Scrutinizing alignment without decoupling in two-Higgs-doublet models

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Based on [arXiv:1511.03682]

and [arXiv:1507.00933] (PRD)

In collaboration with

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SCALARS 2015
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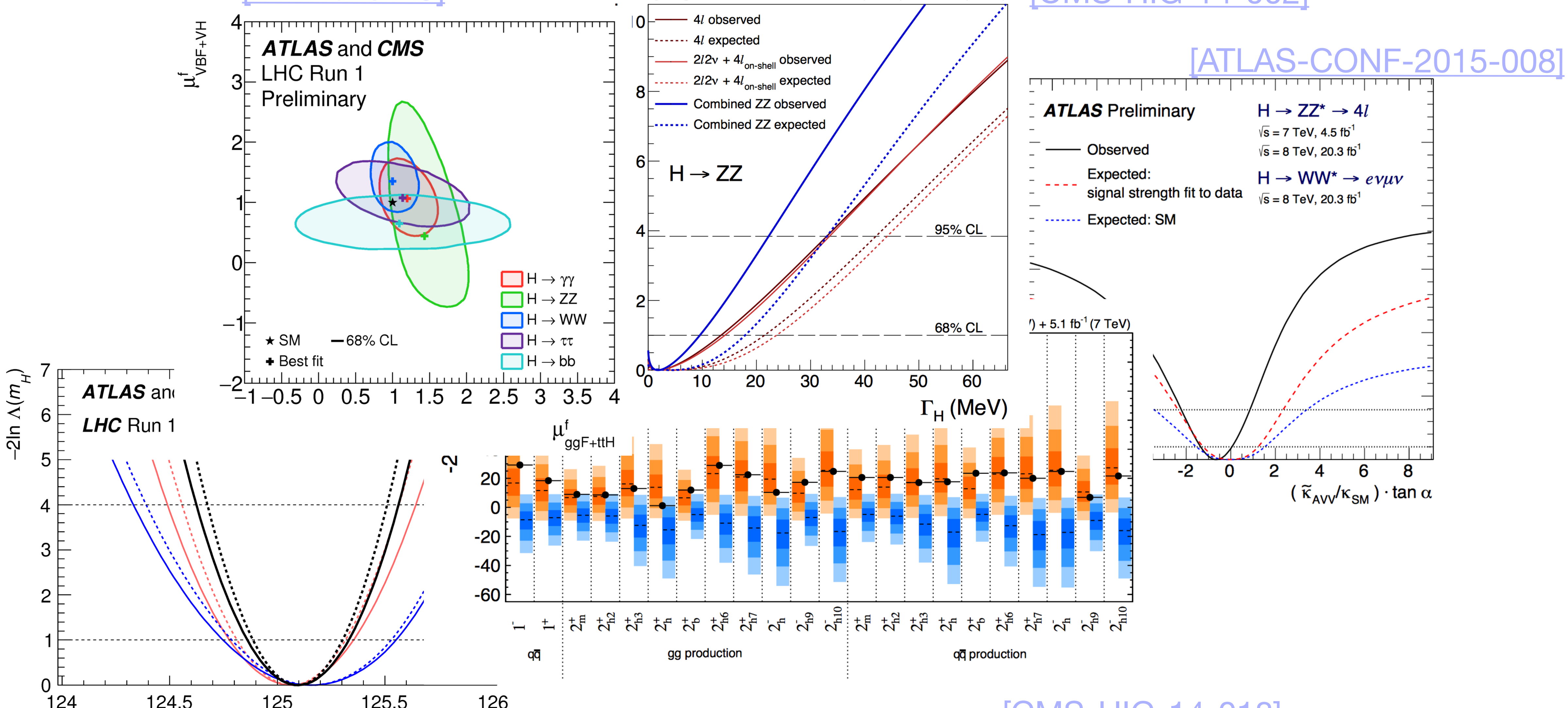
Warsaw, Poland

Motivations

[ATLAS-CMS] [CMS-HIG-14-002] [ATLAS-CONF-2015-008]



[ATLAS-CMS] [CMS-HIG-14-018]

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 two-Higgs-doublet model in the Higgs-basis

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≃246 GeV, resides entirely in one of the two doublets:

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

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

$|Z_i|\lesssim 10$ by virtue of **perturbativity**. At the potential minimum, $2Y_{1,3} = -Z_{1,6}v^2$.

- Masses of the charged Higgs and the CP-odd state:

$$m_{H^\pm}^2 = Y_2 + \frac{1}{2}Z_3 v^2 \qquad m_A^2 = Y_2 + \frac{1}{2}(Z_3 + Z_4 - Z_5)v^2$$

$\Longrightarrow$ Decoupled 2HDM more natural than the general model since the natural scale for Y_2 is Λ^2_{UV}

We still focus on scenarios with non-decoupled states in order to get sizeable experimental signatures ➝ **alignment without decoupling**

The $\mathbb{Z}_2$-basis

- The general 2HDM has large tree-level flavor changing neutral currents. **Natural flavor conservation** is a way to forbid them by imposing a (**softly-broken**) **$\mathbb{Z}_2$-symmetry** in the so-called **$\mathbb{Z}_2$-basis** ($\boldsymbol{\Phi}_1$,$\boldsymbol{\Phi}_2$) (in which the symmetry is explicit):

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

$$\begin{aligned}\mathcal{V} =& m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - [m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}] + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) \\ &+ \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \left\{ \frac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \left[\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2)\right] \Phi_1^\dagger \Phi_2 + \text{h.c.} \right\}\end{aligned}$$

- The softly-broken $\mathbb{Z}_2$-symmetry in this basis <u>does not necessarily</u> lead to a $\mathbb{Z}_2$-symmetry in the Higgs basis (more on this topic later).
- The CP-even mass eigenstates are obtained through $\begin{pmatrix}H\\ h\end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix}\begin{pmatrix}\sqrt{2}\text{Re}\Phi_1^0 - v_1\\ \sqrt{2}\text{Re}\Phi_2^0 - v_2\end{pmatrix}$
- Relations between the two bases parameters can be obtained, *e.g.*

$$\begin{aligned} 2Z_6 &= -s_{2\beta}[\lambda_1 c_\beta^2 - \lambda_2 s_\beta^2 - \lambda_{345} c_{2\beta}] \\ 2Z_7 &= -s_{2\beta}[\lambda_1 s_\beta^2 - \lambda_2 c_\beta^2 + \lambda_{345} c_{2\beta}] \end{aligned} \qquad \lambda_{345} \equiv \lambda_3 + \lambda_4 + \lambda_5$$

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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

$$\begin{aligned} H =& (\sqrt{2}\mathrm{Re}\, H_1^0 - v) c_{\beta-\alpha} - \sqrt{2}\mathrm{Re}\, H_2^0 s_{\beta-\alpha} \,, \\ h =& (\sqrt{2}\mathrm{Re}\, H_1^0 - v) s_{\beta-\alpha} + \sqrt{2}\mathrm{Re}\, H_2^0 c_{\beta-\alpha} \end{aligned} \qquad m_h < m_H$$

$\Longrightarrow$ 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**

- Small mixing between H_1^0 and H_2^0 requires $|Z_6| v^2 \ll |m_A^2 + (Z_5 - Z_1) v^2|$
- Furthermore, when $\mathcal{M}_{11}^2 < (>) \mathcal{M}_{22}^2$ then h (H) is the SM-like state:

Alignment in the **h125 scenario**:

$$h \simeq (\sqrt{2}\mathrm{Re} H_1^0 - v)$$

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

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

Alignment in the **H125 scenario**:

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$\Longrightarrow$ $|Z_6| \ll 1$ and **no decoupling limit**

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 ➙ 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].

➙ The alignment without decoupling regime should be considered as *more fine-tuned* than the general 2HDM for generic choice of the parameters

Numerical Analysis

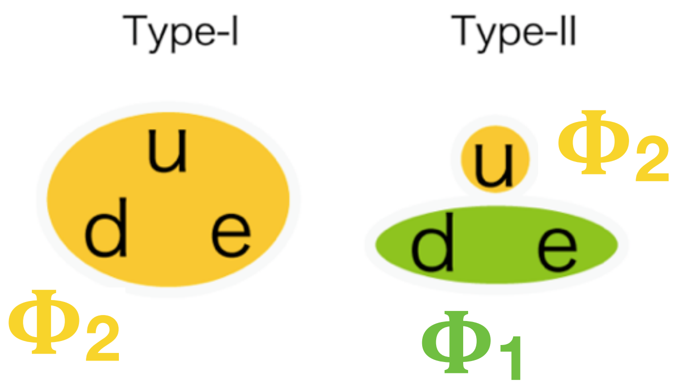
Focus on the H125 scenario
$m_h < m_H = 125.5\ \mathrm{GeV}$

We study the phenomenology of the near-alignment limit by imposing a maximal **1% deviation** of the HVV coupling from 1: $c_{\beta-\alpha} \geq 0.99$ $\sqrt{1-0.99^2} \sim 0.14$

N.B. $c_{\beta-\alpha} > 0$ convention.

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:



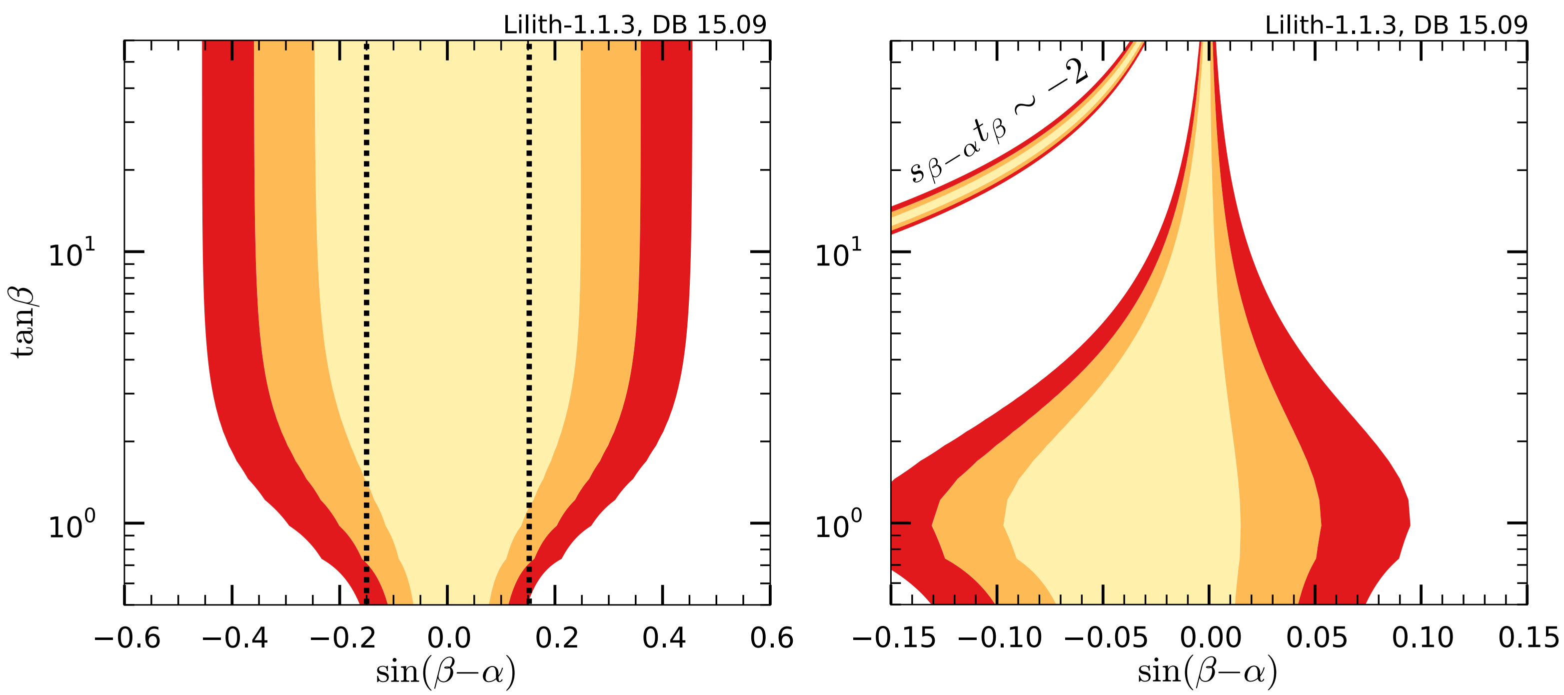
$$C_V^H = c_{\beta-\alpha},\ C_V^h = s_{\beta-\alpha}$$

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

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

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 **LI**kelihood fi**T** for the **H**iggs
[JB, B. Dumont] [arXiv:1502.04138]

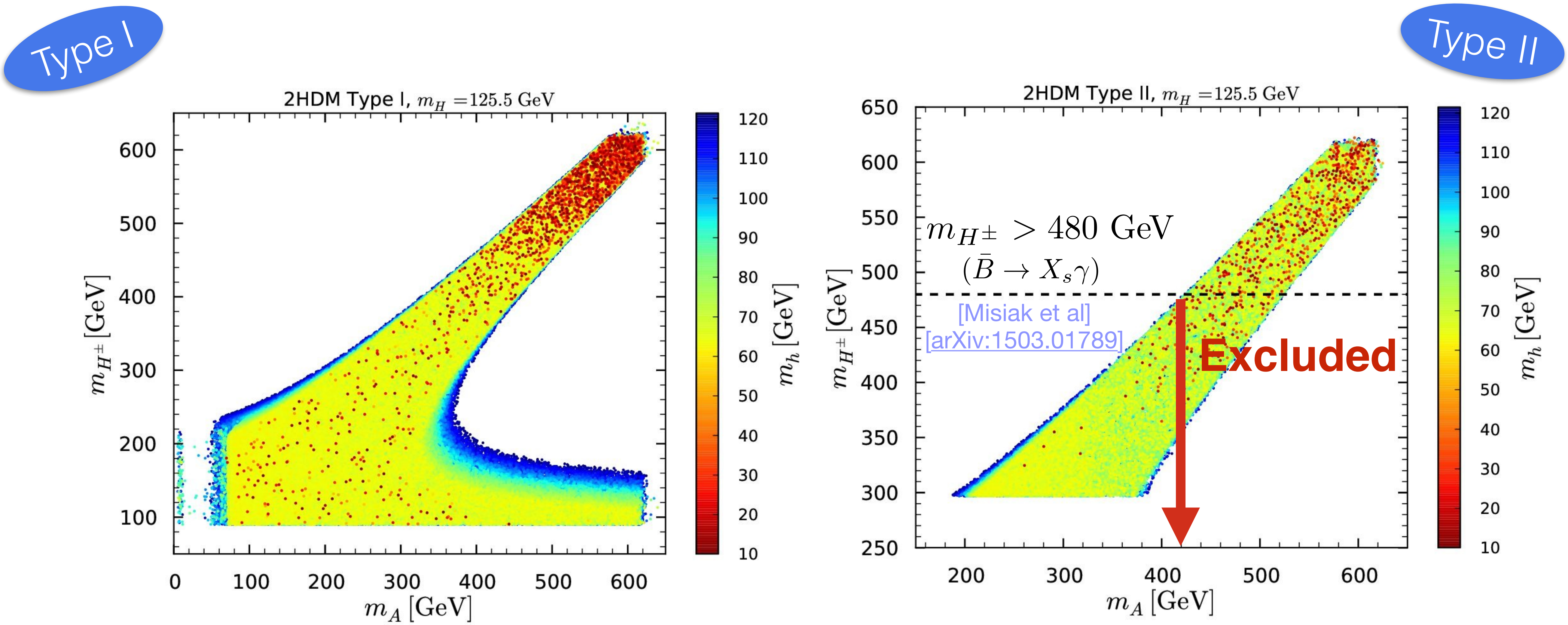
Degeneracy near the **alignment limit**.

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]

Numerical Setup

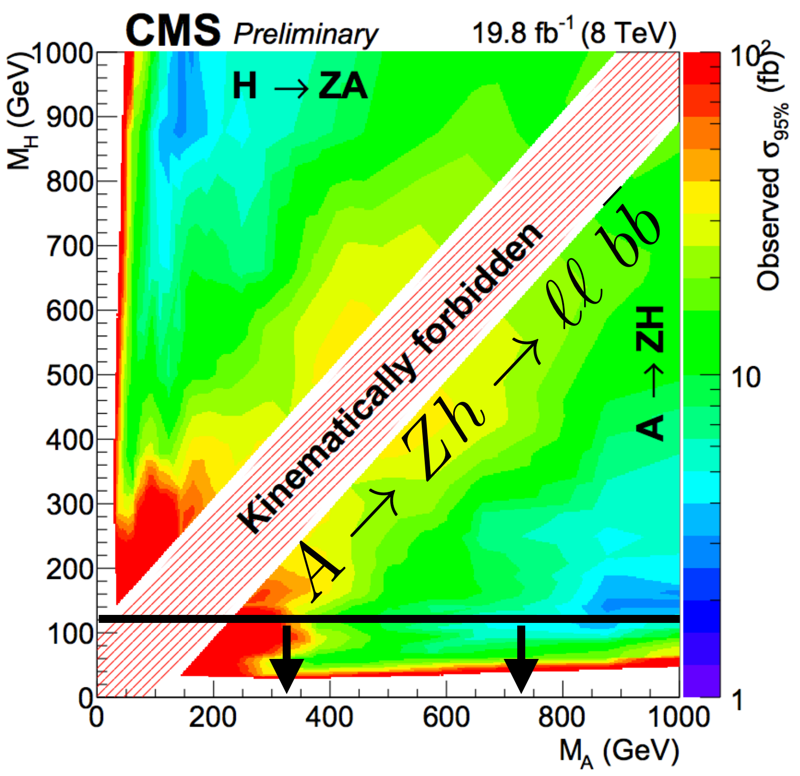
- Branching ratio and theoretical constraints from **2HDMC** [Eriksson, Rathsman, Stål] [arXiv:0902.0851]
- Cross sections from **SusHi**, **VBFNLO** [Herlander, Liebler, Mantler] [arXiv:1212.3942] [Arnold et al] [arXiv:0811:4559]
- Theoretical constraints:
  - ✓ **Stability** of the scalar potential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

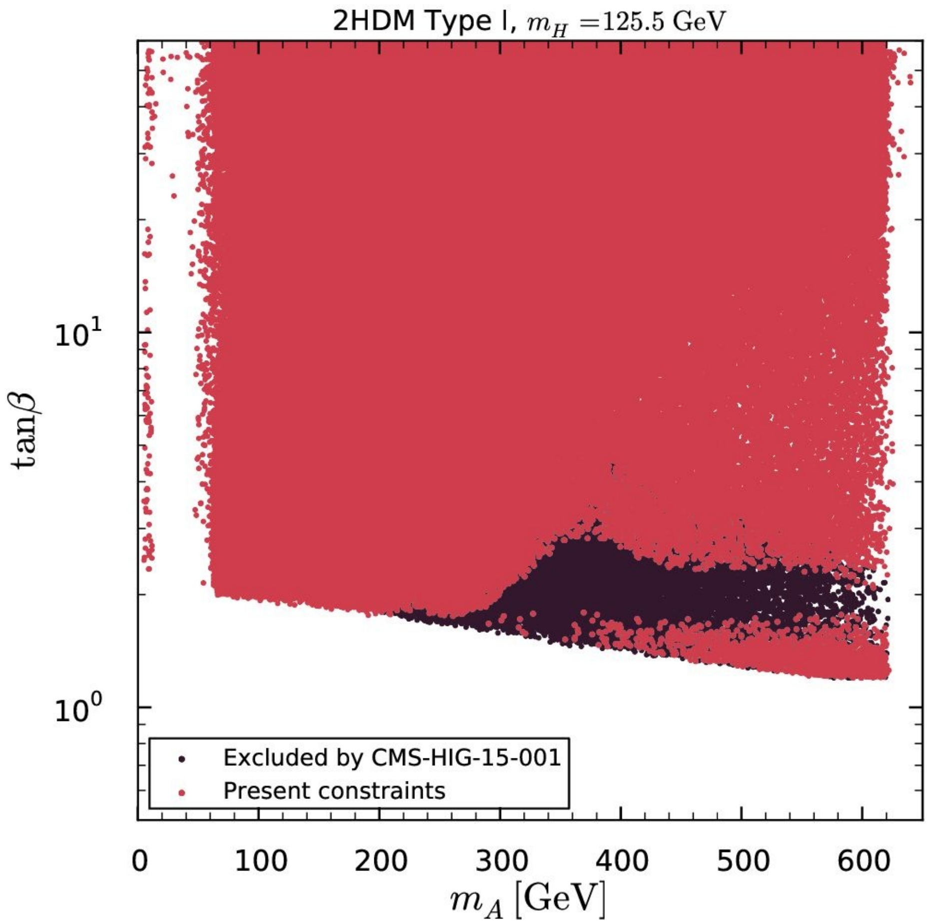
Mass of the extra states

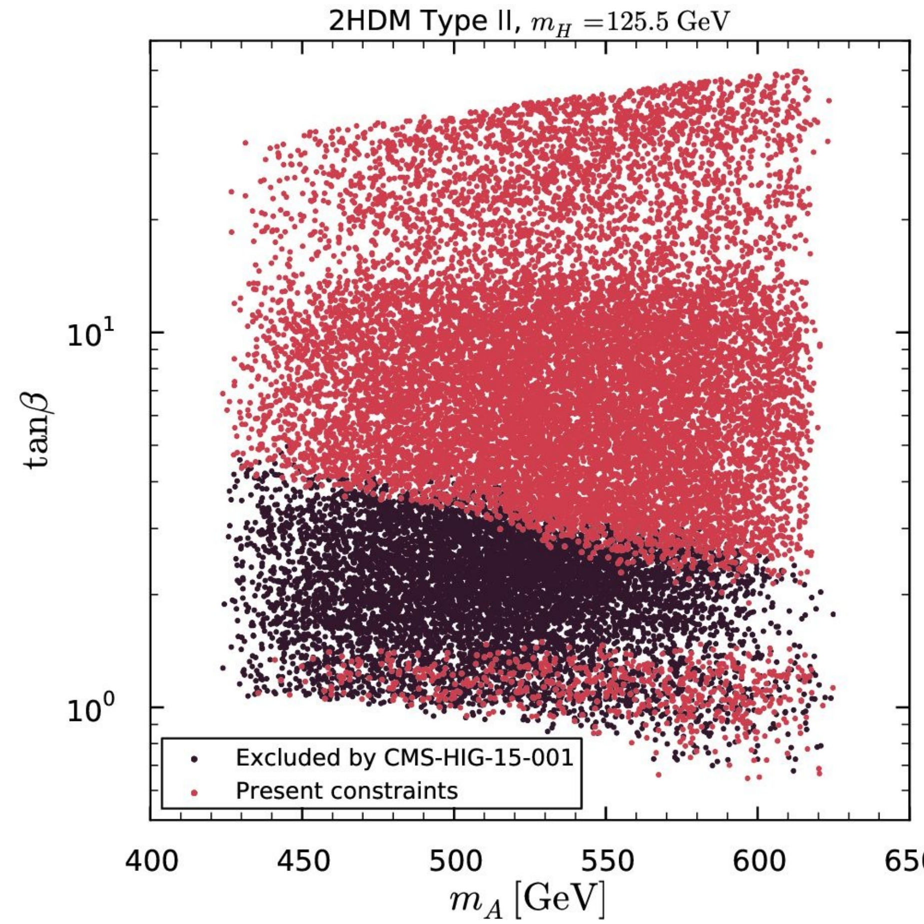


- In both Types, due to the perturbativity constraint $m_A, m_{H^\pm} \lesssim 630$ GeV.
- In Type II, due to the charged Higgs mass bound and the T parameter constraint: $m_A \gtrsim 420$ GeV.
- In Type I, due to weaker flavor constraints, charged Higgs masses down to the LEP bound are allowed. For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

Impact of the CMS $A \to Zh \to \ell\ell\ b\bar{b}/\tau\tau$ search







[CMS-PAS-HIG-15-001]

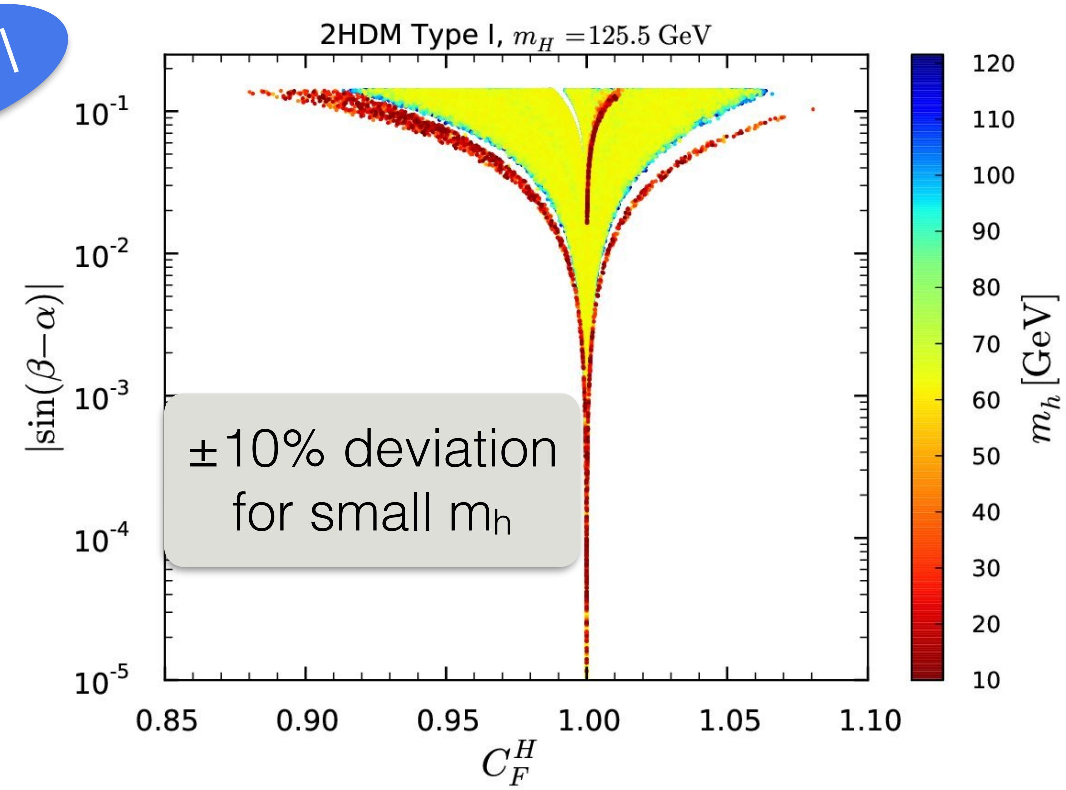
- The two resonance masses are free parameters, the search is sensitive to light resonance masses down to ~40GeV.
- h➝bb has the largest excluded cross-section
- In our scenario, h has mass below 125 GeV and has therefore large BR(h➝bb)~0.9

➡ Severe constraints on the low t_b region ⟹ « gaps » in subsequent plots

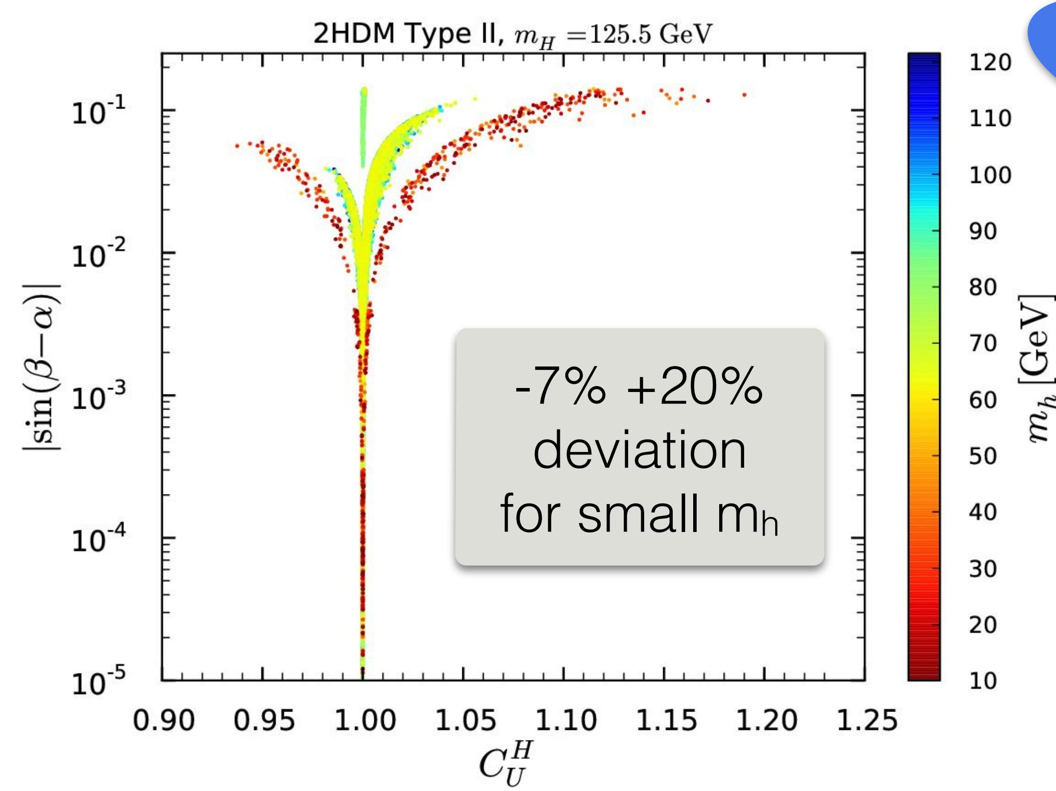
Note that the corresponding ATLAS search requires m_h=125 GeV and does not provide significant constraints in this scenario. [ATLAS-HIGG-2013-06]

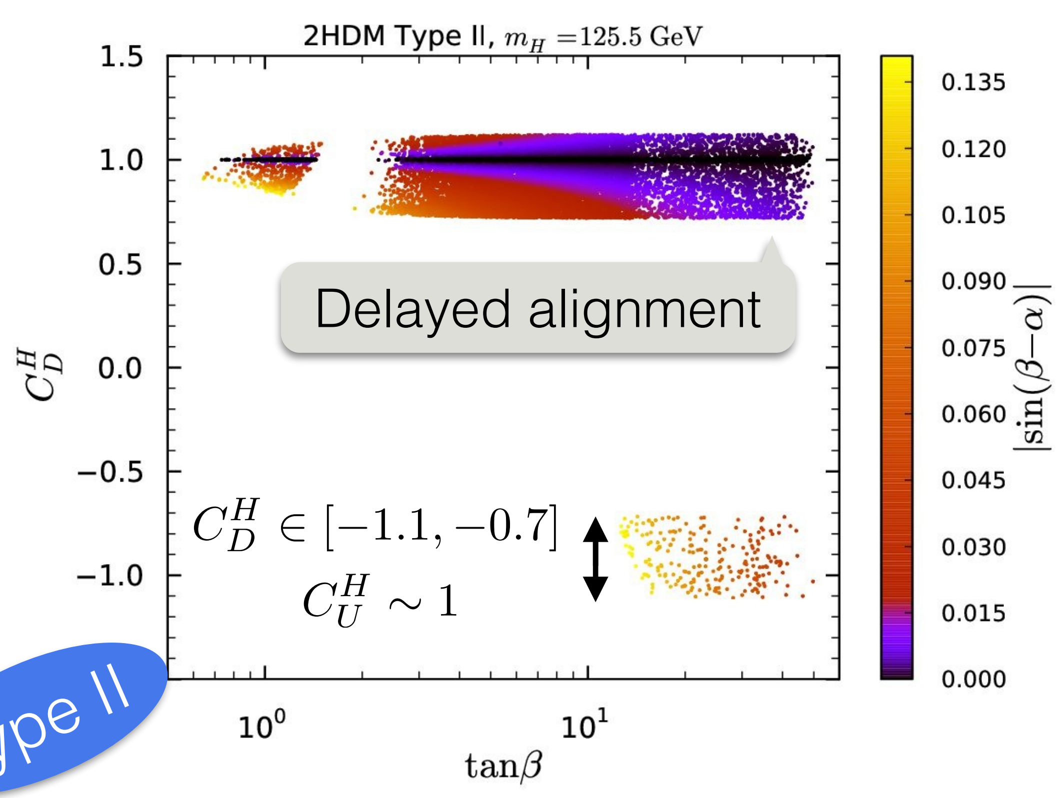
Fermion couplings of the 125 GeV state

Type I



Type II



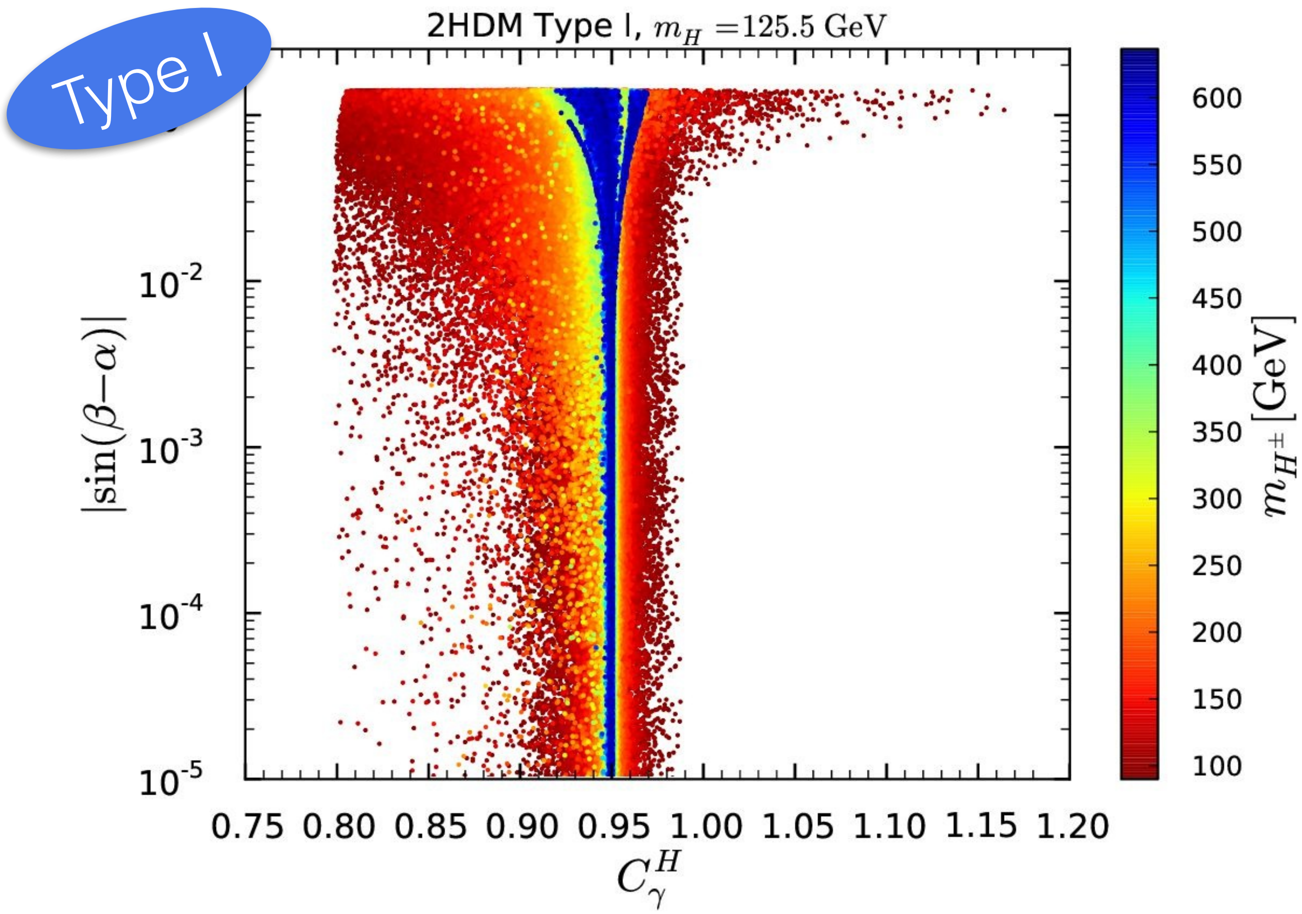


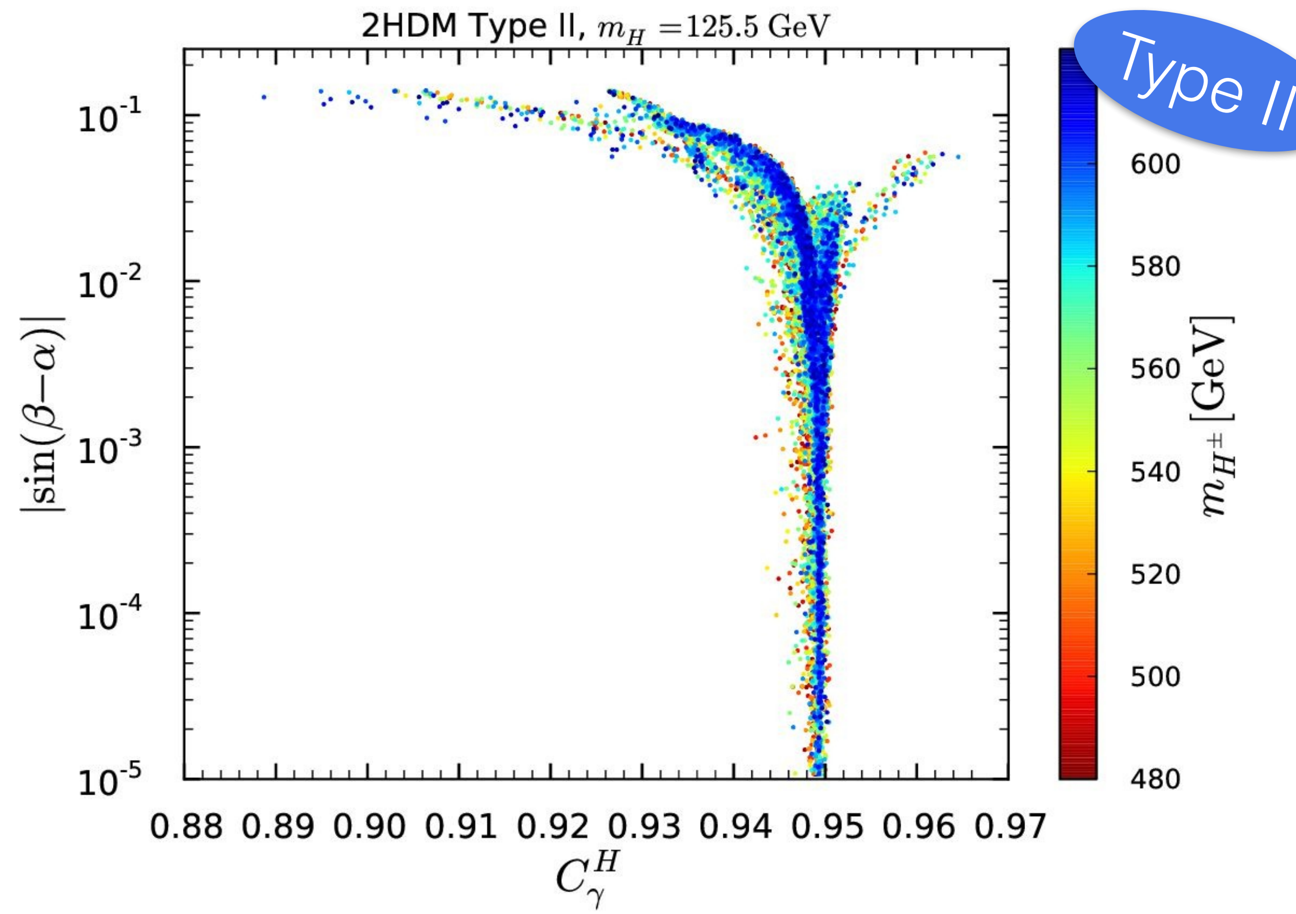
Type II

- In Type I, large C_F deviations are associated to m_h<60 GeV, m_A close to its upper bound and $t_\beta \sim 1$ see [JB, Gunion, Jiang, Kraml] [arXiv:1412.3385]
- For C_F in Type I and C_U in Type II, the couplings quickly reach their SM value as $|s_{\beta-\alpha}| \to 0$
- On the contrary C_D in Type II, still shows large deviations at small $|s_{\beta-\alpha}|$ and large t_β. In particular, for $|s_{\beta-\alpha}| \sim 5 \times 10^{-3}$, $C_D^H \in [0.7, 1.1]$

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 $C_g^H \simeq 1.06$.



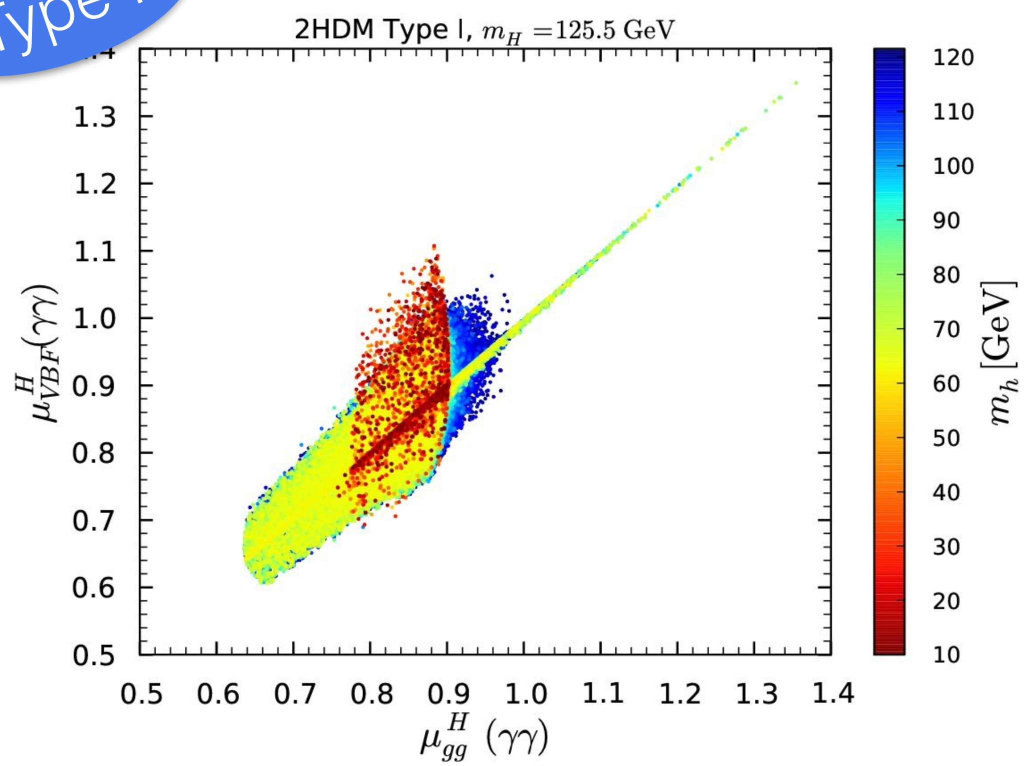


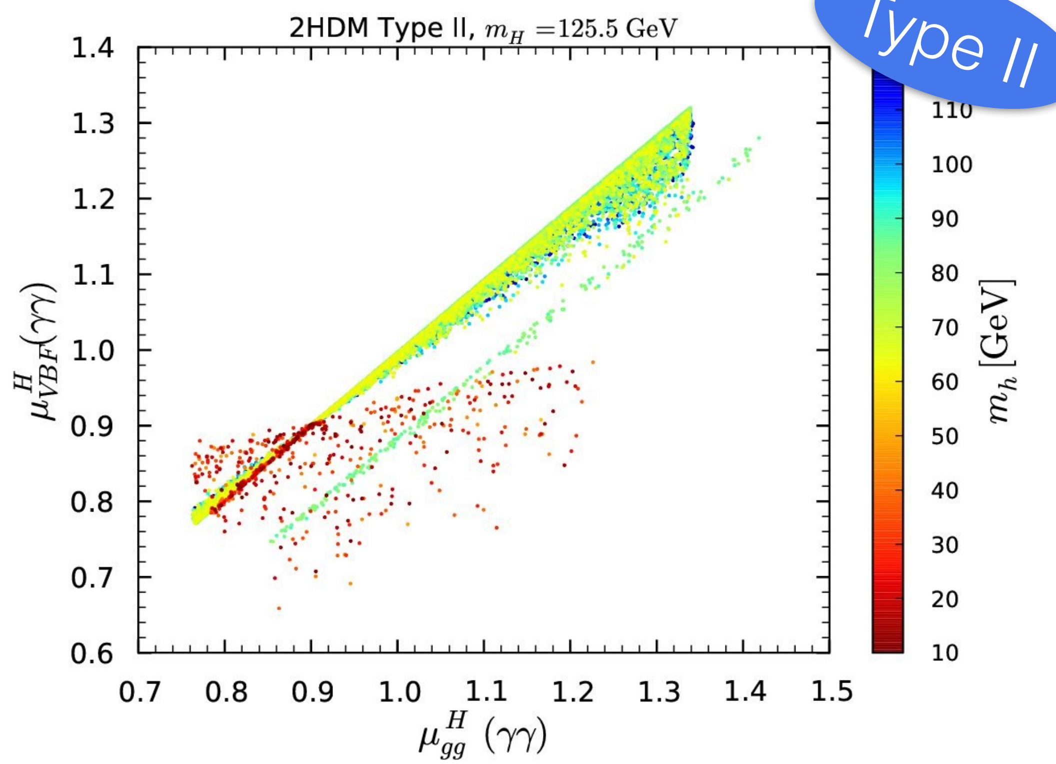
- In the alignment limit: $g_{HH^+H^-} = -\frac{1}{v}(m_H^2 + 2m_{H^\pm}^2 - 2\overline{m}^2)$ $\quad \overline{m}^2 \in \begin{cases} \text{I:} & [-(350\ \text{GeV})^2, (150\ \text{GeV})^2] \\ \text{II:} & [-(200\ \text{GeV})^2, (150\ \text{GeV})^2] \end{cases}$

- For large $m_{H^\pm}$, $g_{HH^+H^-} \simeq -\frac{2m_{H^\pm}}{v}$ and this leads to $C_\gamma^H \simeq 0.95$.

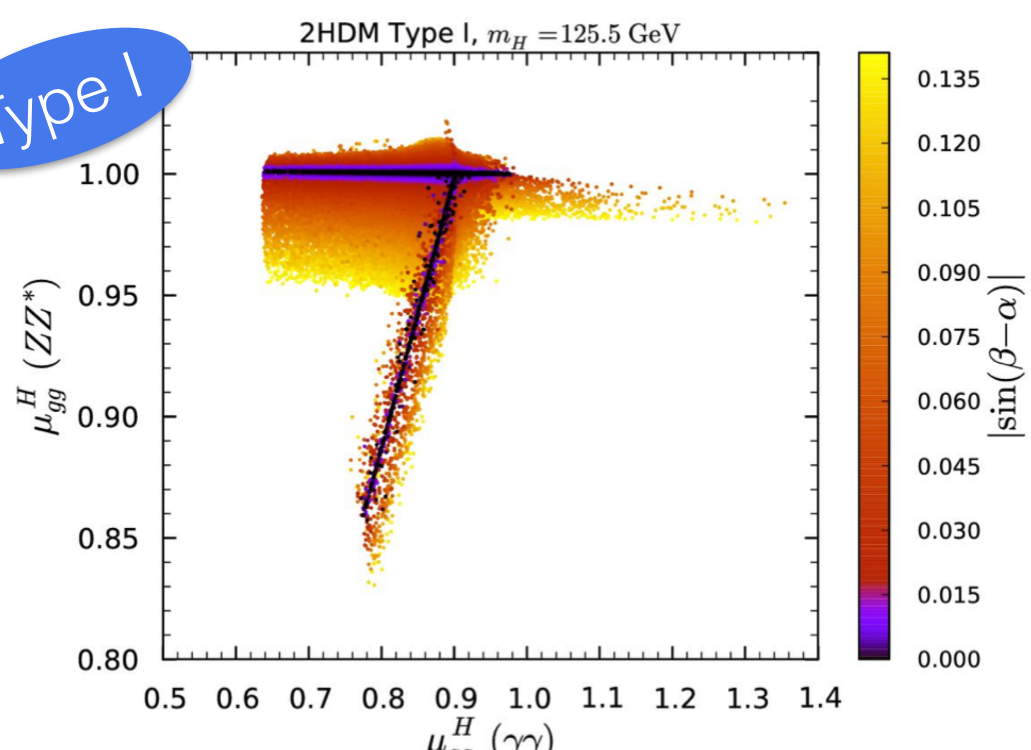
- $C_\gamma^H > 1$ possible if positive $\overline{m}^2$ and light charged Higgs: only in Type I.

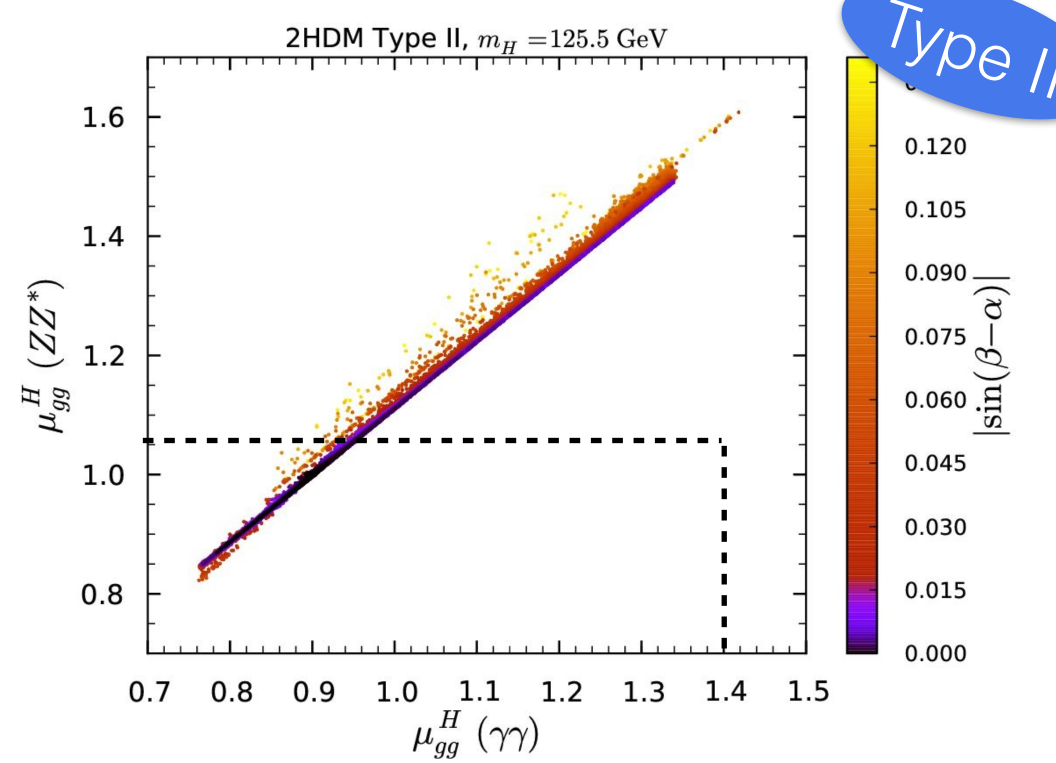
Signal strengths of the 125 GeV state: $\mu(X,Y) = \dfrac{\sigma(X)\mathcal{B}(H \to Y)}{\sigma(X_{\mathrm{SM}})\mathcal{B}(H_{\mathrm{SM}} \to Y)}$





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





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

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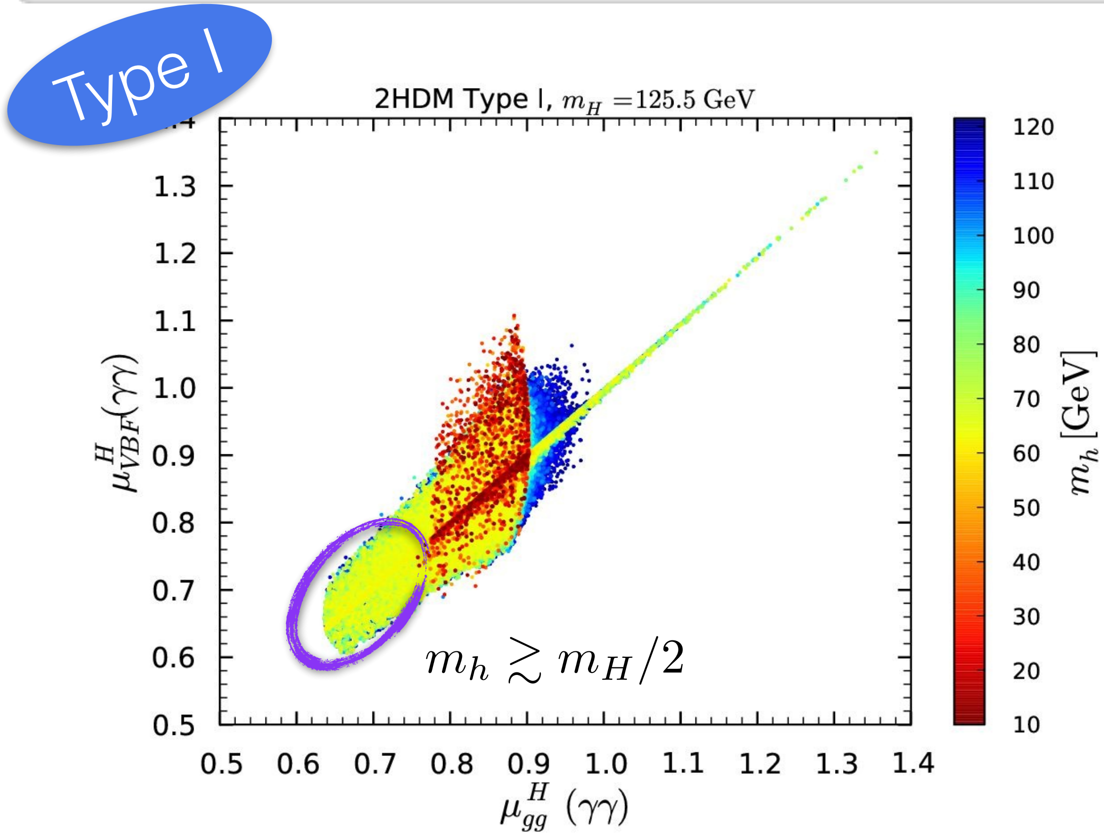

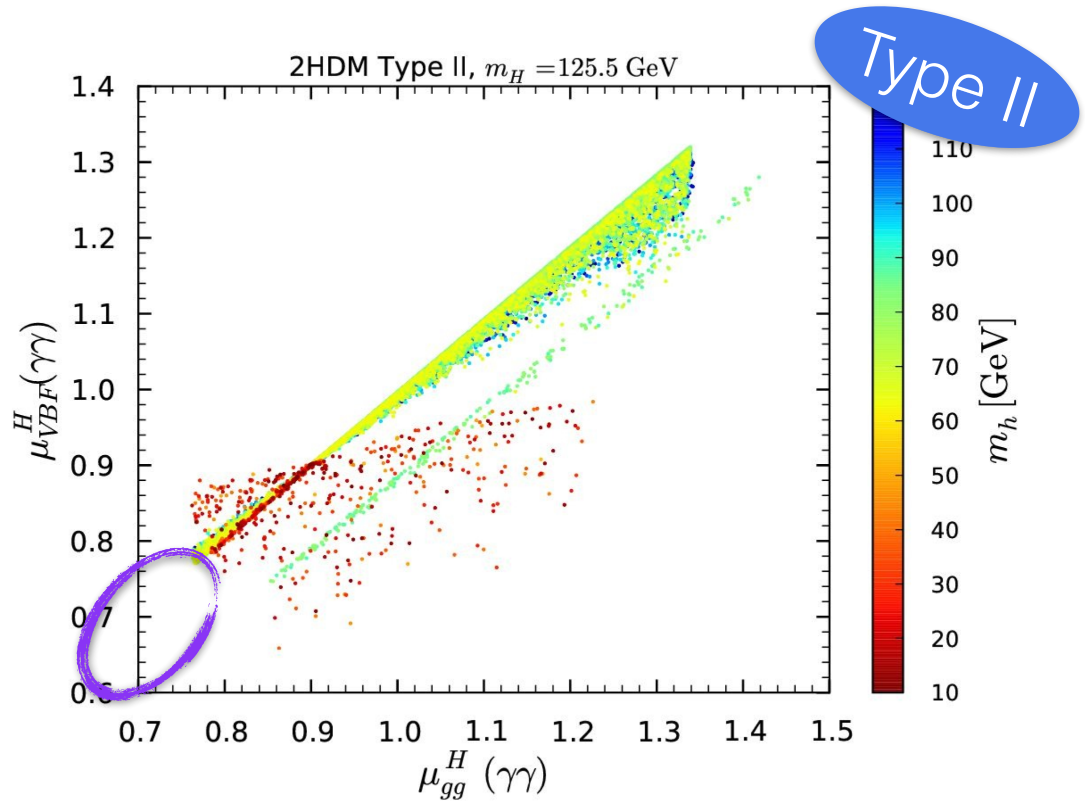

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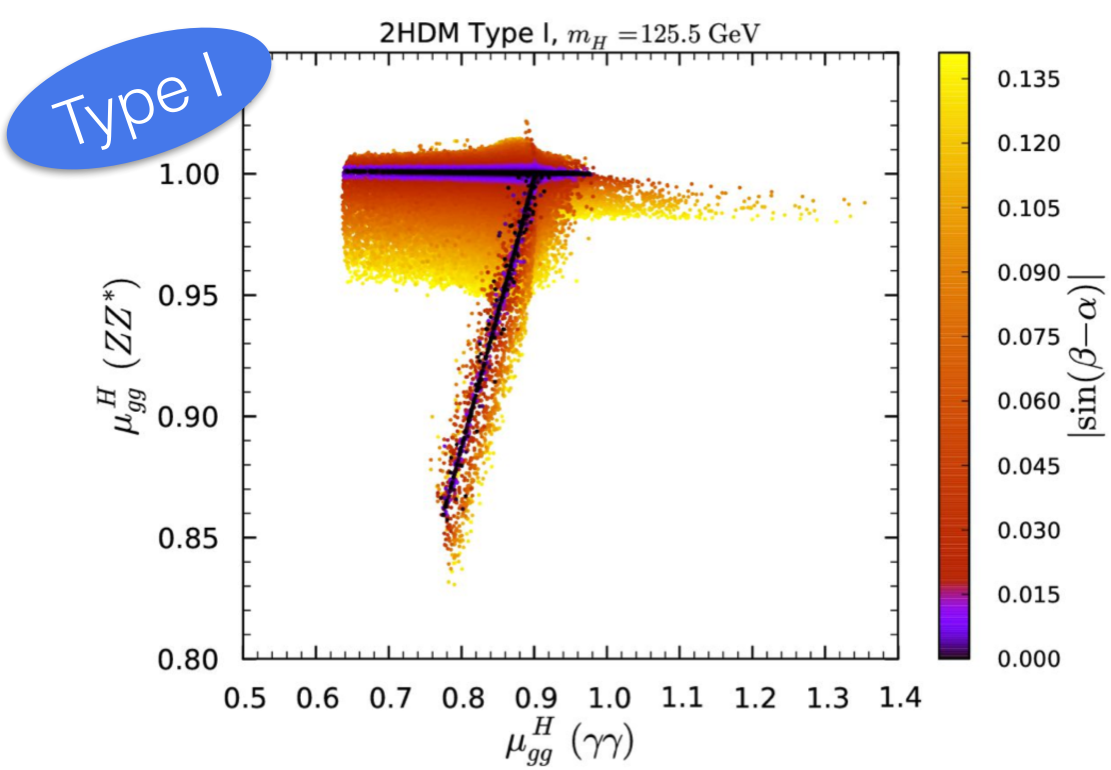

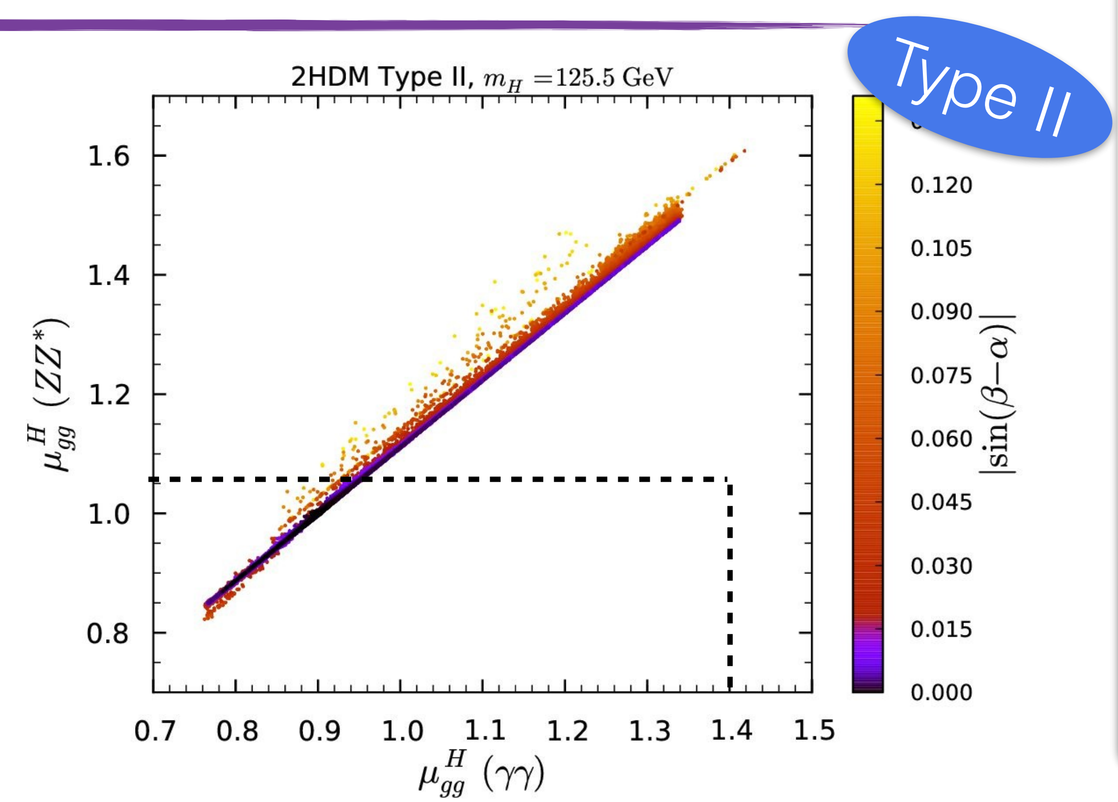

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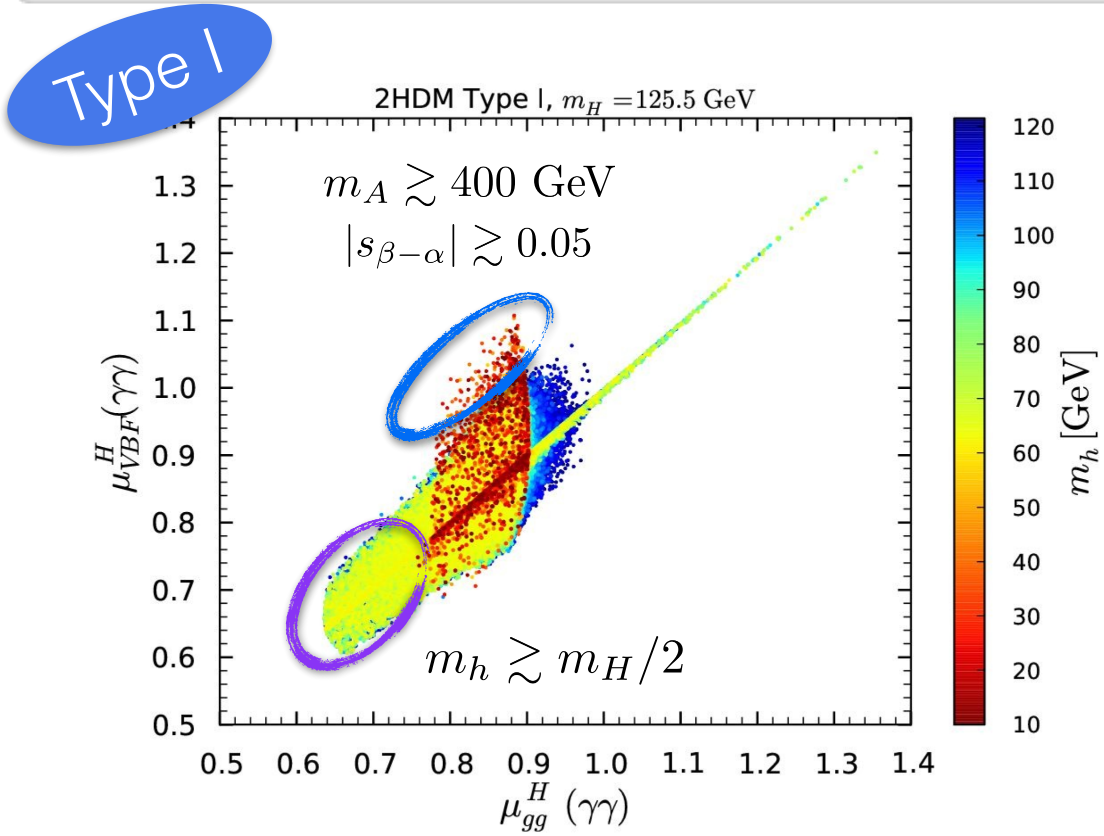

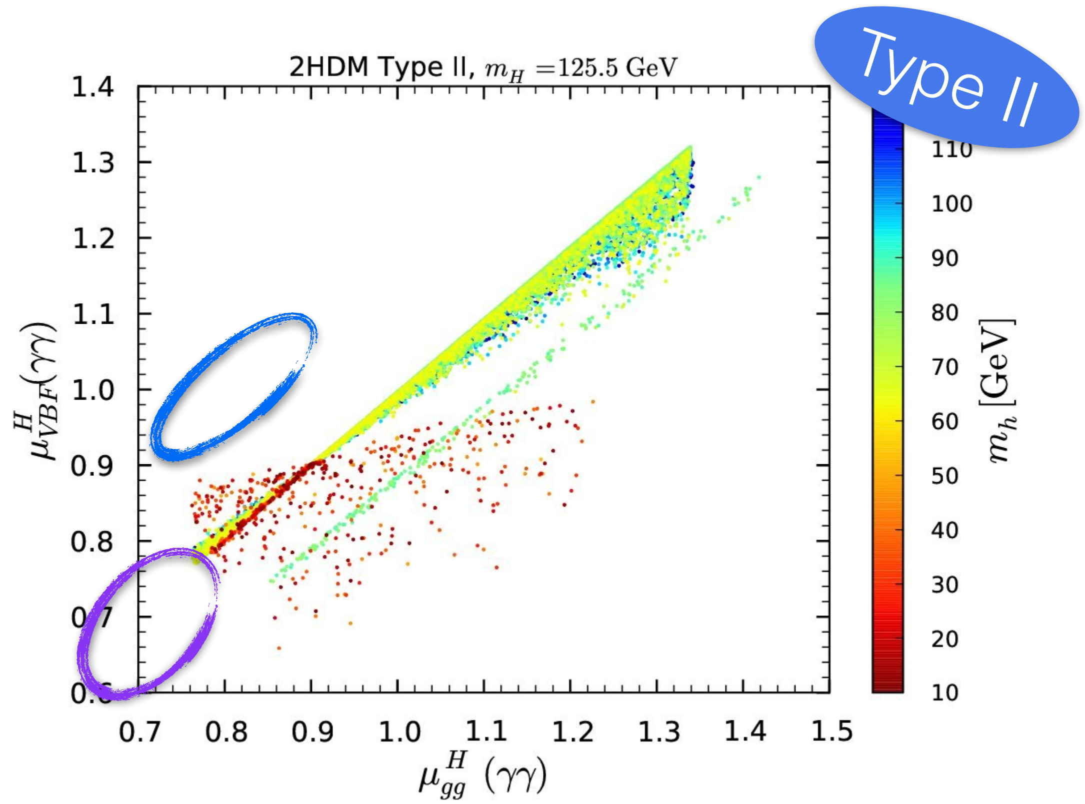

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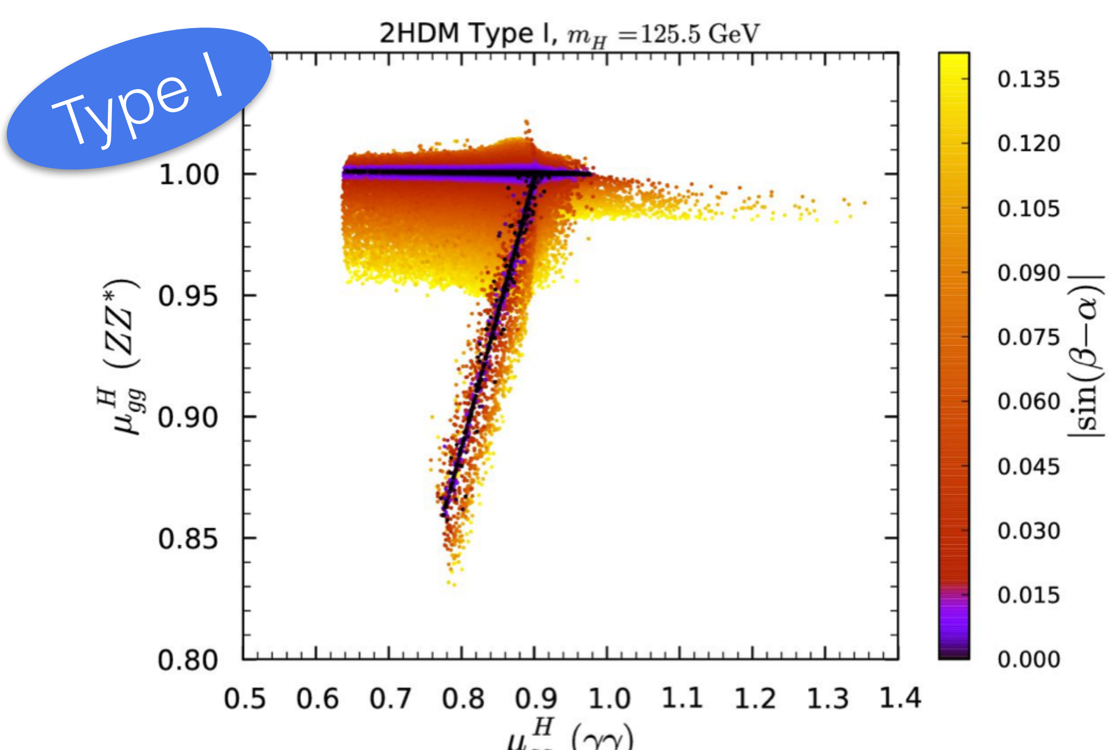

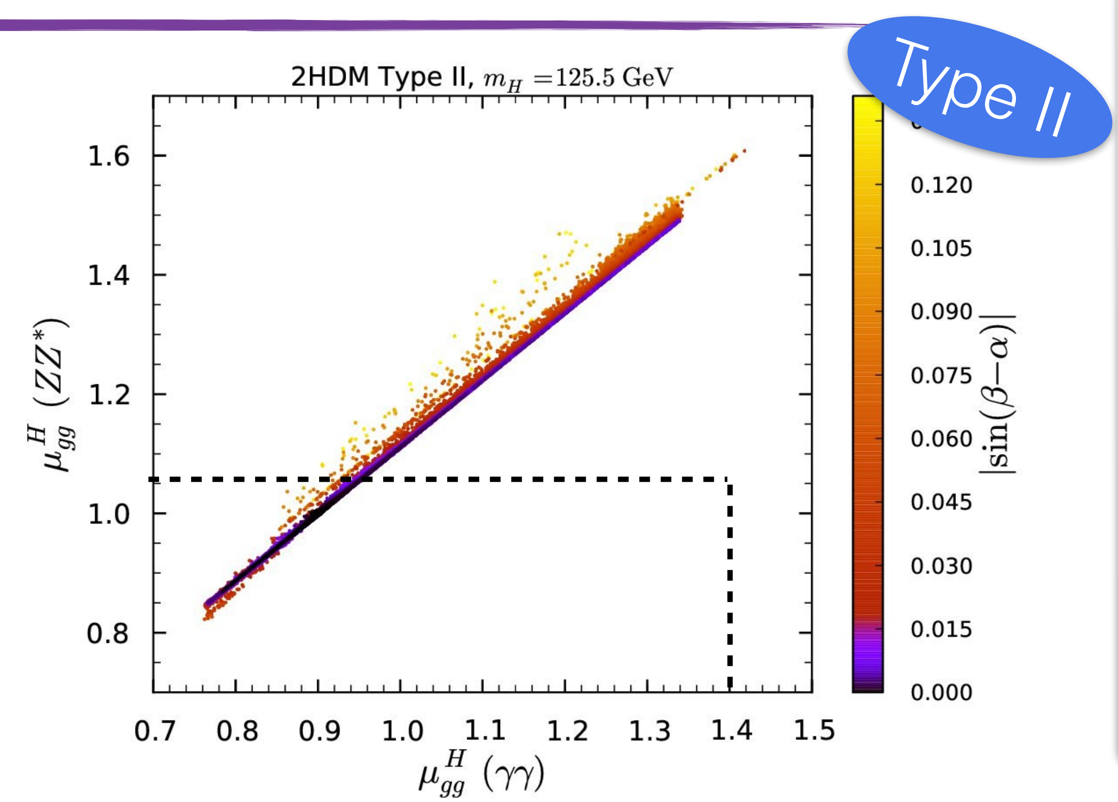

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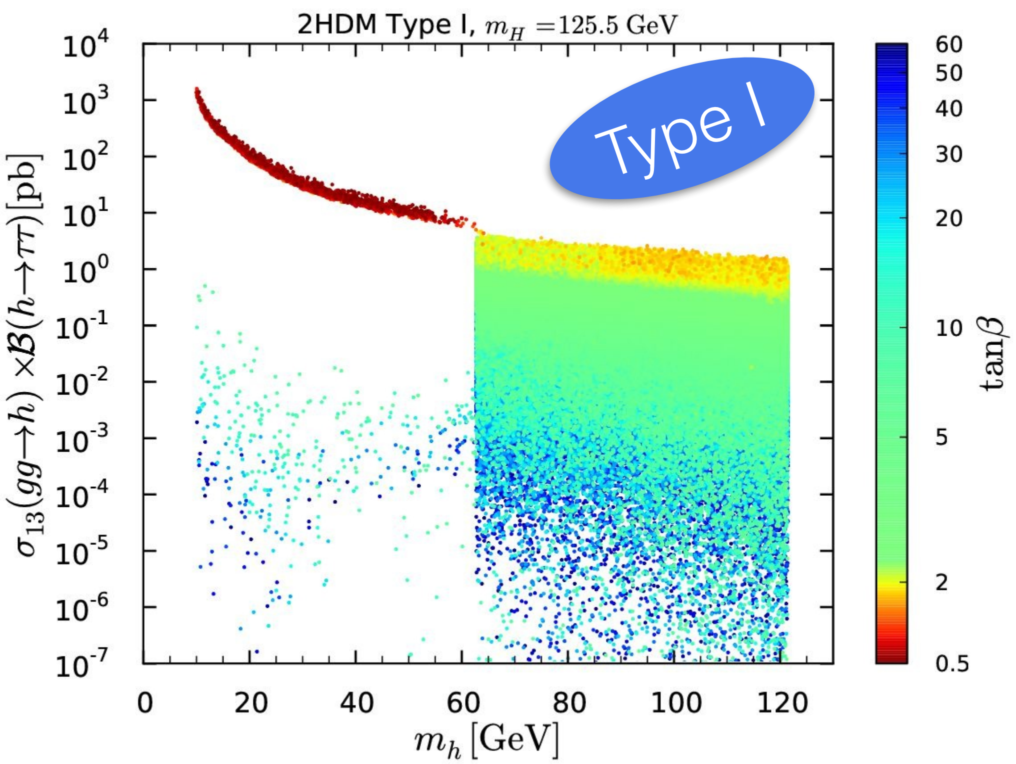
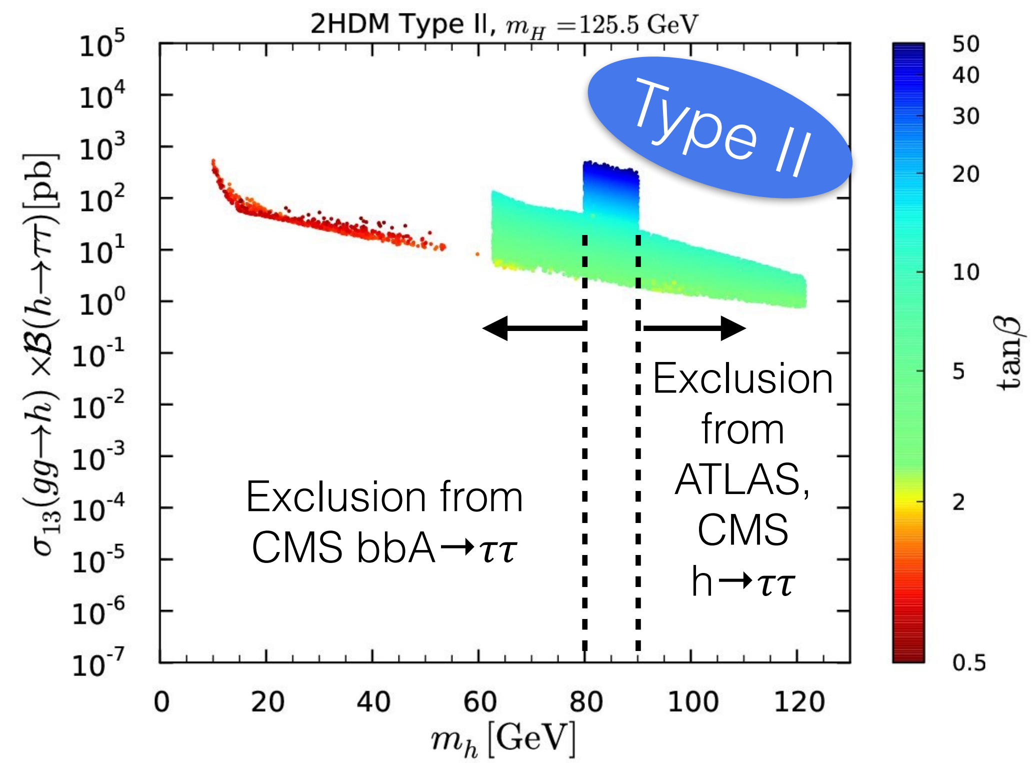
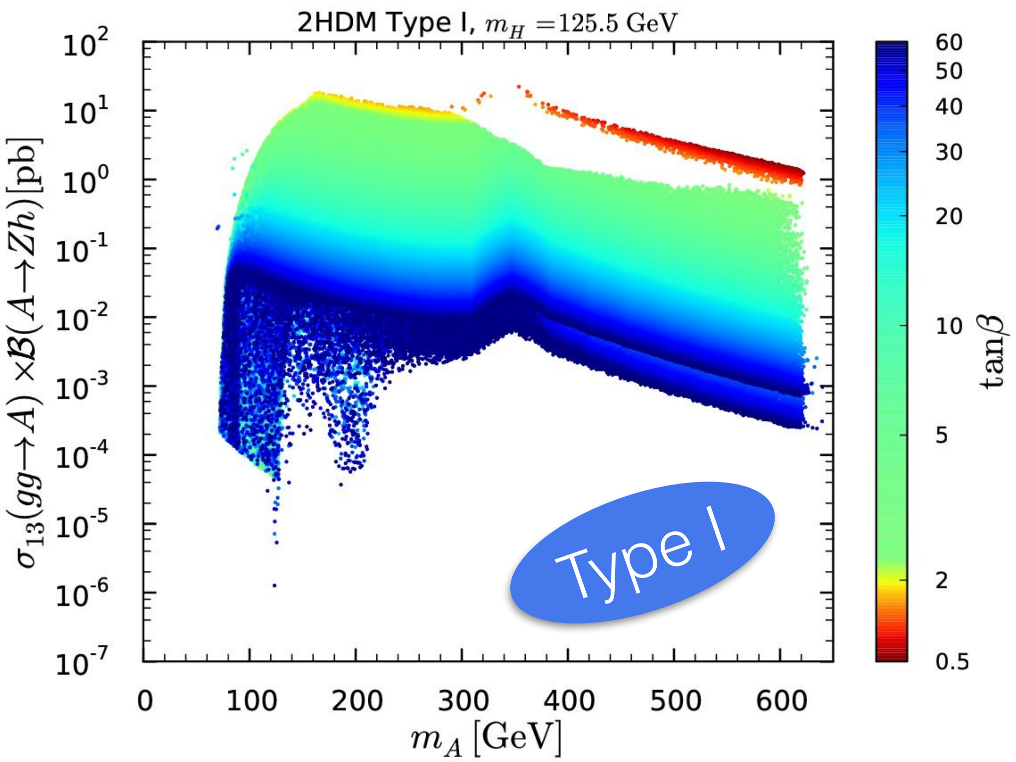
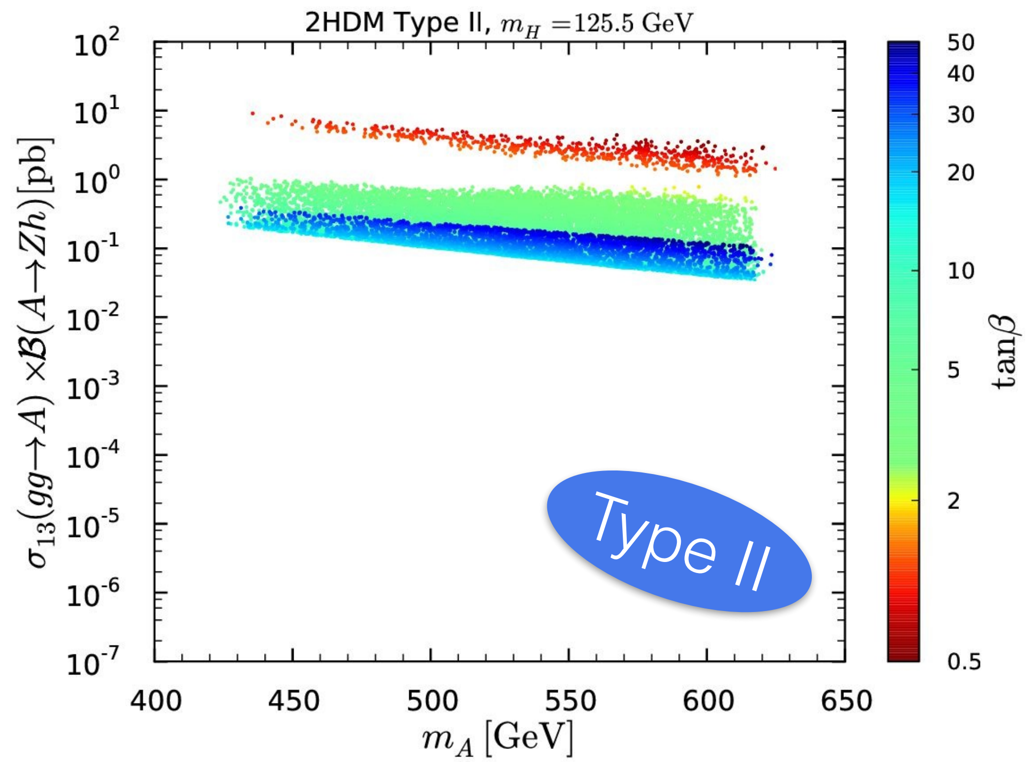
$gg \to h \to \tau\tau,\ gg \to A \to Zh$ at the LHC 13 TeV





Cross section above 1pb 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 t_β





A→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≃0.7–1.1 down to $|s_{\beta-\alpha}| \sim 5 \times 10^{-3}$
  Presence of a **« wrong-sign » solution** C_D≃-1.1– -0.7, C_U≃1
- Signal strengths can thus largely deviate from the SM predictions close to alignment. Their correlations can be used to distinguish the model. Their deviations are correlated with the masses of the extra-states.
- The h, A→$\tau\tau$ channels are of high interest for potential discovery. Most exciting is the **A→Zh channel**.
- In general, looking for **low mass states** is a real experimental challenge but it could be **very rewarding**.

Backup

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

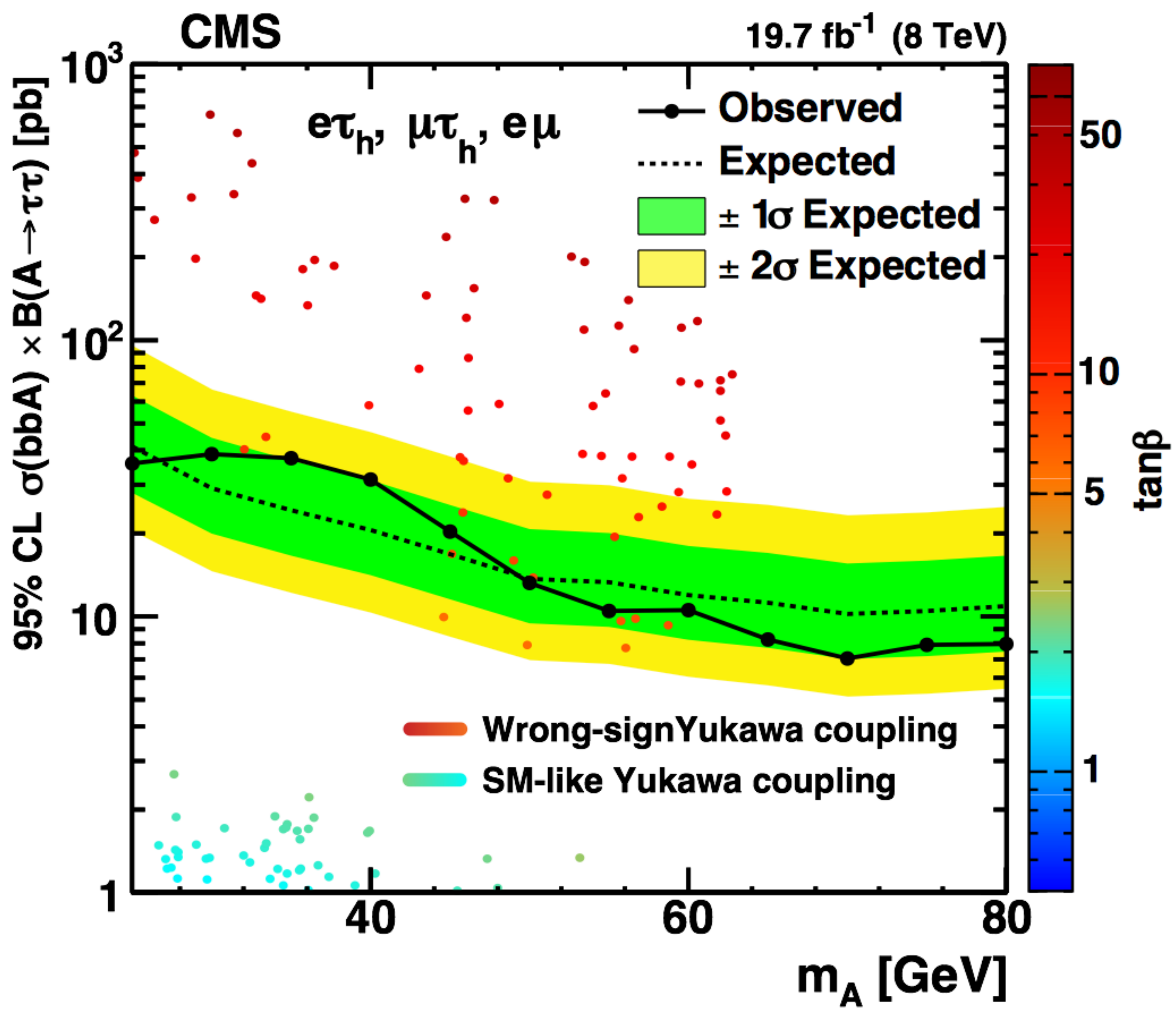
Higgs family transformations: $\begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} \to X \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix}$

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

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

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

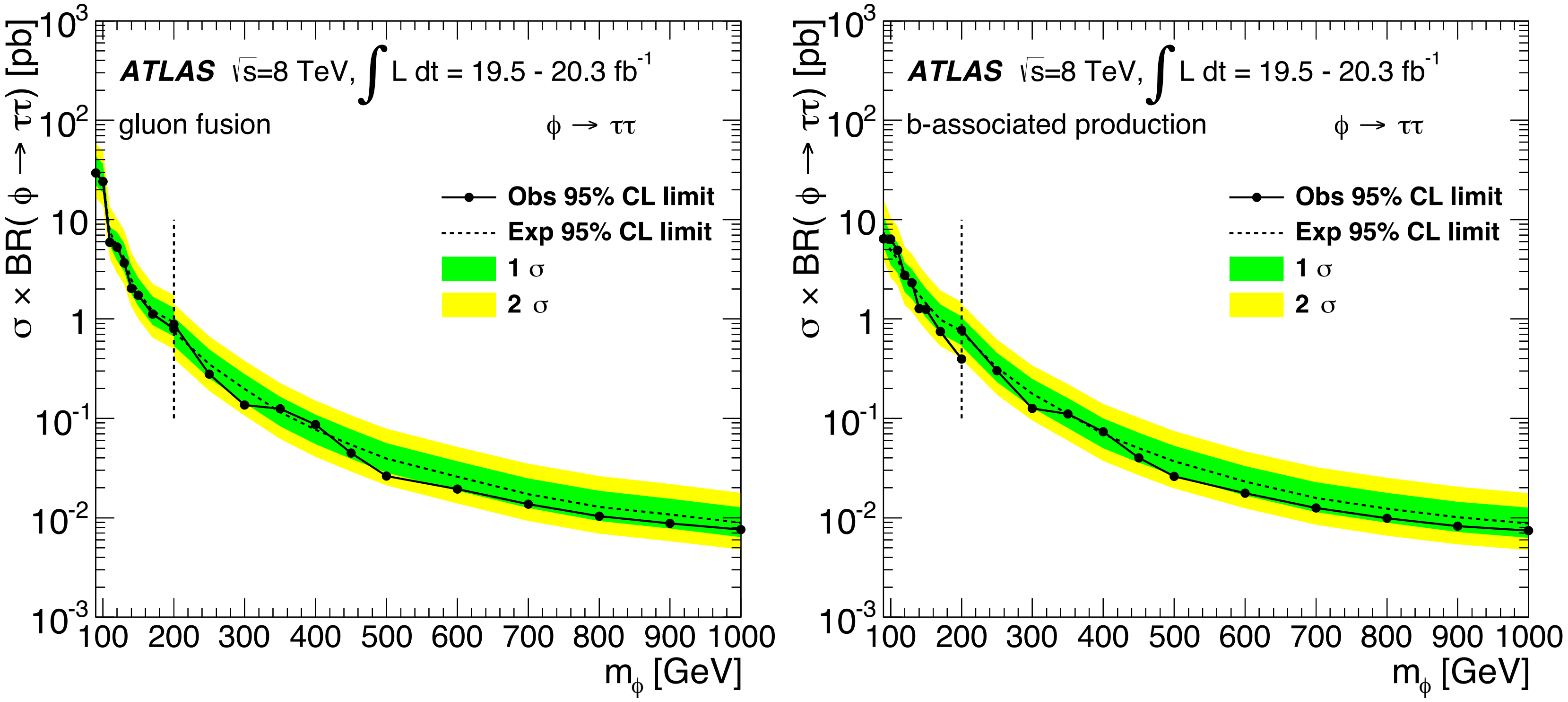
[CMS-HIG-14-033]



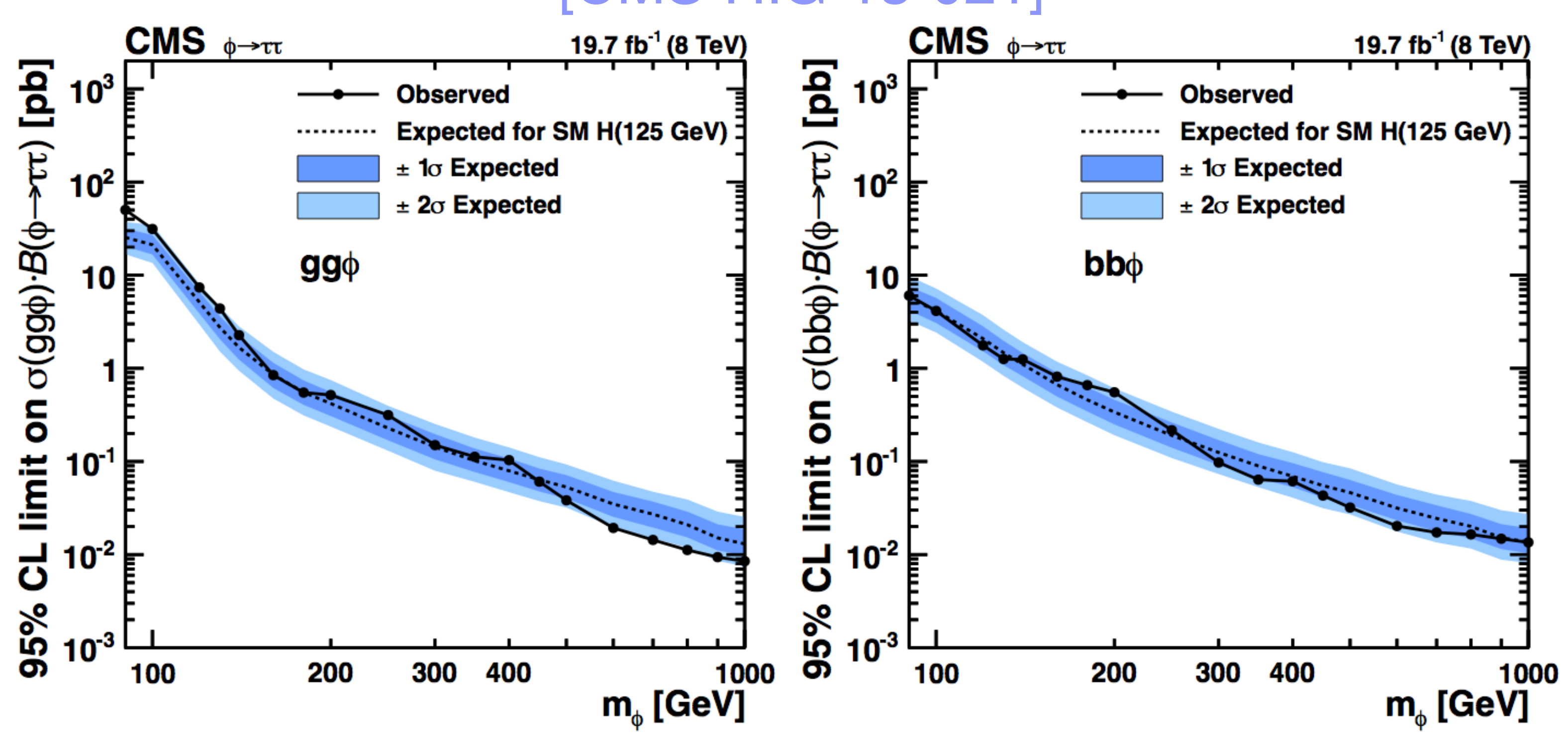
(Points from [JB, Gunion, Jiang, Kraml] [arXiv:1412.3385])

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

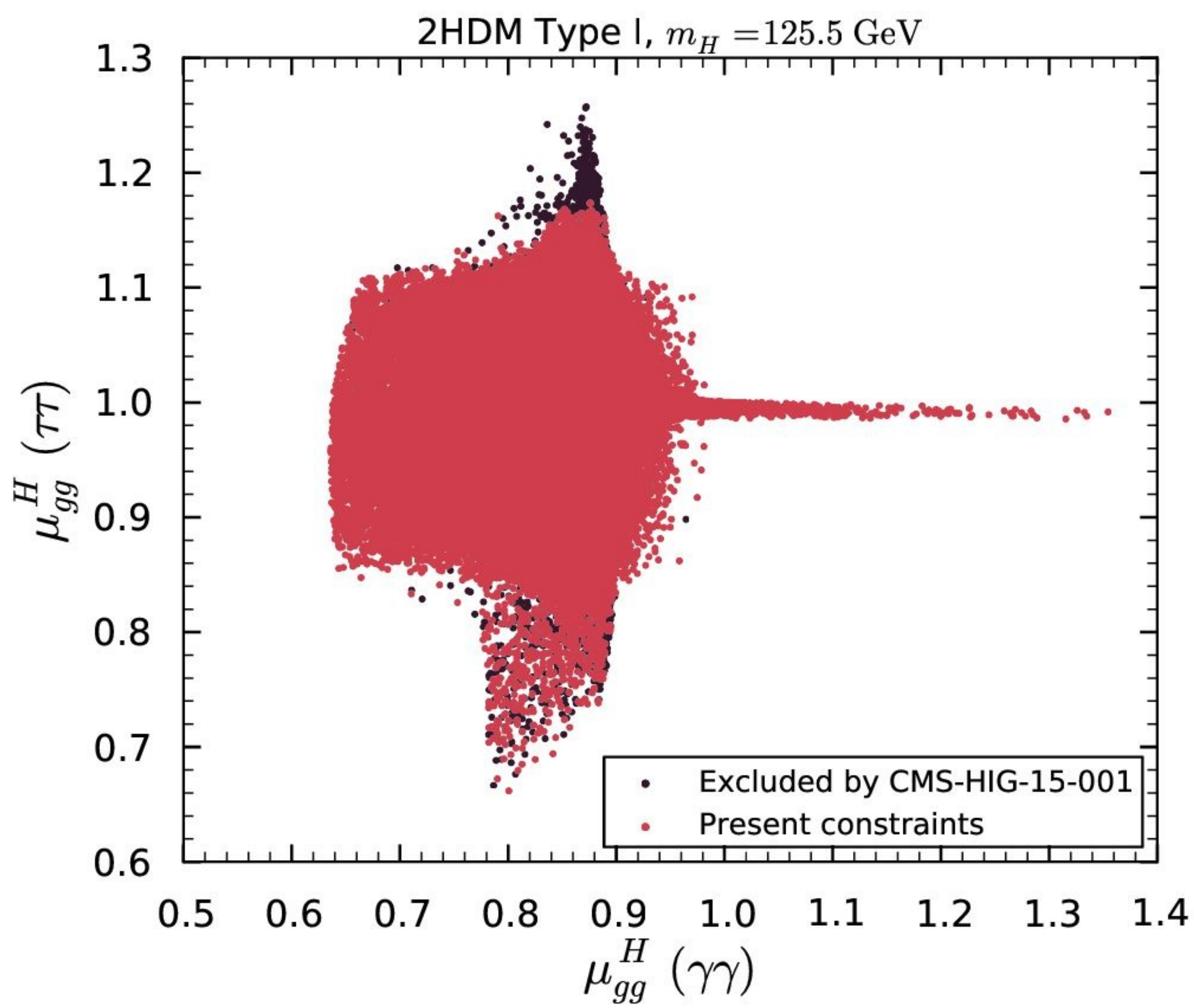
[ATLAS-HIGG-2013-31]

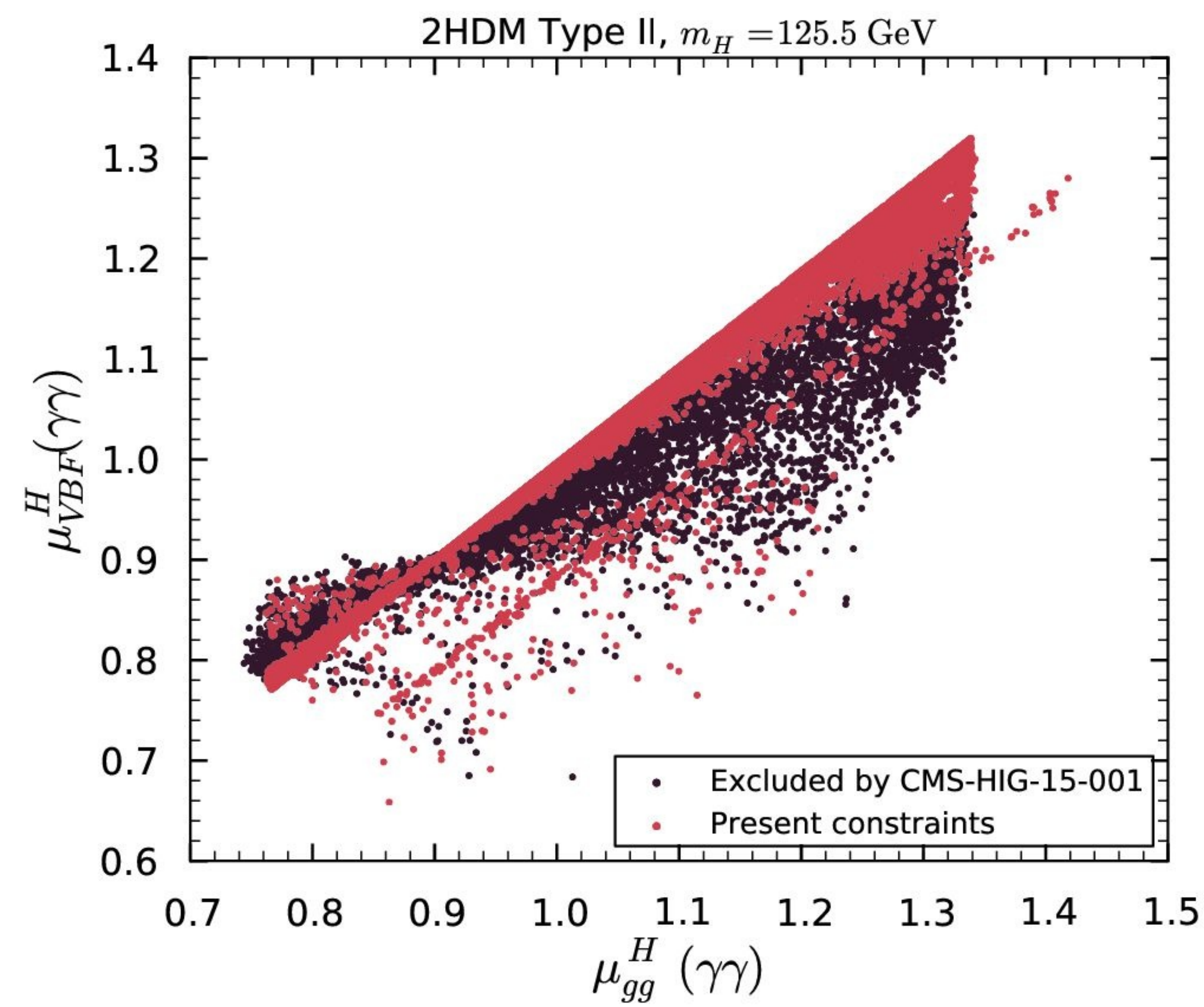


[CMS-HIG-13-021]

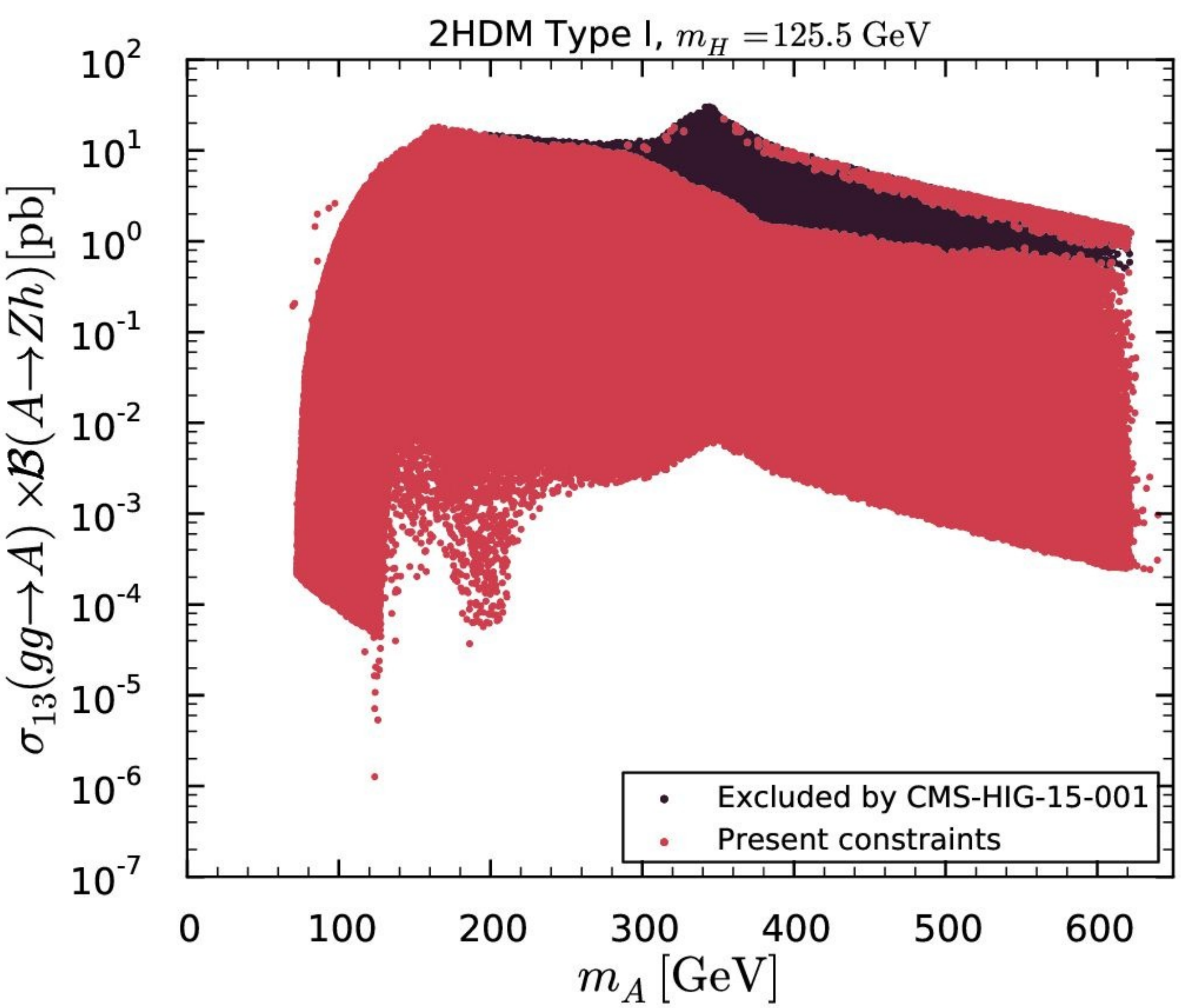


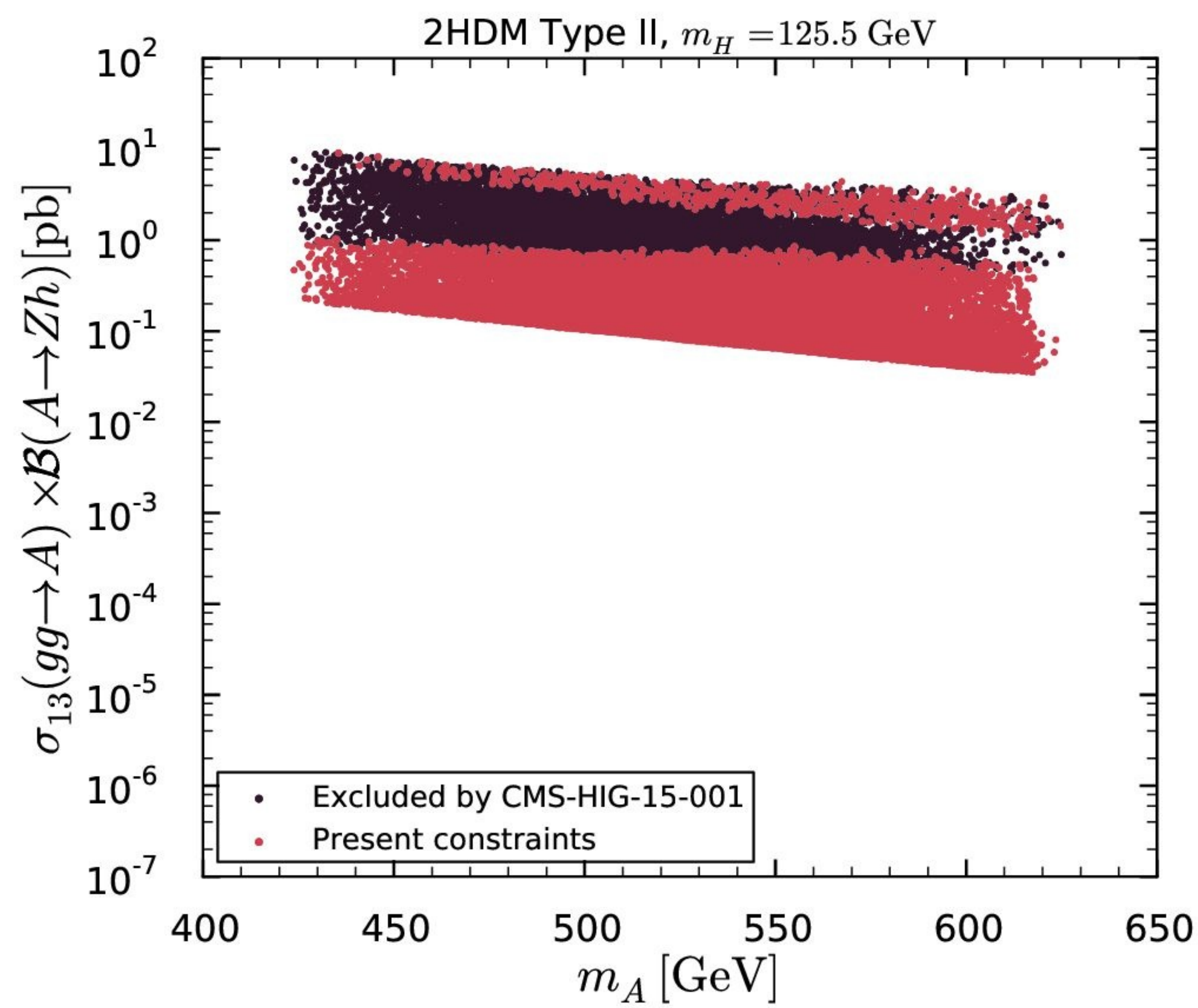
Impact of the CMS A→Zh search for signal strengths



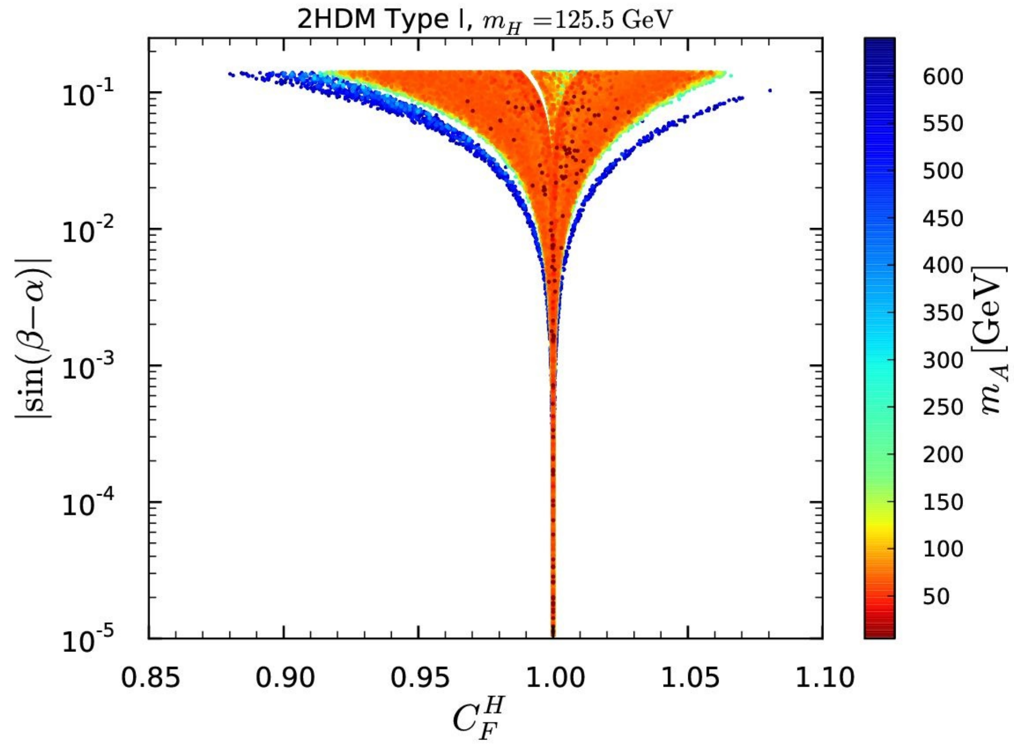


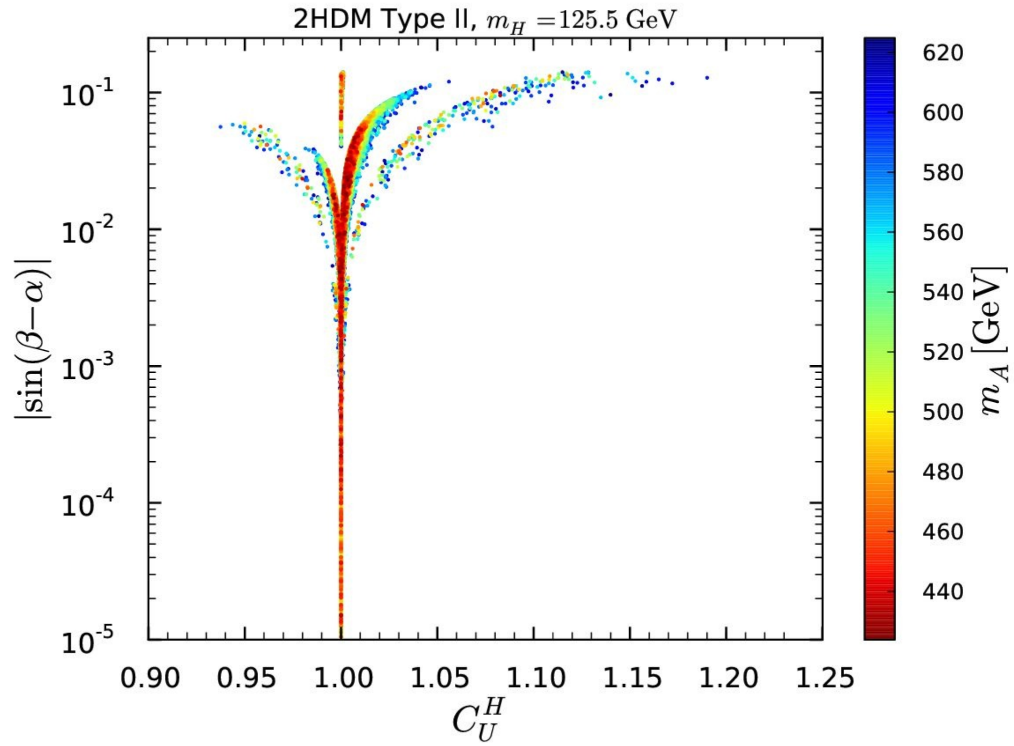
Impact of the CMS A→Zh search for cross sections

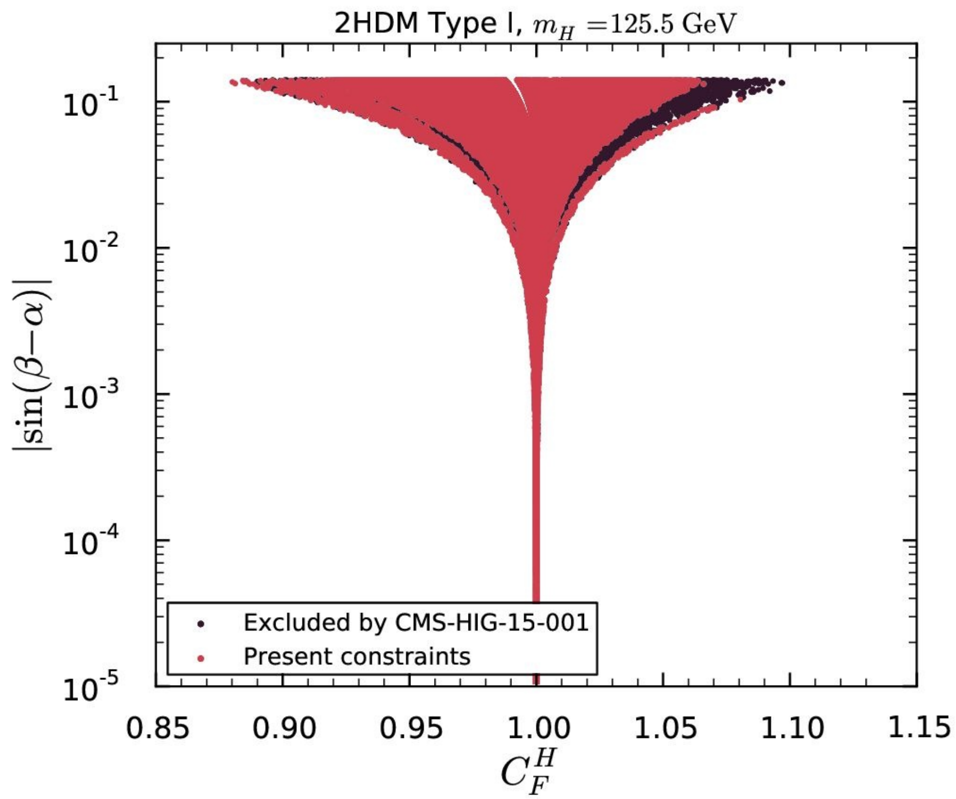


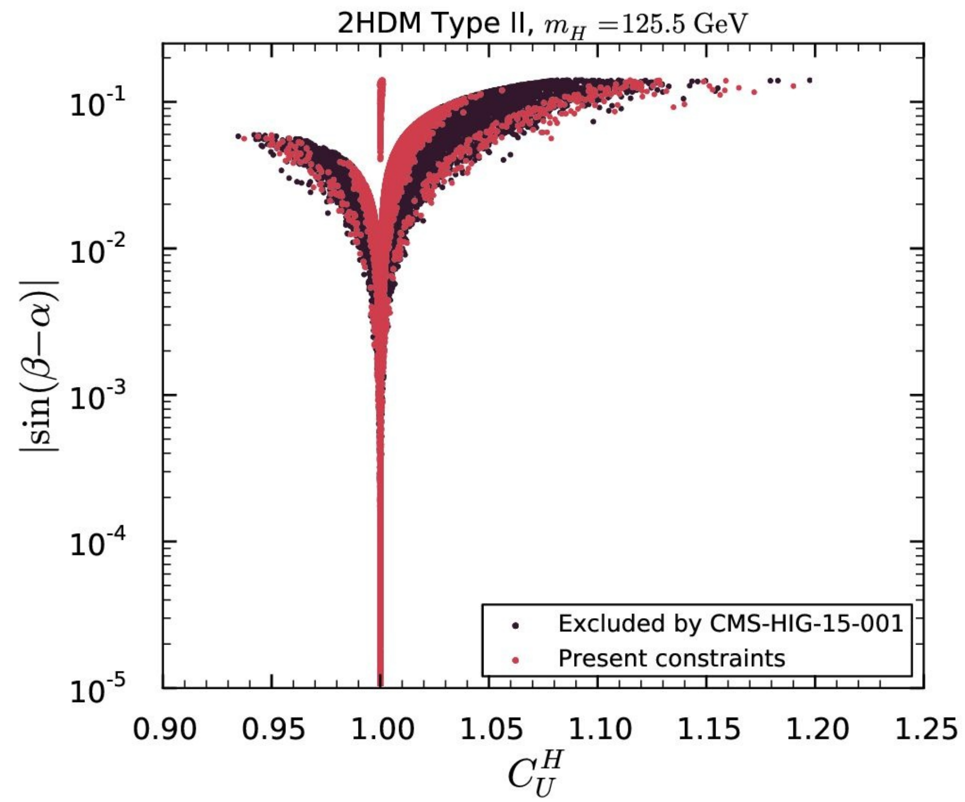


Fermion couplings of the 125 GeV state

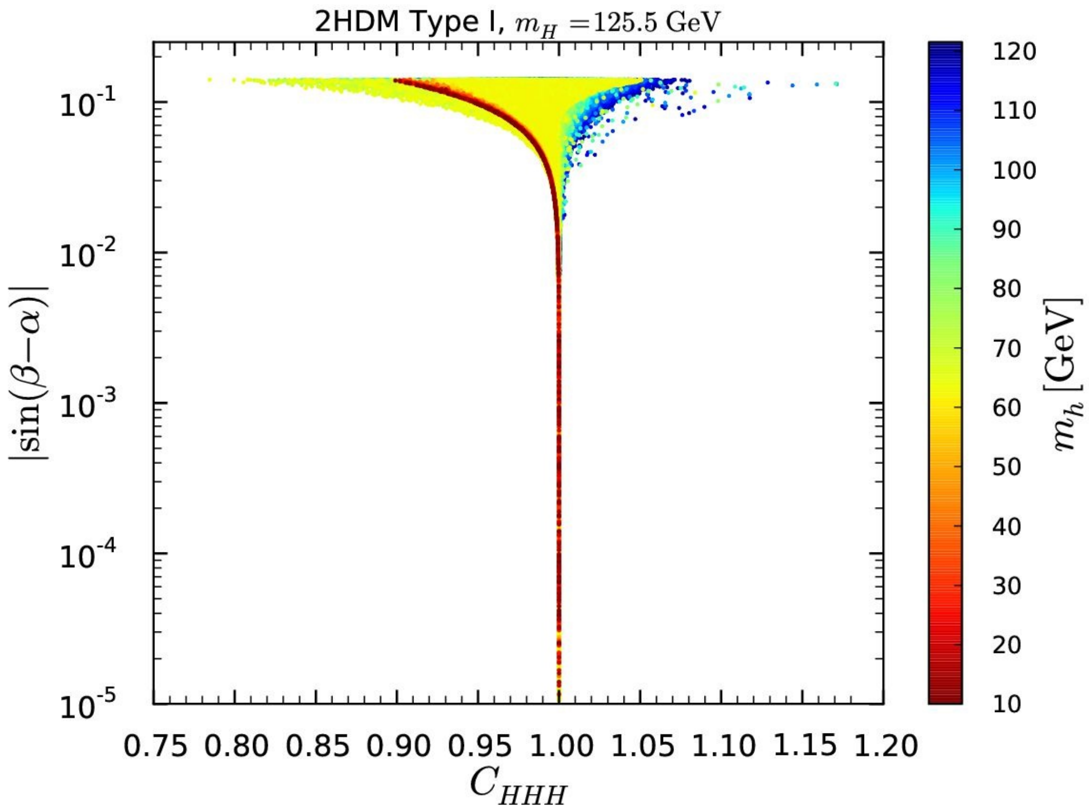


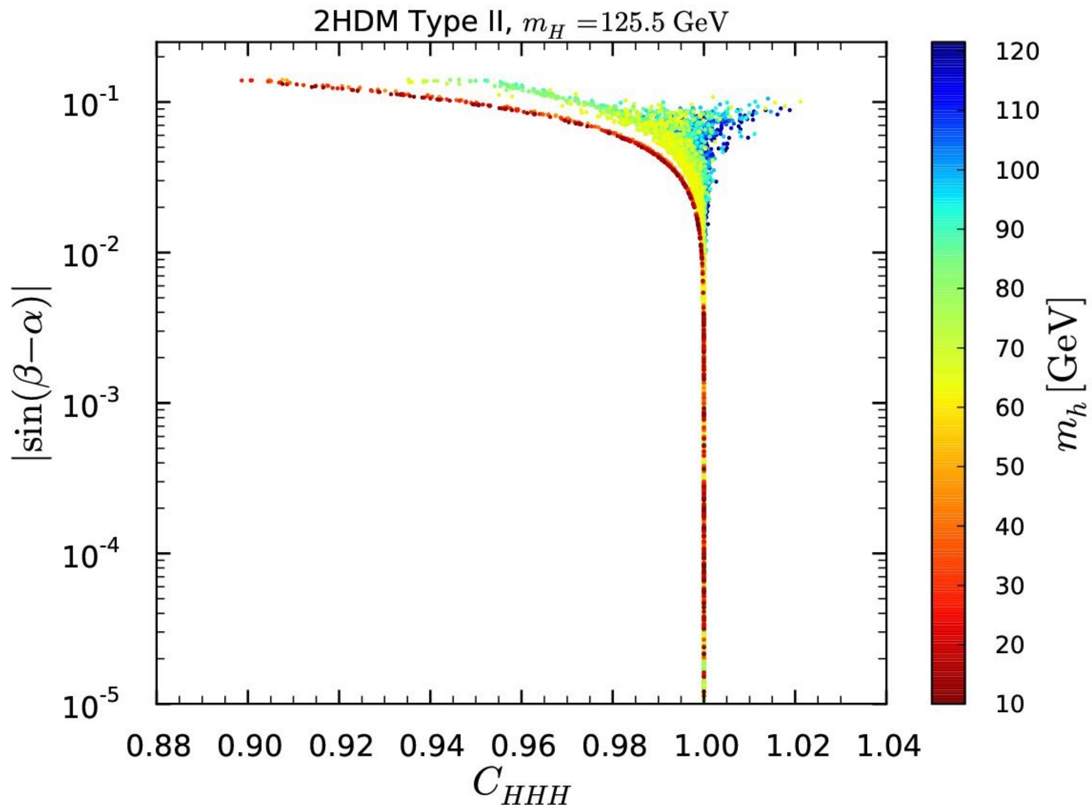


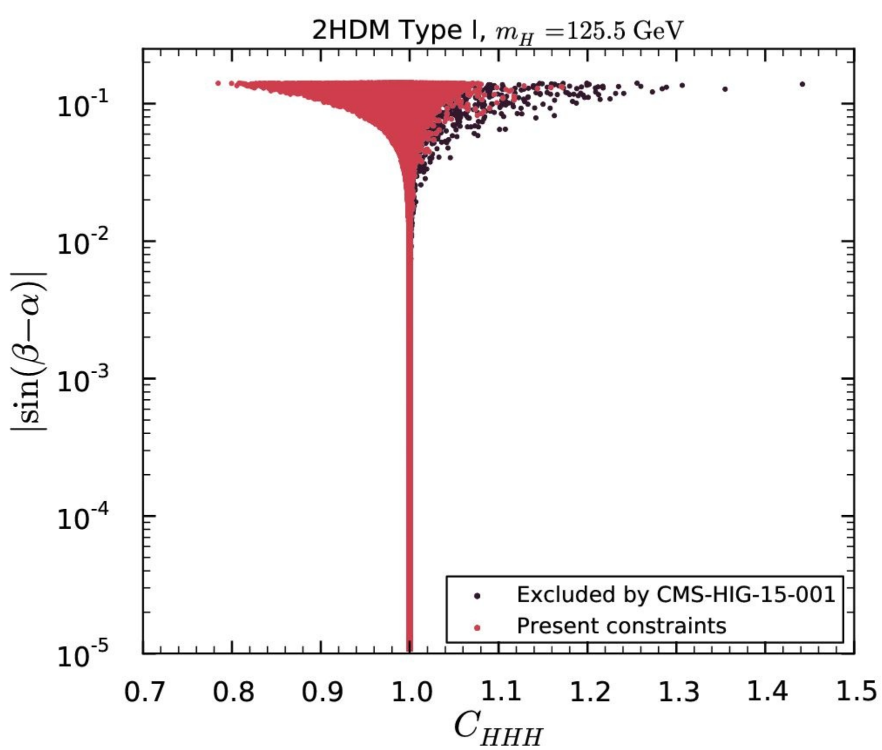


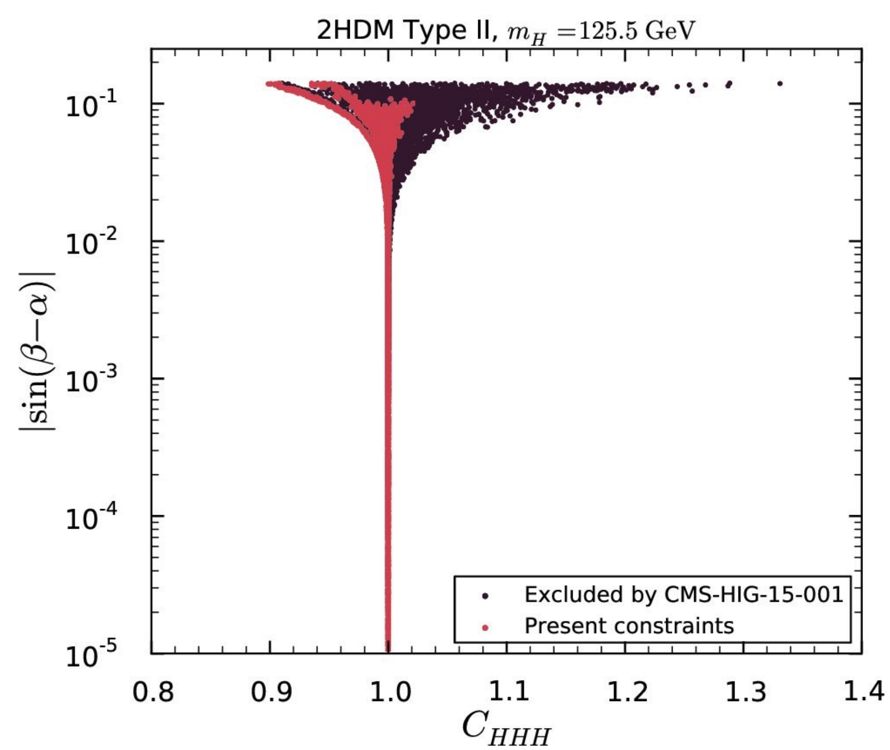


Trilinear Higgs coupling

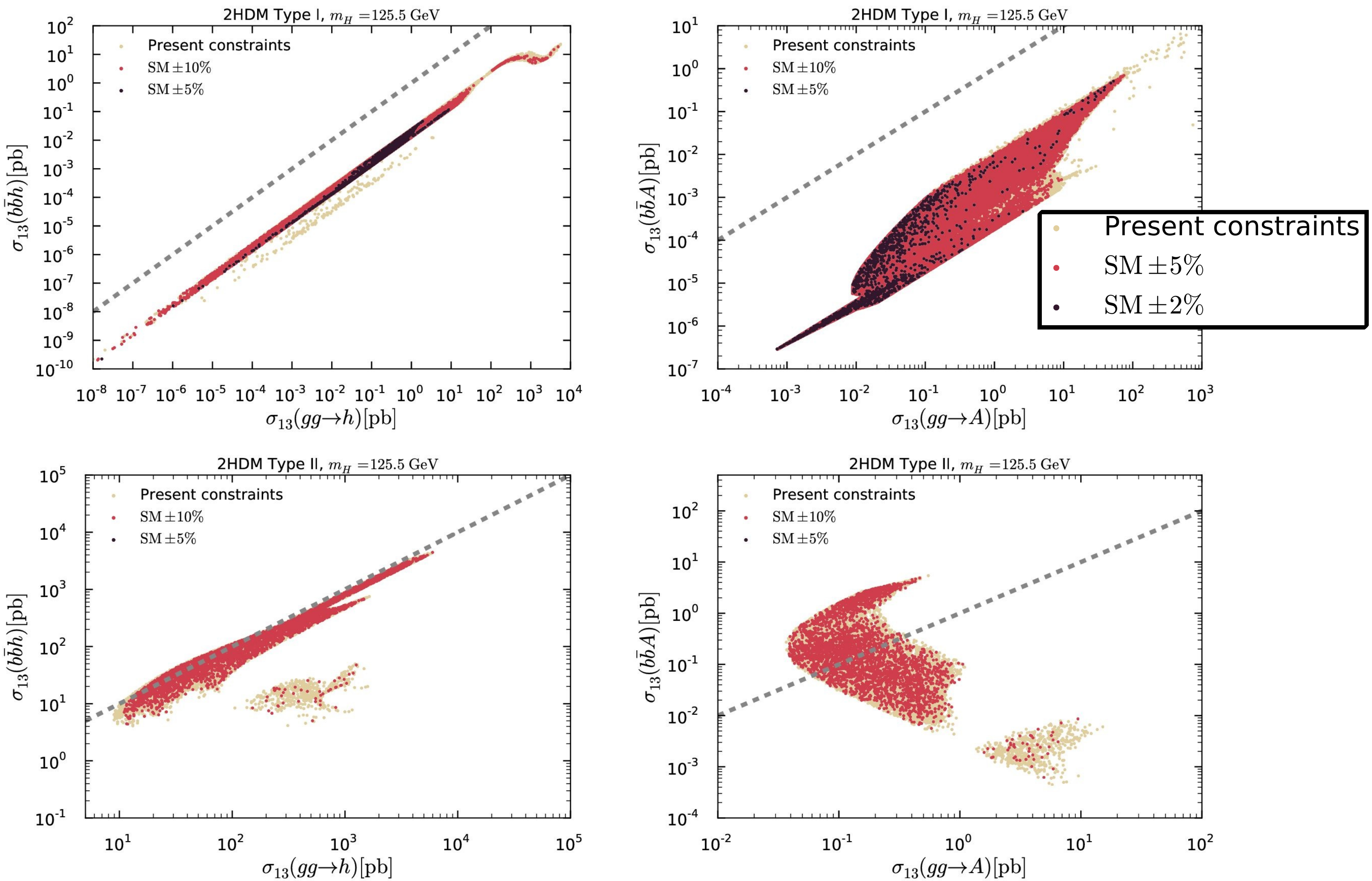




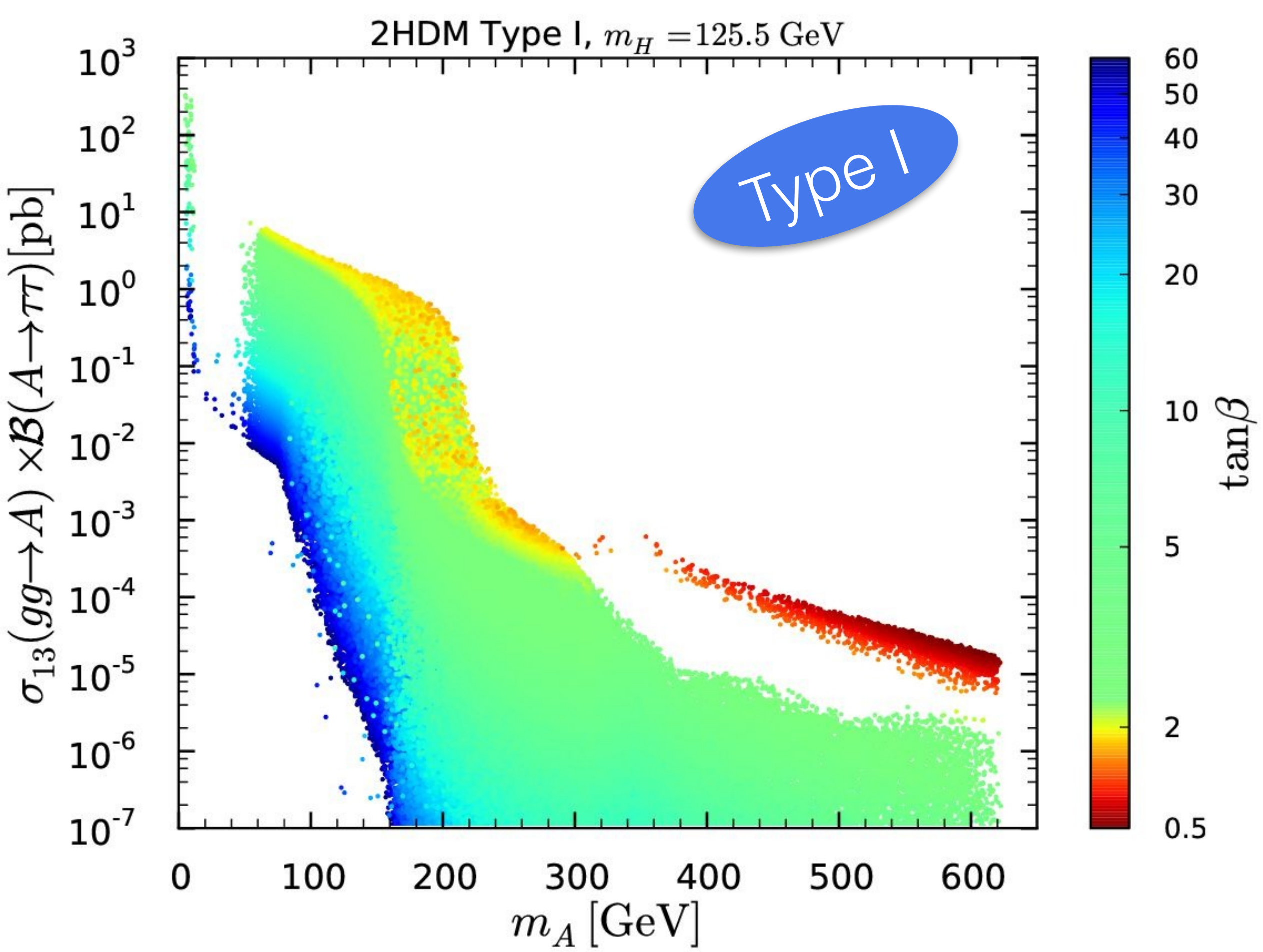


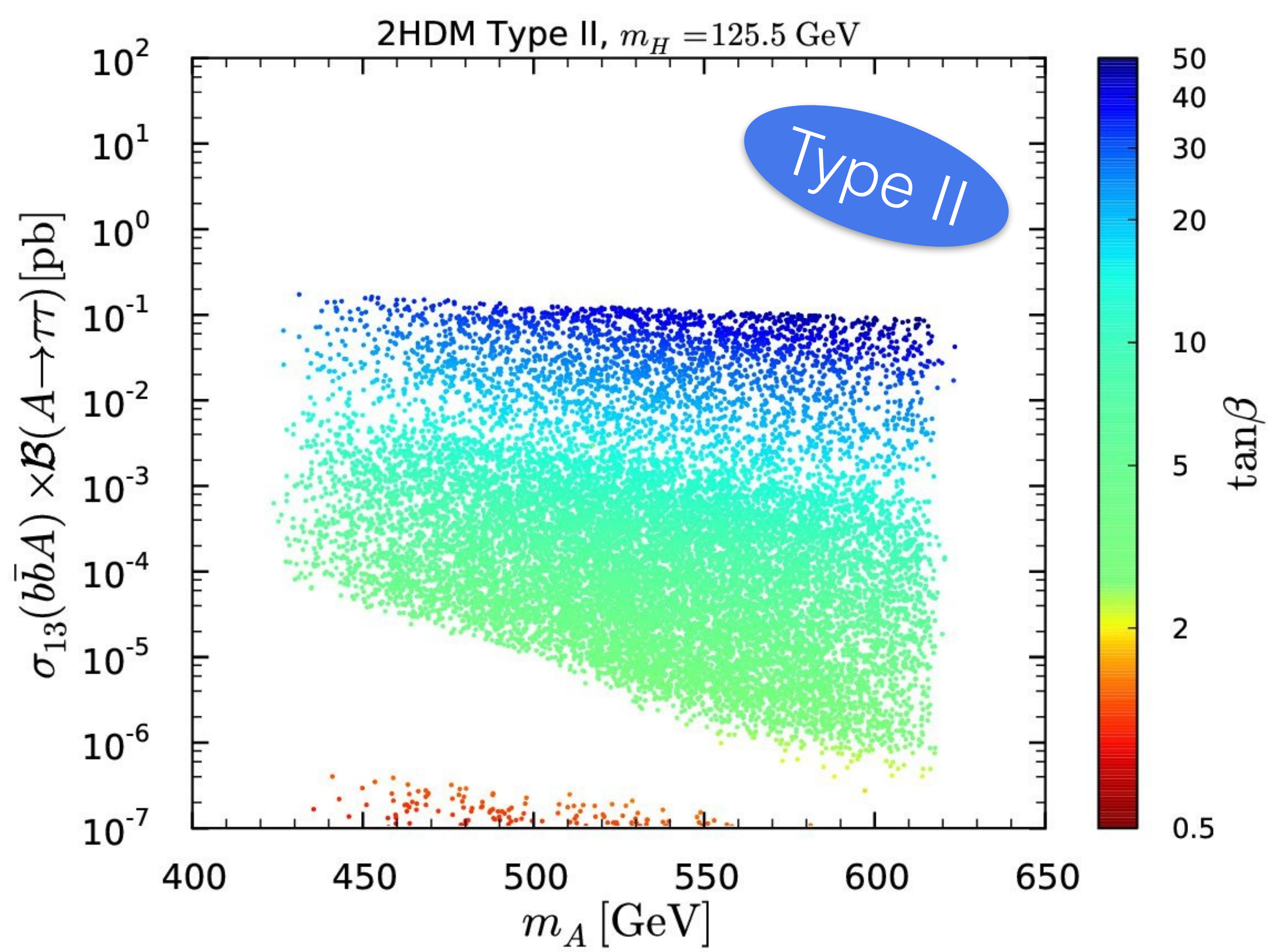


h, A production cross sections at the LHC 13 TeV



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





A→γγ, tt at the LHC 13 TeV