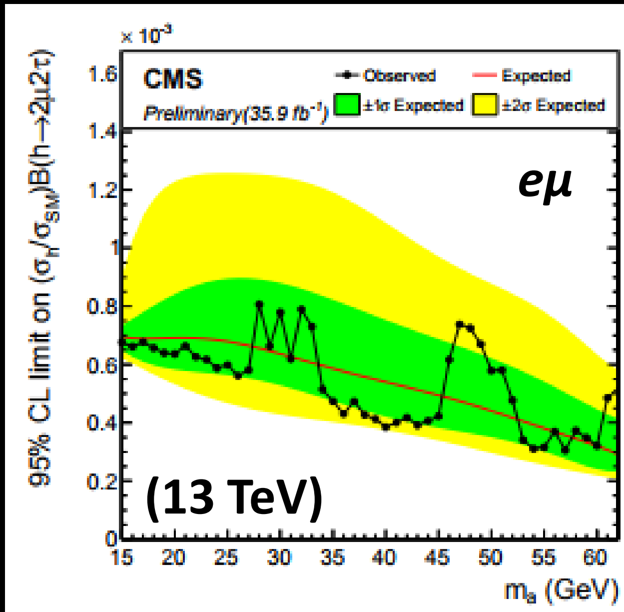
Background Brocess

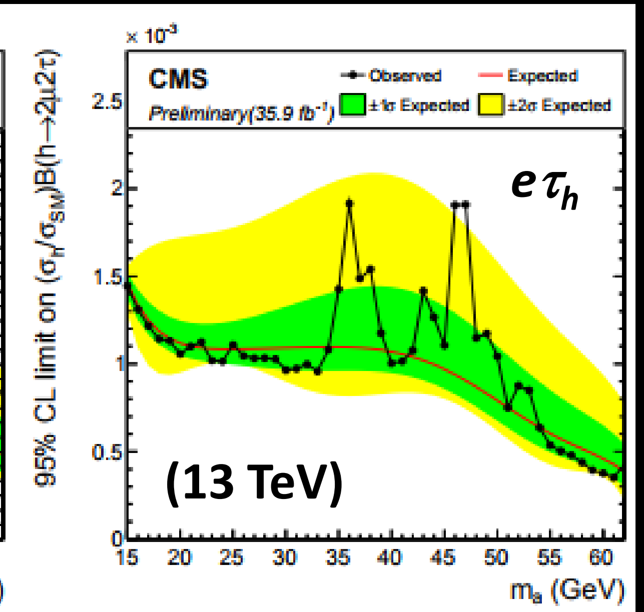
$$A \rightarrow Zh \rightarrow \ell^+\ell^-\tau^+\tau^-$$

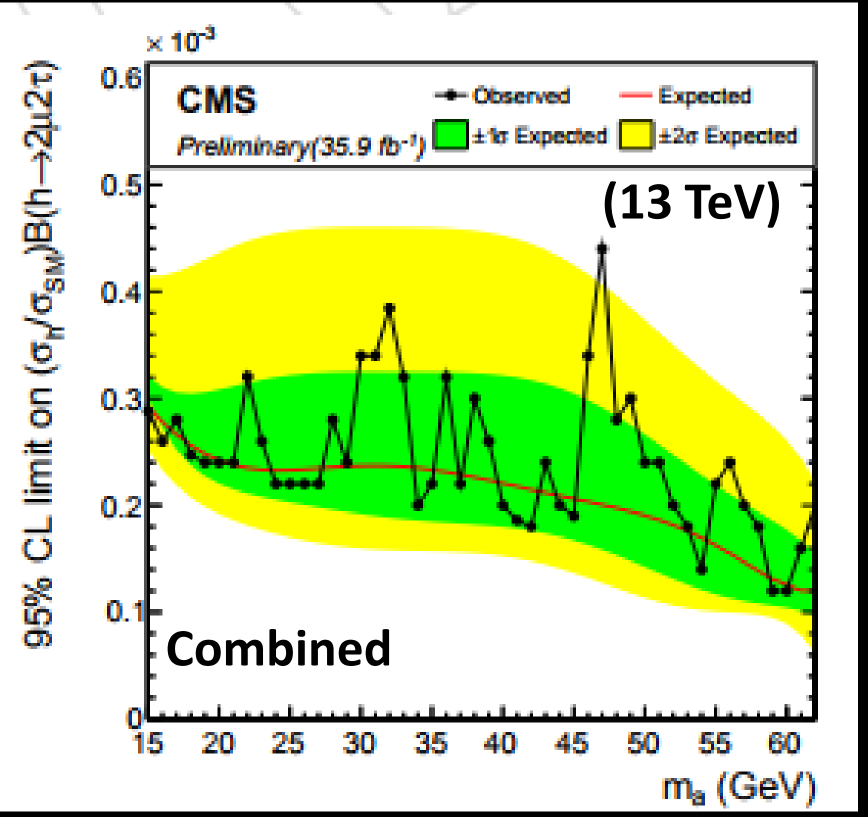
- **WZ+jets**: Misidentified light leptons arise from semileptonic decays of heavy flavor quarks, decays in flight of hadrons, and photon conversions, while jets originating from quarks or gluons can be misidentified as τ_h.
- **Z+jets**: The Z+jets background is characterised by a softer lepton transverse momentum spectrum than the signal one, this background is reduced.
- **tt +jets**: It will be assumed that top quarks decay only SM-like, i.e. via t→Wb. Two leptons or hadrons and neutrino that produce missing momentum can originate from the decays of the two *W* bosons. The tagging jets can be faked by *b-jets* that are misidentified as light jets, or by jets from additional gluon radiation in the event.
- **Diboson production (WW, ZZ, and WZ):** The background is dominated by ZZ^* production with $Z \rightarrow ee/\mu\mu$ decays
- **tW**: There are two W produced in the tW → bWW process. This background is similar to that of the di-boson processes.

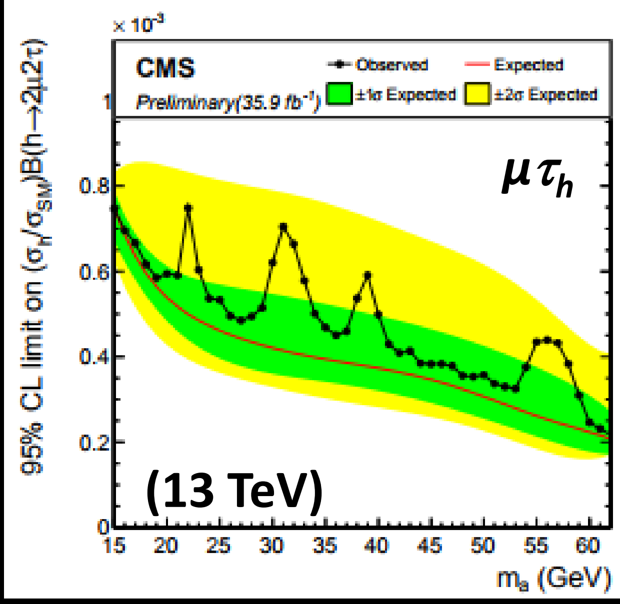
Results

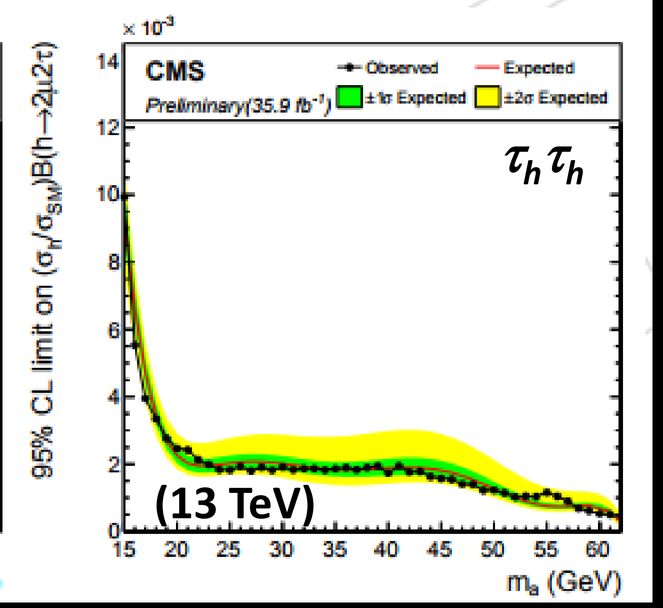
Expected Limits on σ_h/σ_{SM} x BR(h(125) → αα → 2μ2τ)





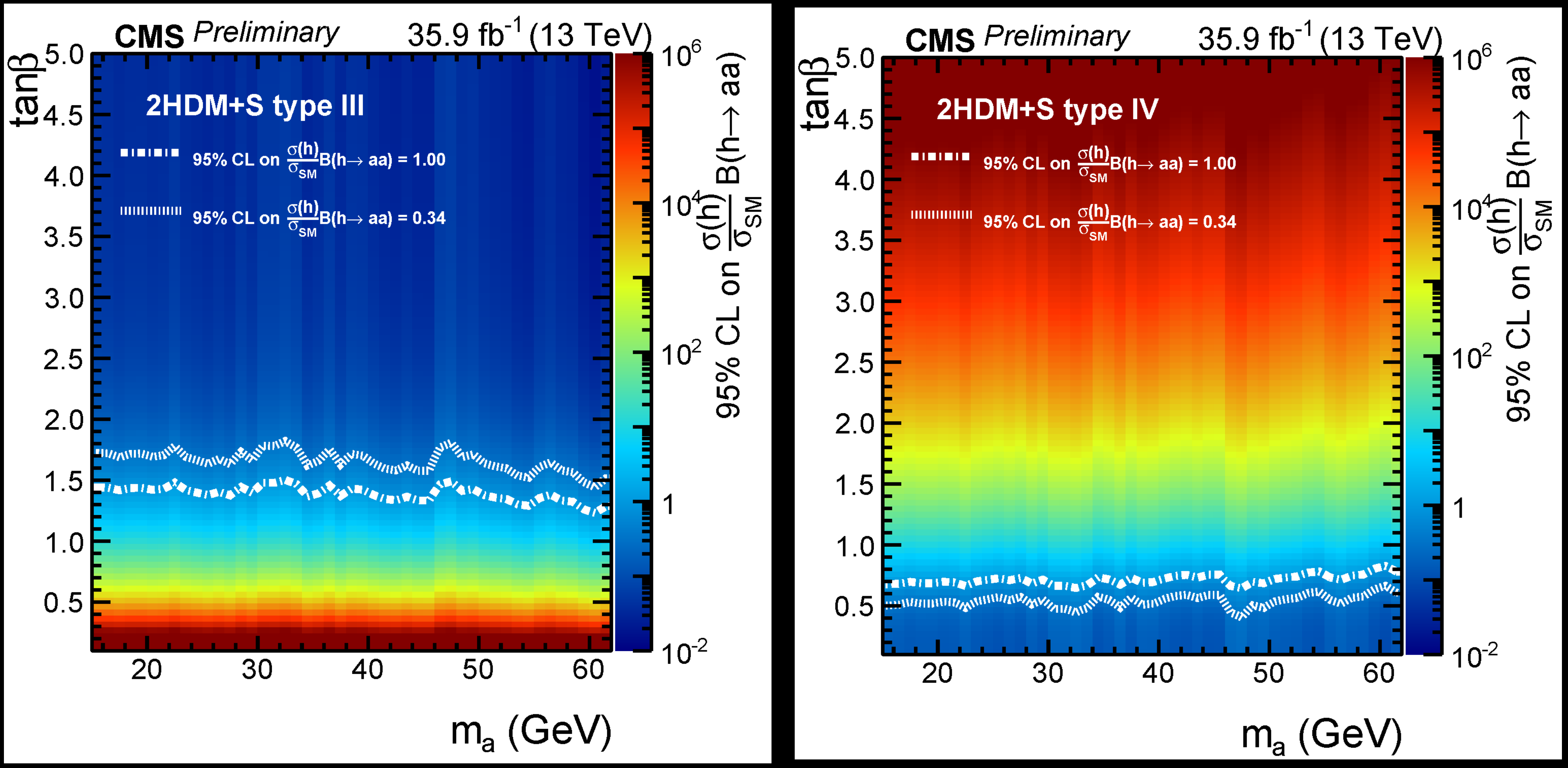






Upper limits at 95% CL on σ_h/σ_{SM} x B(h → αα) for masses of α between 15 and 62.5 GeV are as low as 1.2 x 10^{-4}.

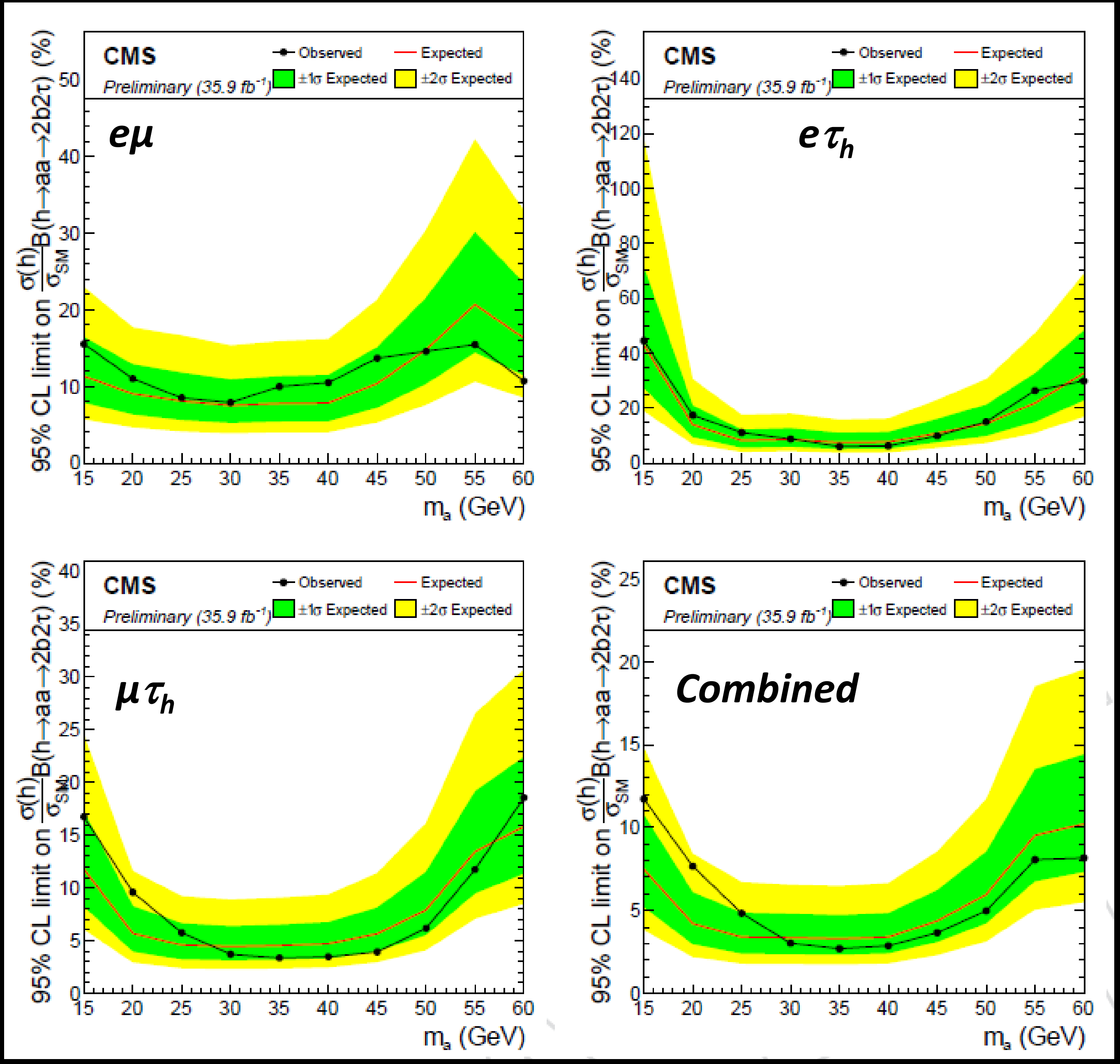
Upper limits on σ_h/σ_{SM} x BR(h → αα) in the different 2HDM+S models



The most stringent limits are obtained in 2HDM+S type III at large tan β, where the couplings to leptons are enhanced, and where limits as low as about 1% can be set.

Results

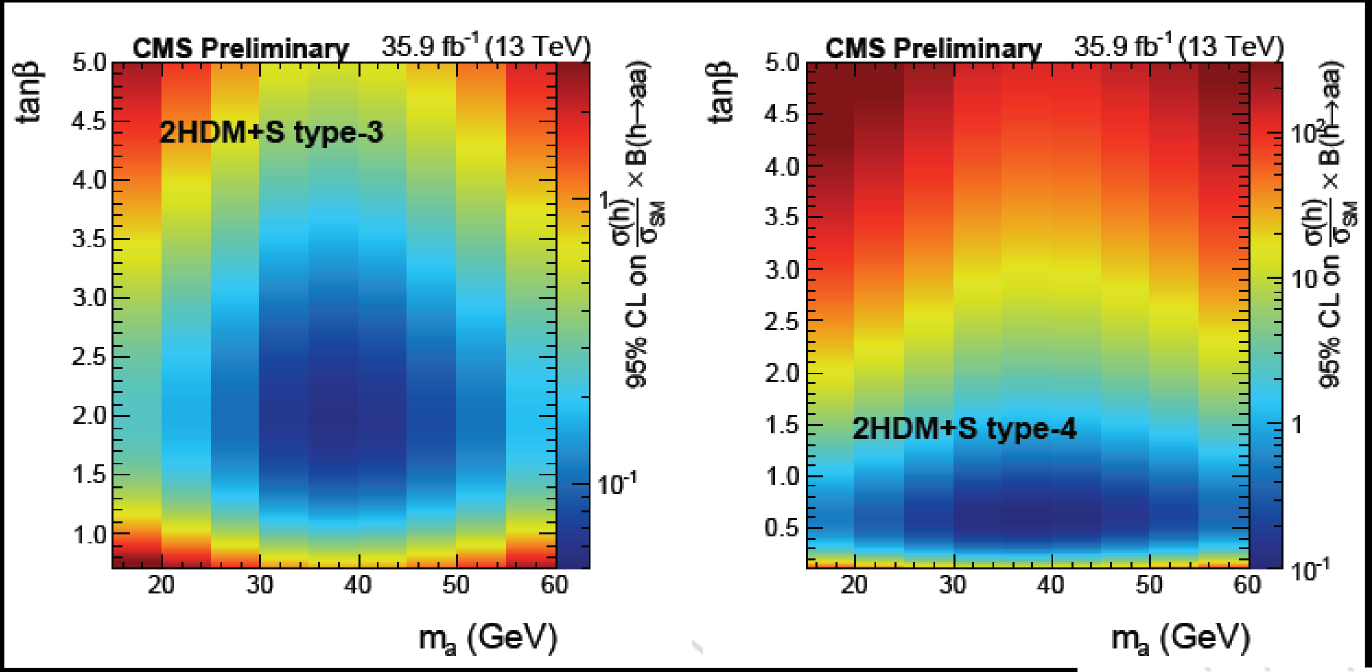
Expected Limits on σ_h/σ_{SM} x BR(h(125) → αα → 2b2τ)



- Upper limits at 95% CL on σ_h/σ_{SM} x B(h → αα) are range from 4 to 12% over the pseudoscalar mass range between 15 and 60 GeV.

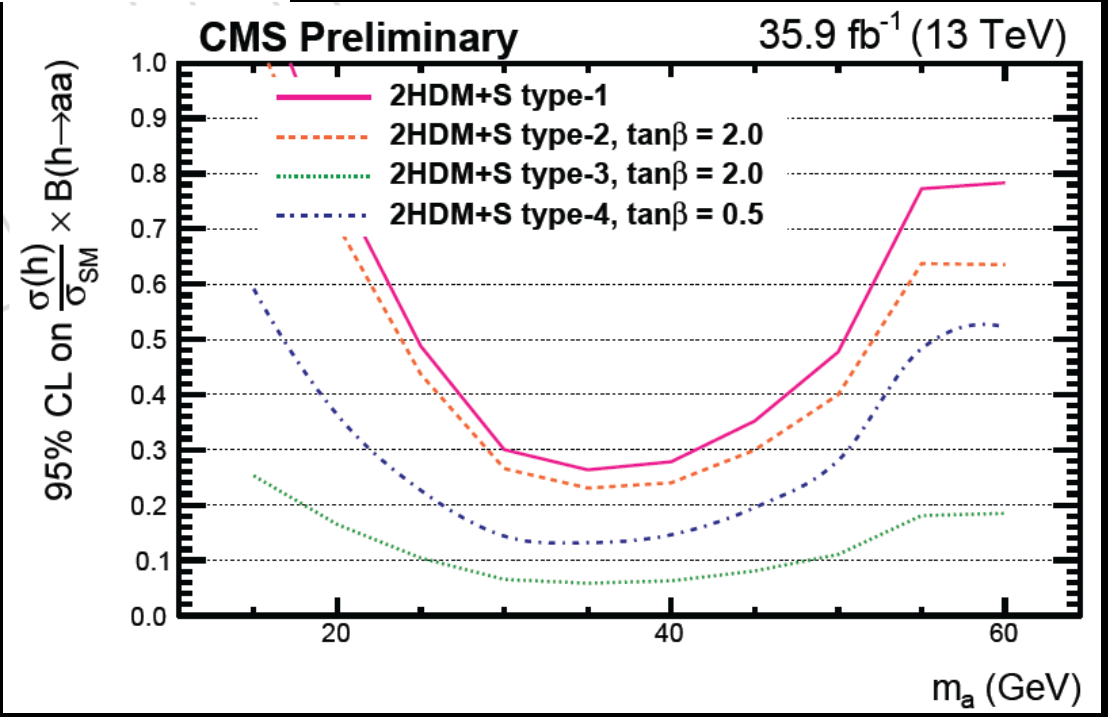
The combined limit at intermediate mass is about 3.5%

Expected Limits on σ_h/σ_{SM} x BR(h → αα) for all types of 2HDM+S

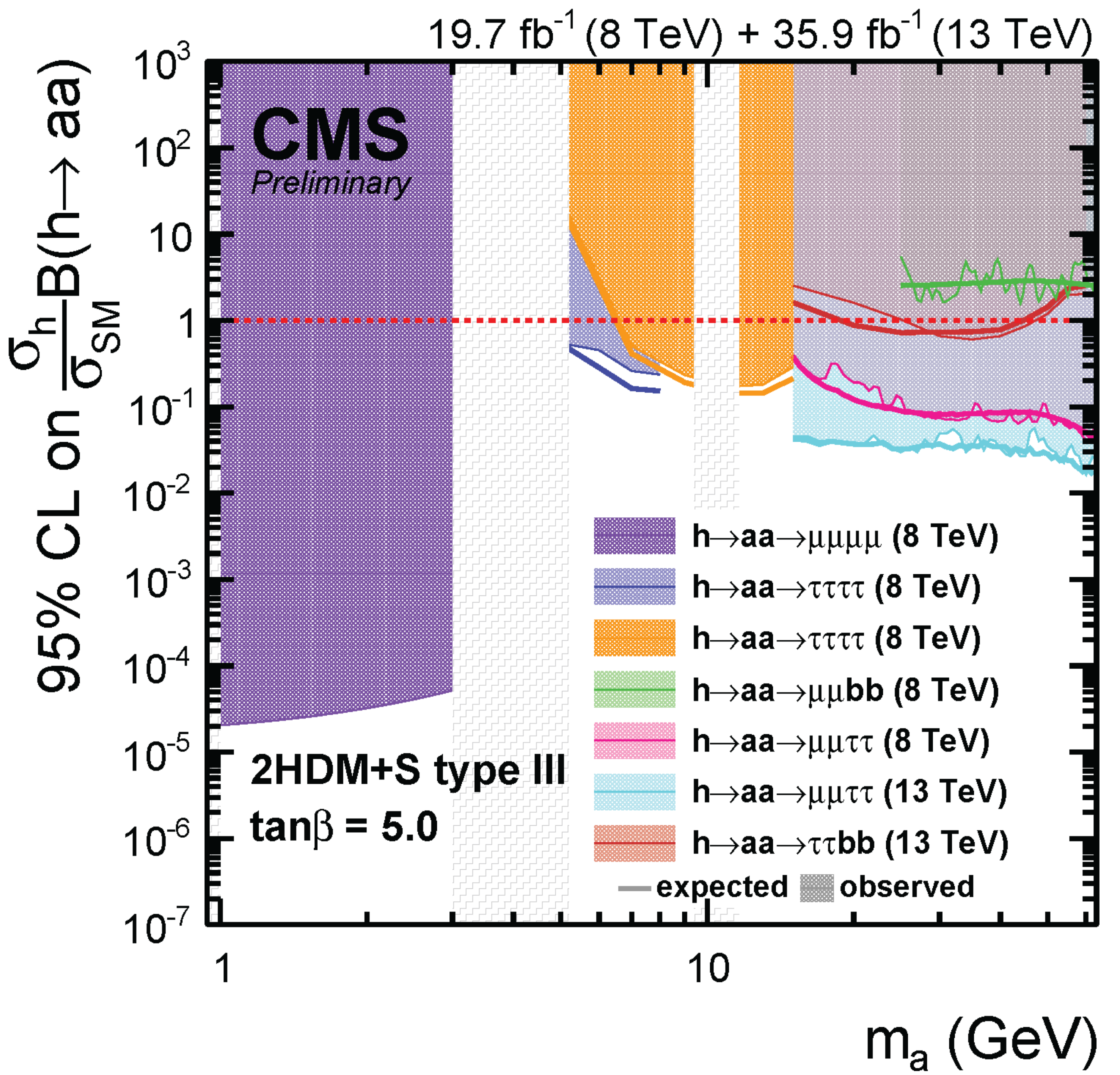


- The Higgs boson pair production rate σ_h/σ_{SM} x BR(h → αα) for all types of 2HDM+S depends on tan *β*.

- In the scenario with the highest branching fraction, 2HDM+S type-3 with tan *β* = 2, the expected limit is as low as 6% for m_α = 35 GeV.

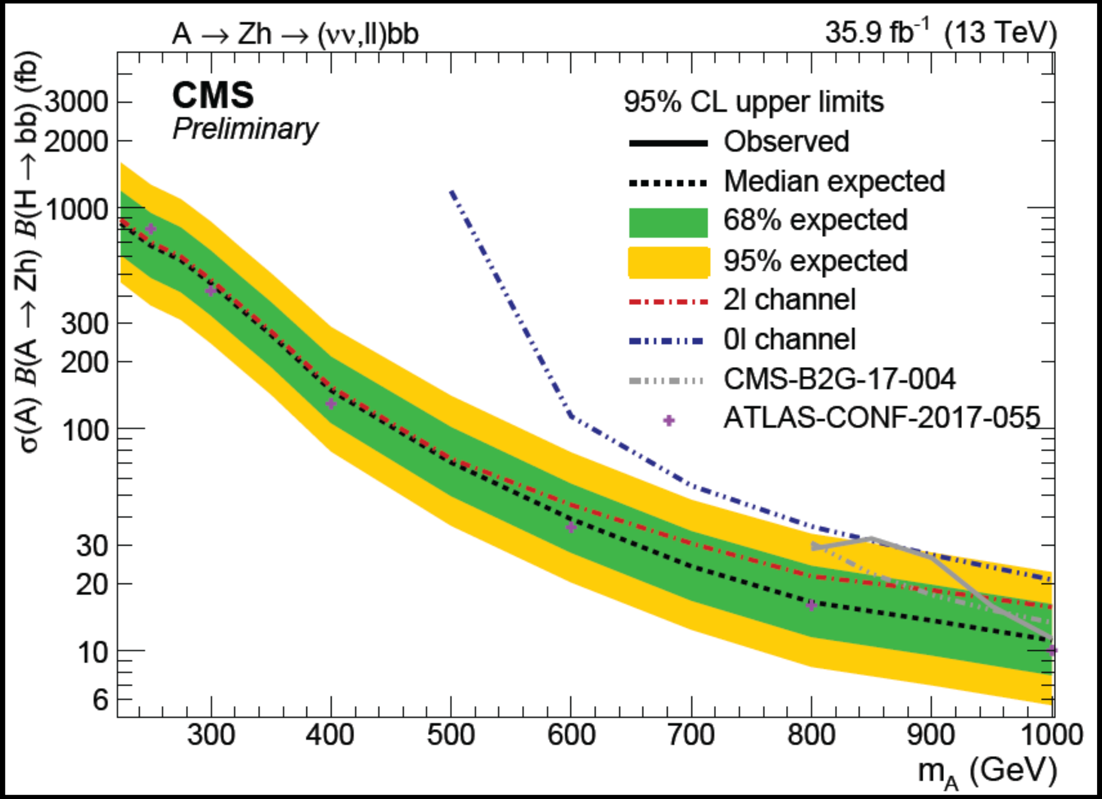


Expected and observed 95% CL limits on σ_h/σ_{SM} x BR h(→ αα) in 2HDM+S type III for tan β = 5.

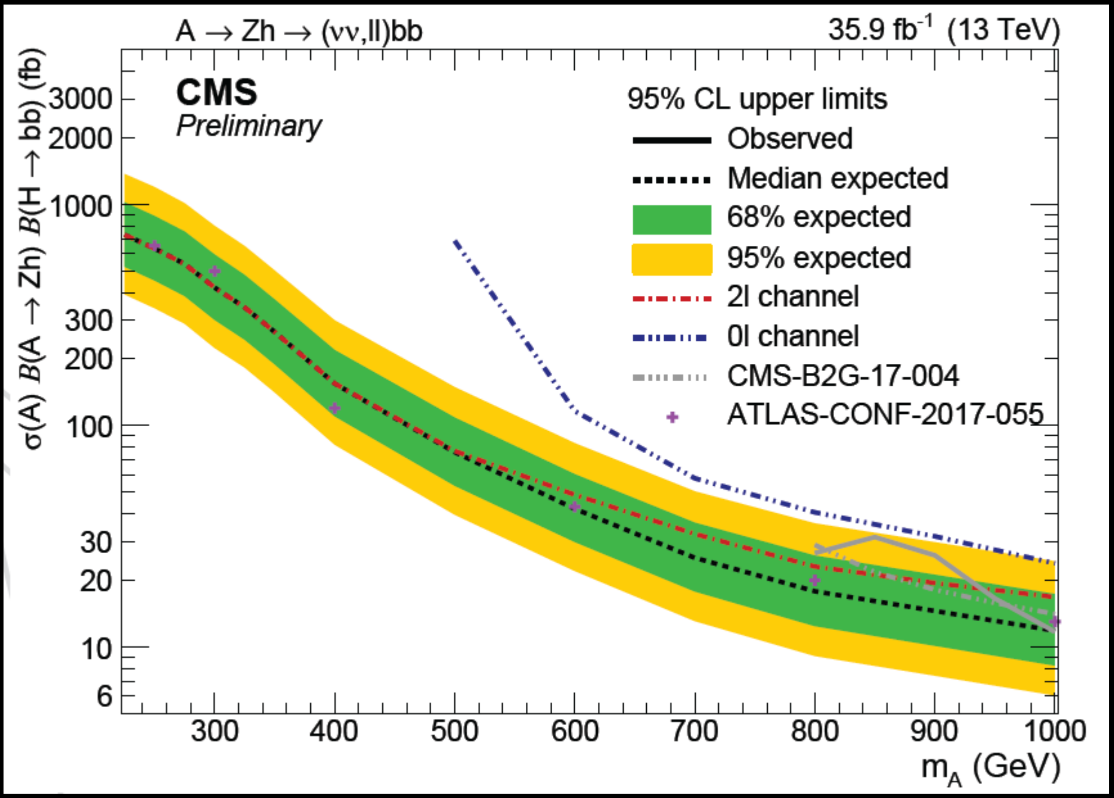


Expected Limits on $\sigma_A \times BR(A \to Zh) \times BR(h \to b\bar{b})$

gluon-gluon fusion



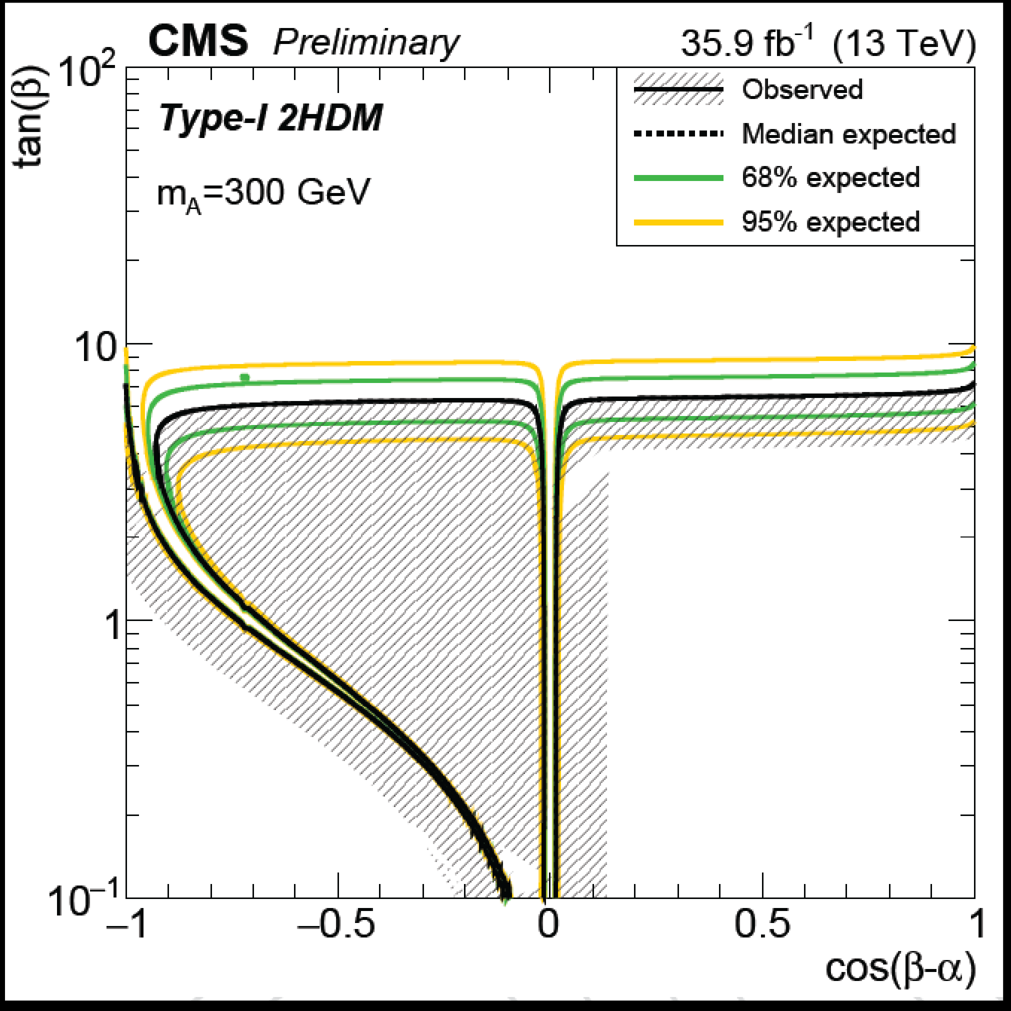
b-quark associated

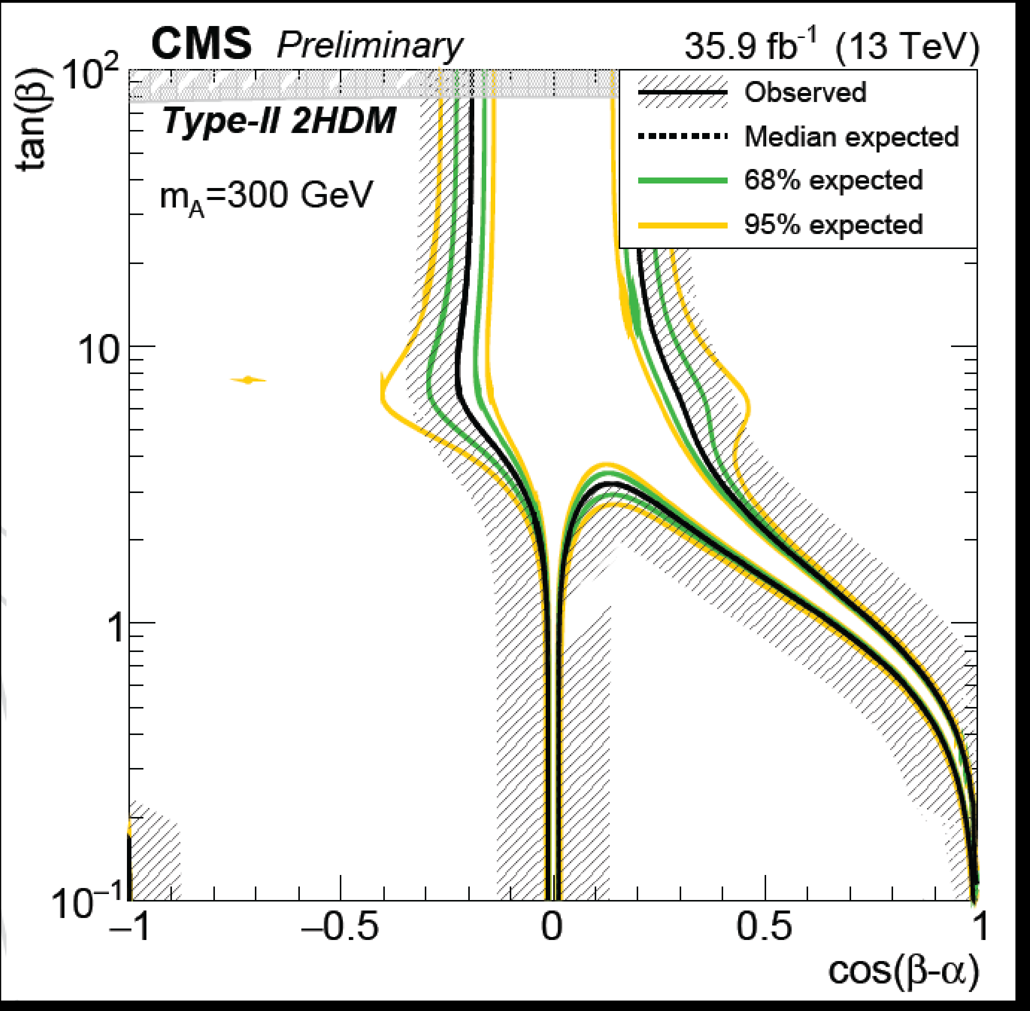


The observed $\sigma_{ggA} \cdot BR_{bb}$ exclusion limits are 0.012−0.8 pb

The observed $\sigma_{bqA} \cdot BR_{bb}$ exclusion limits are 0.012−0.7 pb

- The exclusion region in the cos(*β*-*α*) versus tan*β* for $m_A = 300$ GeV for two 2HDM models.
- The newly discovered Higgs boson (m_A= 125GeV), is actually the lighter one of the CP-even Higgs bosons predicted by 2HDMs.
- Another assumption made: $m_A = m_H = m_{H\pm}$
- The potential parameter which softly breaks Z_2 symmetry is chosen as: $m_{12}^2 = m_A^2 \frac{\tan\beta}{1+\tan^2\beta}$





Summary

- No significant excess of data is observed above the expected SM background, upper limits at 95% CL are set on on σ_h/σ_{SM} x BR(h(125) → αα → 2μ2τ for the pseudoscalar masses between 15 and 62.5 GeV.
- No excess of events is found on top of the expected SM background. Upper limits are set on B(h → αα → 2b2τ). They range from 4 to 12% over the pseudoscalar mass range between 15 and 60 GeV. This corresponds to upper limits on B(h → aa) between 6 and 26% in the most favorable 2HDM+S scenario (namely 2HDM+S type-3 with tan *b* = 2).
- No signal is observed in the search for a pseudoscalar Higgs boson. Upper limits are set at the 95% CL for $\sigma_A \times BR(A \rightarrow Zh) \times BR(h \rightarrow b\bar{b})$ of 0.012 − 0.80 pb in the range of m_A = 220 – 1000 GeV.

Thank you