

Alignment without decoupling in two-Higgs-doublet models

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Based on

[arXiv:1507.00933] (PRD)

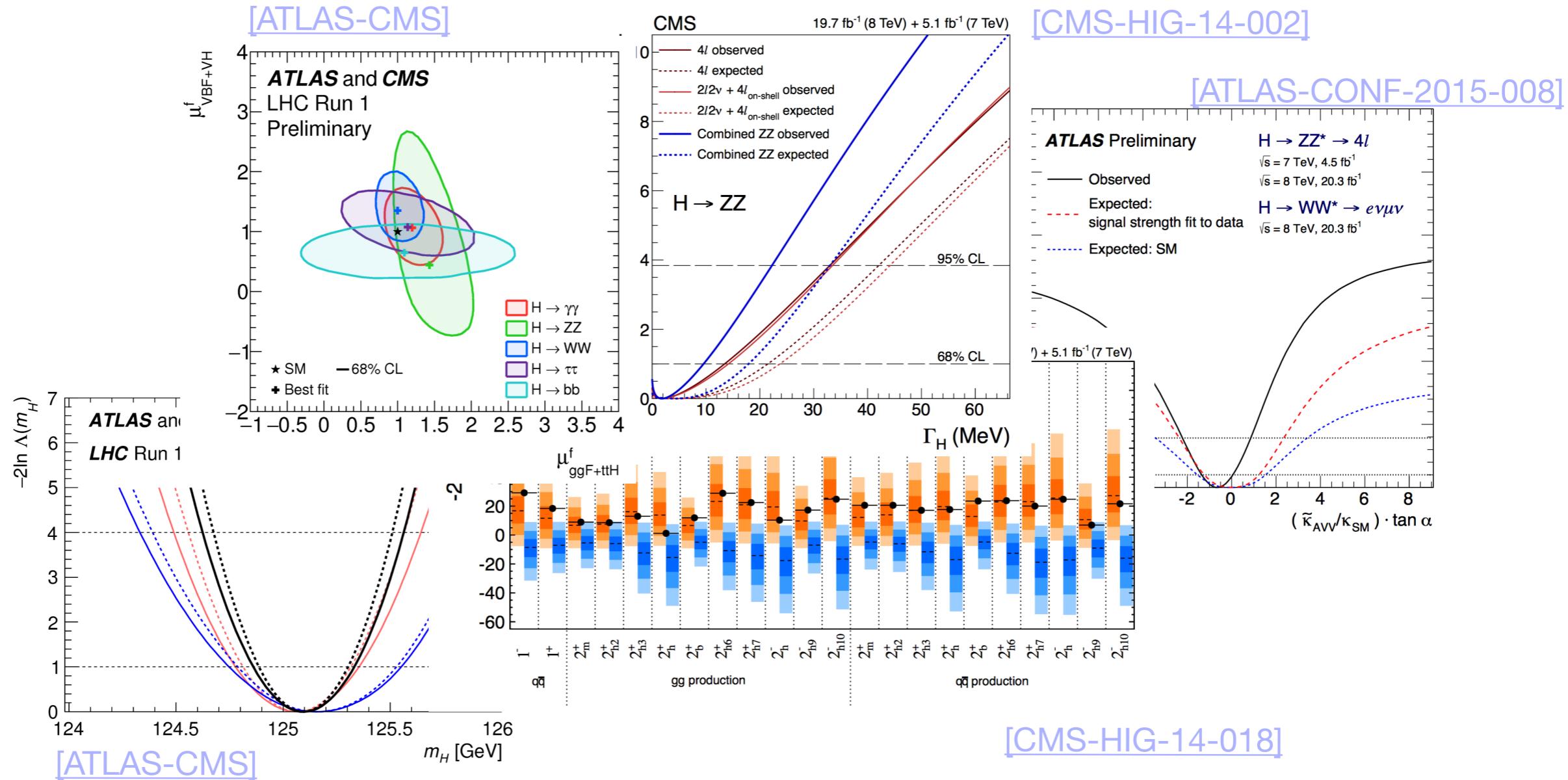
and **[arXiv:1511.03682]** (to appear in PRD)

In collaboration with

John F. Gunion (UC Davis), **Howard E. Haber** (UC Santa Cruz),

Yun Jiang (UC Davis & Niels Bohr Institute) and **Sabine Kraml** (LPSC Grenoble)

Motivations



All measurements point towards a **SM-like state**.

Could it be the consequence of the **alignment limit** of a
multi-doublet Higgs sector (two doublets here) ?

What would then be the implications for LHC Run II ?

The Framework

The 2HDM in the Higgs and \mathbb{Z}_2 bases

We consider here the **CP-conserving two-Higgs-doublet models (2HDMs)** as a framework relevant for LHC phenomenology (no assumption on the high energy behavior)

- In the **Higgs basis** (H_1, H_2), the vacuum expectation value (vev), $v \approx 246$ GeV, resides entirely in one of the two doublets:

$$H_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}G^+ \\ v + h_1 + iG^0 \end{pmatrix}, \quad H_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}H^+ \\ h_2 + iA \end{pmatrix}$$

$|Z_i| \lesssim 10$ by virtue of **perturbativity**

$$\begin{aligned} \mathcal{V} = & Y_1 H_1^\dagger H_1 + Y_2 H_2^\dagger H_2 + Y_3 [H_1^\dagger H_2 + \text{h.c.}] + \frac{1}{2} Z_1 (H_1^\dagger H_1)^2 + \frac{1}{2} Z_2 (H_2^\dagger H_2)^2 + Z_3 (H_1^\dagger H_1)(H_2^\dagger H_2) \\ & + Z_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + \left\{ \frac{1}{2} Z_5 (H_1^\dagger H_2)^2 + [Z_6 (H_1^\dagger H_1) + Z_7 (H_2^\dagger H_2)] H_1^\dagger H_2 + \text{h.c.} \right\} \end{aligned}$$


- The general 2HDM has large tree-level flavor changing neutral currents. **Natural flavor conservation** is a way to forbid them by imposing a **\mathbb{Z}_2 -symmetry** in the so-called **\mathbb{Z}_2 -basis** (Φ_1, Φ_2) (in which the symmetry is explicit):

$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} \equiv \begin{pmatrix} c_\beta & -s_\beta \\ s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix} \quad \mathbb{Z}_2 : \Phi_1 \rightarrow \Phi_1, \quad \Phi_2 \rightarrow -\Phi_2 \quad \langle \Phi_i^0 \rangle = v_i / \sqrt{2} > 0$$

$$\mathcal{V} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - [m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}] + \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \dots$$

- The CP-even mass eigenstates are obtained through $\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} \sqrt{2}\text{Re}\Phi_1^0 - v_1 \\ \sqrt{2}\text{Re}\Phi_2^0 - v_2 \end{pmatrix}$

The alignment limit

- In the Higgs basis, the CP-even mass matrix is $\mathcal{M}_H^2 = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & m_A^2 + Z_5 v^2 \end{pmatrix}$
- The CP-even mass eigenstates are

$$\begin{aligned} H &= h_1 c_{\beta-\alpha} - h_2 s_{\beta-\alpha} & m_h < m_H \\ h &= h_1 s_{\beta-\alpha} + h_2 c_{\beta-\alpha} \end{aligned}$$

⇒ There is a SM state (with SM tree-level couplings and self-couplings) if one of the two eigenstates **aligns with the direction of the vev**: this is the **alignment limit**

- Furthermore, when $\mathcal{M}_{11}^2 < (>) \mathcal{M}_{22}^2$ then h (H) is the SM-like state:

Alignment in the **h125 scenario**:

$$h \simeq h_1$$

$$c_{\beta-\alpha} = \frac{-Z_6 v^2}{\sqrt{(m_H^2 - m_h^2)(m_H^2 - Z_1 v^2)}} \simeq 0$$

$\Rightarrow \begin{cases} m_H^2 \gg v^2: \text{Decoupling limit} \\ |Z_6| \ll 1: \text{Alignment w/o decoupling} \end{cases}$

Alignment in the **H125 scenario**:

$$H \simeq h_1$$

$$s_{\beta-\alpha} = \frac{-Z_6 v^2}{\sqrt{(m_H^2 - m_h^2)(Z_1 v^2 - m_h^2)}} \simeq 0$$

$\Rightarrow |Z_6| \ll 1$ and **no decoupling limit**
 \Rightarrow The light state h remains to be observed

Numerical Aspects

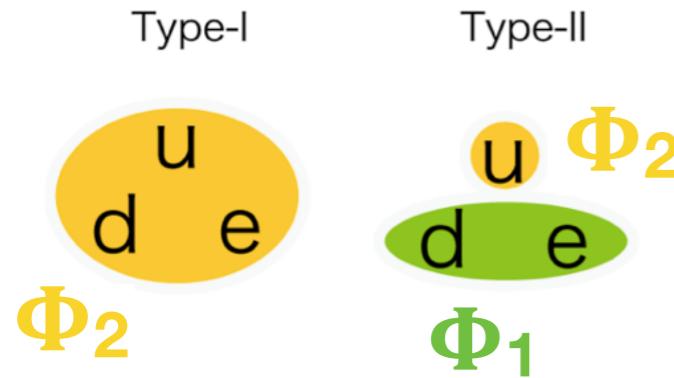
Focus on the H125 scenario:

$$m_h < m_H = 125.5 \text{ GeV}$$

We study the phenomenology of the near-alignment limit by imposing a maximal
1% deviation of the HVV coupling from 1: $c_{\beta-\alpha} \geq 0.99 \implies |s_{\beta-\alpha}| \lesssim 0.14$

Alignment limit and the LHC Higgs measurements

Couplings to gauge bosons are determined from gauge invariance, couplings to fermions are determined from the \mathbb{Z}_2 charges:



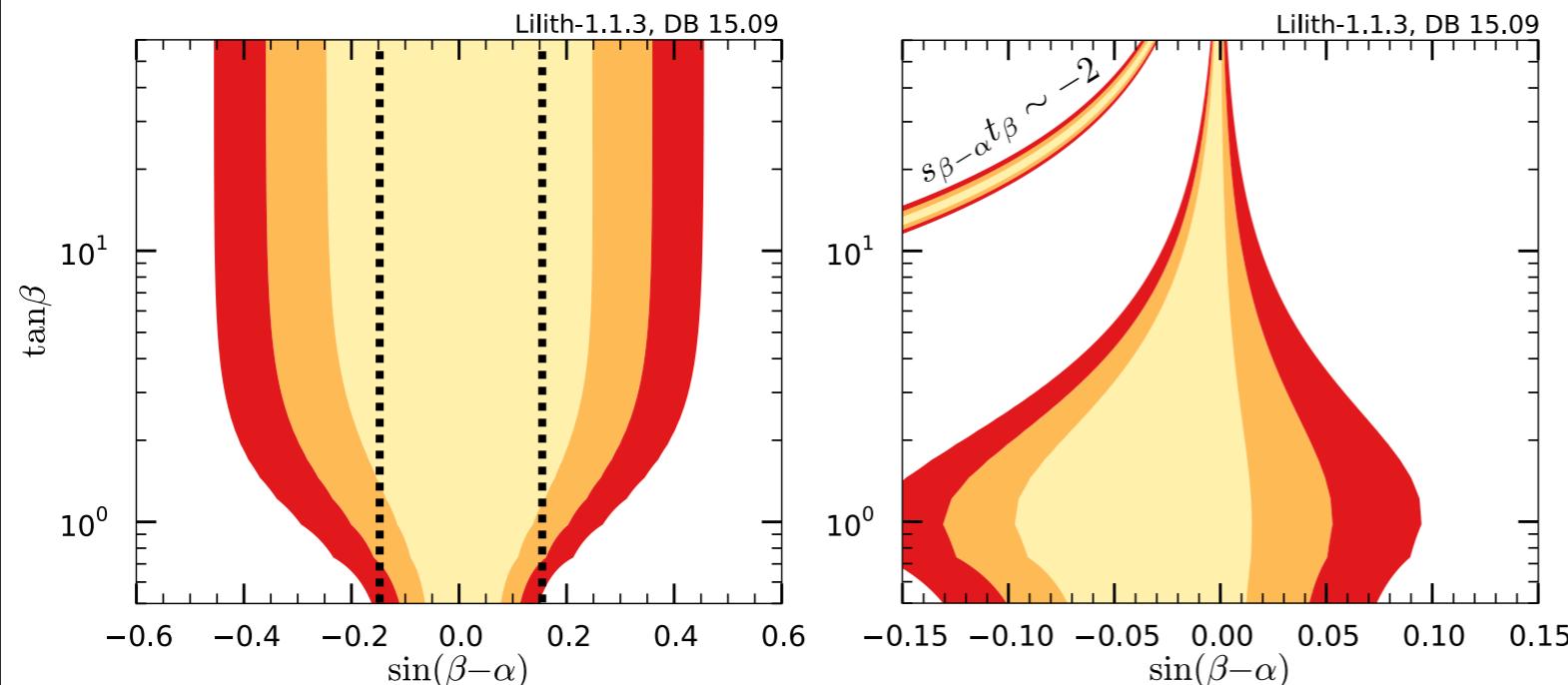
$$C_V^H = c_{\beta-\alpha}, \quad C_V^h = s_{\beta-\alpha}$$

$$\text{I: } C_F^H = \frac{\sin \alpha}{\sin \beta} = c_{\beta-\alpha} - s_{\beta-\alpha} \cot \beta$$

$$\text{II: } C_D^H = \frac{\cos \alpha}{\cos \beta} = c_{\beta-\alpha} + s_{\beta-\alpha} \tan \beta, \quad C_U^H = C_F^H$$

Possibility of **delayed alignment** and negative C_D

ATLAS and CMS precise measurements of signal strengths impose substantial constraints.
Using **Lilith**, in the **H125** scenario:



see also [JB, B. Dumont, S. Kraml] [arXiv:1409.1588]

Lilith
Light LIkelihood fiT for the Higgs
[JB, B. Dumont] [arXiv:1502.04138]

Degeneracy near the **alignment limit**.

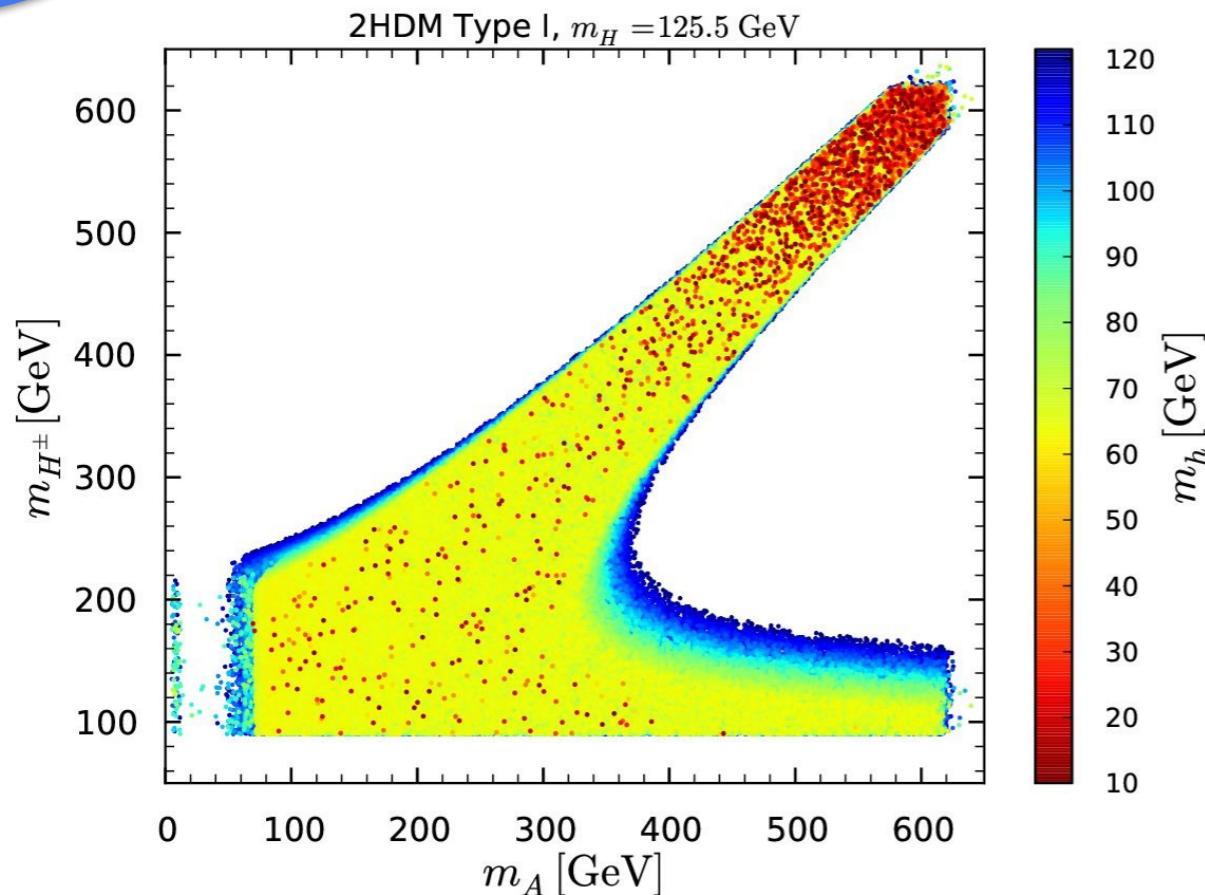
In Type II: presence of a sharp branch, characterized by $C_D \sim -1$:
the « **wrong-sign solution** »,
see [Ferreira, Gunion, Haber, Santos]
[arXiv:1403.4736]

Setup

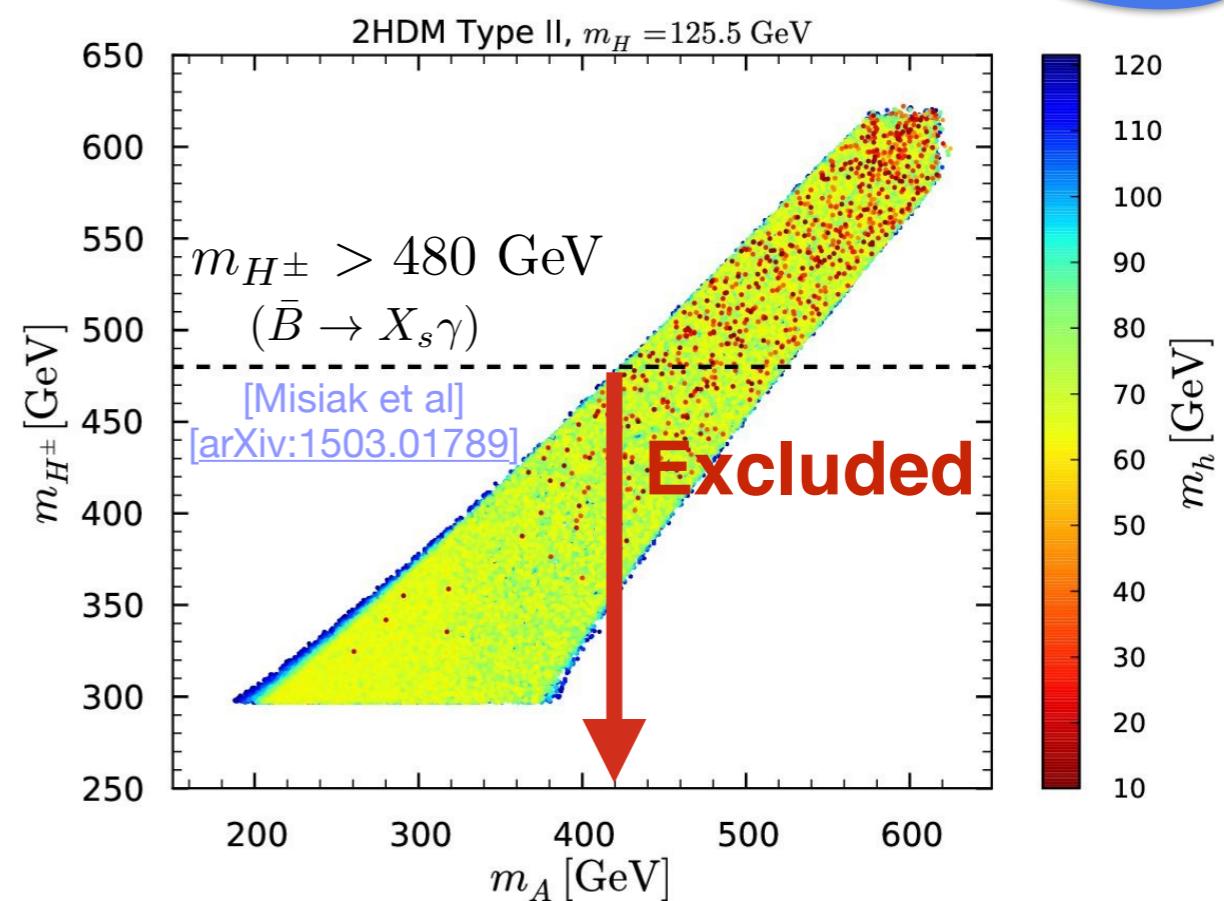
- Branching ratio and theoretical constraints from **2HDMC** [Eriksson, Rathsman, Stål] [arXiv:0902.0851]
- Cross sections from **SusHi**, **VBFNLO** [Herlander, Liebler, Mantler] [arXiv:1212.3942]
[Arnold et al] [arXiv:0811:4559]
- Theoretical constraints:
 - ✓ **Stability** of the scalar potential
 - ✓ **Perturbativity** of the self-couplings
 - ✓ Tree-level **unitarity** of the Higgs-Higgs scattering matrices
- Experimental constraints:
 - ✓ **S**, **T**, **U** Peskin-Takeuchi parameters (\rightarrow Higgs mass splitting)
 - ✓ **Flavor** constraints (\rightarrow tb, charged Higgs mass bounds, CP-odd mass)
 - ✓ **LEP** Higgs searches ($e^+e^- \rightarrow Z h$, $e^+e^- \rightarrow Z^* \rightarrow A h$, $e^+e^- \rightarrow H^+H^-$)
 - ✓ **LHC Higgs** searches ($A \rightarrow \mu\mu$, $bb(A,h) \rightarrow \tau\tau$, $h,H,A \rightarrow \tau\tau$, **A \rightarrow Zh**, $H \rightarrow hh$, ...)
 - ✓ 125 GeV Higgs **signal strengths** from **Lilith** [Bernon, Dumont] [arXiv:1502.04138]

Mass of the extra states

Type I

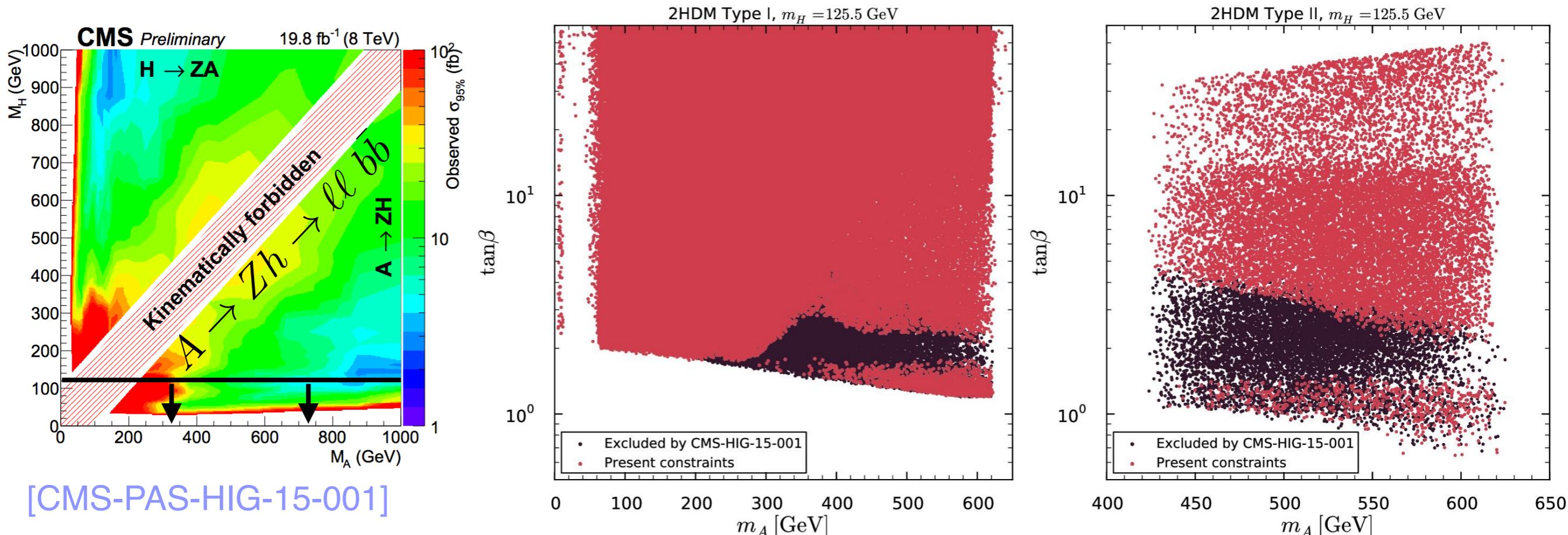


Type II



- In both Types, $m_A, m_{H^\pm} \lesssim 630$ GeV from **perturbativity**.
- In Type II, due to the charged Higgs mass bound and the T parameter constraint: $m_A \gtrsim 420$ GeV.
- In Type I, due to weaker flavor constraints, charged Higgs masses down to the LEP bound are allowed. For $m_{H^\pm} \lesssim 160$ GeV, all allowed m_A values are possible.

Impact of the CMS $A \rightarrow Zh \rightarrow ll\bar{b}b/\tau\tau$ search

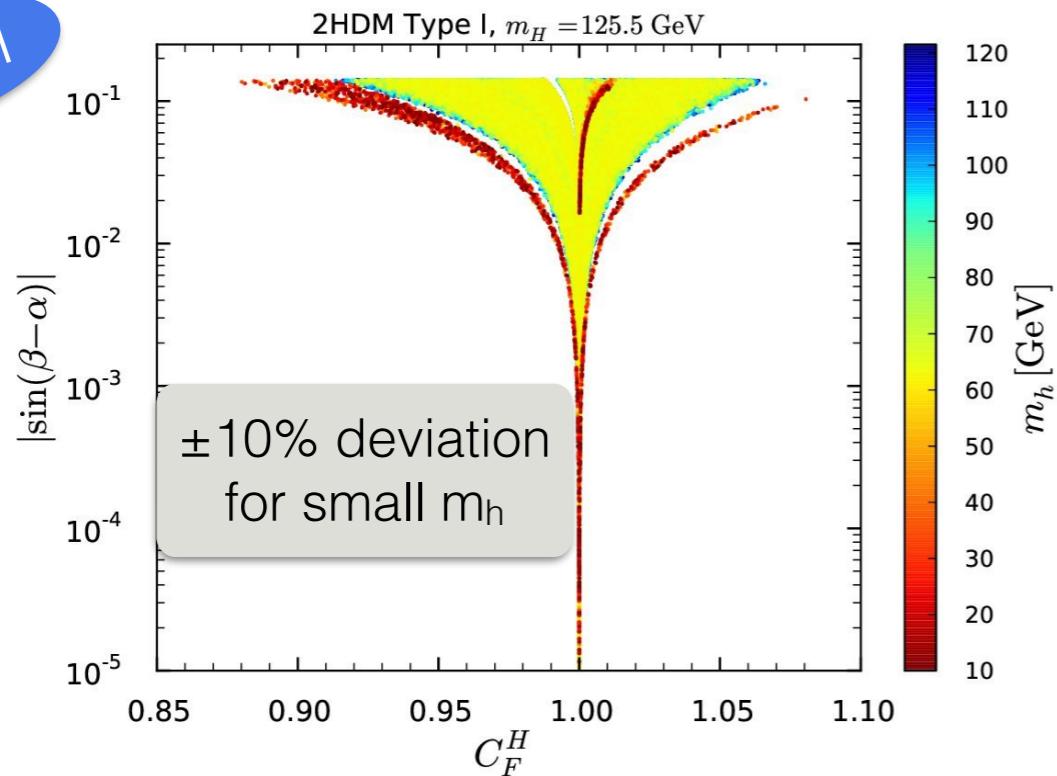


- The two resonance masses are free parameters, the search is sensitive to light resonance masses **down to $\sim 40 \text{ GeV}$** .
- $h \rightarrow bb$ has the largest excluded cross-section
- In our scenario, h has mass below 125 GeV and has therefore large $\text{BR}(h \rightarrow bb) \sim 0.9$
- **Severe constraints on the low t_b region** ⇒ « gaps » in subsequent plots

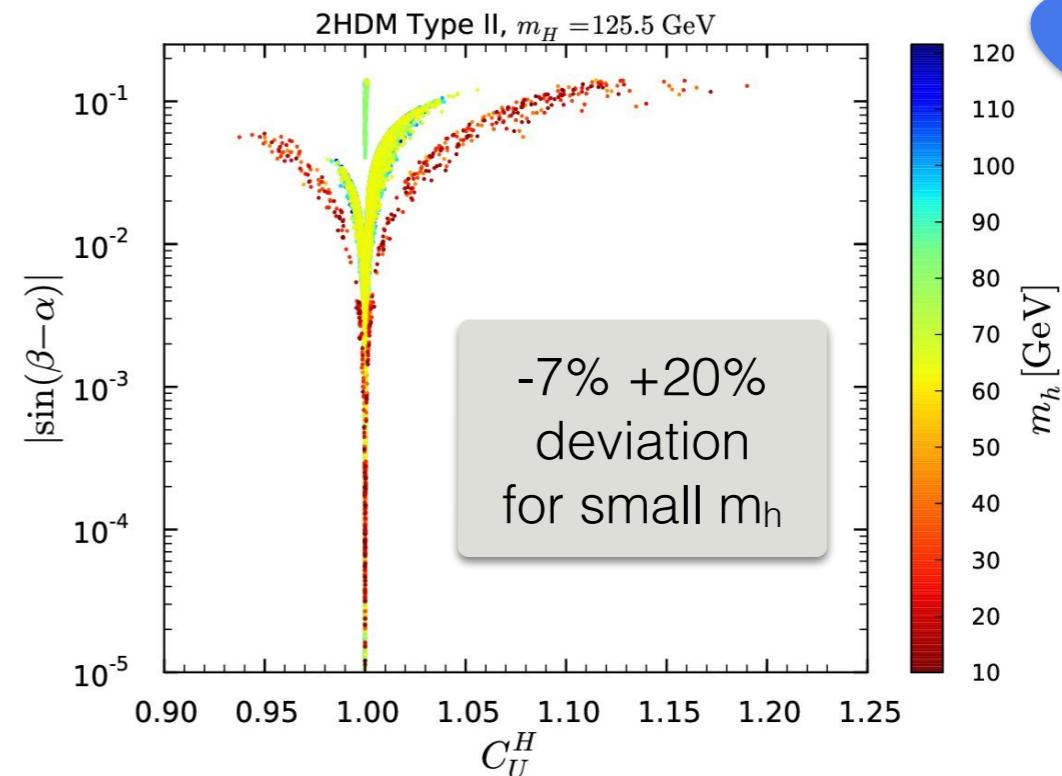
Note that the corresponding ATLAS search requires $m_h = 125 \text{ GeV}$ and does not provide significant constraints in this scenario. [ATLAS-HIGG-2013-06]

Fermion couplings of the 125 GeV state

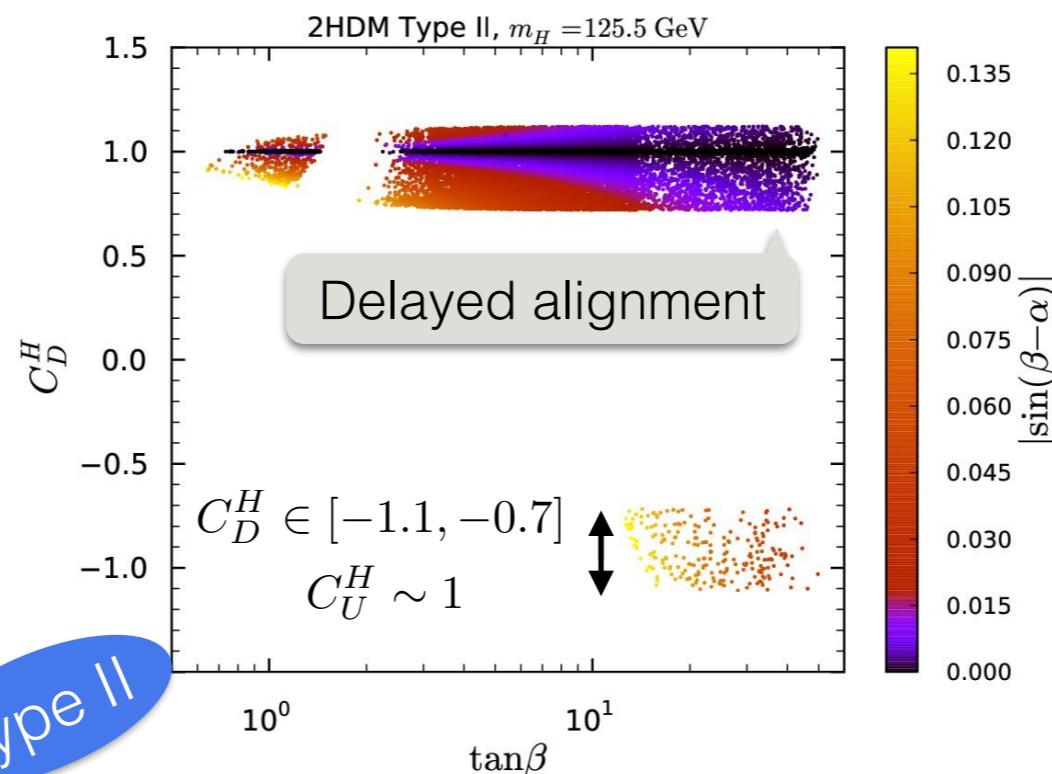
Type I



Type II

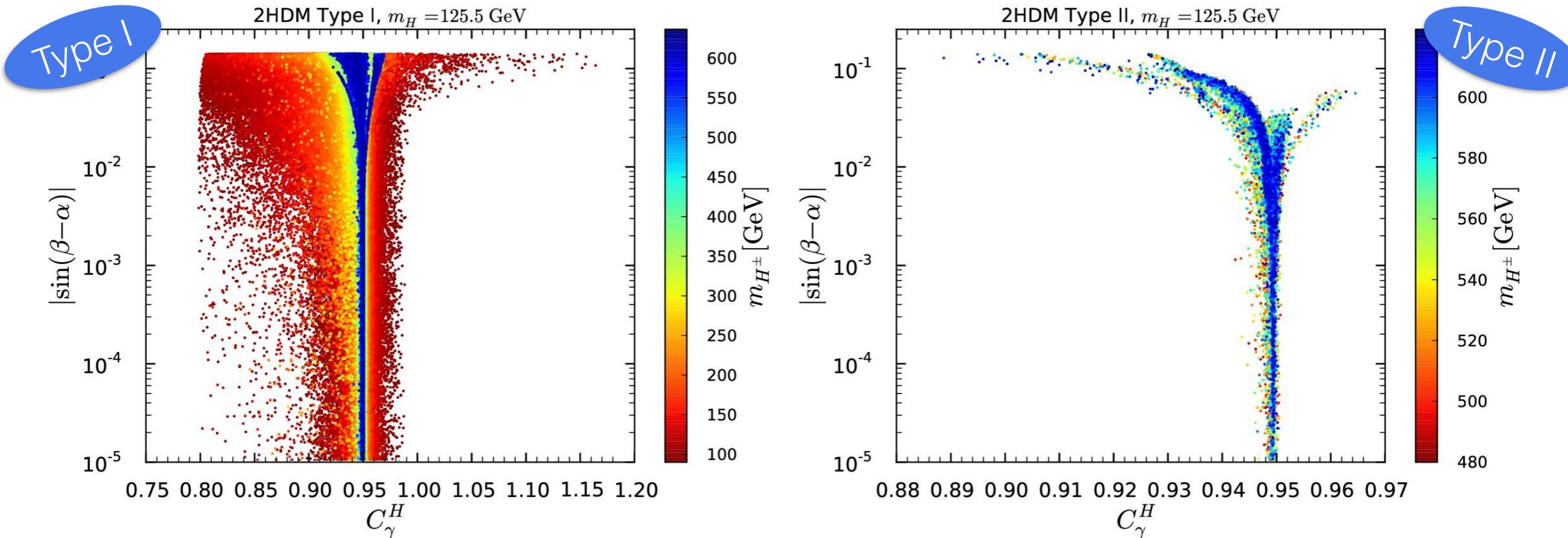


Type II



Loop-induced couplings of the 125 GeV state

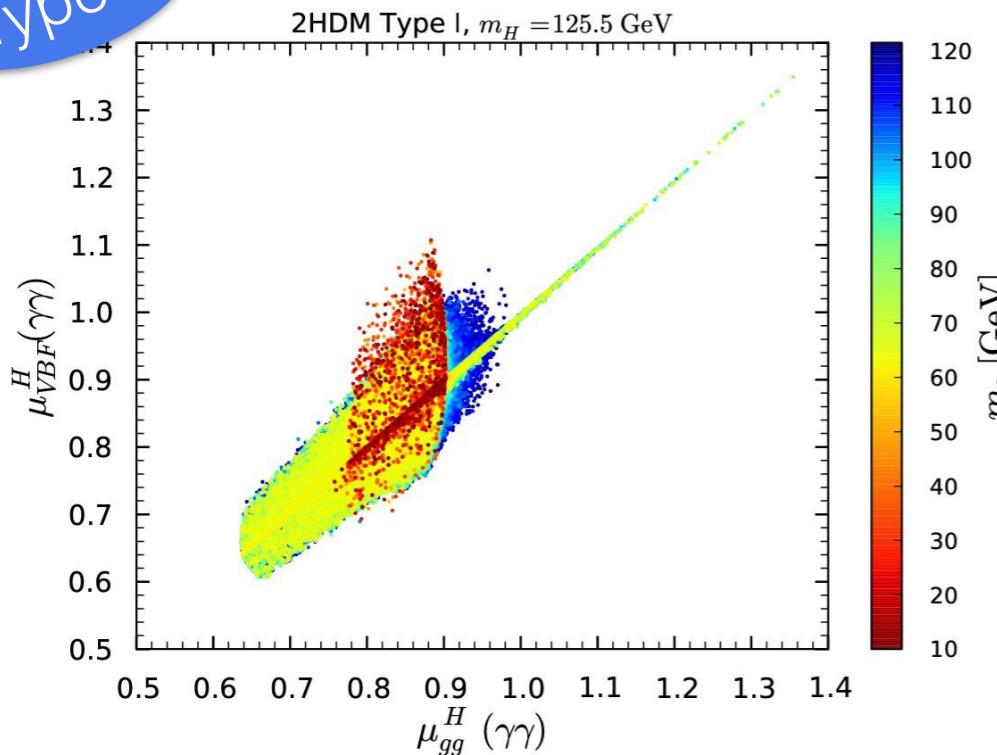
- The Hgg coupling is dominated by C_U in both Types. In the wrong-sign region of Type II however, the top and bottom loop interfere constructively and $C_g^H \simeq 1.06$.



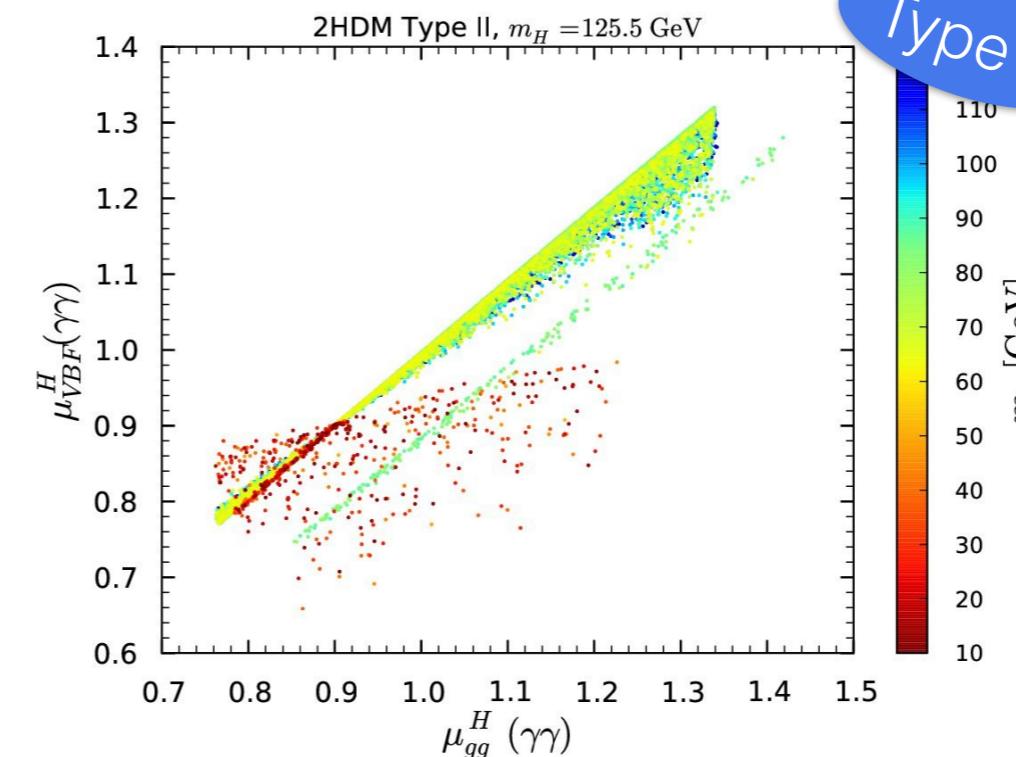
- In the alignment limit: $g_{HH^+H^-} = -\frac{1}{v}(m_H^2 + 2m_{H^\pm}^2 - 2\bar{m}^2)$ $\bar{m}^2 \in \begin{cases} \text{I: } [-(350 \text{ GeV})^2, (150 \text{ GeV})^2] \\ \text{II: } [-(200 \text{ GeV})^2, (150 \text{ GeV})^2] \end{cases}$
- For large m_{H^\pm} , $g_{HH^+H^-} \simeq -\frac{2m_{H^\pm}}{v}$ and this leads to $C_\gamma^H \simeq 0.95$.
- $C_\gamma^H > 1$ possible if light charged Higgs (and positive \bar{m}^2): only in Type I.

Signal strengths of the 125 GeV state: $\mu(X, Y) = \frac{\sigma(X)\mathcal{B}(H \rightarrow Y)}{\sigma(X_{\text{SM}})\mathcal{B}(H_{\text{SM}} \rightarrow Y)}$

Type I

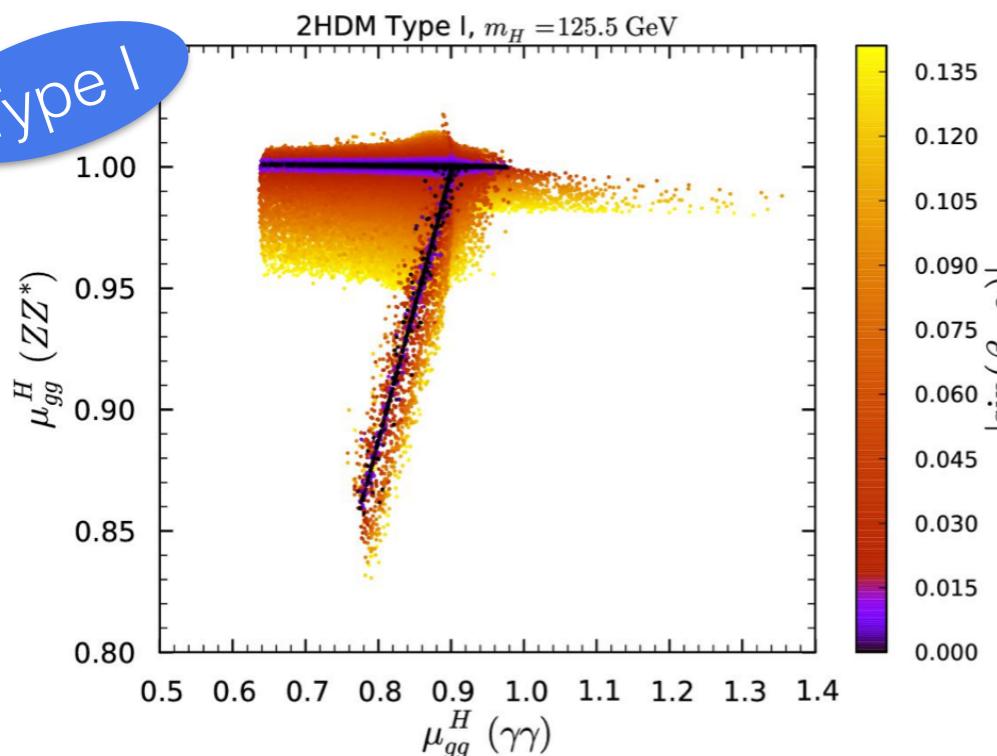


Type II

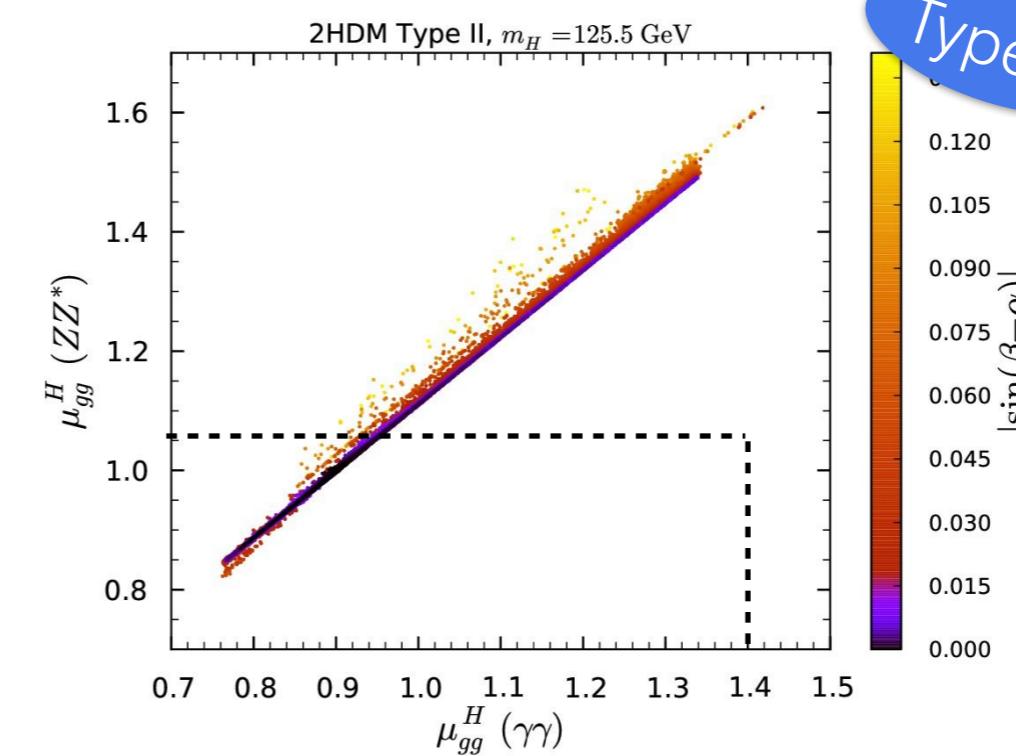


Study of signal strength correlations can lead to Type separation and extra-state mass inference

Type I



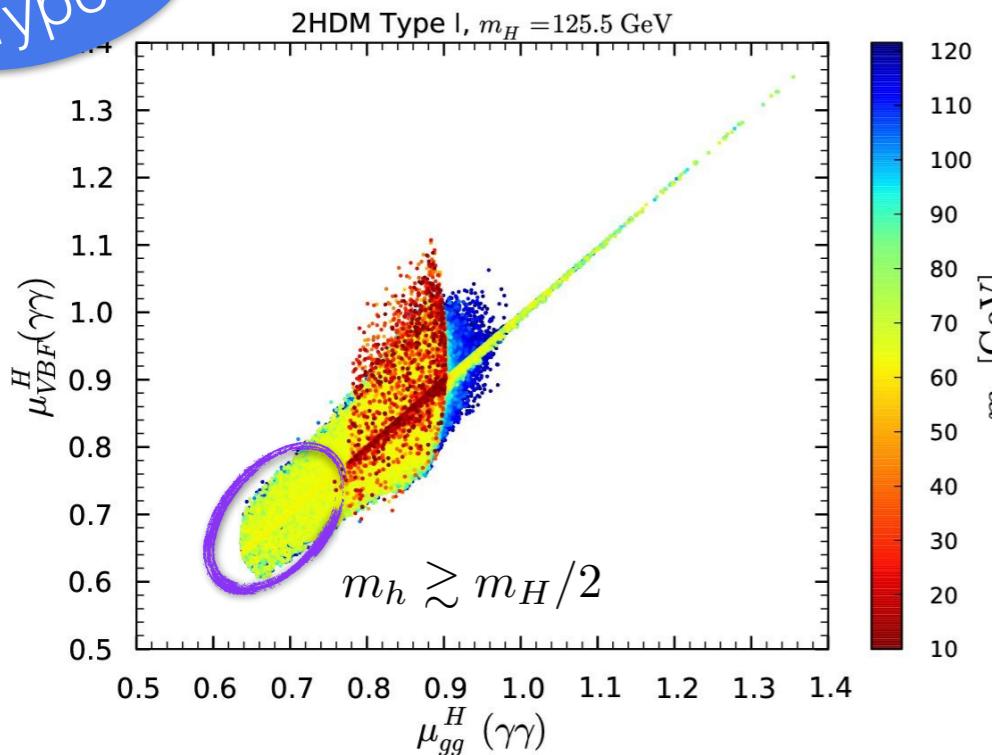
Type II



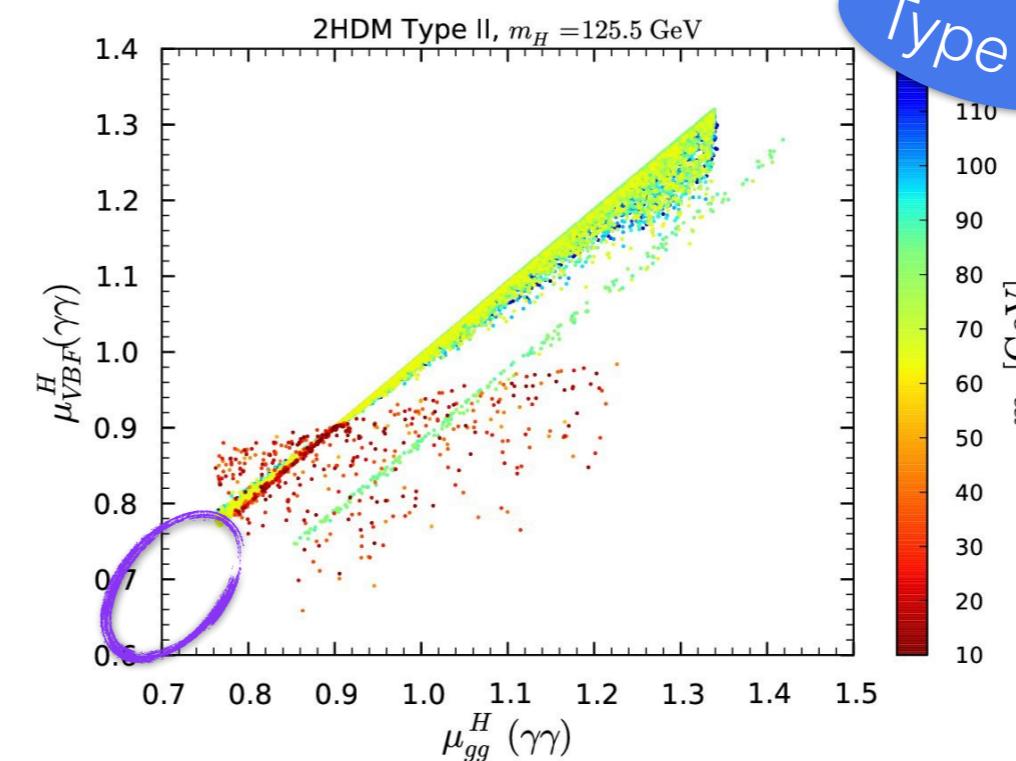
Even in near the alignment limit, signal strengths can deviate much from the SM because of the charged Higgs presence and delayed alignment in Type II

Signal strengths of the 125 GeV state: $\mu(X, Y) = \frac{\sigma(X)\mathcal{B}(H \rightarrow Y)}{\sigma(X_{\text{SM}})\mathcal{B}(H_{\text{SM}} \rightarrow Y)}$

Type I

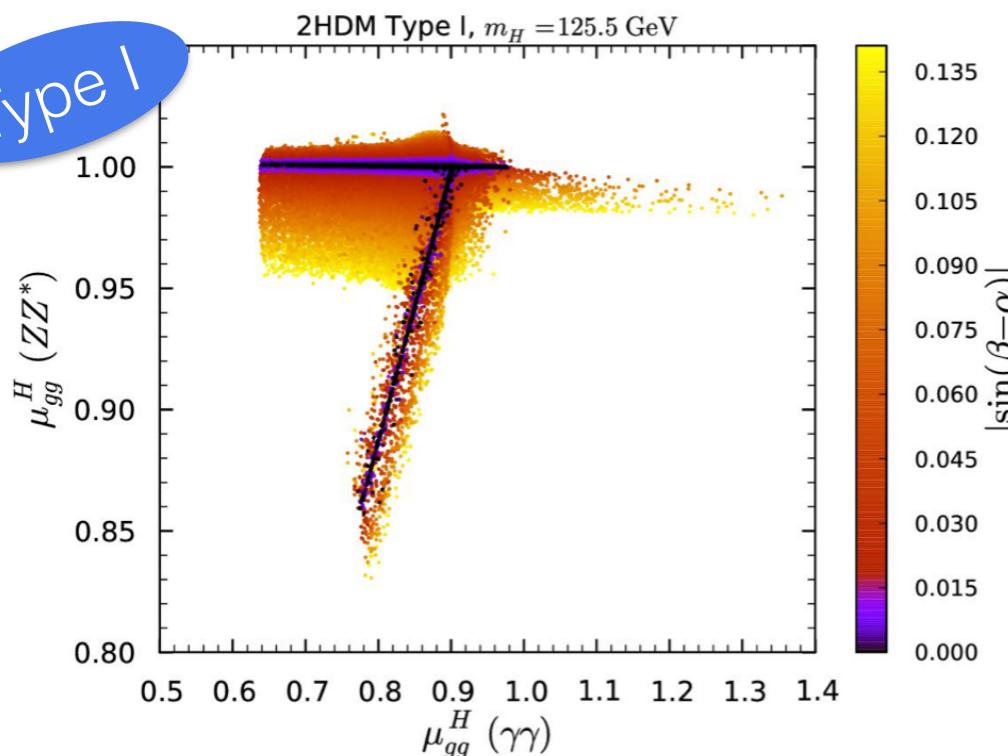


Type II

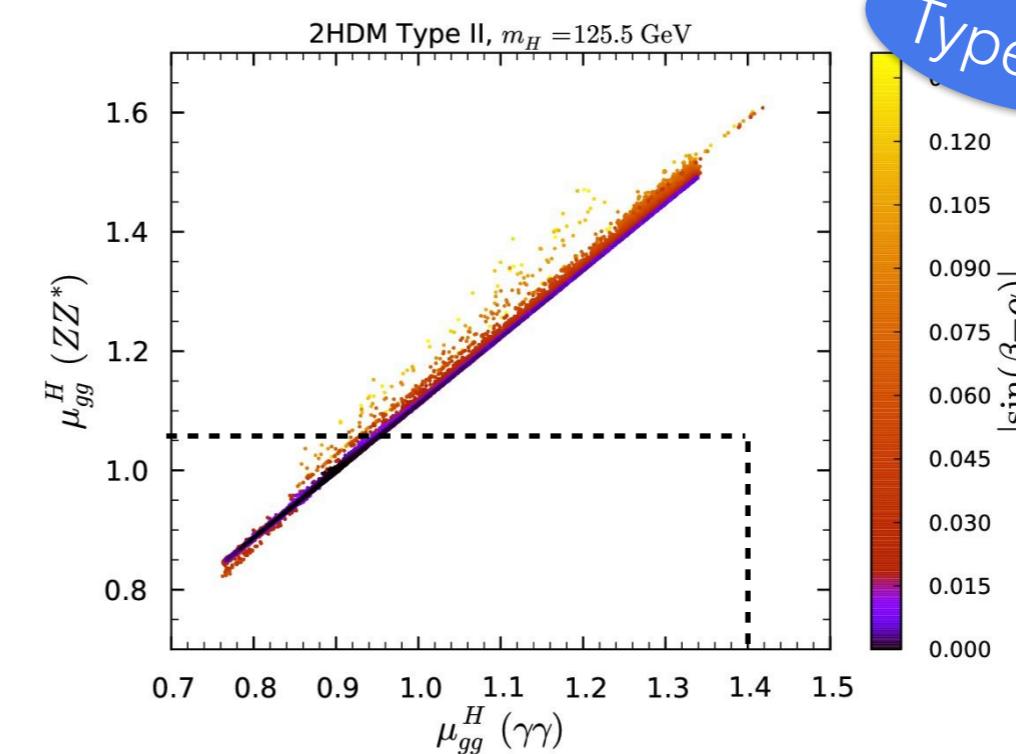


Study of signal strength correlations can lead to Type separation and extra-state mass inference

Type I



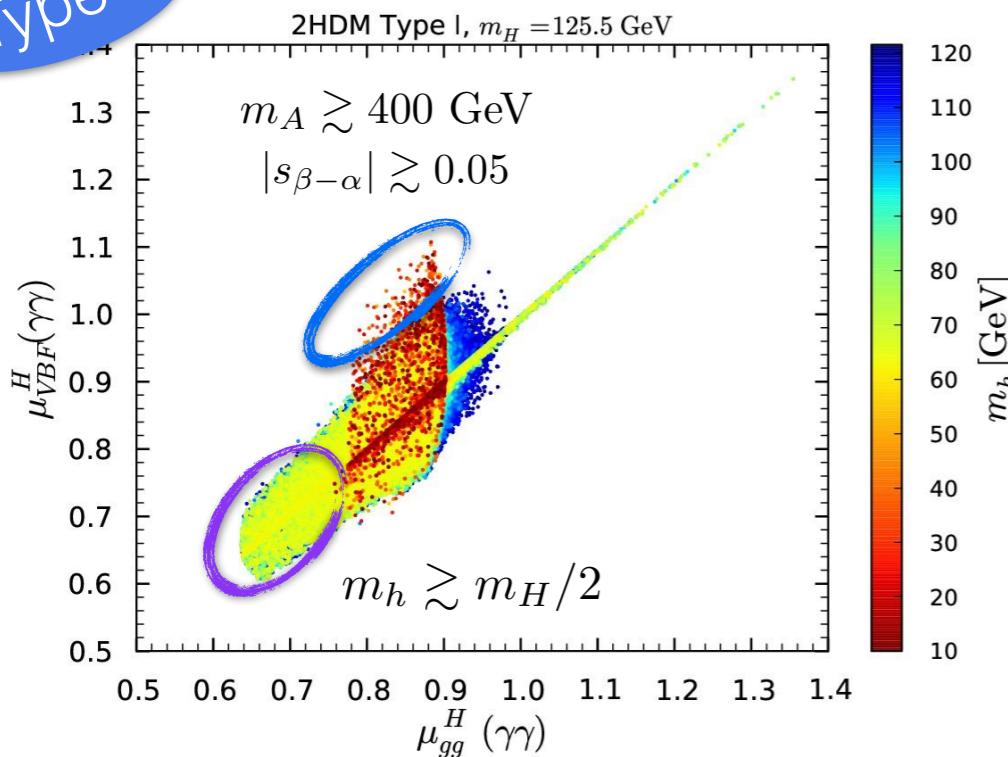
Type II



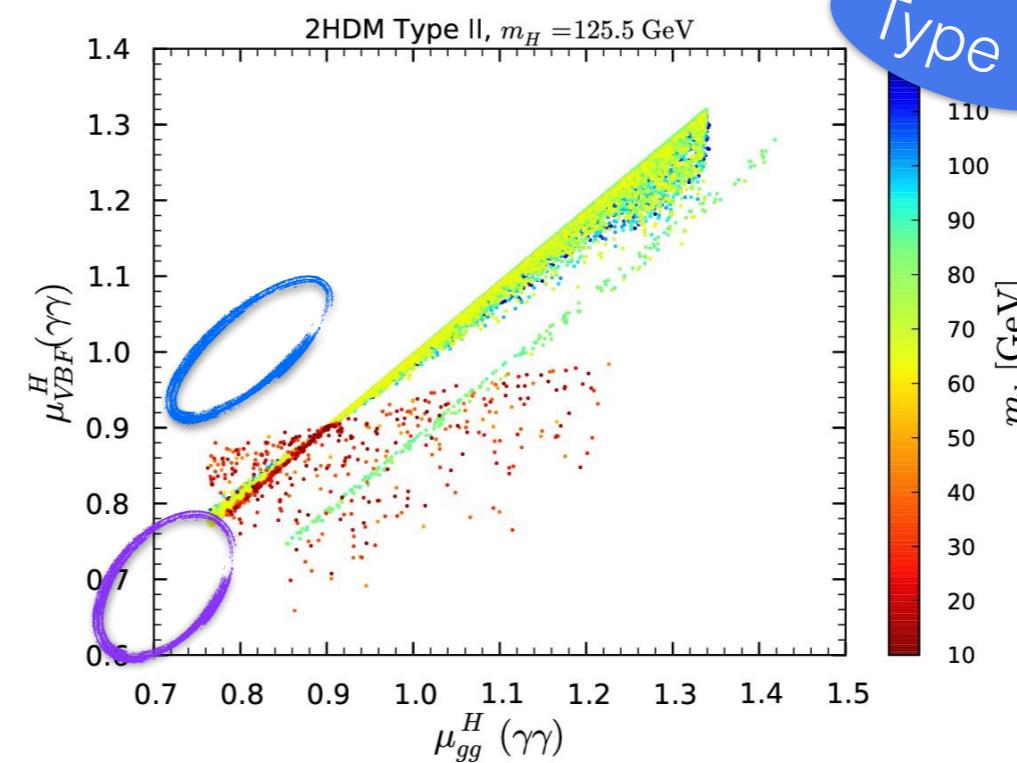
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Signal strengths of the 125 GeV state: $\mu(X, Y) = \frac{\sigma(X)\mathcal{B}(H \rightarrow Y)}{\sigma(X_{\text{SM}})\mathcal{B}(H_{\text{SM}} \rightarrow Y)}$

Type I

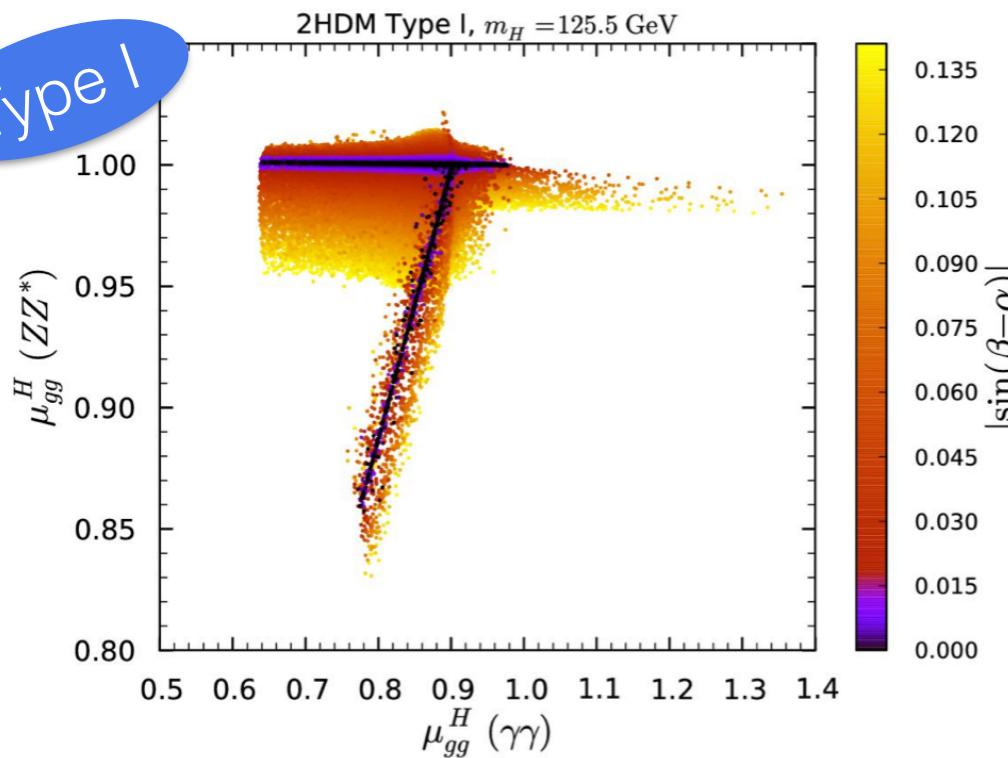


Type II

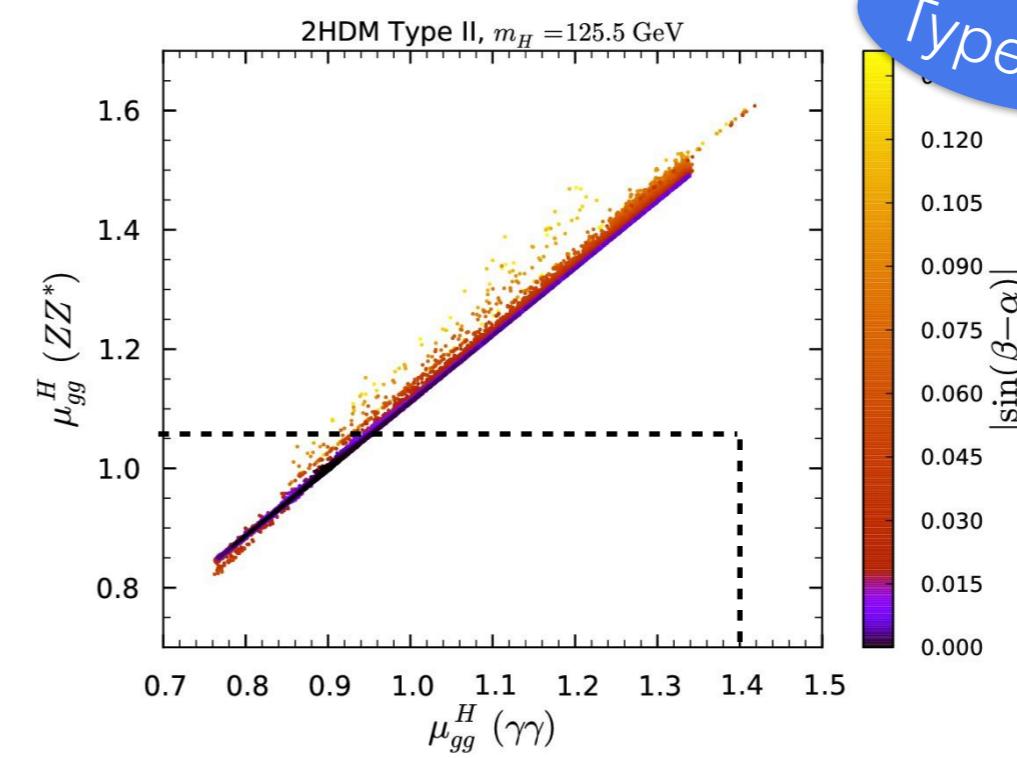


Study of signal strength correlations can lead to Type separation and extra-state mass inference

Type I

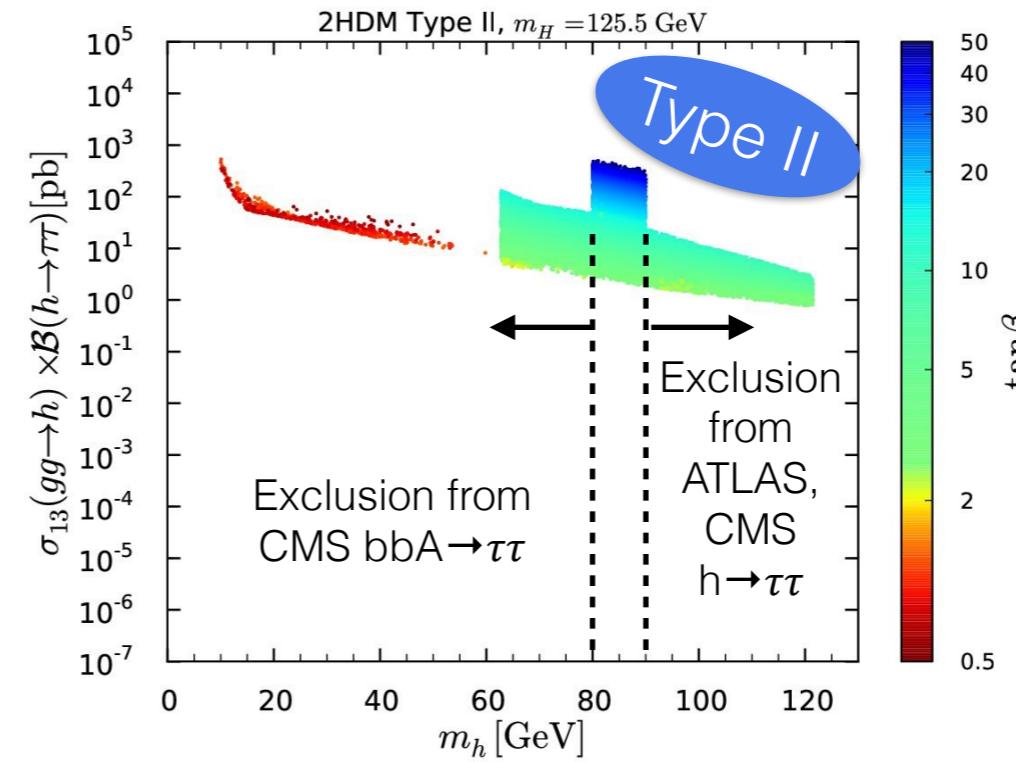
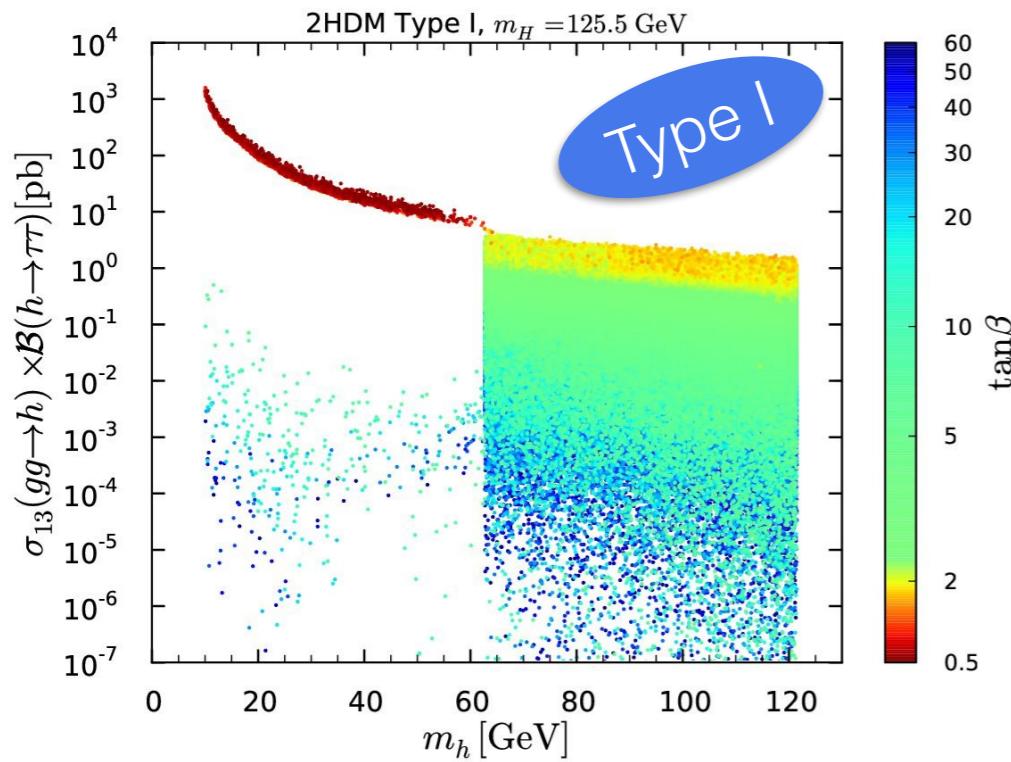


Type II

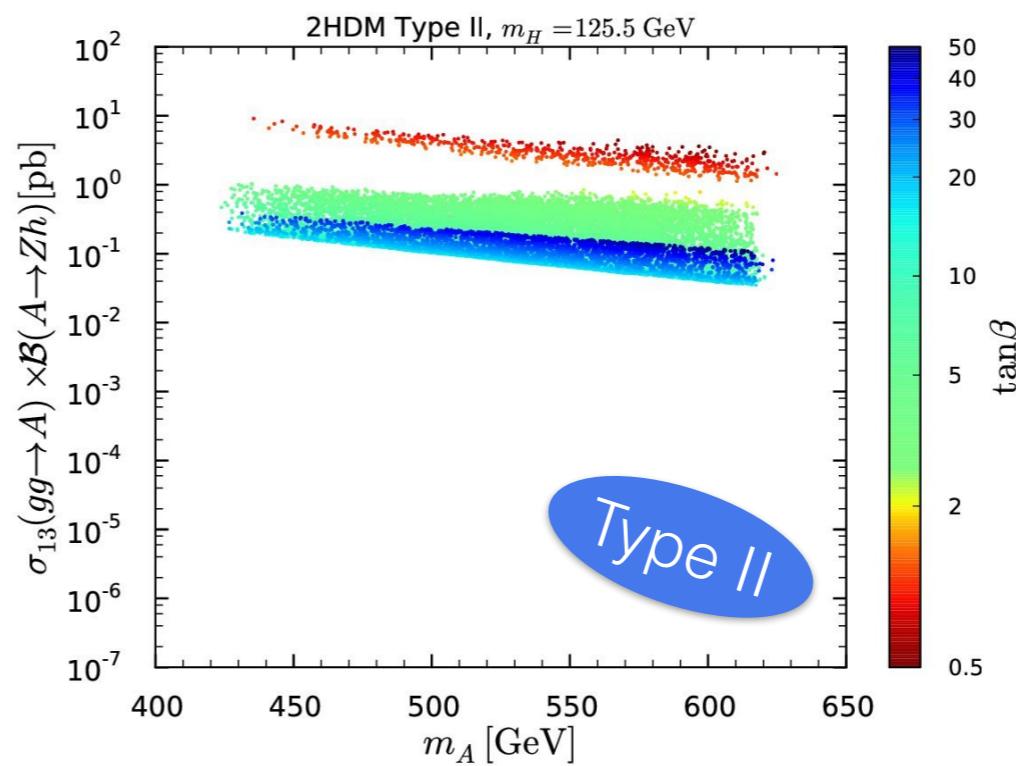
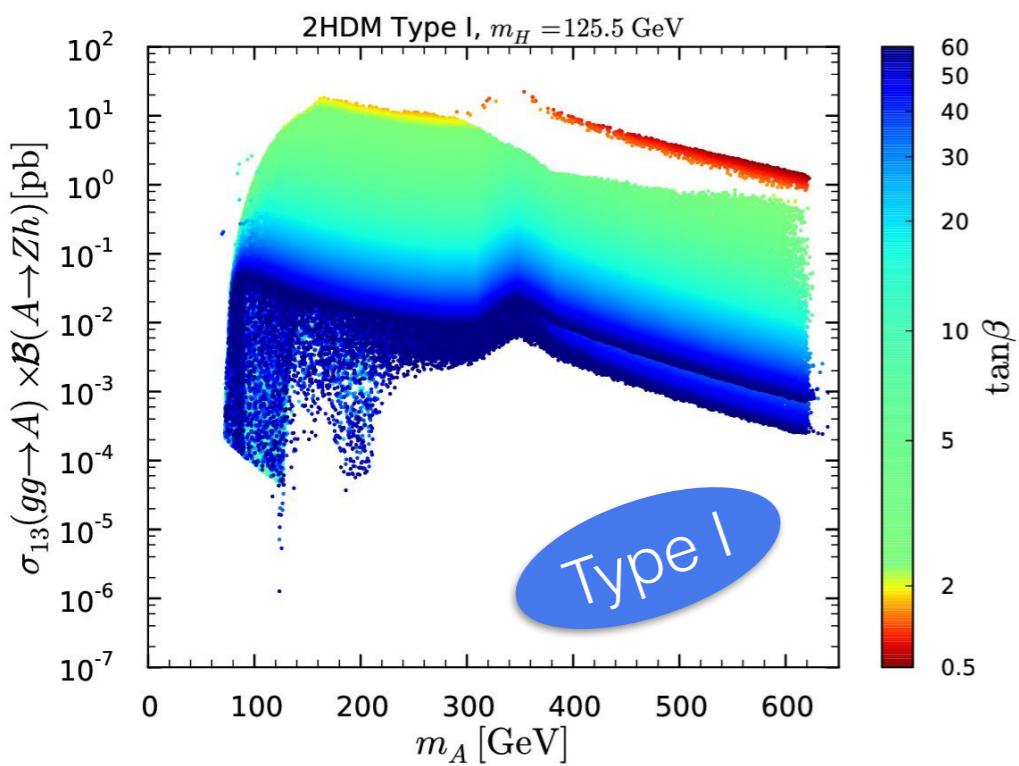


Even in near the alignment limit, signal strengths can deviate much from the SM because of the charged Higgs presence and delayed alignment in Type II

$gg \rightarrow h \rightarrow \tau\tau, gg \rightarrow A \rightarrow Zh$ at the LHC 13 TeV



Cross section above 1 pb guaranteed in Type II in the $\tau\tau$ final state, and over 10 pb in Type I for $m_h \lesssim 60$ GeV at low $\tan\beta$



$A \rightarrow Zh$ particularly promising with cross sections as high as 10 pb in both Types.

The Run II search could substantially further constraint this scenario

Conclusions

Conclusions

The regime of **alignment without decoupling** of multi-doublet Higgs sectors is particularly relevant to consider in light of the Run I LHC results.

Near the **alignment limit of the H125 scenario** of the 2HDM:

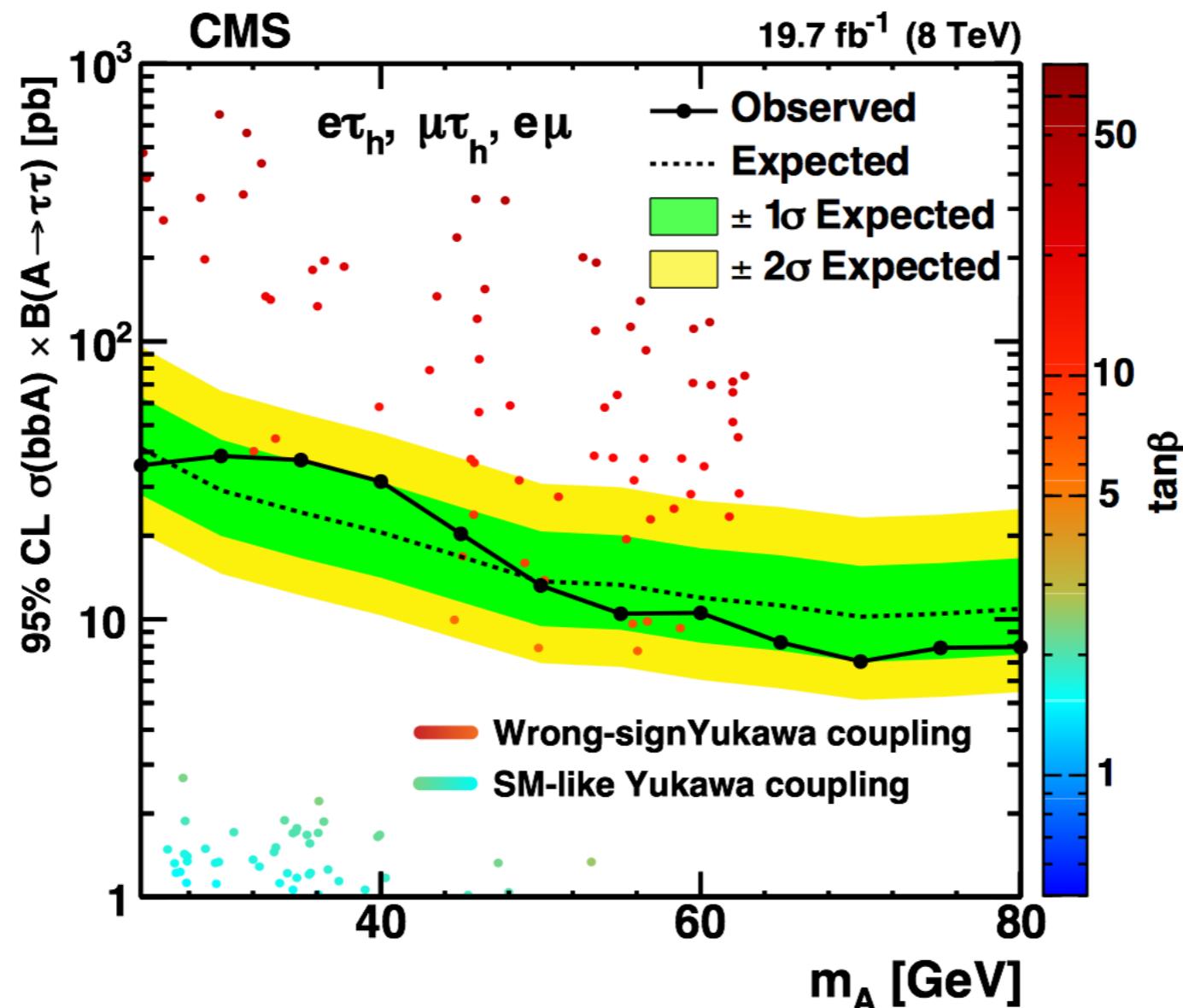
- **No decoupling limit**, restricted spectrum.
- 10-20% deviations of the H couplings to fermions are possible
- **Delayed alignment** in Type II: $C_D \approx 0.7 - 1.1$ down to $|s_{\beta-\alpha}| \sim 5 \times 10^{-3}$
Presence of a « **wrong-sign** » **solution** $C_D \approx -1.1 - -0.7$, $C_U \approx 1$
- Signal strengths can largely deviate from 1 close to alignment.
Their deviations are correlated with the masses of the extra-states.
Their correlations can be used to distinguish the model.
- The $h, A \rightarrow \tau\tau$ channels are of high interest for potential discovery.
Most exciting is the **A \rightarrow Zh channel**.

In general, looking for **low mass states** is a real experimental challenge
but could still be **extremely rewarding**

Backup

CMS $b\bar{b}(A, h) \rightarrow \tau\tau$ search: [25 GeV, 80 GeV]

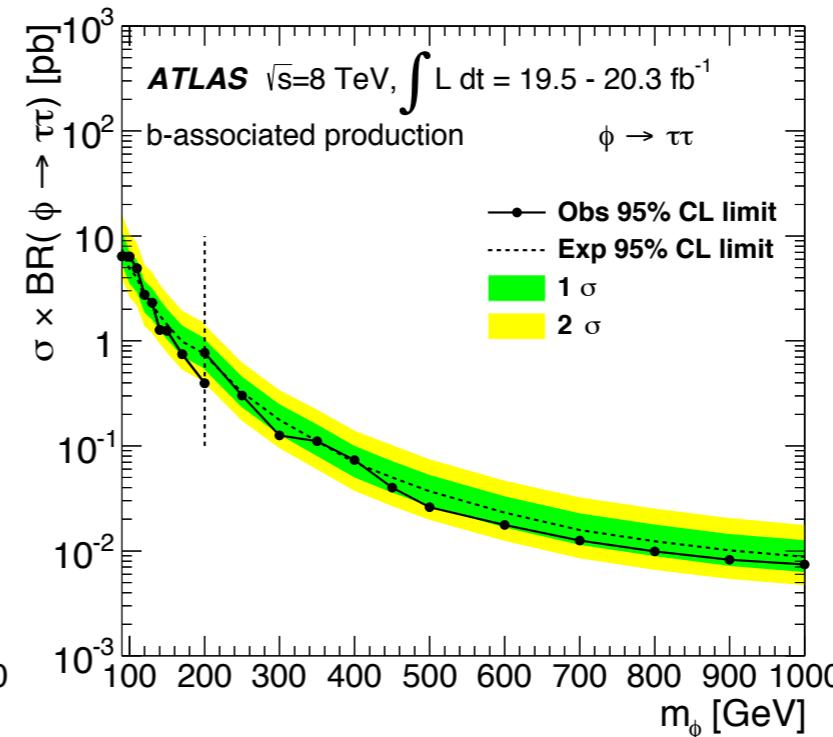
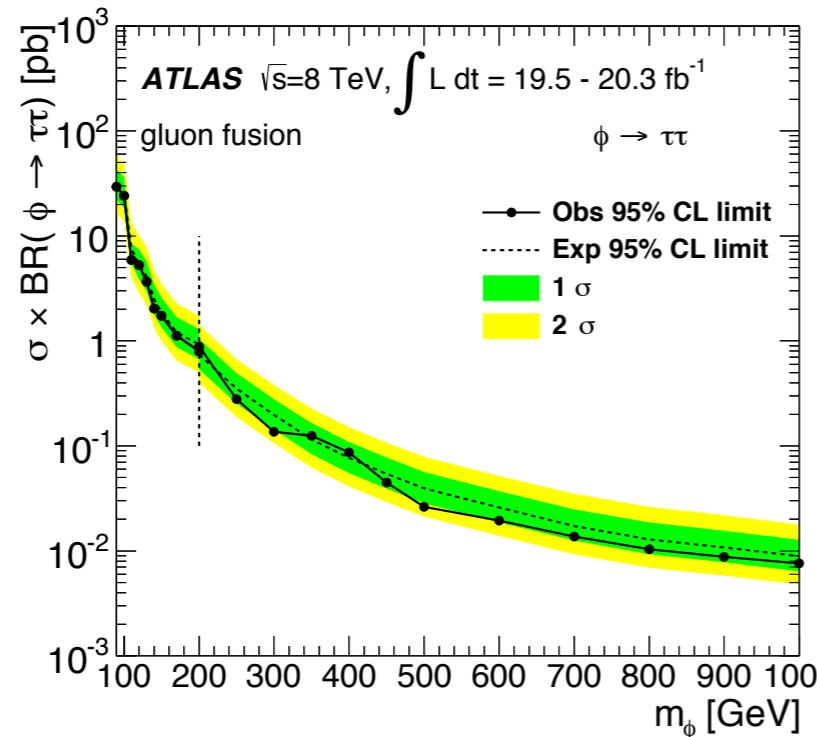
[CMS-HIG-14-033]



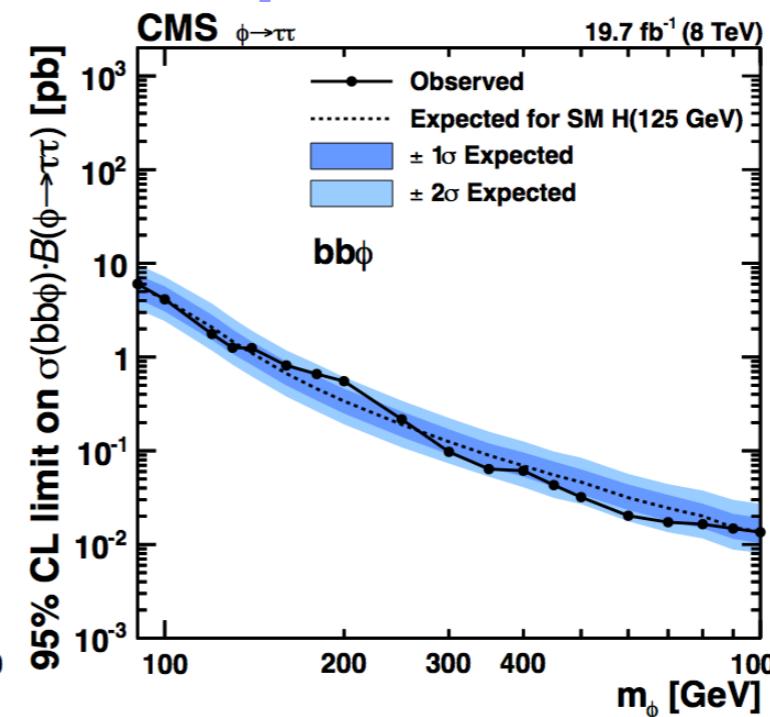
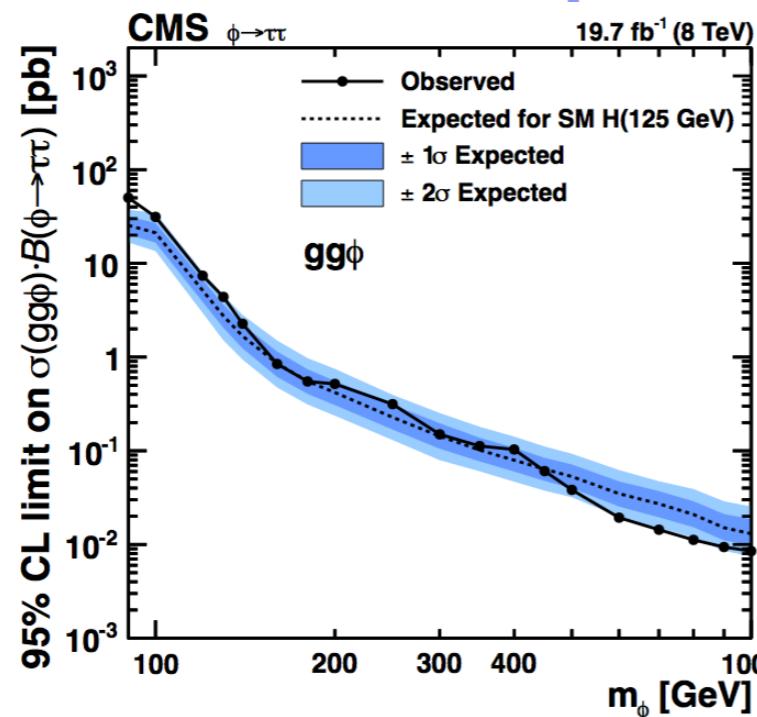
(Points from [JB, Gunion, Jiang, Kraml] [arXiv:1412.3385])

ATLAS, CMS $h, A \rightarrow \tau\tau$ searches: [90 GeV, 1 TeV]

[ATLAS-HIGG-2013-31]



[CMS-HIG-13-021]



Is alignment without decoupling ($|Z_6| \ll 1$) natural ?

It is natural in the sense of 't Hooft, if for $Z_6=0$ the model exhibits an enhanced symmetry.

$Z_6=Z_7=0$ actually corresponds to an exact \mathbb{Z}_2 -symmetry in the Higgs basis \rightarrow is it present in these scenarios ?

1. If $s_{2\beta} = 0$, either v_1 or v_2 vanishes: **the \mathbb{Z}_2 and Higgs bases coincide**, the original \mathbb{Z}_2 symmetry is unbroken in the Higgs basis
2. If $s_{2\beta}c_{2\beta} \neq 0$, imposing $Z_6=Z_7=0$ leads to $\lambda_1 = \lambda_2 = \lambda_{345}$. This actually corresponds to one of the three generalized CP symmetries of the 2HDM (CP3) [[Ferreira, Haber, Silva](#) [\[arXiv:0902.1537\]](#)]. The CP2 symmetry also leads to the desired result.

What if we now include the **Yukawa sector** ?

1. If $s_{2\beta} = 0$, the \mathbb{Z}_2 -symmetry in the Higgs basis can lead to a 2HDM of Type I with an odd doublet: this is the **Inert Doublet Model**
2. If $s_{2\beta} \neq 0$, the CP2/3 symmetry should be extended to the Yukawa sector, it was shown that **no such extension is phenomenologically viable** [[Ferreira, Silva](#) [\[arXiv:1001.0574\]](#)].
 \rightarrow The alignment without decoupling regime should be considered as *more fine-tuned* than the general 2HDM for generic choice of the parameters

Family and CP symmetries of the 2HDM

[Ferreira, Haber, Silva] [arXiv:0902.1537]

TABLE I: Impact of the symmetries on the coefficients of the Higgs potential in a specified basis.

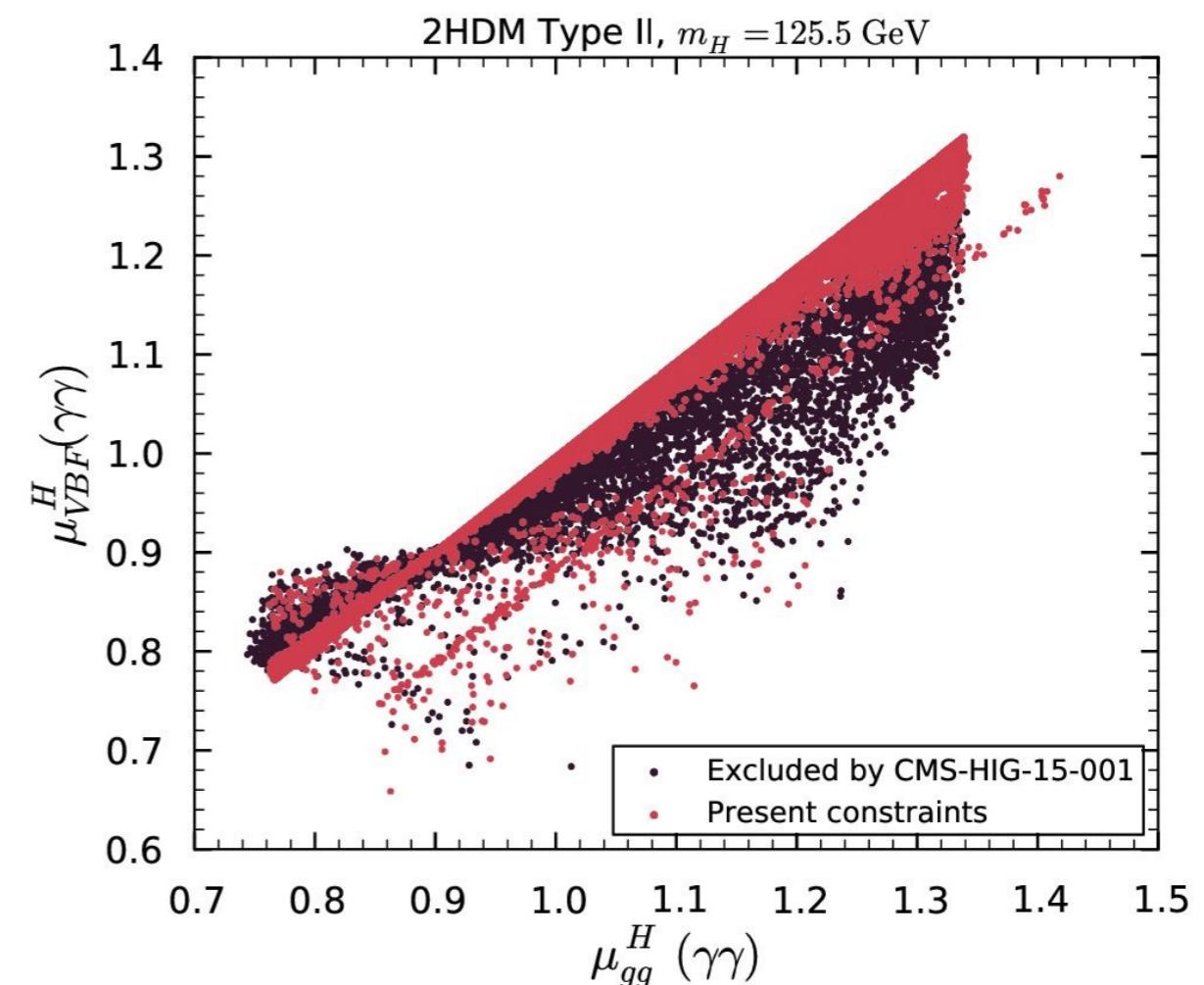
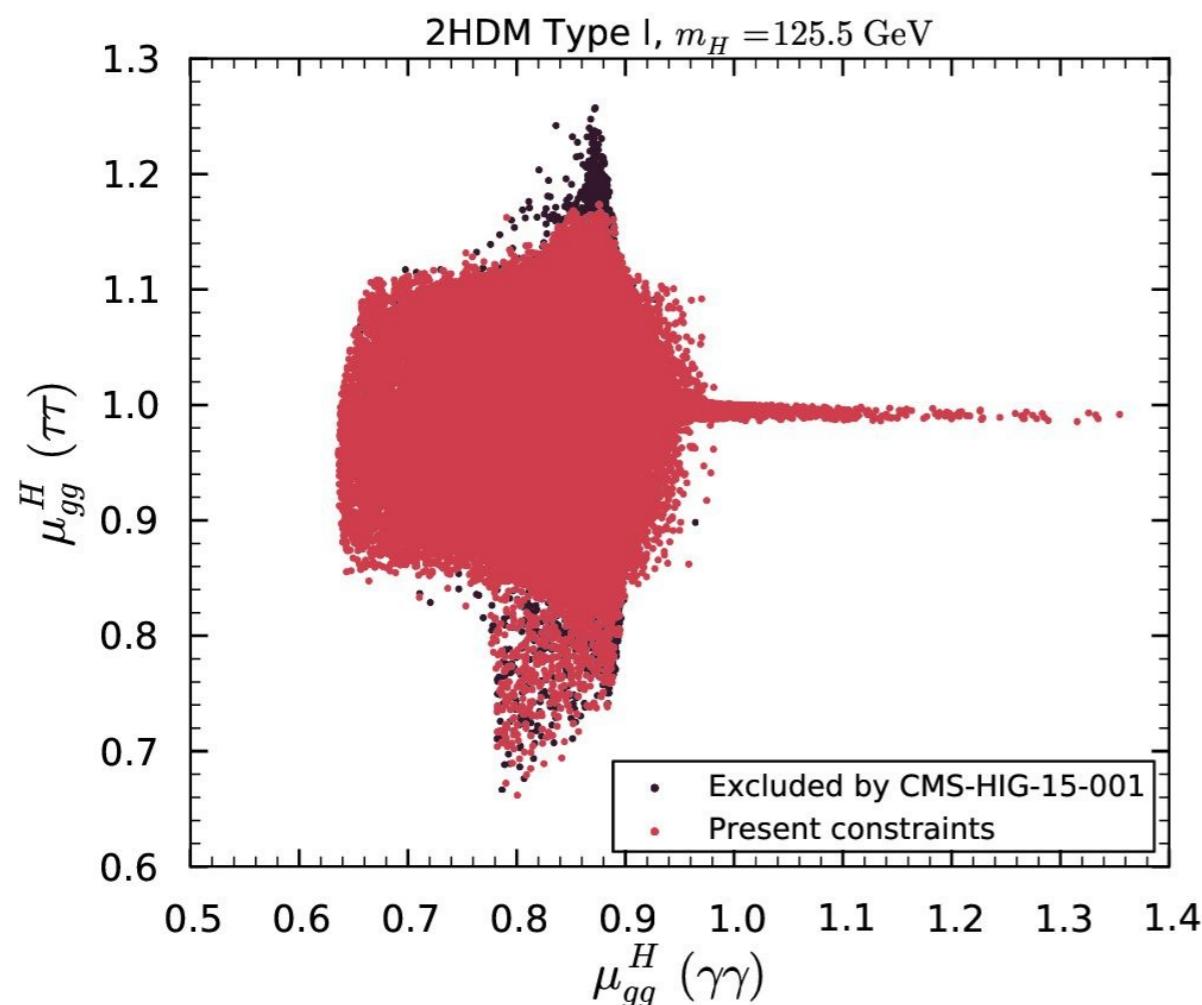
symmetry	m_{11}^2	m_{22}^2	m_{12}^2	λ_1	λ_2	λ_3	λ_4	λ_5	λ_6	λ_7
Z_2			0						0	0
$U(1)$			0					0	0	0
$SO(3)$		m_{11}^2	0		λ_1		$\lambda_1 - \lambda_3$	0	0	0
Π_2		m_{11}^2	real		λ_1			real		λ_6^*
CP1			real					real	real	real
CP2		m_{11}^2	0		λ_1					$-\lambda_6$
CP3		m_{11}^2	0		λ_1			$\lambda_1 - \lambda_3 - \lambda_4$ (real)	0	0

Higgs family transformations: $\begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} \rightarrow X \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix}$

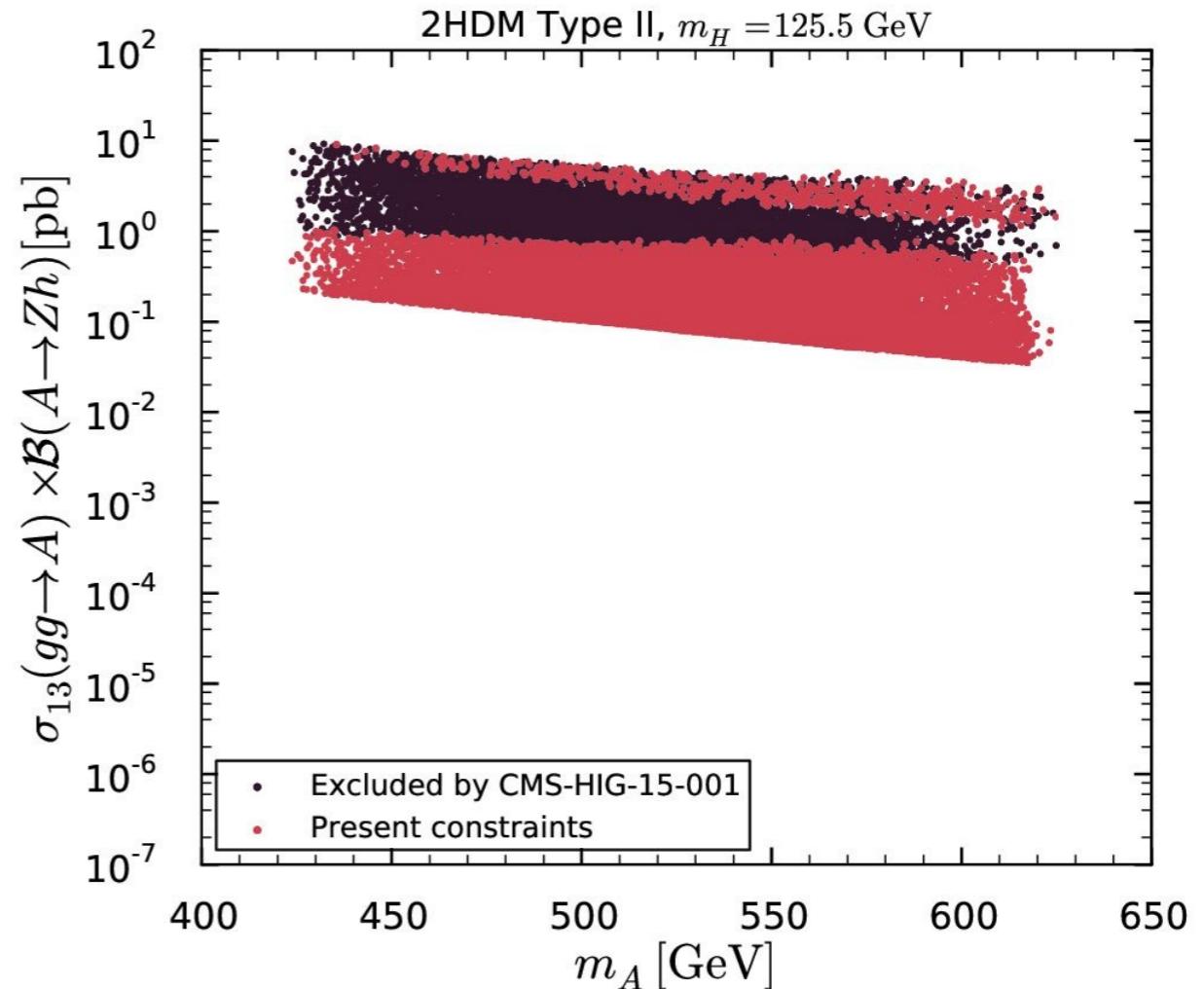
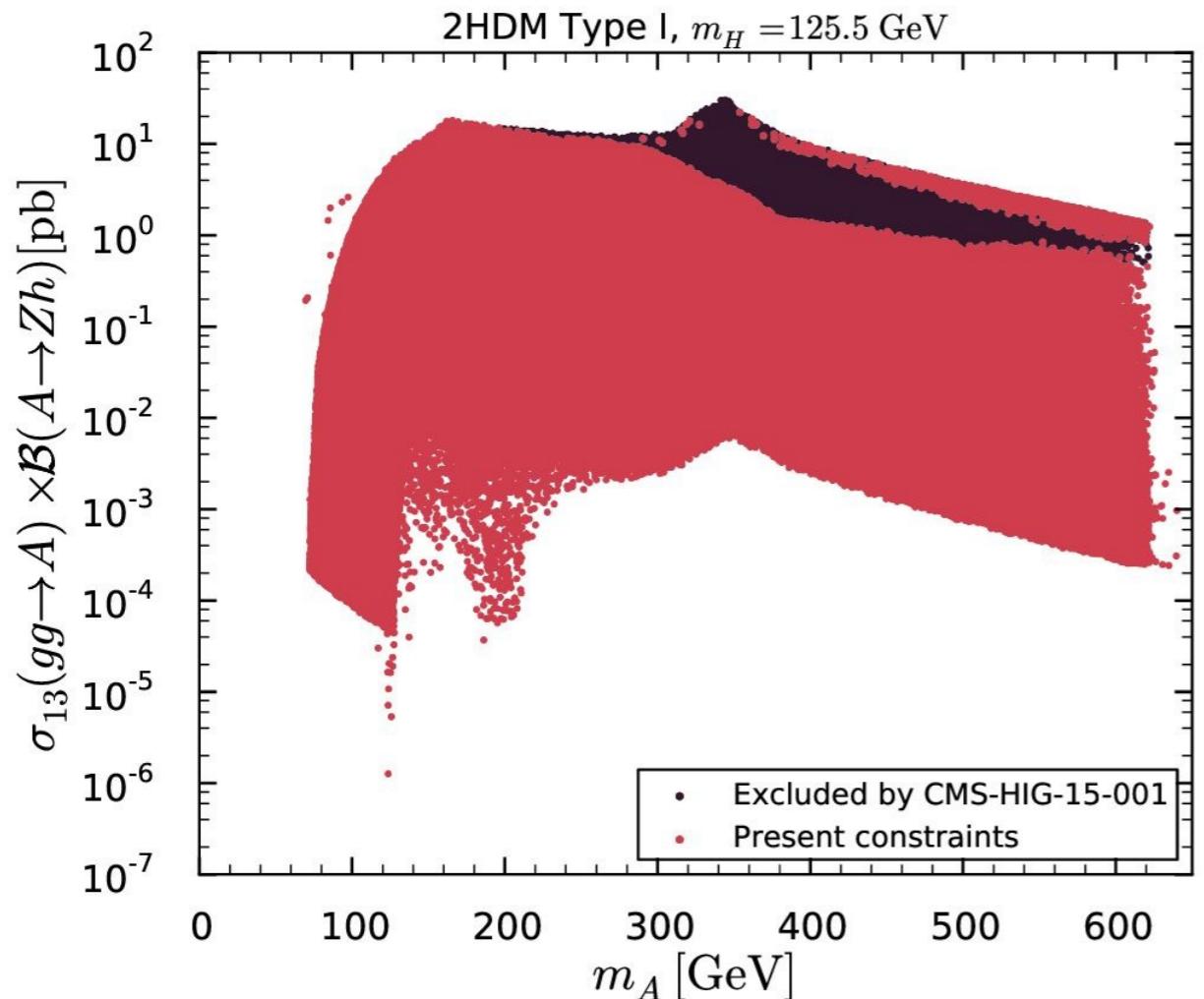
Generalized CP transformations: $\begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} \rightarrow \begin{pmatrix} c_\theta & s_\theta \\ -s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} \Phi_1^* \\ \Phi_2^* \end{pmatrix}$

CP1: $\theta = 0$
 CP2: $\theta = \pi/2$
 CP3: $0 < \theta < \pi/2$

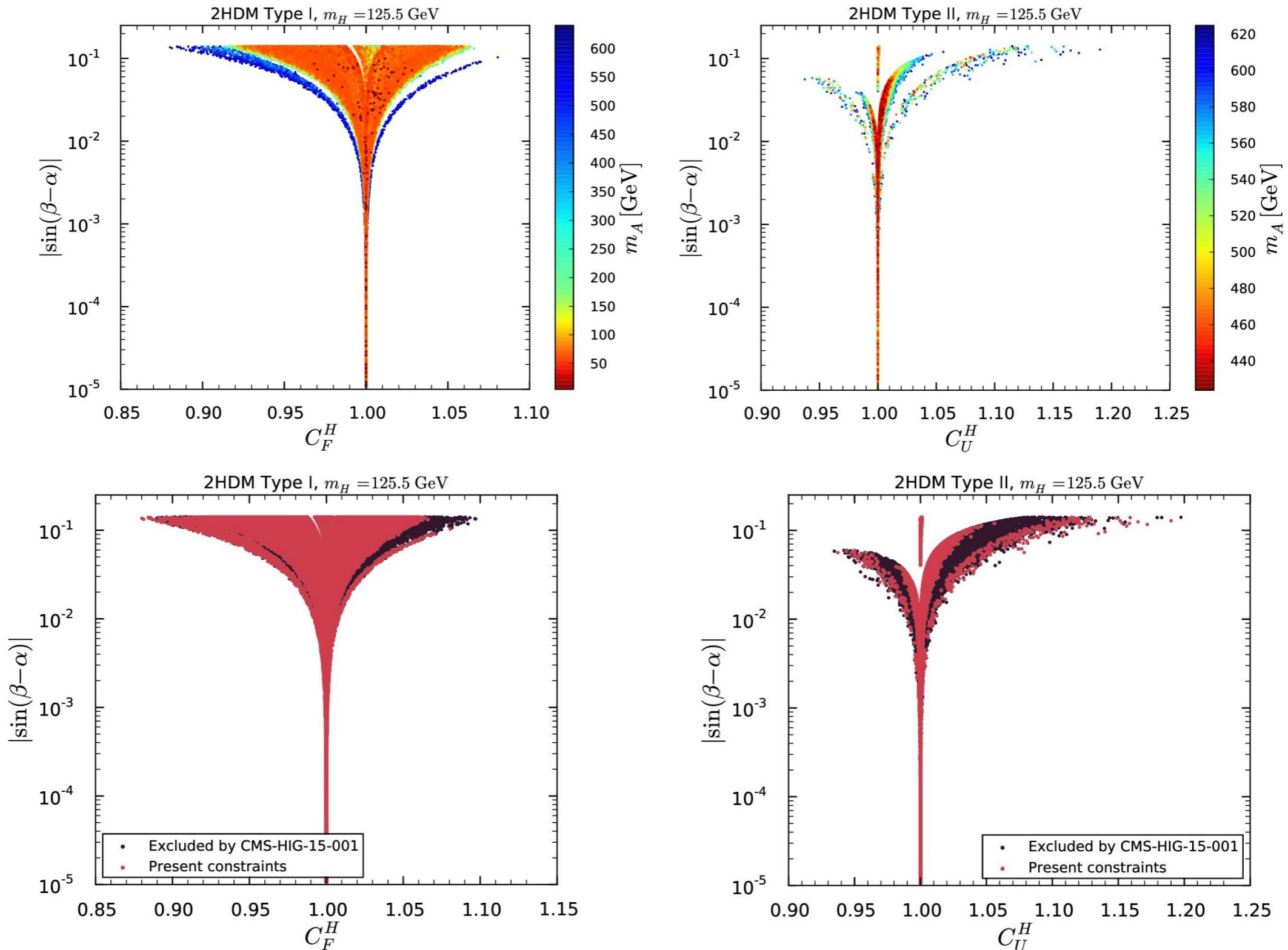
Impact of the CMS A \rightarrow Zh search for signal strengths



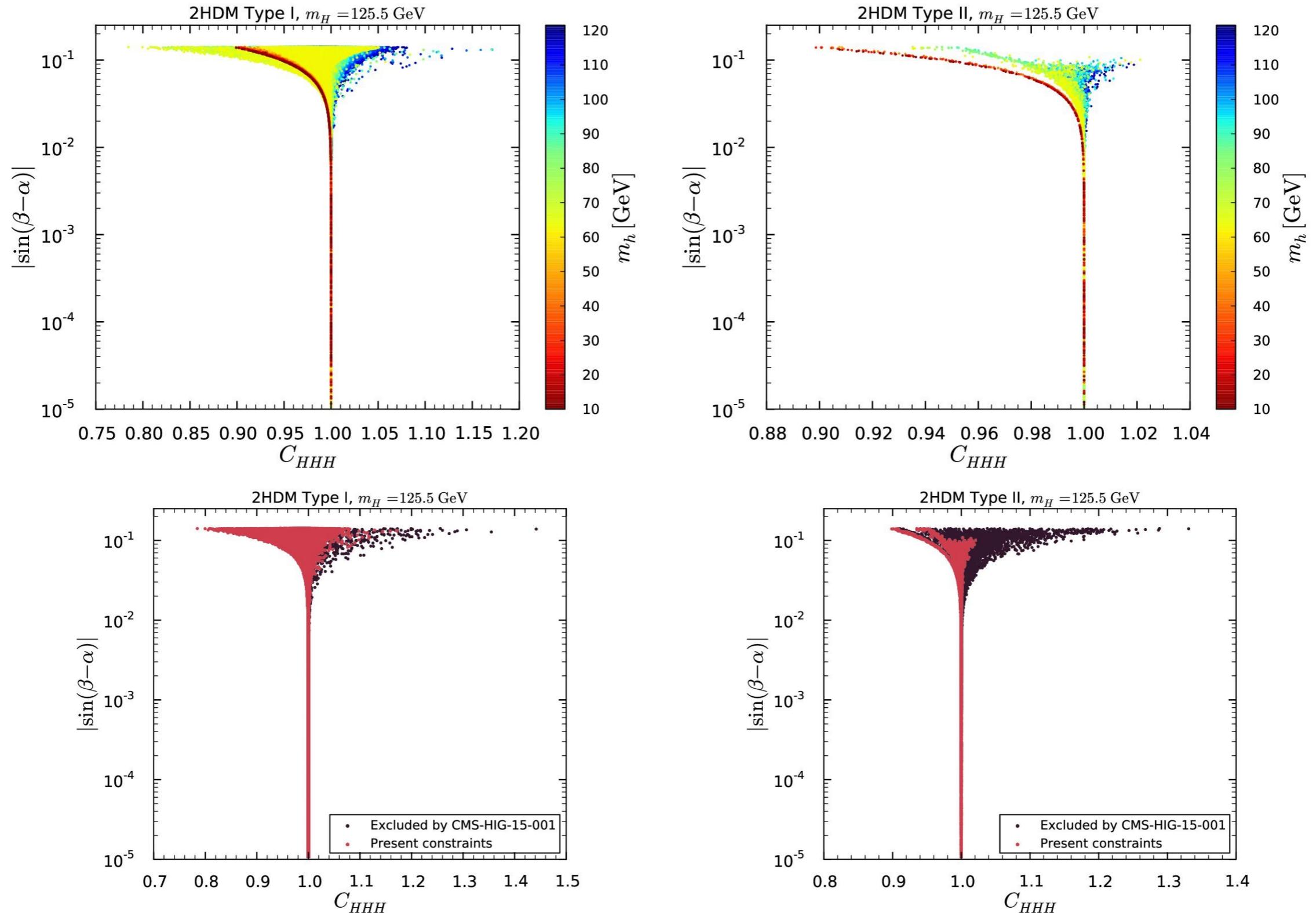
Impact of the CMS A \rightarrow Zh search for cross sections



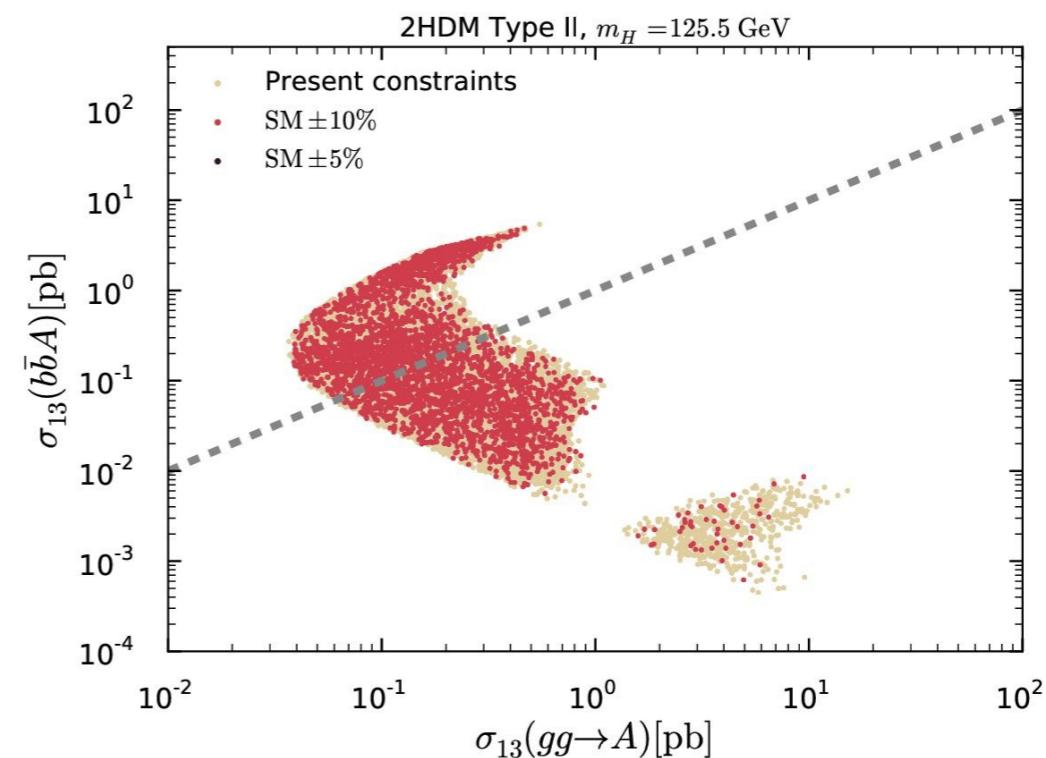
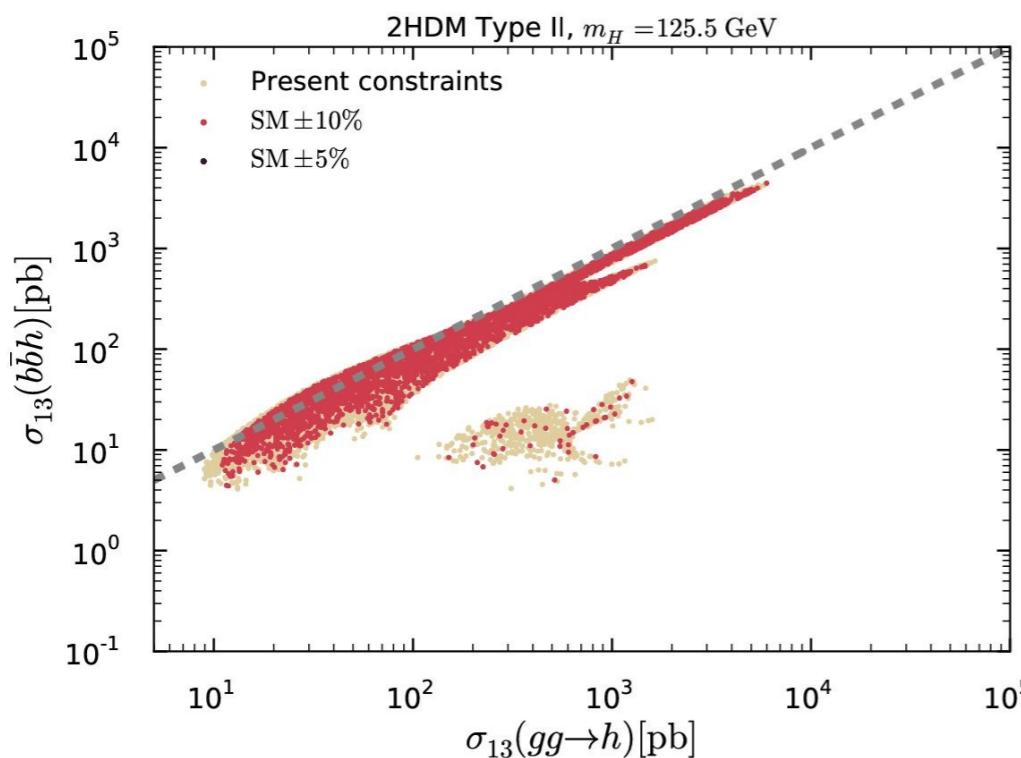
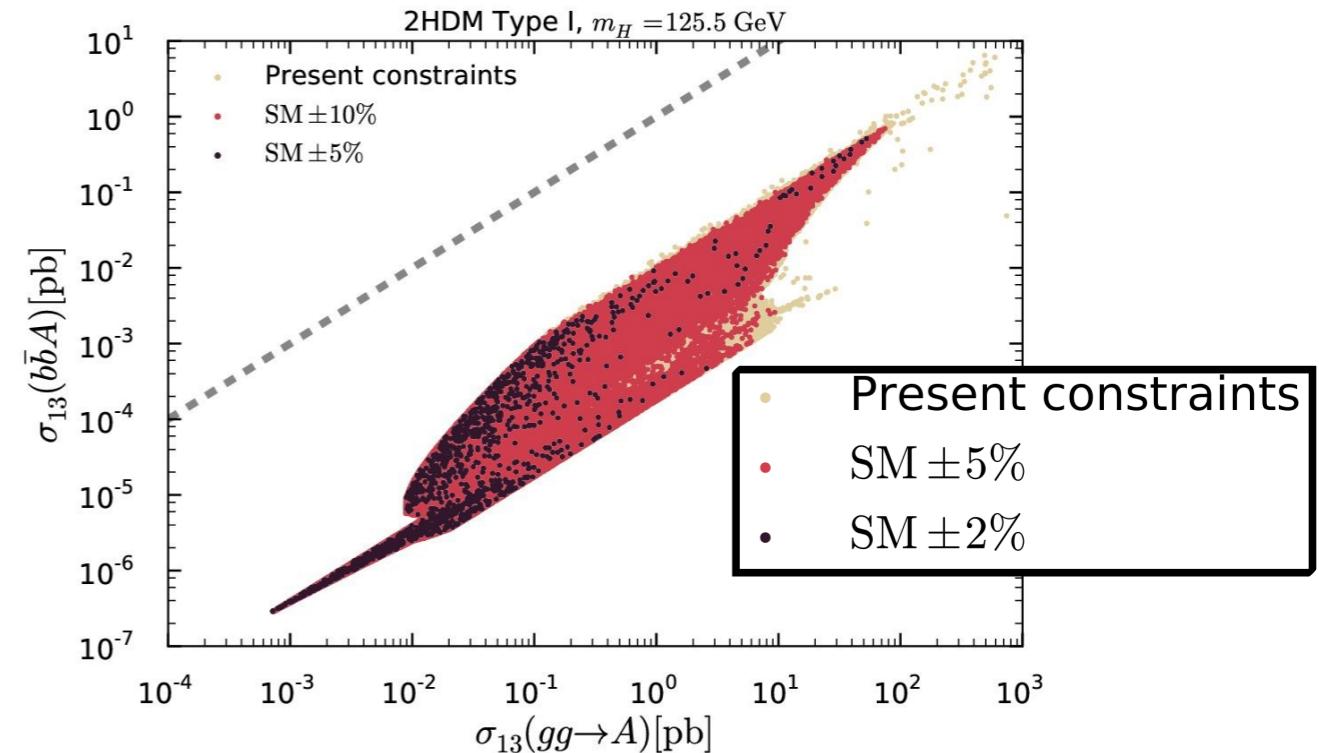
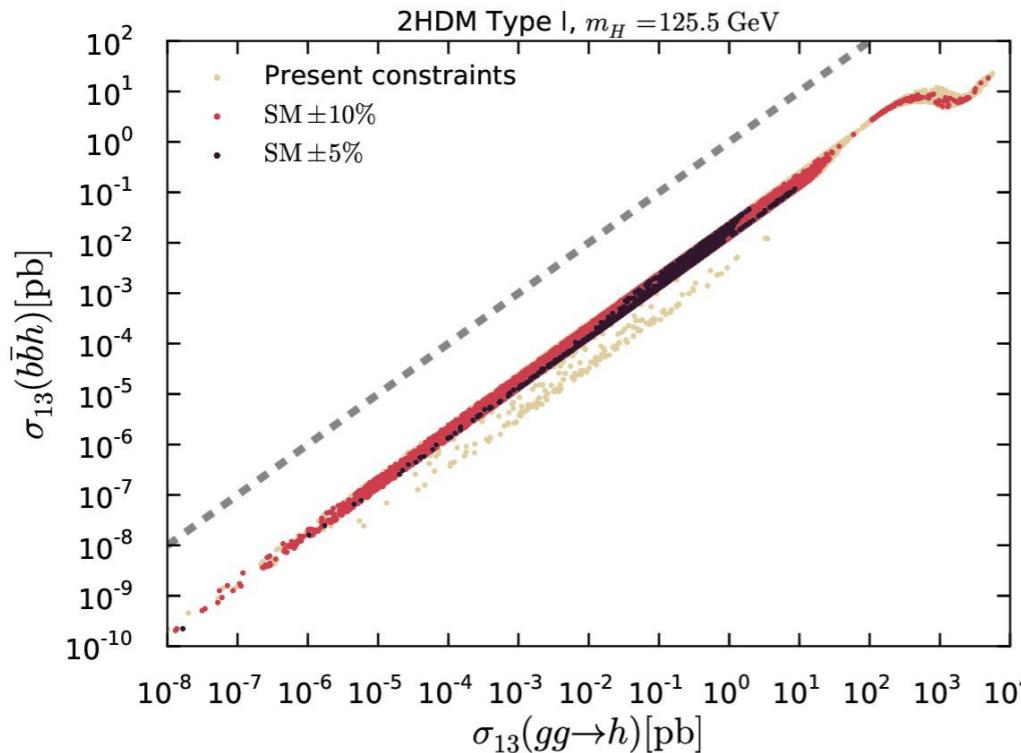
Fermion couplings of the 125 GeV state



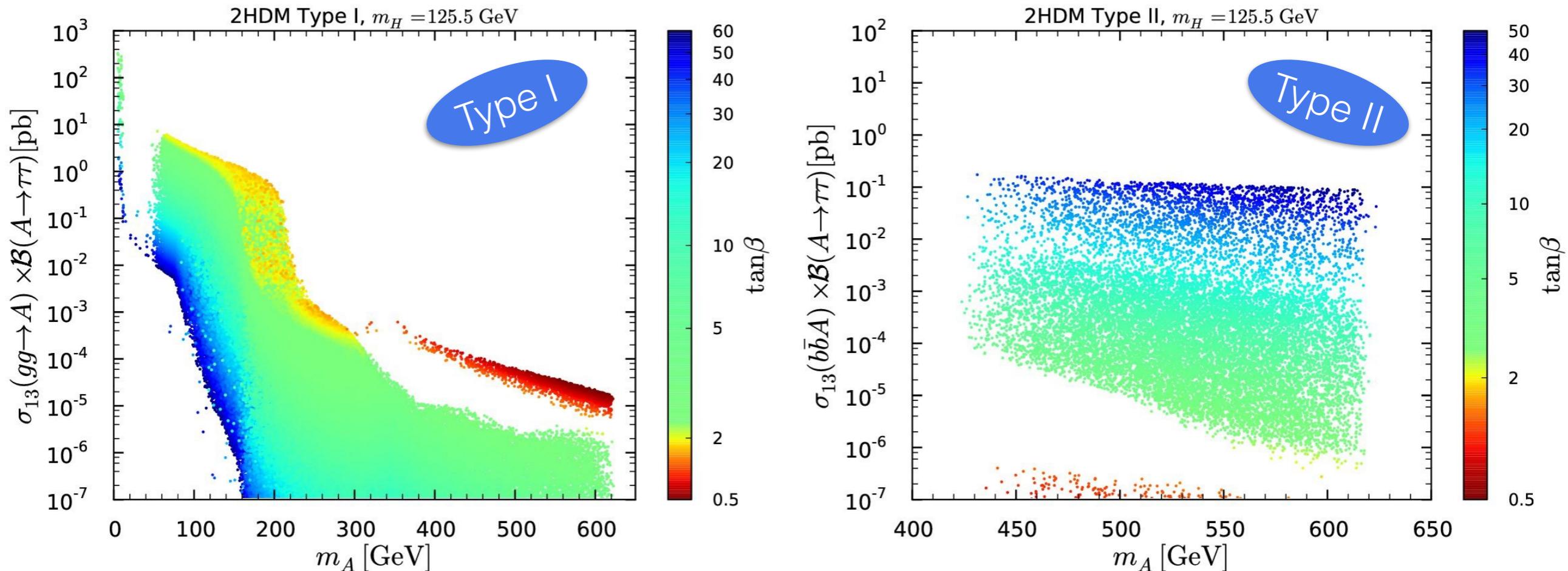
Trilinear Higgs coupling



h, A production cross sections at the LHC 13 TeV



$A \rightarrow \tau\tau$ at the LHC 13 TeV



$A \rightarrow \gamma\gamma, t\bar{t}$ at the LHC 13 TeV

