Scrutinizing the alignment limit in two-Higgs-doublet models: The m_H=125 GeV case

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Based on [arXiv:1511.03682-v2]

[and [arXiv:1507.00933] (PRD) (m_h=125 GeV case)]

In collaboration with

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GDR Terascale
Grenoble, November 17th, 2015

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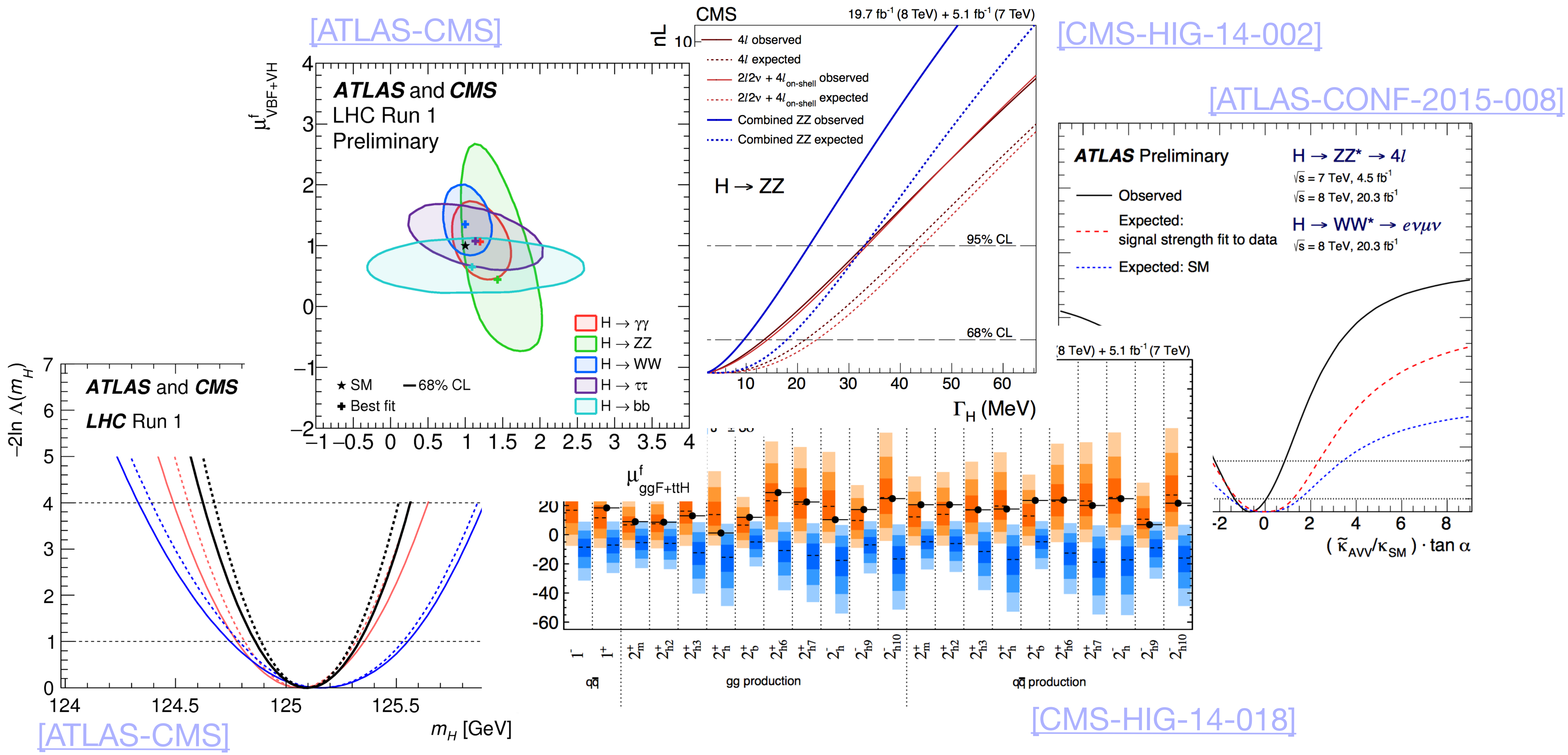
Motivations



[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 models

We consider here the **CP-conserving two-Higgs-doublet models (2HDMs)** as a framework relevant for LHC phenomenology.

- In the **Higgs basis** (H_1,H_2), the vacuum expectation value (vev), v≃246 GeV, resides entirely in one of the two Higgs doublets: $\langle H_1^0\rangle = v/\sqrt{2}, \quad \langle H_2^0\rangle = 0$

  Higgs scalar potential:

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

  $|Z_i|\lesssim 10$ by virtue of perturbativity and unitarity. We assume that $Z_{5,6,7}$ are **real**.

- **5 physical scalar states**: two CP-even (h, H) (**$m_h<m_H=125$ GeV**: **our focus**), a CP-odd (A) and a pair of charged Higgs ($H^\pm$).

⟹ **No decoupling limit** in this scenario: at least two states in the low-energy theory

- To avoid tree-level flavor changing neutral currents we impose **natural flavor conservation** in the **$\mathbb{Z}_2$-basis** ($\mathbf{\Phi}_1$,$\mathbf{\Phi}_2$). We consider **Type I and II models**. (details are skipped)

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

The alignment limit

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

With $\boldsymbol{\alpha}$ the CP-even mixing angle in the $\mathbb{Z}_2$-basis, the two mass eigenstates are

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

$\Longrightarrow$ There exists a SM state (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**

Looking at the mass matrix, a SM-like H state requires $\begin{cases} |Z_6| v^2 \ll |m_A^2 + (Z_5 - Z_1) v^2| \\ m_A^2 + Z_5 v^2 < Z_1 v^2 \end{cases}$

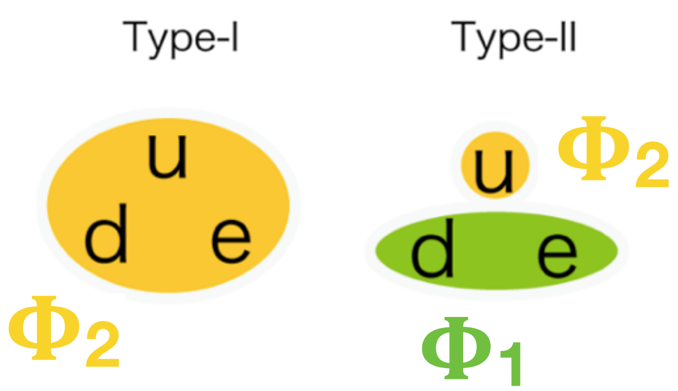
$s_{\beta-\alpha} = \dfrac{-Z_6 v^2}{\sqrt{(m_H^2 - m_h^2)(Z_1 v^2 - m_h^2)}}$ then leads to $c_{\beta-\alpha} \sim 1$ $(|s_{\beta-\alpha}| \ll 1)$ as expected.

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

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

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:



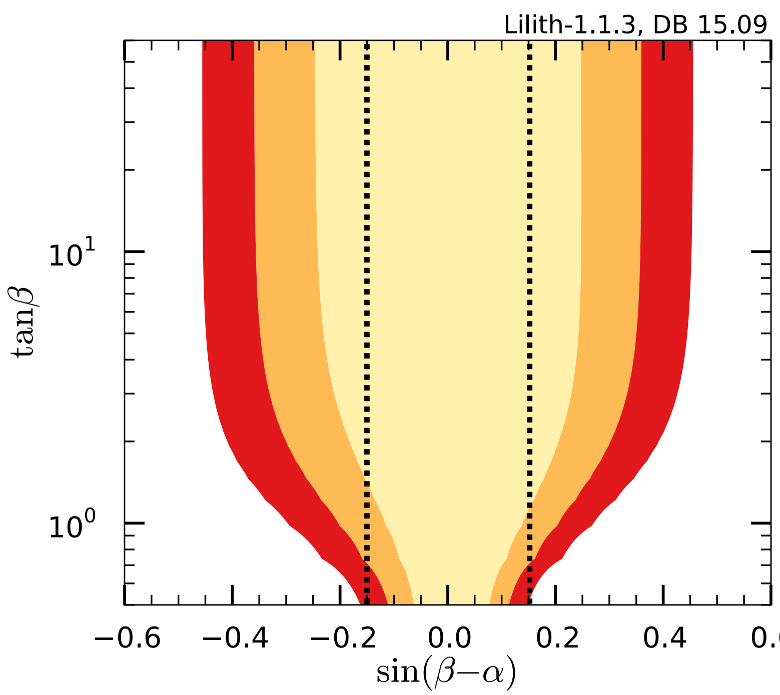
$$C_V^H = c_{\beta-\alpha},\; C_V^h = s_{\beta-\alpha}$$

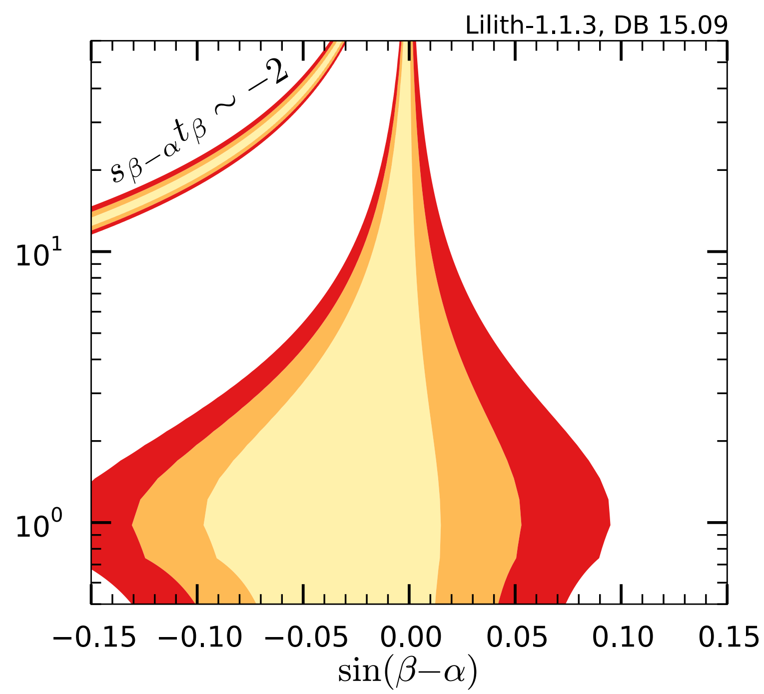
$$\text{I: } C_F^H = \frac{\sin\alpha}{\sin\beta} = c_{\beta-\alpha} - s_{\beta-\alpha}\cot\beta$$

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

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**.

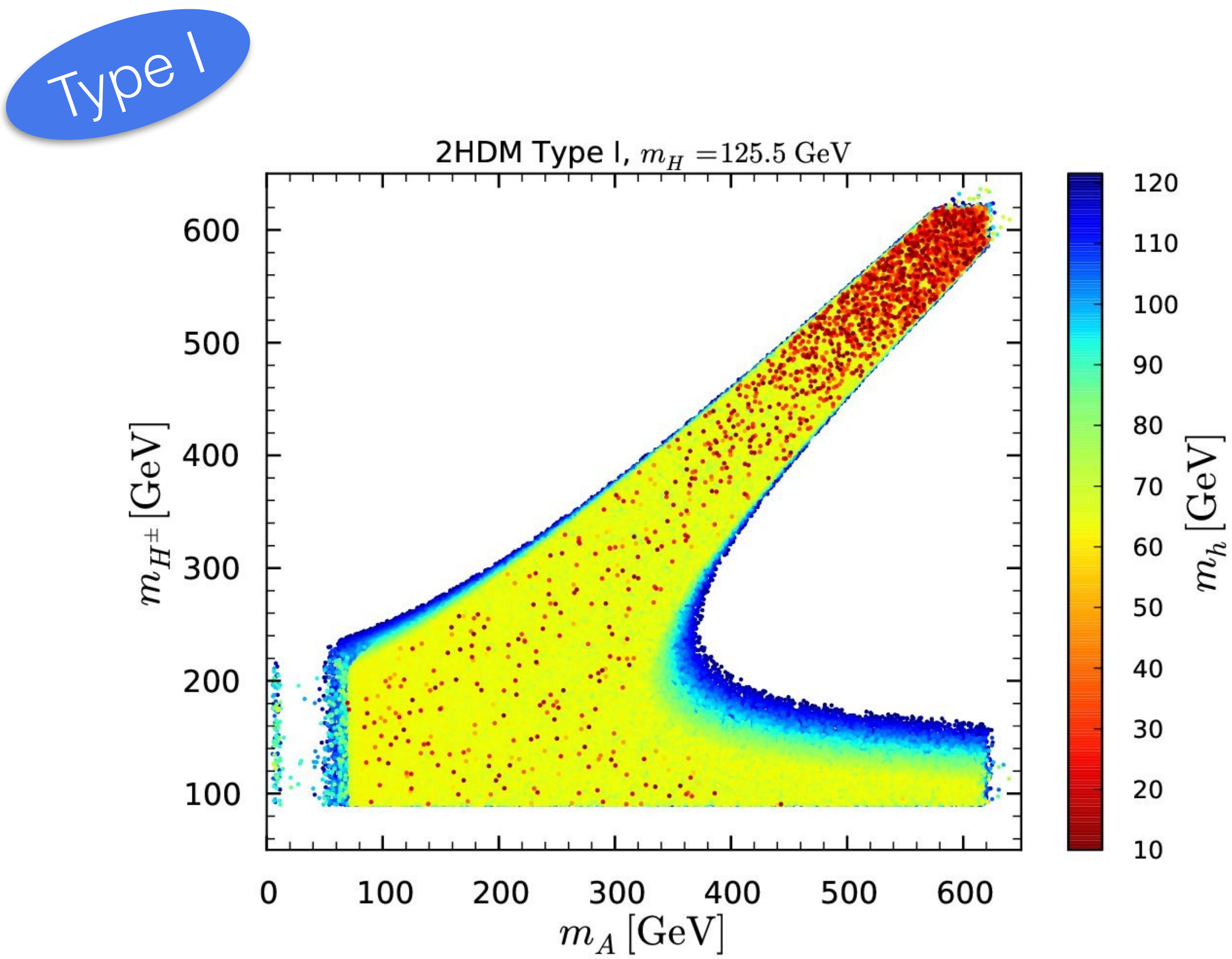
In Type II: presence of a sharp branch, characterized by $C_D \sim -1$: the **« wrong-sign solution »**, see [Ferreira, Gunion, Haber, Santos] [arXiv:1403.4736]

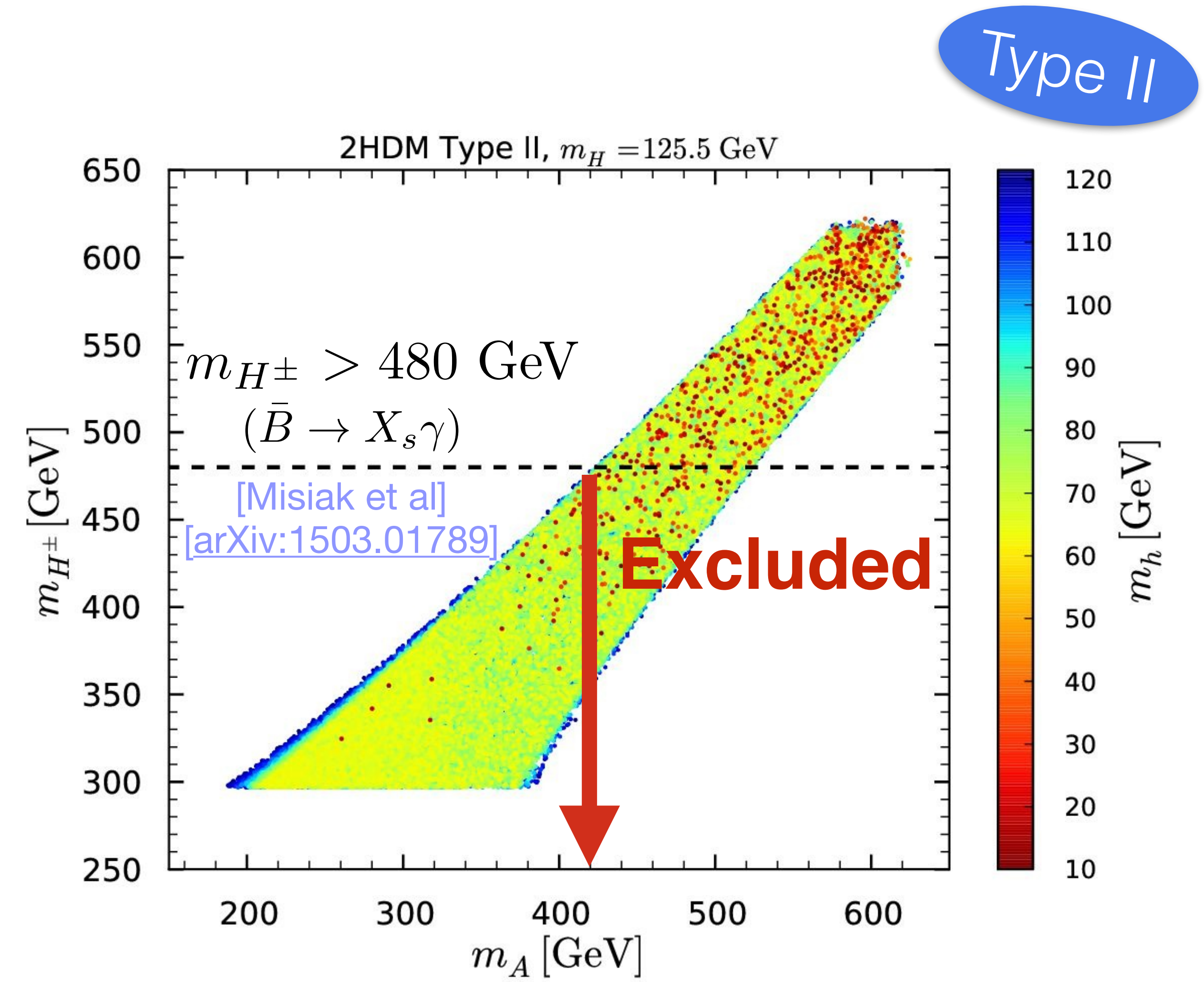
Numerical Analysis

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 ($A \to \mu\mu$, $bb(A,h) \to \tau\tau$, $h,H,A \to \tau\tau$, **$A \to Zh$**, $H \to hh$, …)
  - ✓ 125 GeV Higgs **signal strengths** from **Lilith** [Bernon, Dumont] [arXiv:1502.04138]

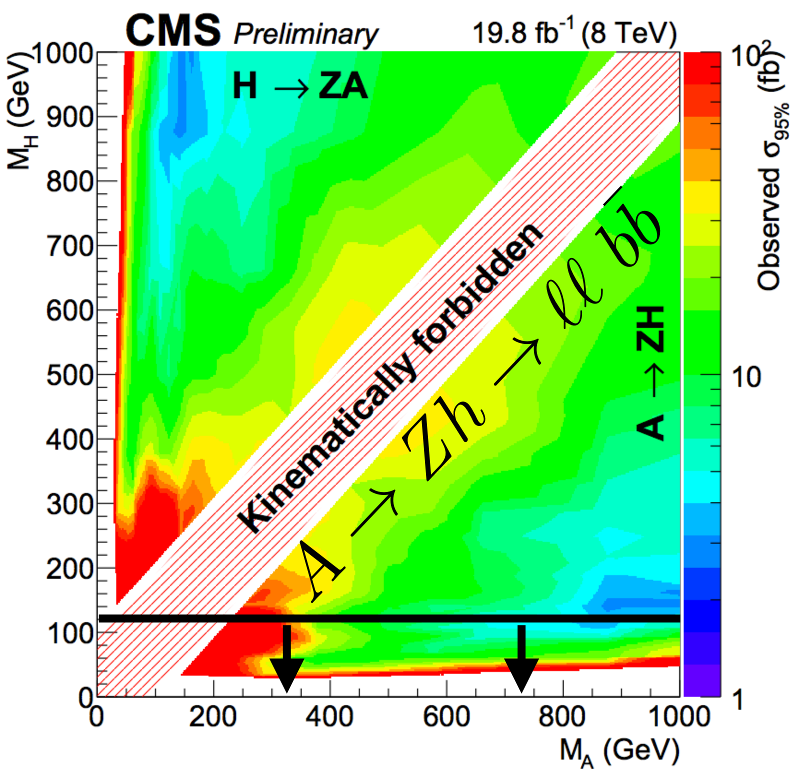
Mass of the extra states



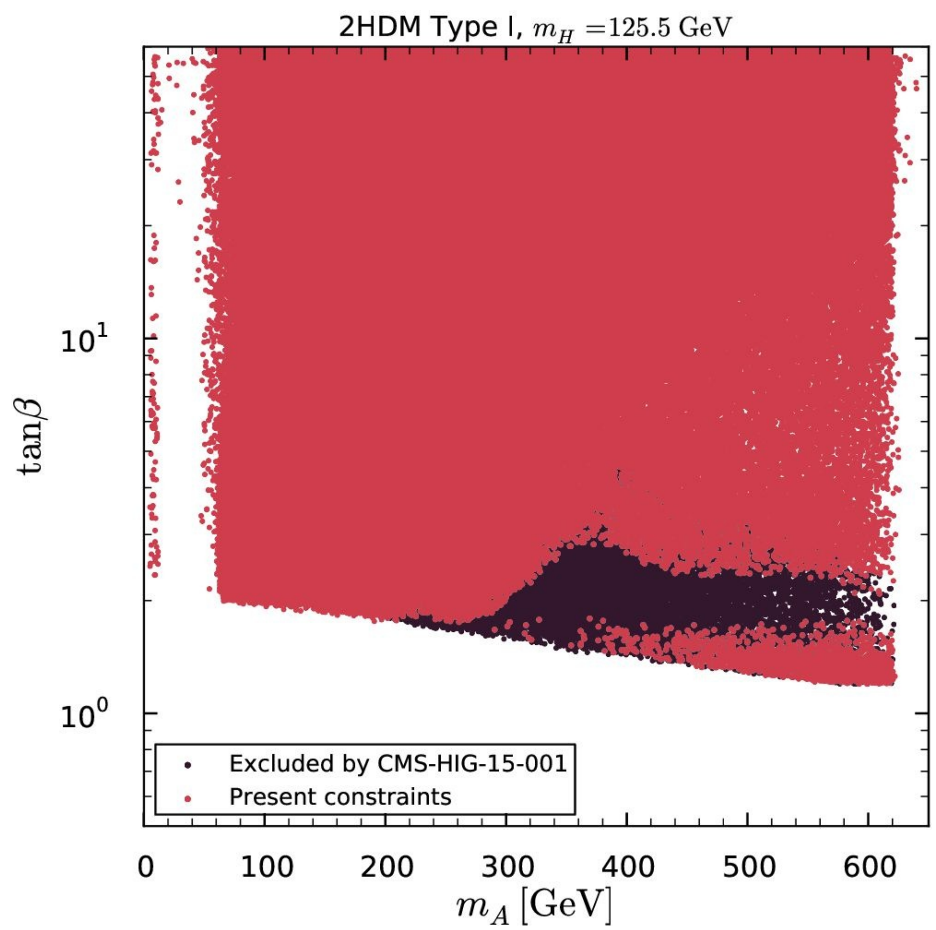


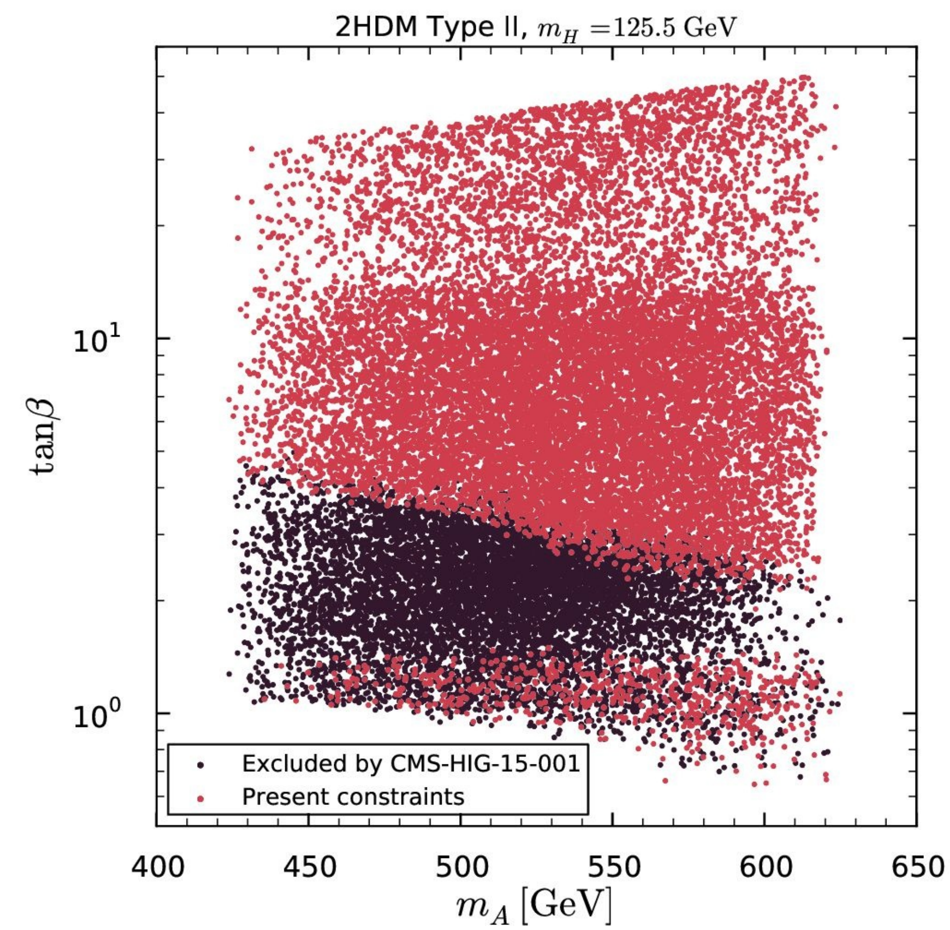
- In both Types, due to the perturbativity constraint: $m_A, m_{H^\pm} \lesssim 630$ GeV.
- In Type II, due to the charged Higgs mass bound and the T parameter constraint: $m_A \gtrsim 420$ GeV.
- In Type I, due to weaker flavor constraints, charged Higgs masses down to the LEP bound are allowed. For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





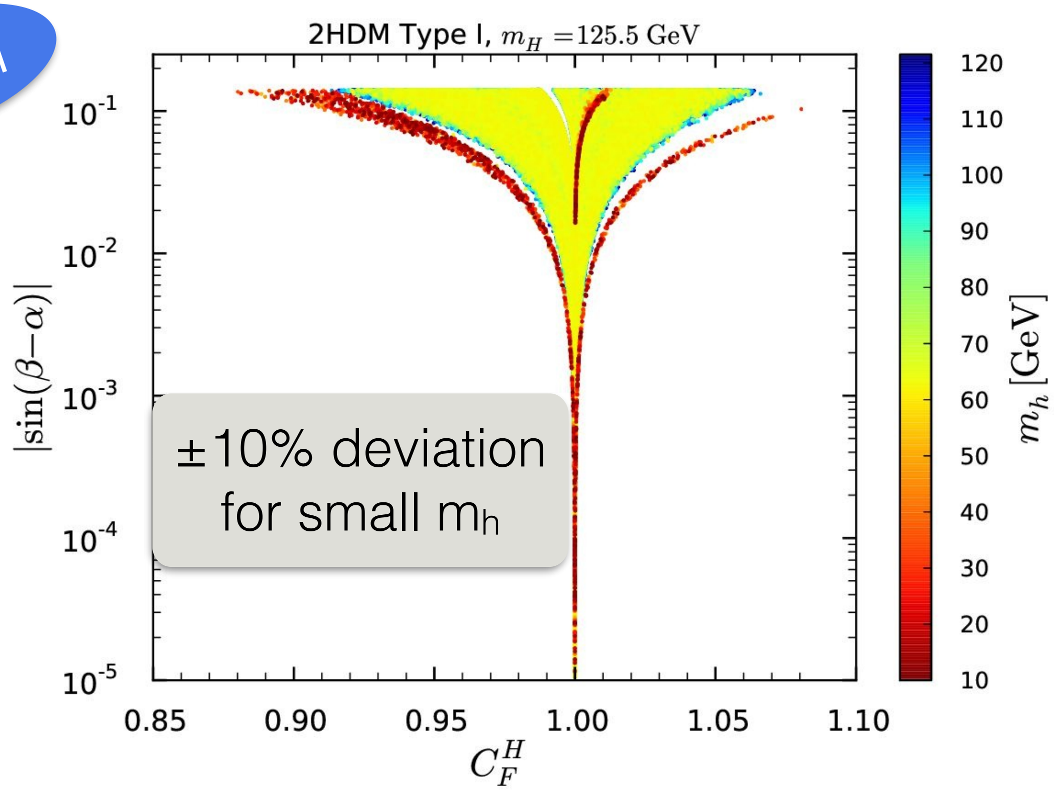
- The two resonance masses are free parameters, the search is sensitive to light resonance masses down to ~40GeV.
- h➝bb has the largest excluded cross-section
- In our scenario, h has mass below 125 GeV and has therefore large BR(h➝bb)~0.9

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

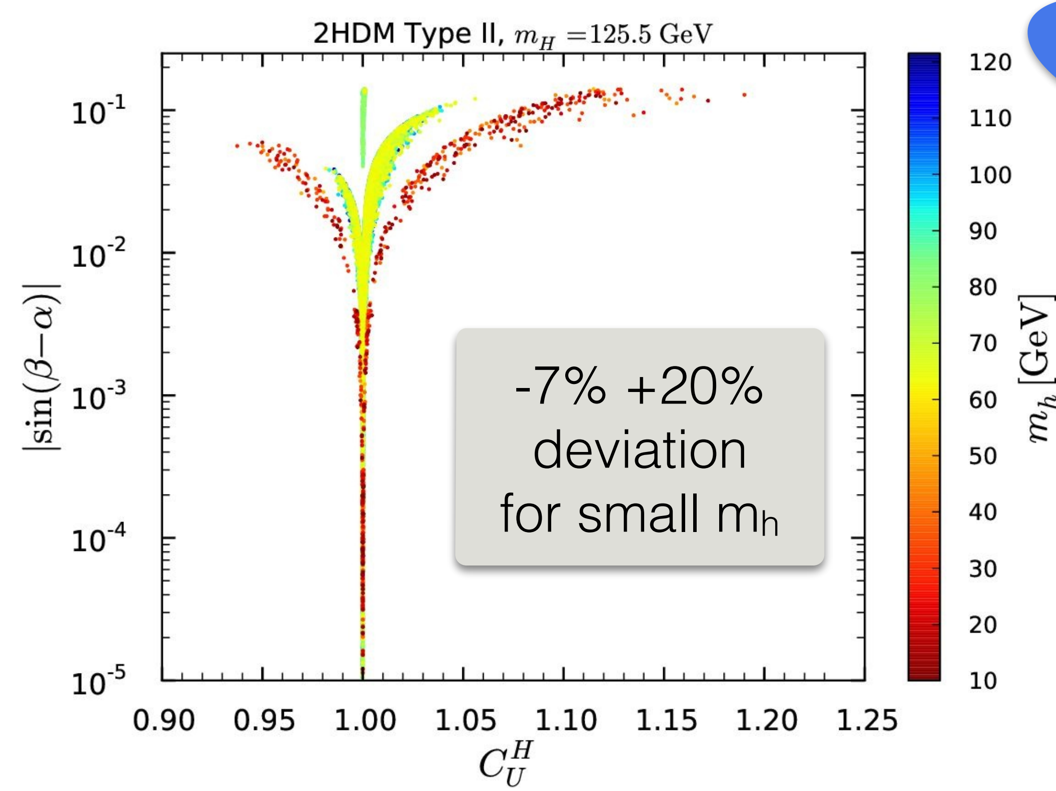
Note that the corresponding ATLAS search requires m_h=125 GeV and does not provide significant constraints in this scenario. [ATLAS-HIGG-2013-06]

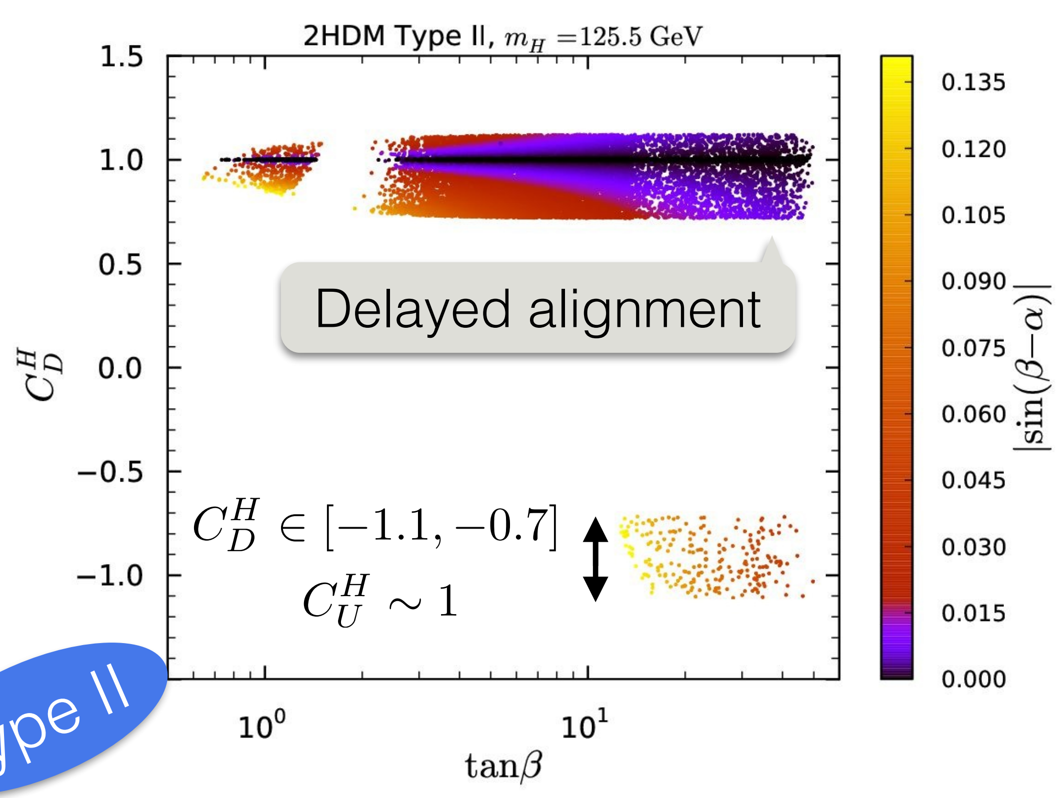
Fermion couplings of the 125 GeV state

Type I



Type II



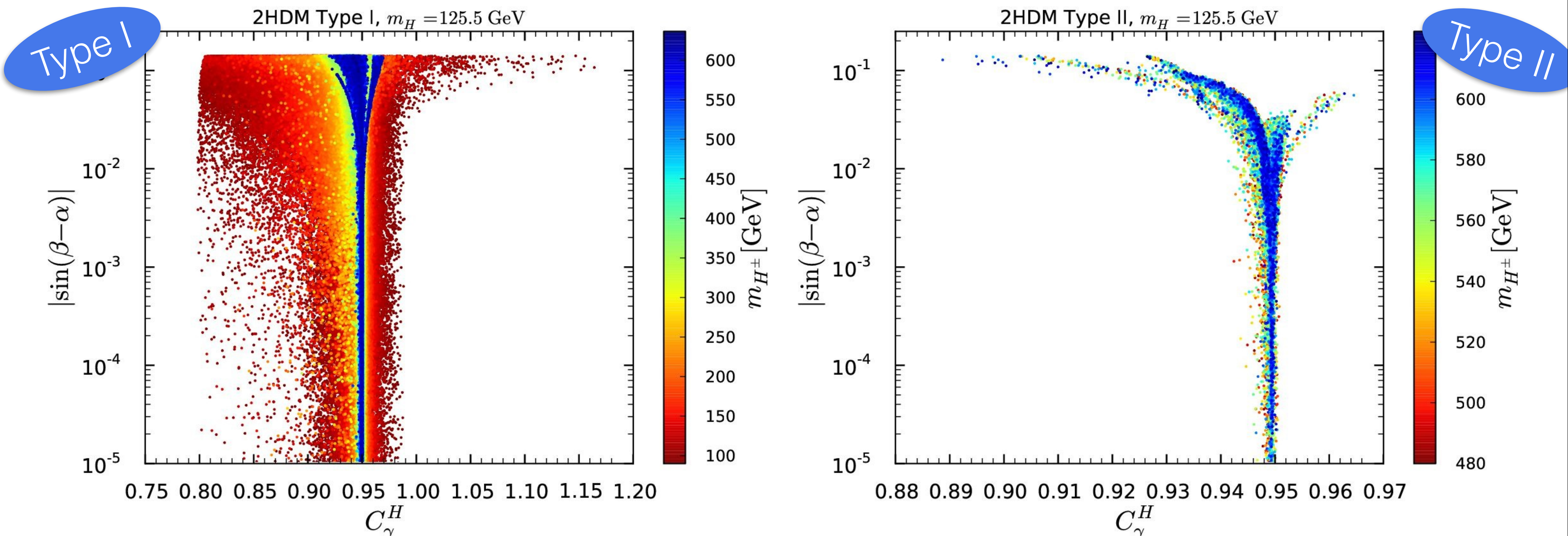


Type II

- 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 $C_g^H \simeq 1.06$.

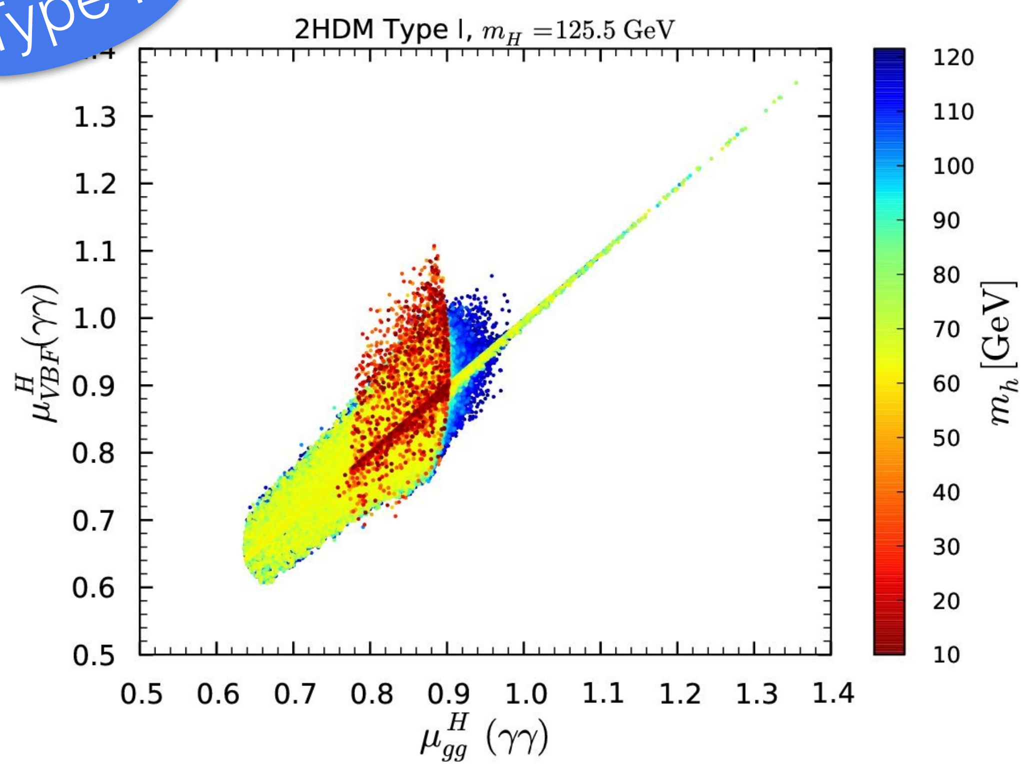


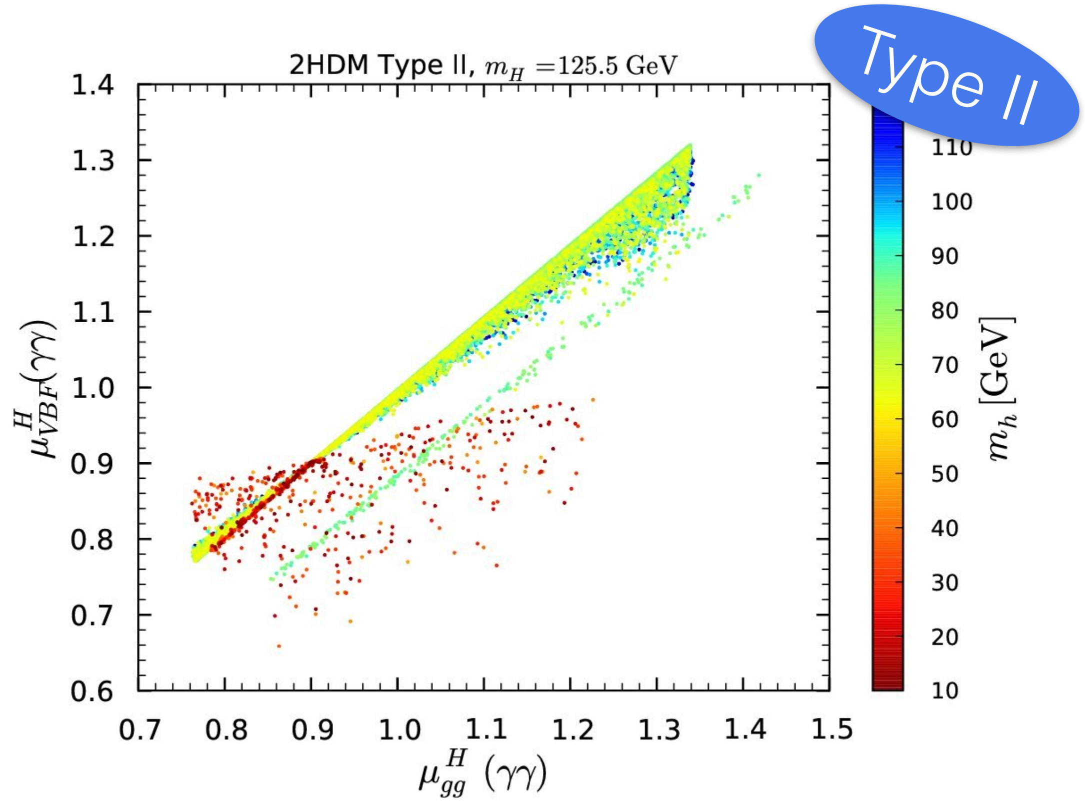
- In the alignment limit: $g_{HH^+H^-} = -\frac{1}{v}(m_H^2 + 2m_{H^\pm}^2 - 2\overline{m}^2)$ $\quad \overline{m}^2 \in \begin{cases} \text{I: } [-(350 \text{ GeV})^2, (150 \text{ GeV})^2] \\ \text{II: } [-(200 \text{ GeV})^2, (150 \text{ GeV})^2] \end{cases}$

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

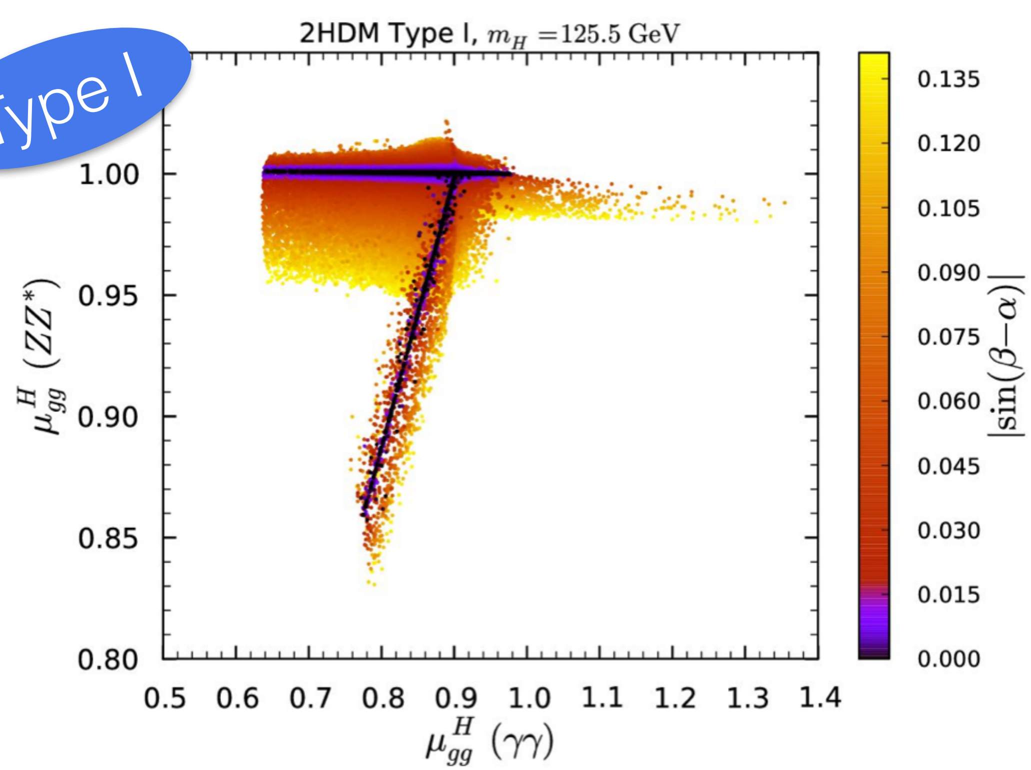
- $C_\gamma^H > 1$ possible if positive $\overline{m}^2$ and light charged Higgs: only in Type I.

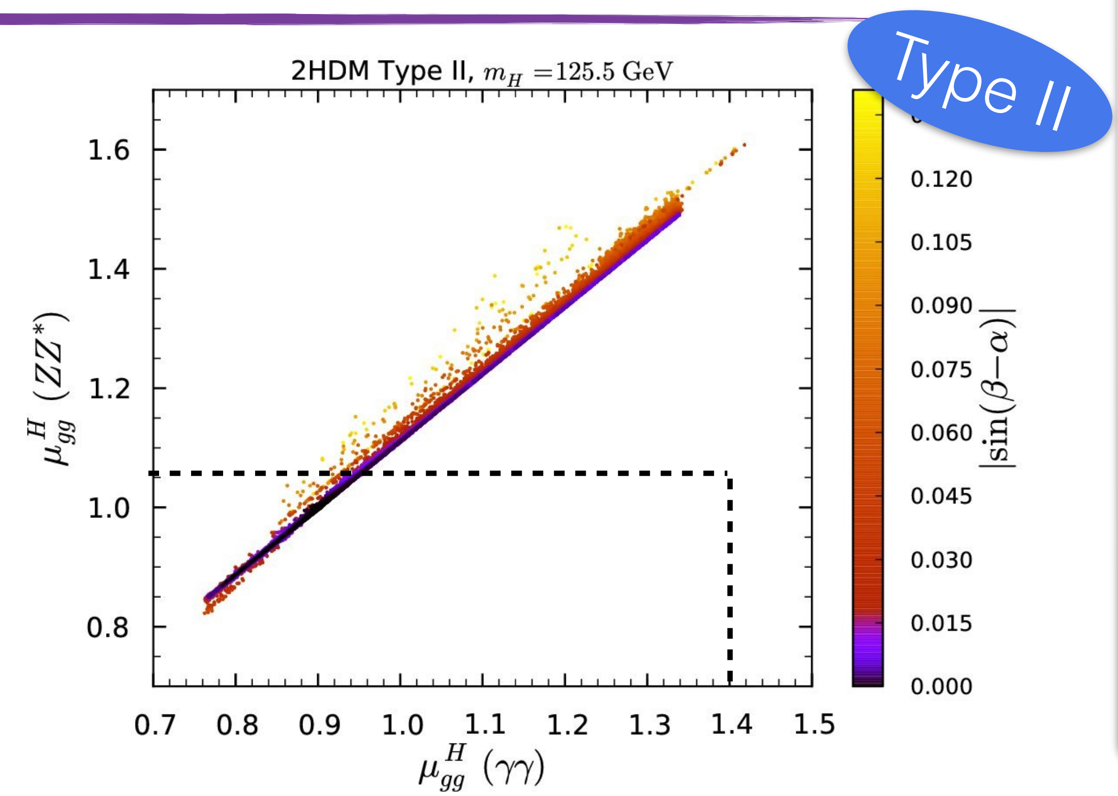
Signal strengths of the 125 GeV state: $\mu(X,Y) = \frac{\sigma(X)\mathcal{B}(H \to Y)}{\sigma(X_{\rm SM})\mathcal{B}(H_{\rm SM} \to Y)}$





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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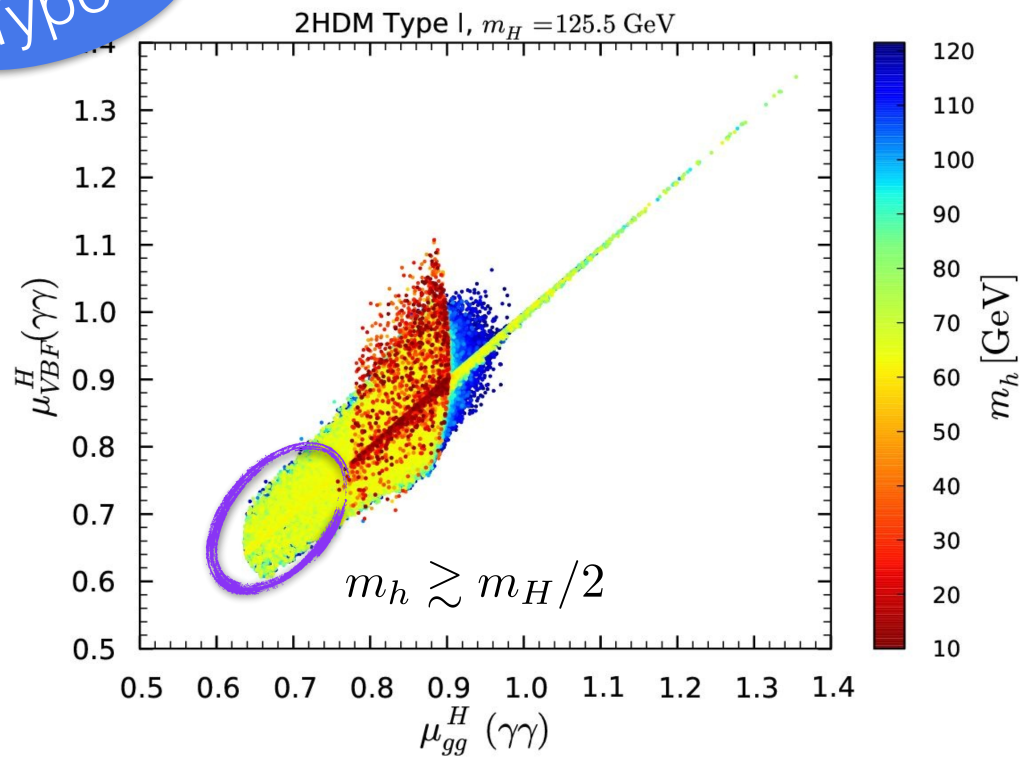

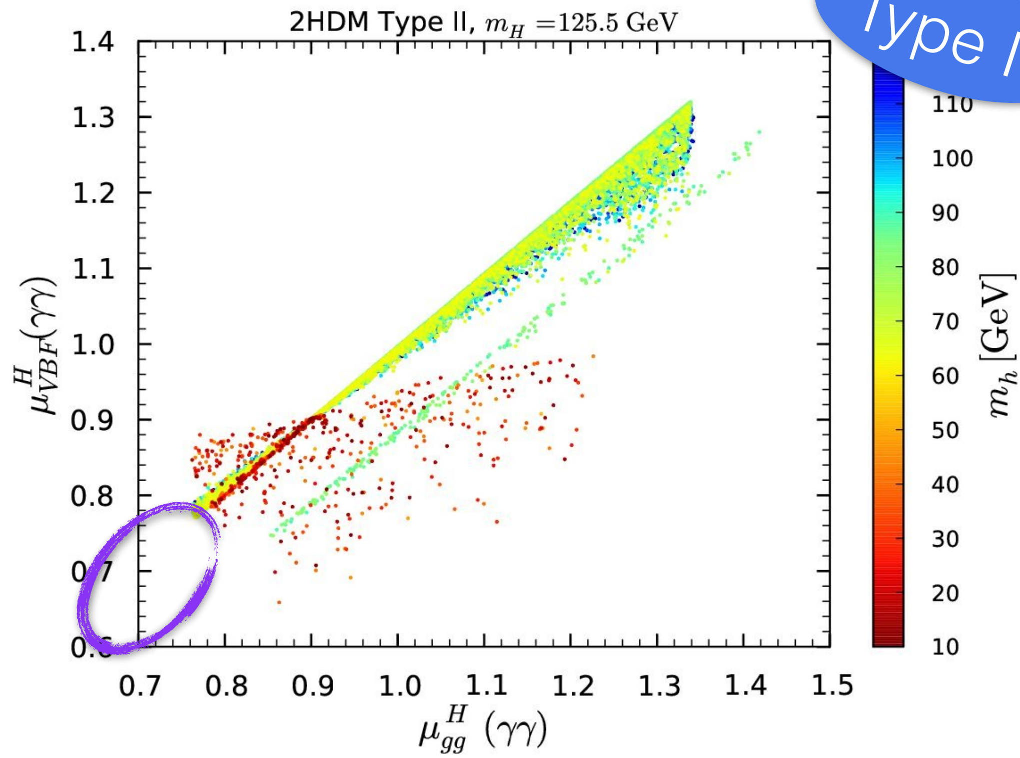

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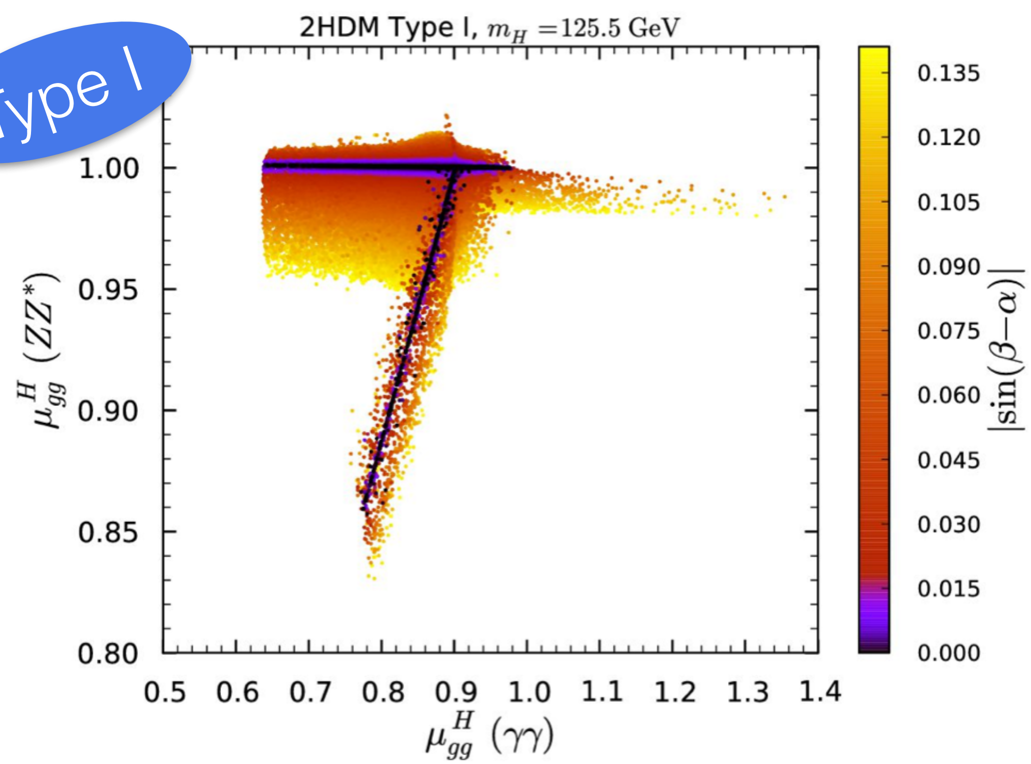

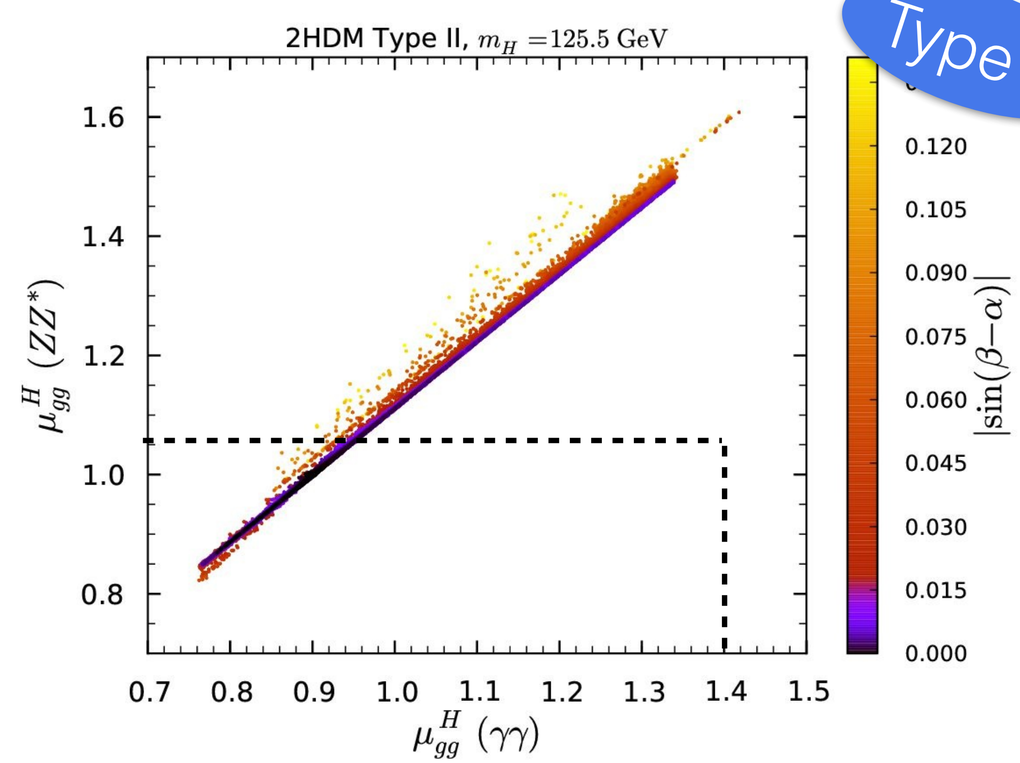

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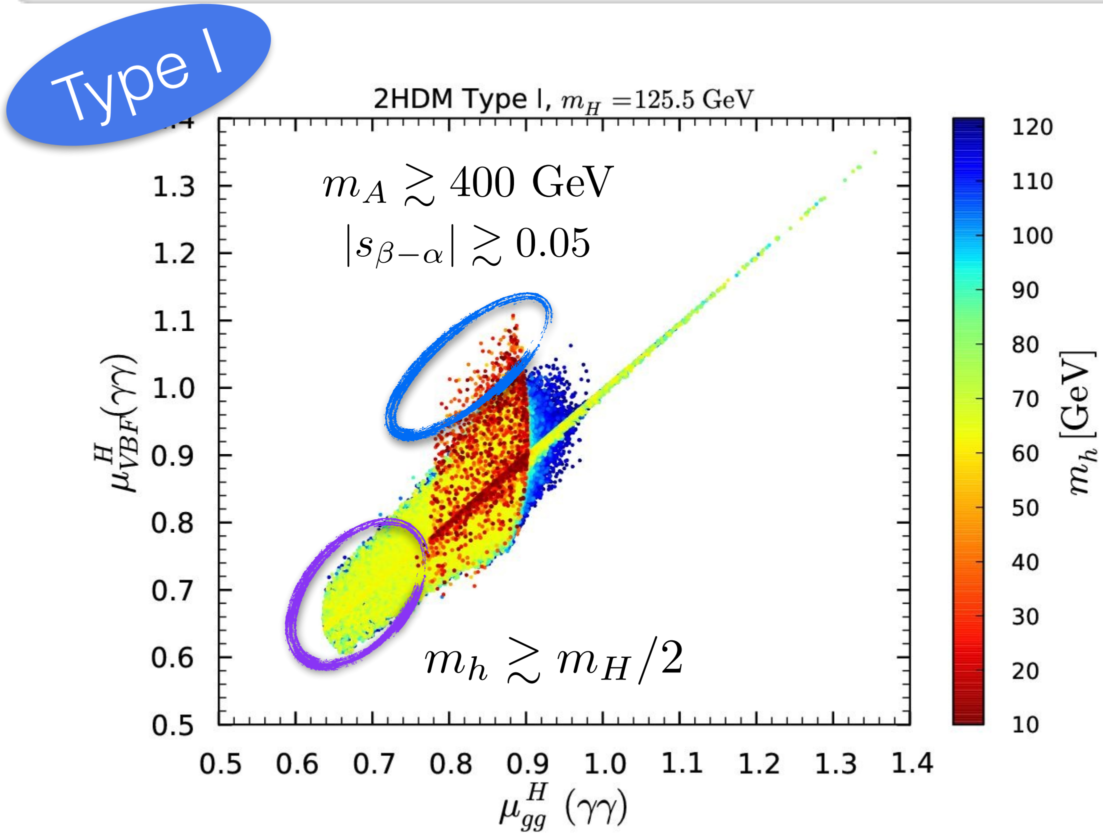
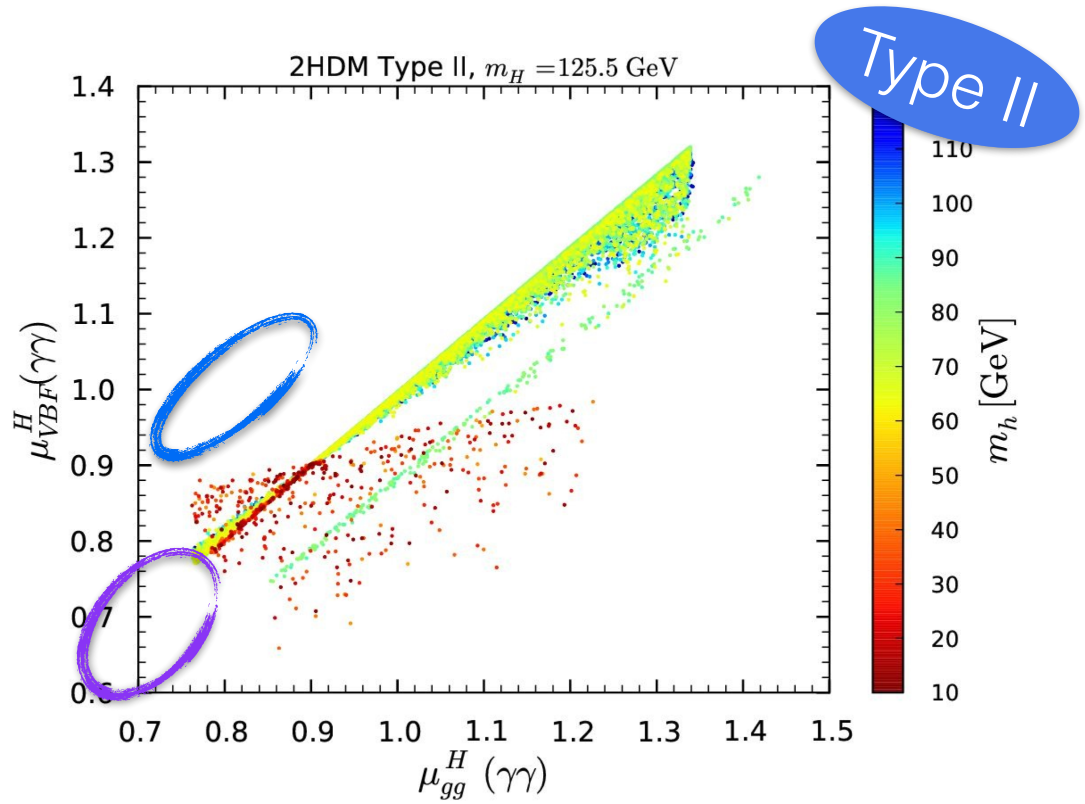
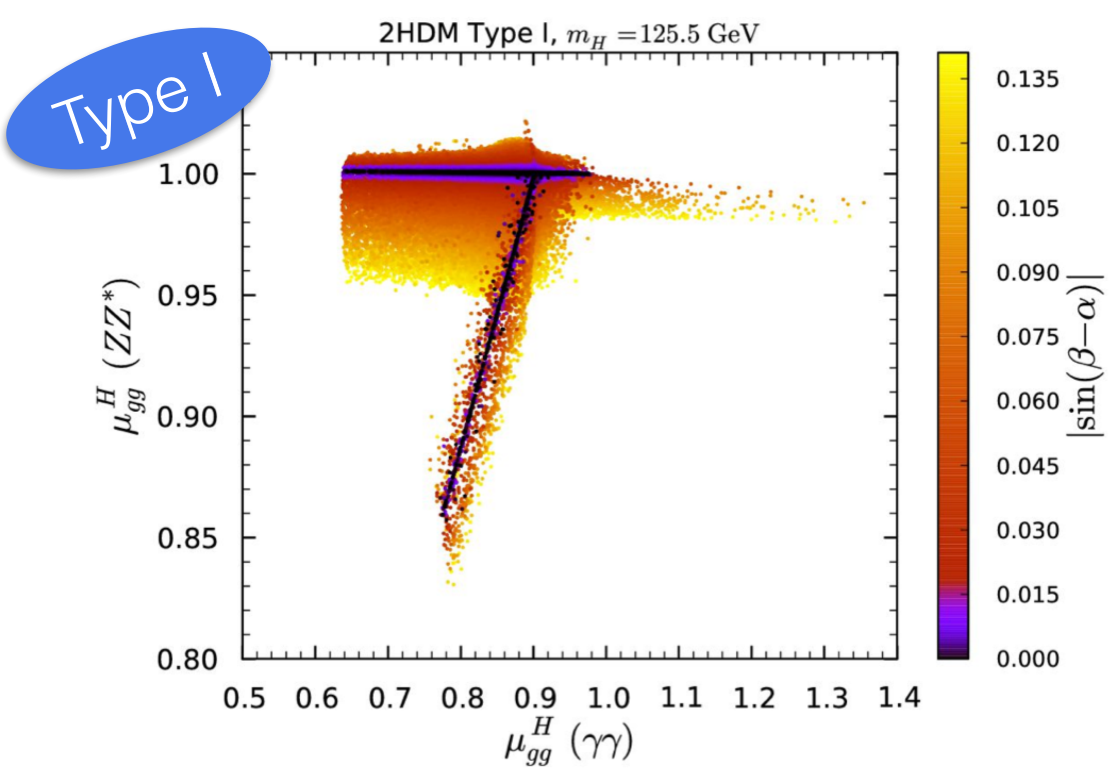
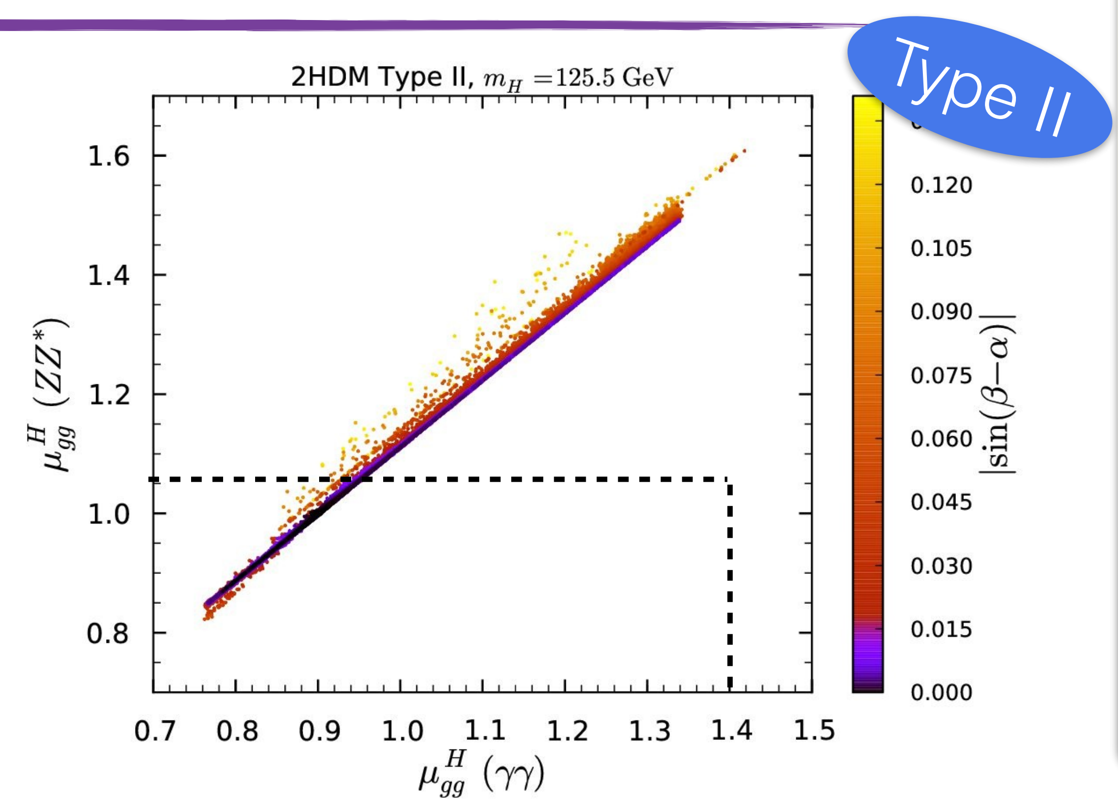




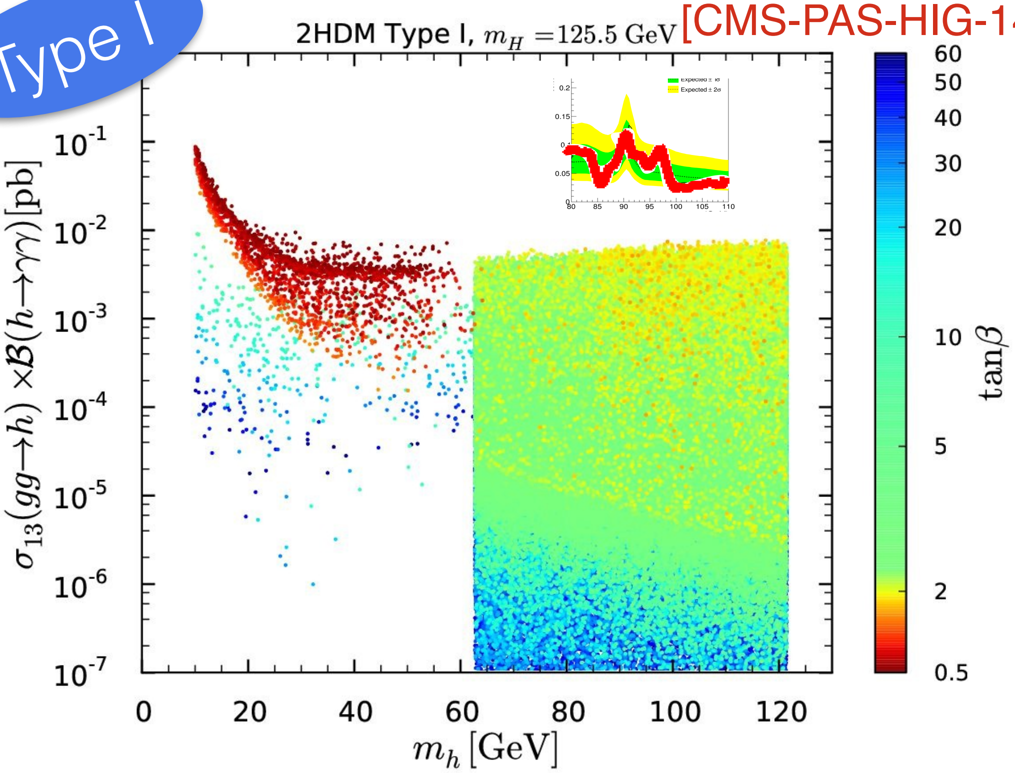
Study of signal strength correlations can lead to Type separation and extra-state mass inference

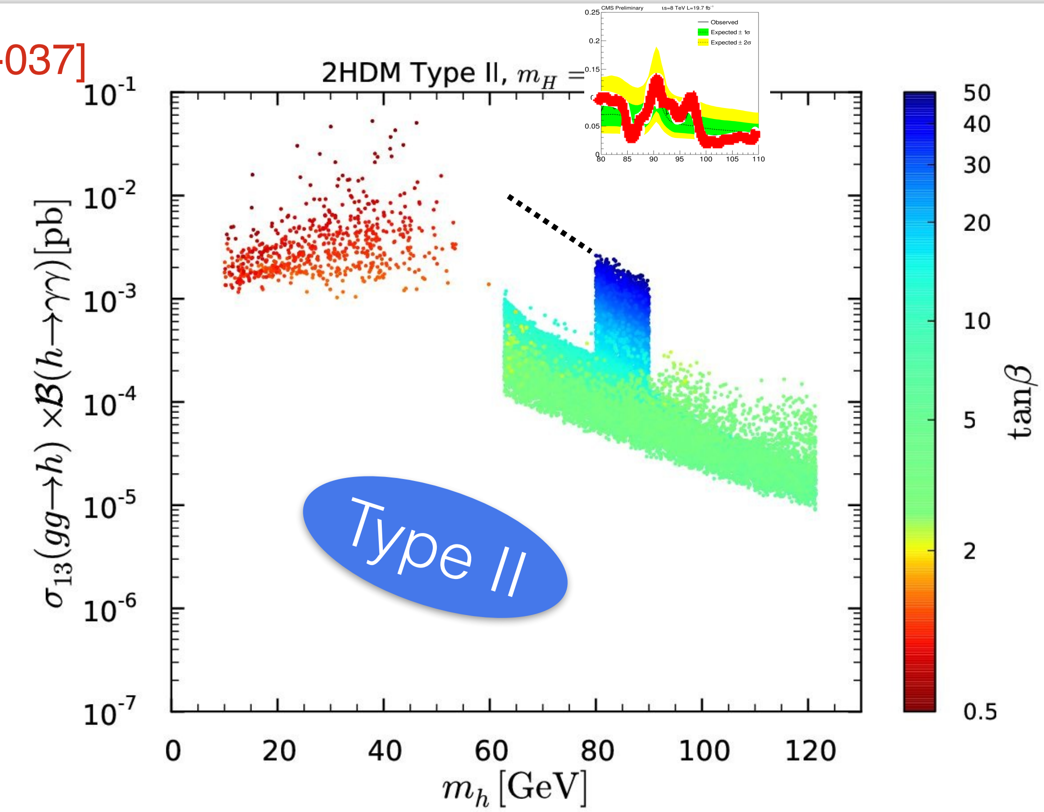




Even in near the alignment limit, signal strengths can deviate much from the SM because of the charged Higgs presence and delayed alignment in Type II

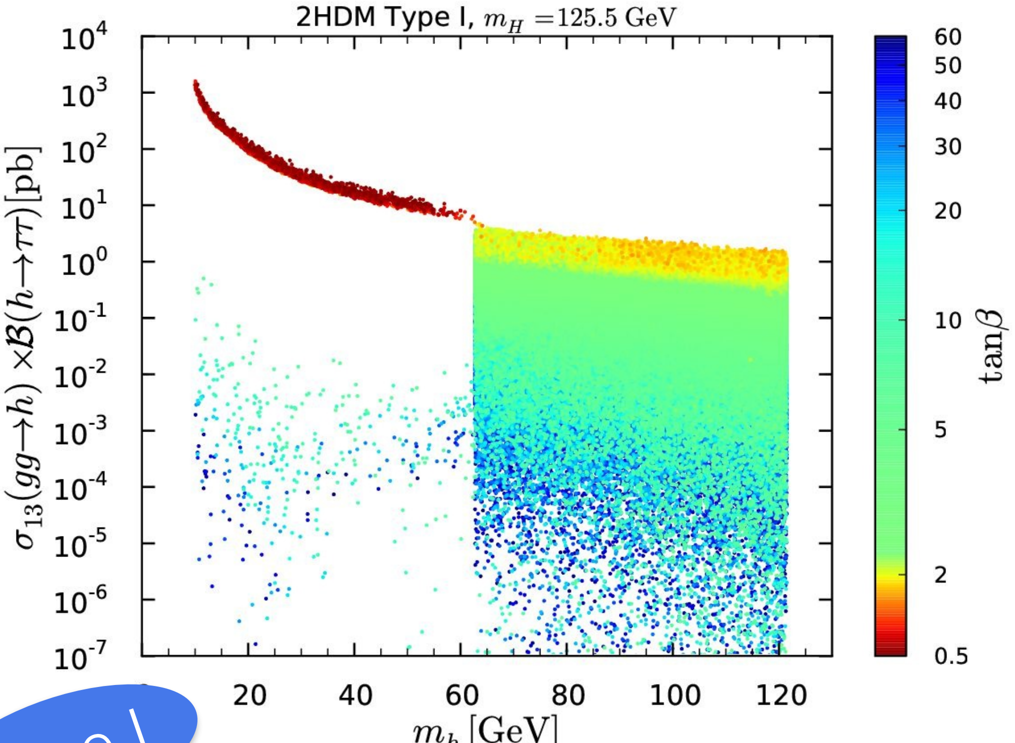
$gg \to h \to \gamma\gamma, \tau\tau$ at the LHC 13 TeV

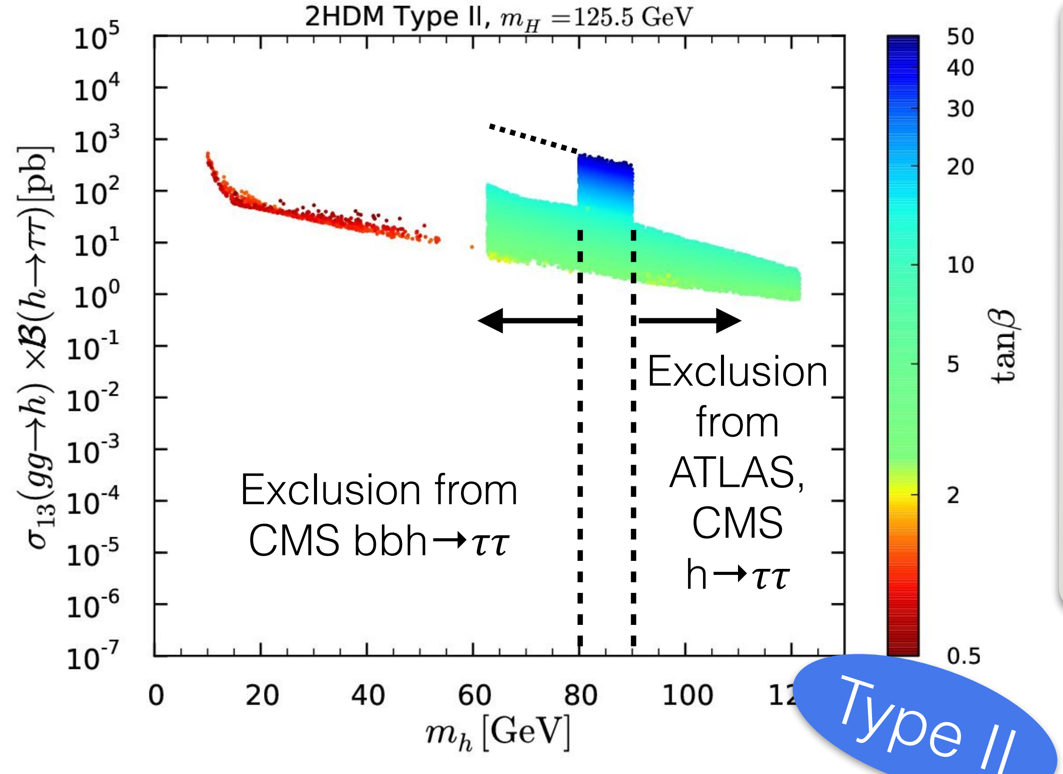




Run II may probe light h→γγ.

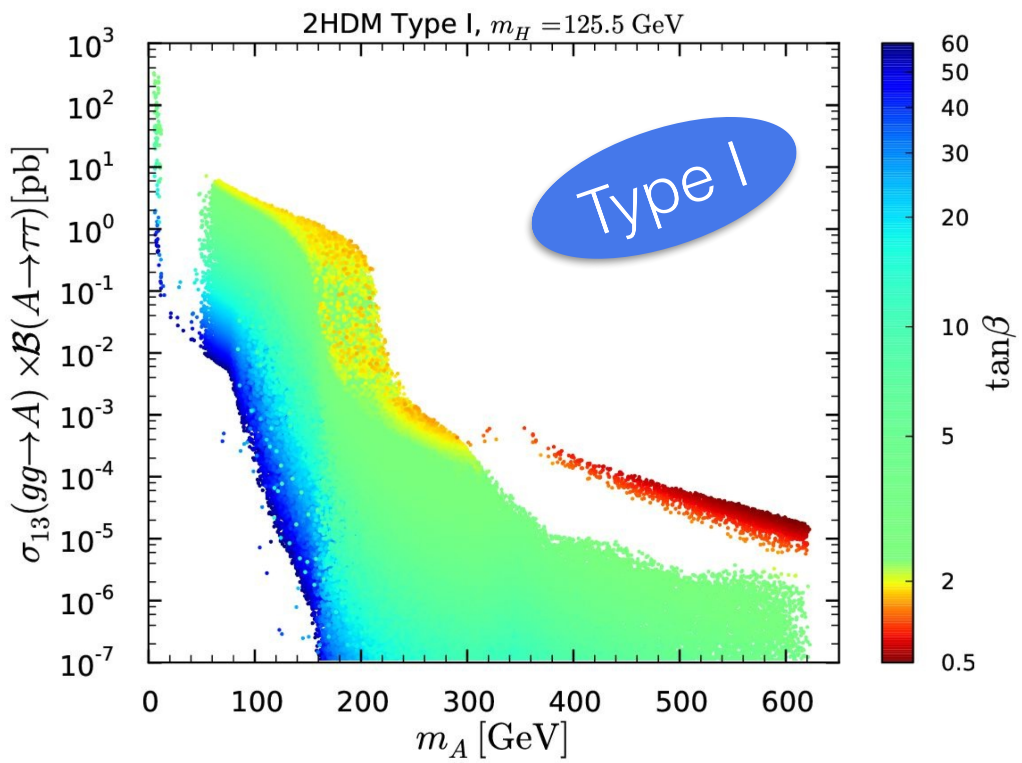
Below 60 GeV the search would be particularly interesting

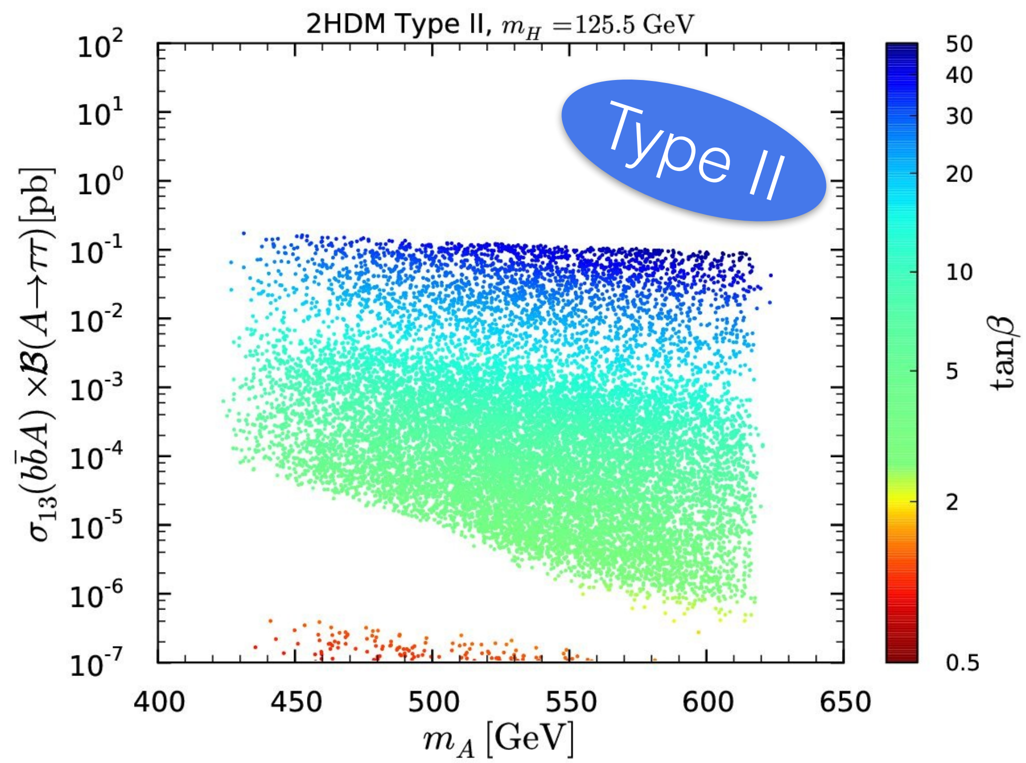




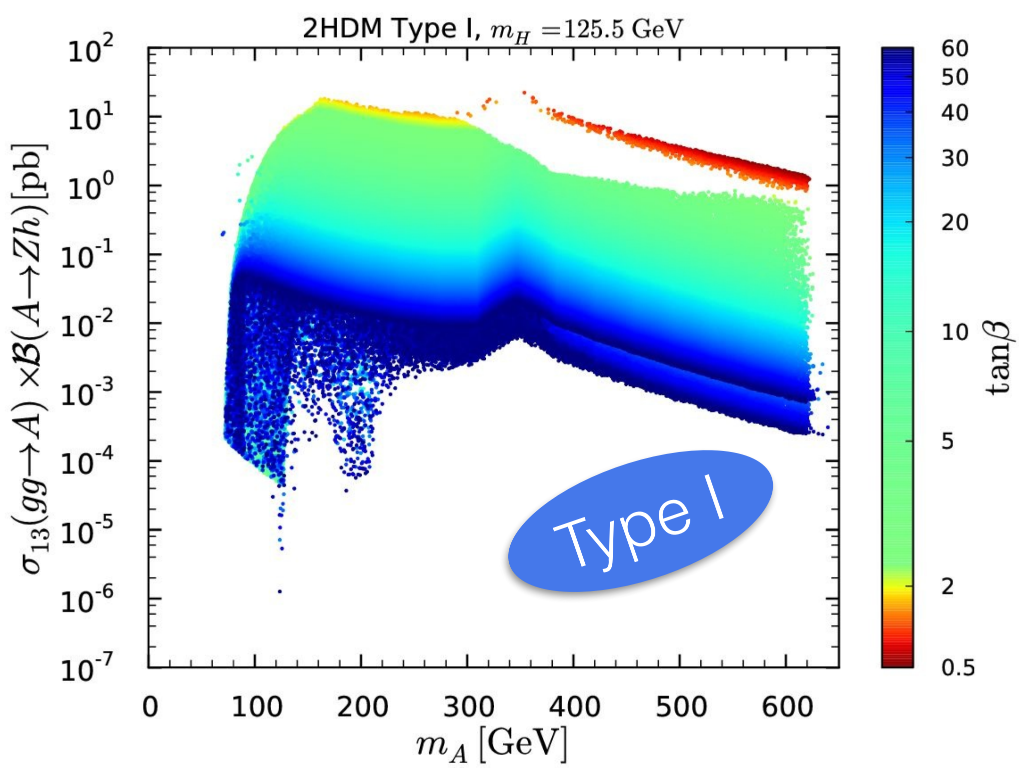
Cross section above 1pb guaranteed in Type II in the $\tau\tau$ final state, and over 10 pb in Type I for $m_h \lesssim 60$ GeV at low t_β

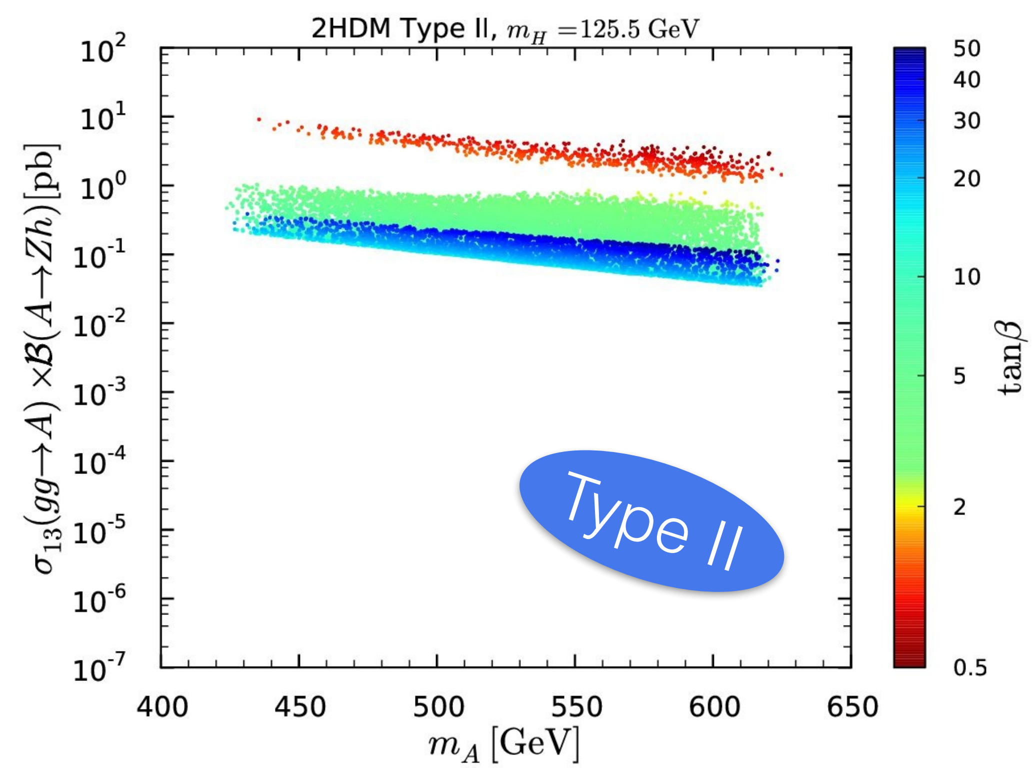
$A \to \tau\tau, Zh$ at the LHC 13 TeV





gg➝A➝$\tau\tau$ interesting in Type I for light A, in Type II bbA is preferable





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 H125 scenario near the alignment limit is particularly interesting to confront to the latest and future experimental results:

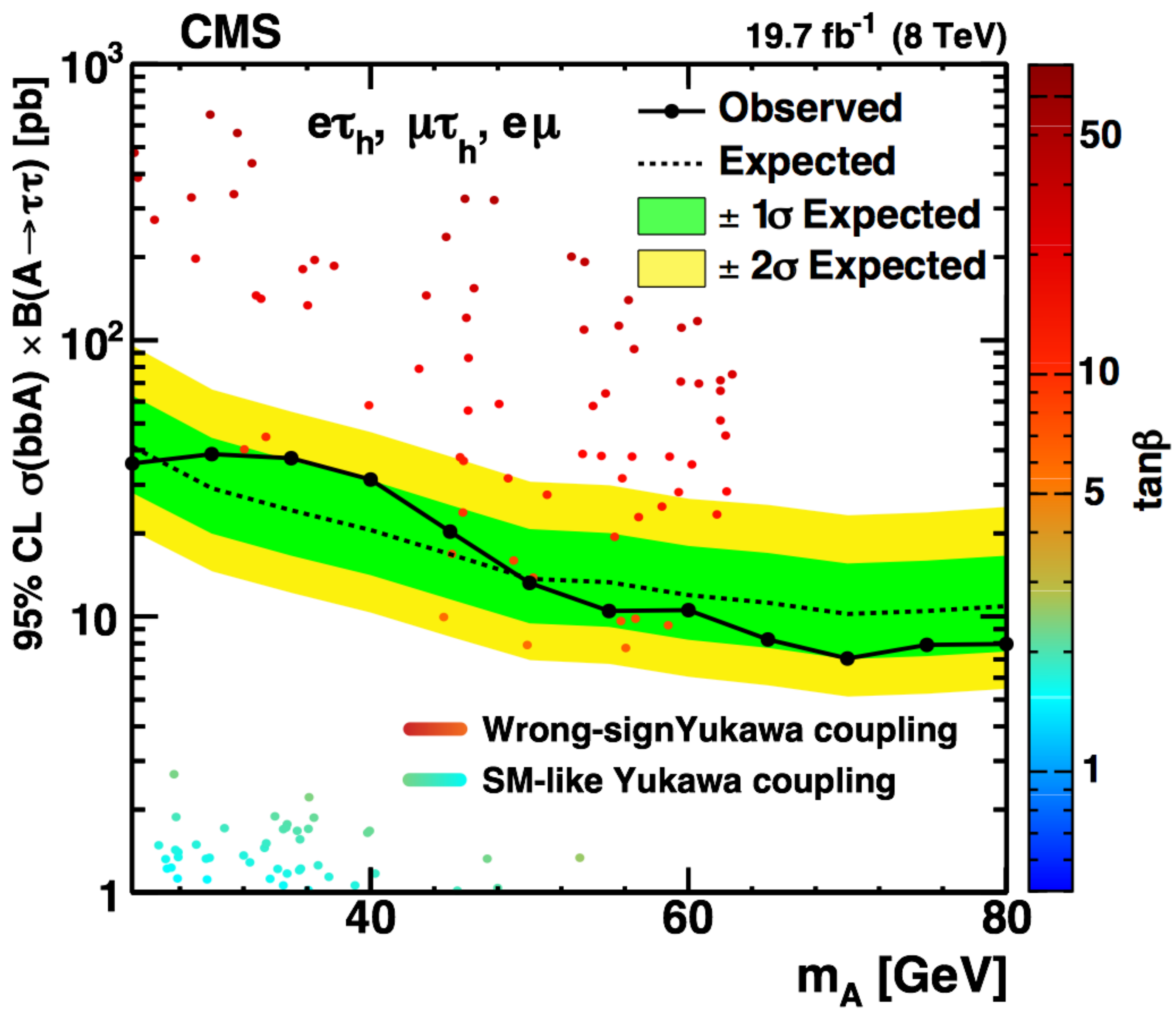
- **No decoupling limit**, restricted spectrum.
- 10-20% deviations of the H couplings to fermions are possible
- **Delayed alignment** in Type II: C_D≃0.7–1.1 down to $|s_{\beta-\alpha}| \sim 5 \times 10^{-3}$
  Presence of a **« wrong-sign » solution** C_D≃-1.1– -0.7, C_U≃1
- Signal strengths can thus 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**.

Were the observed state be the heavy CP-even Higgs in the alignment limit of the 2HDM, numerous exciting effects could be probed at the LHC Run II

Backup

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

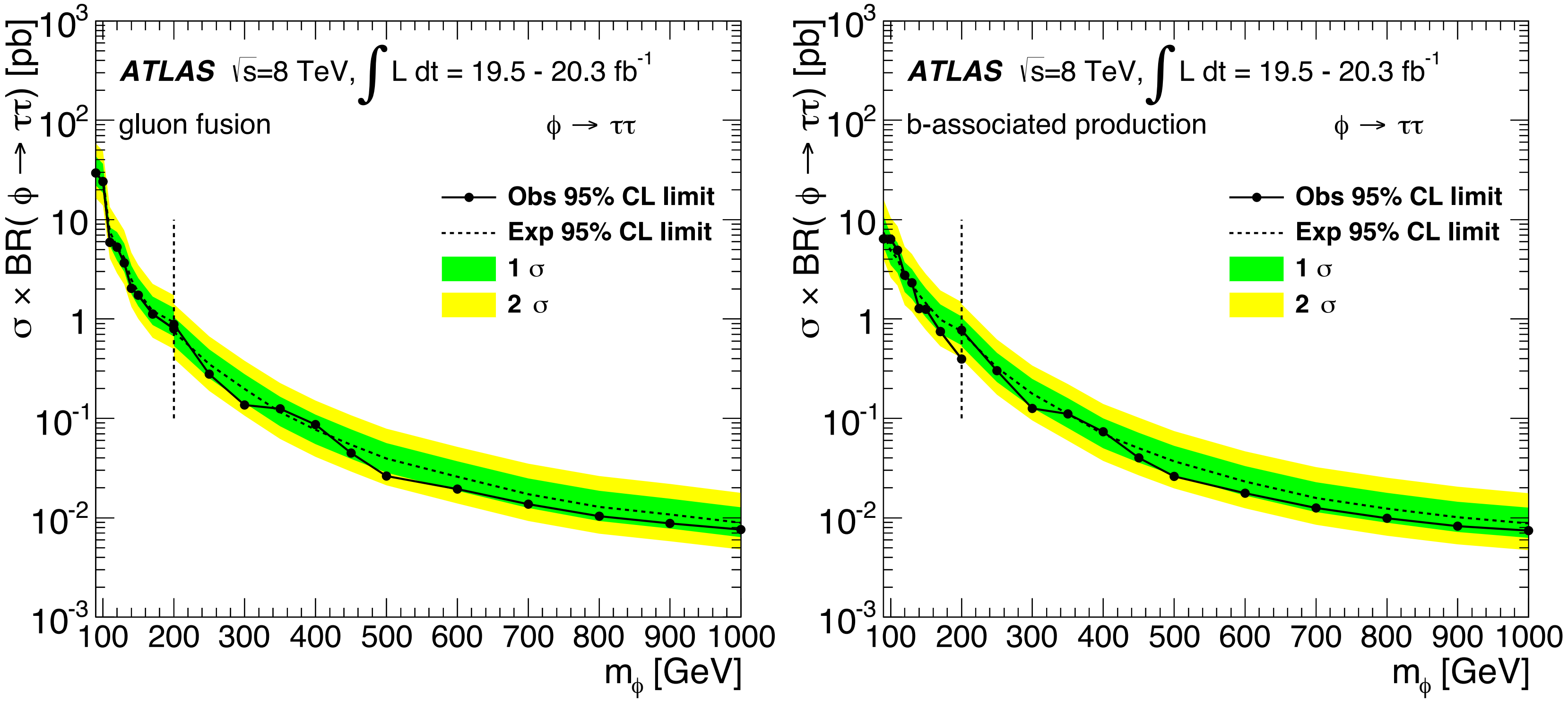
[CMS-HIG-14-033]



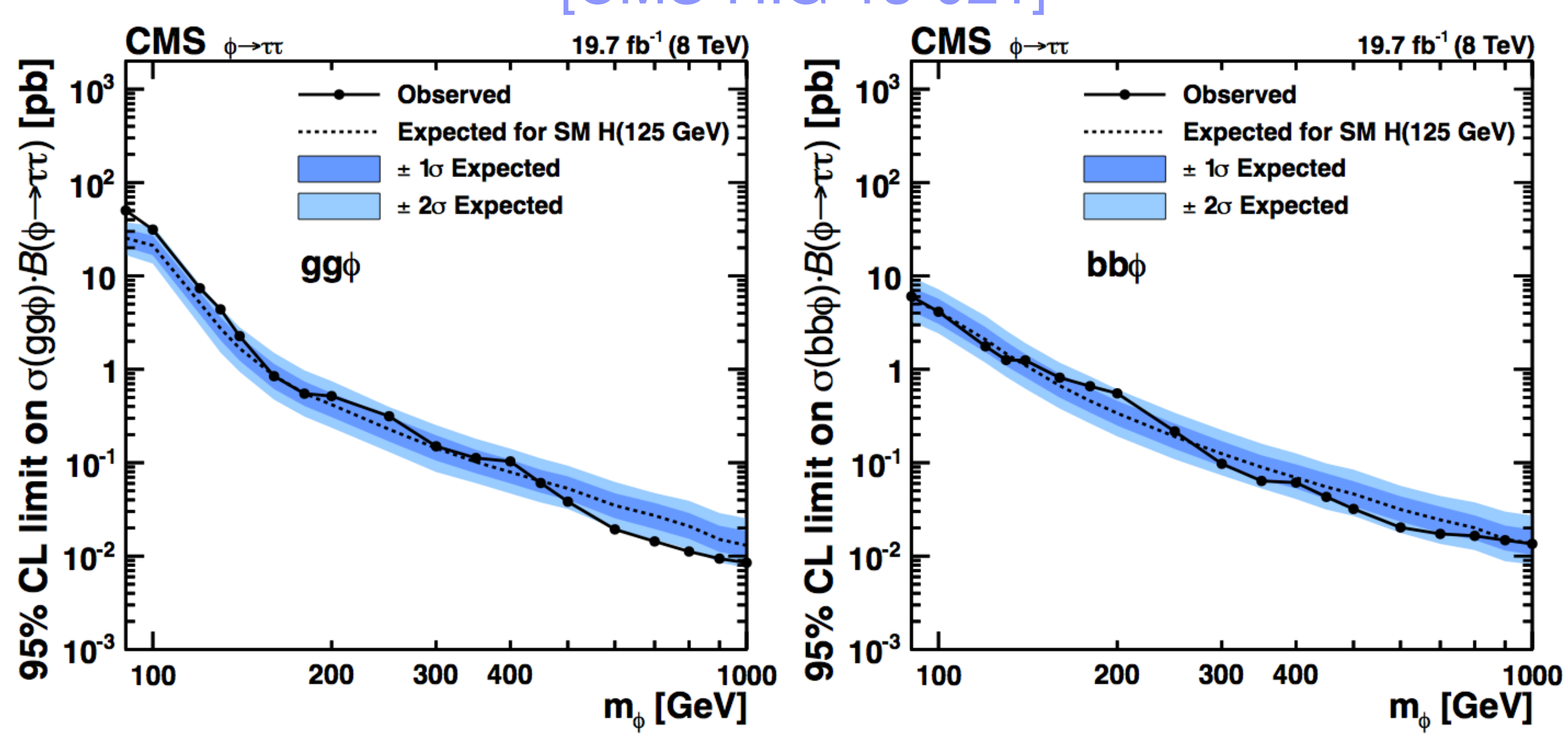
(Points from [JB, Gunion, Jiang, Kraml] [arXiv:1412.3385])

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

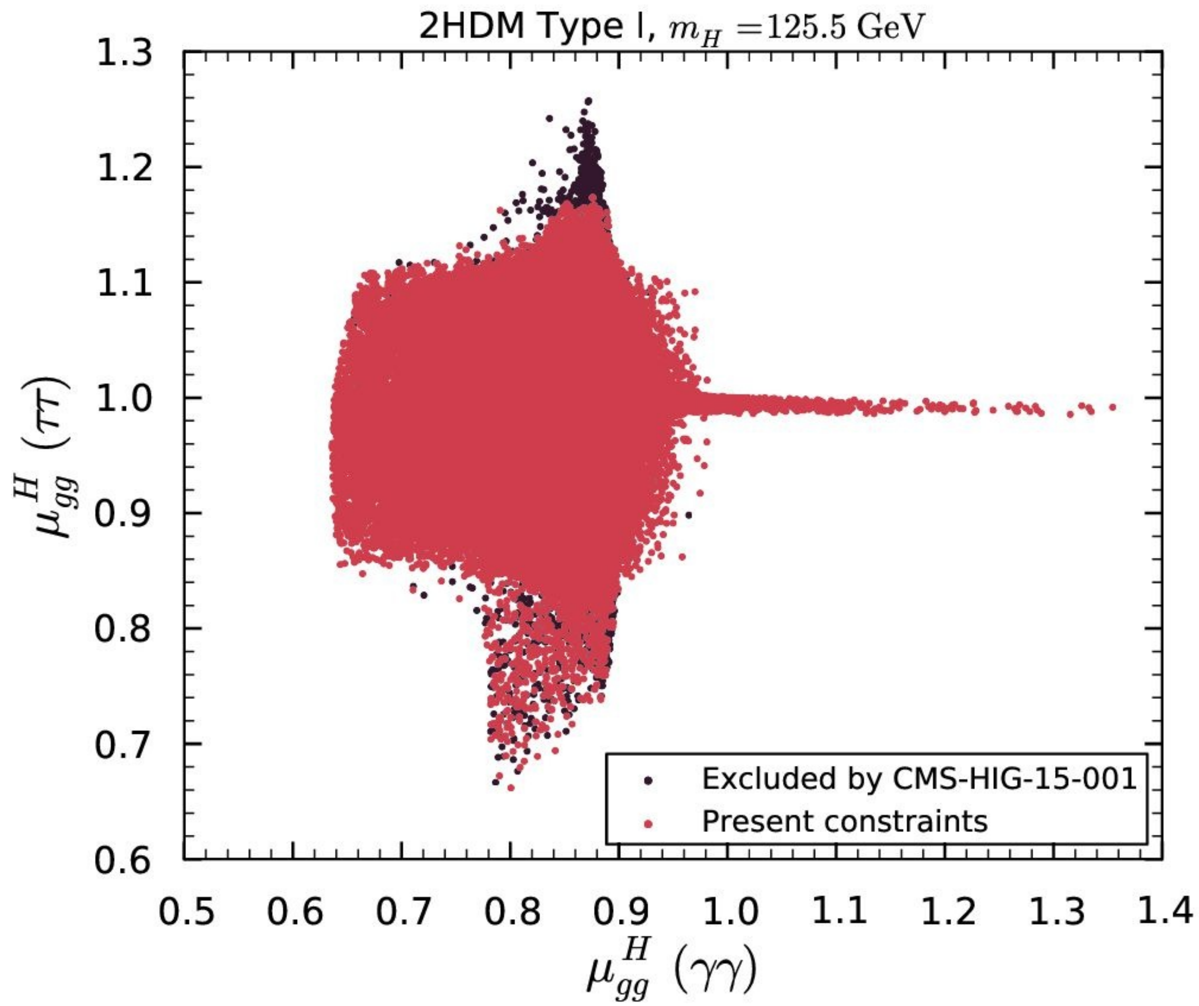
[ATLAS-HIGG-2013-31]

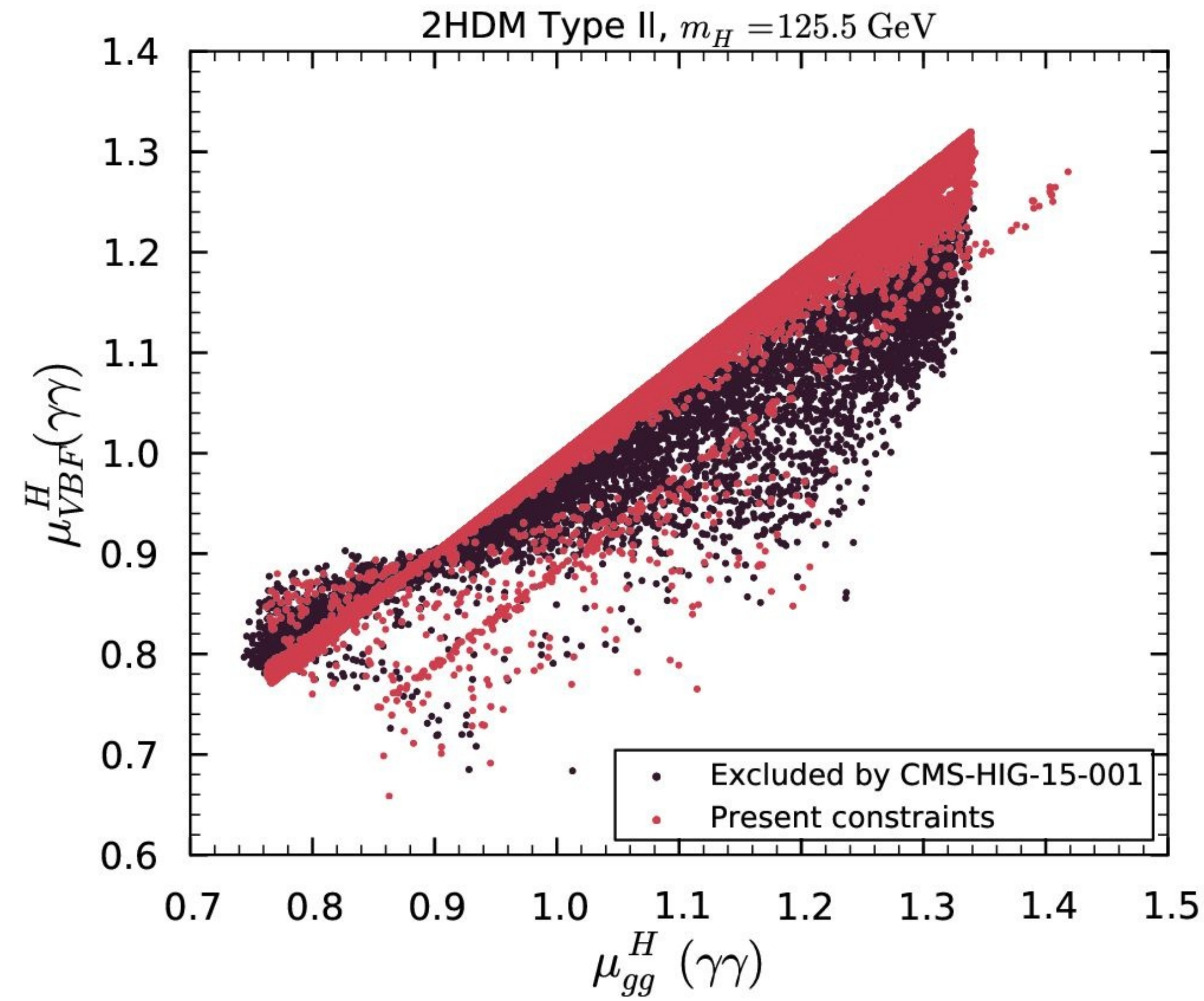


[CMS-HIG-13-021]

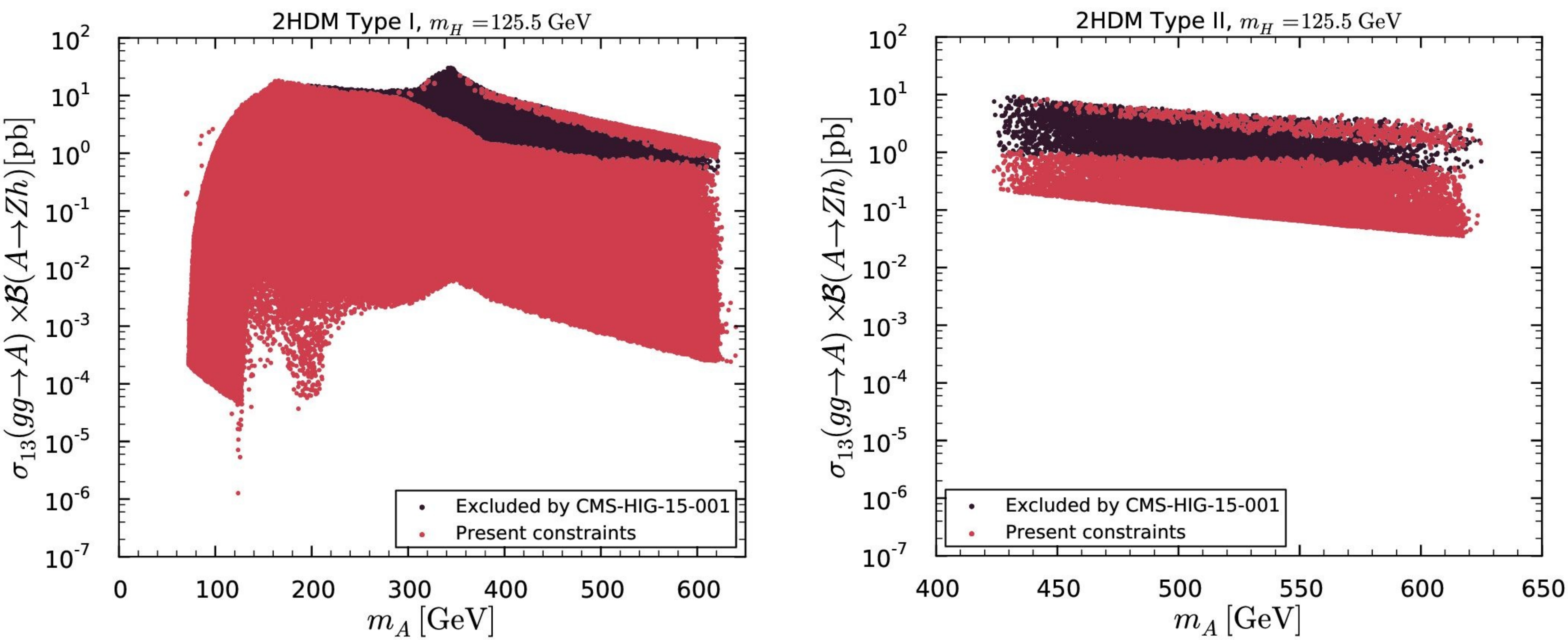


Impact of the CMS A→Zh search for signal strengths

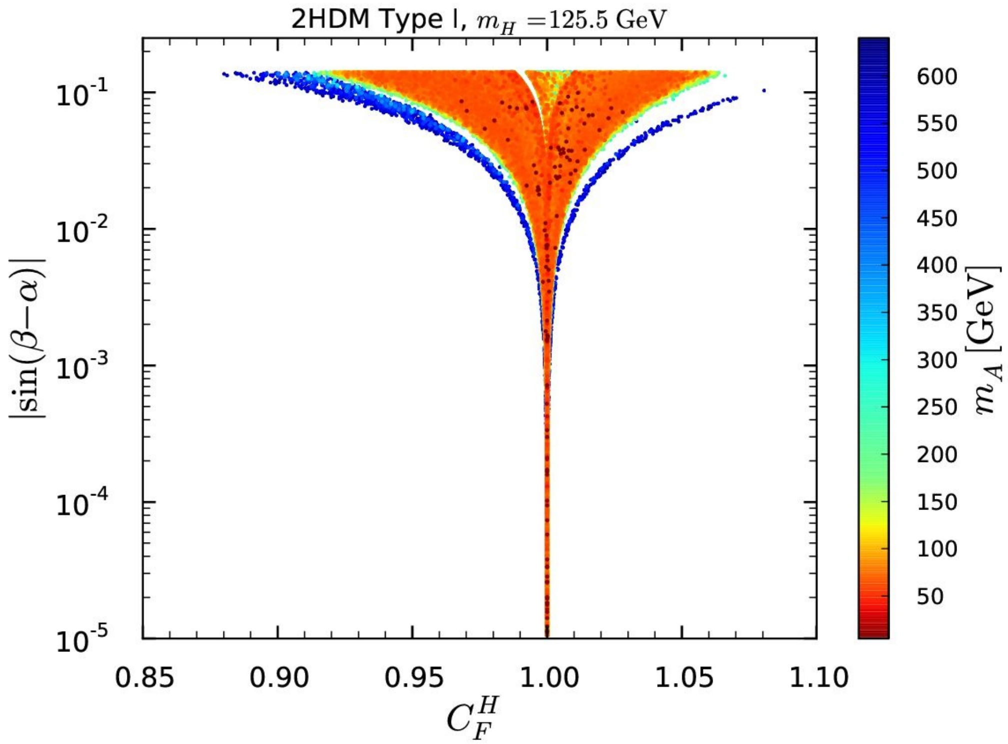


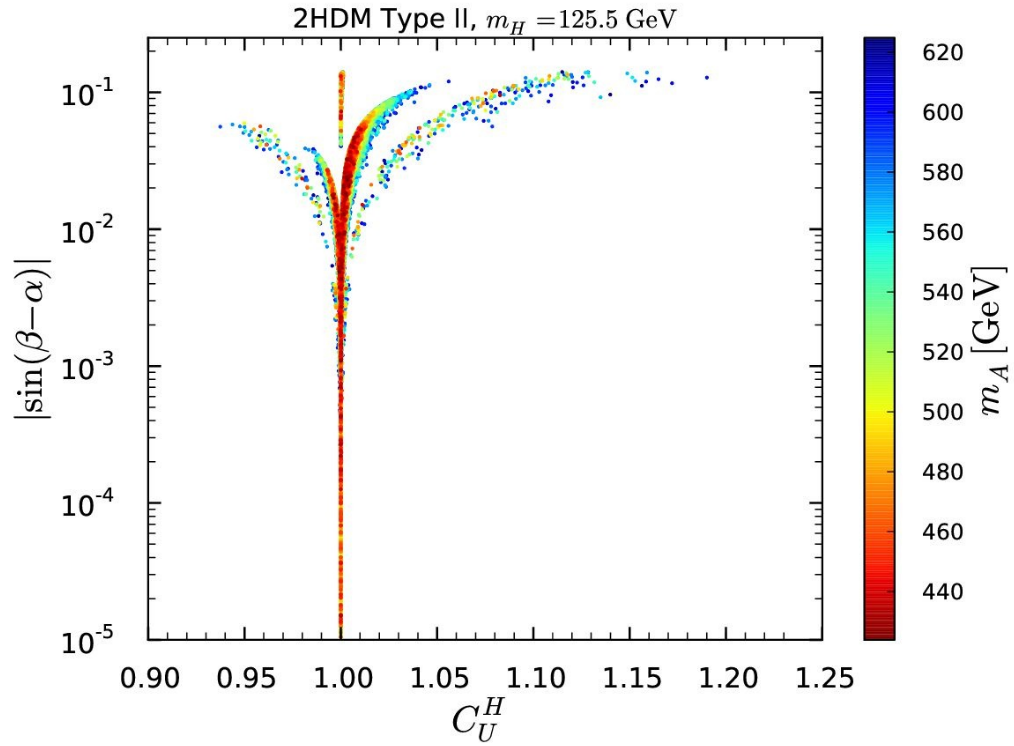


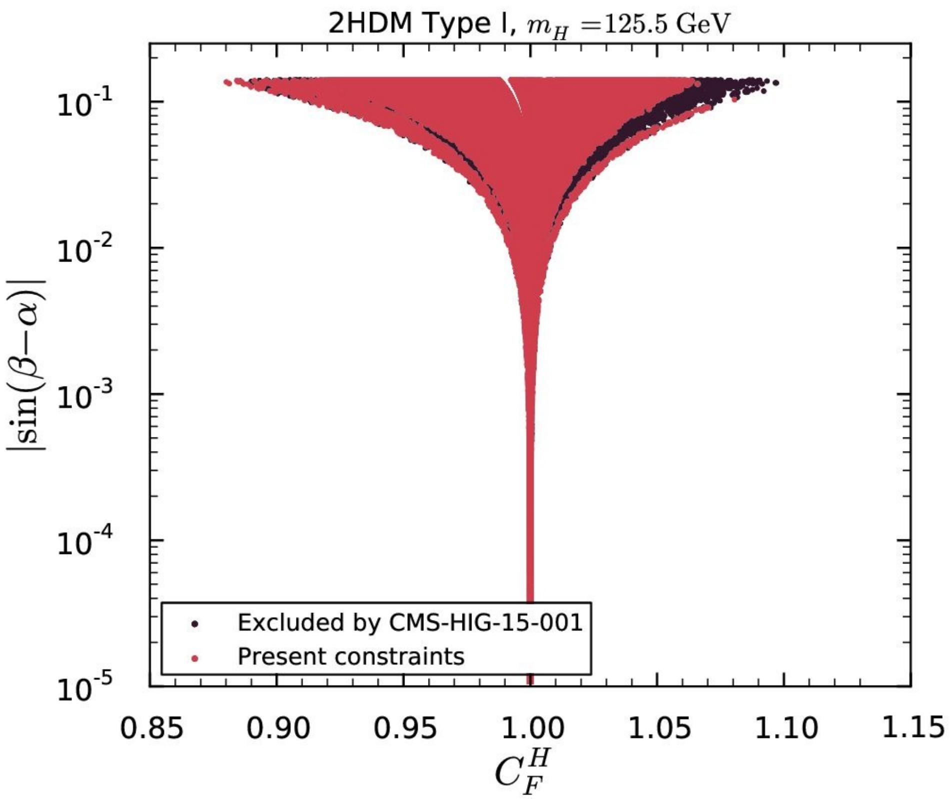
Impact of the CMS A→Zh search for cross sections

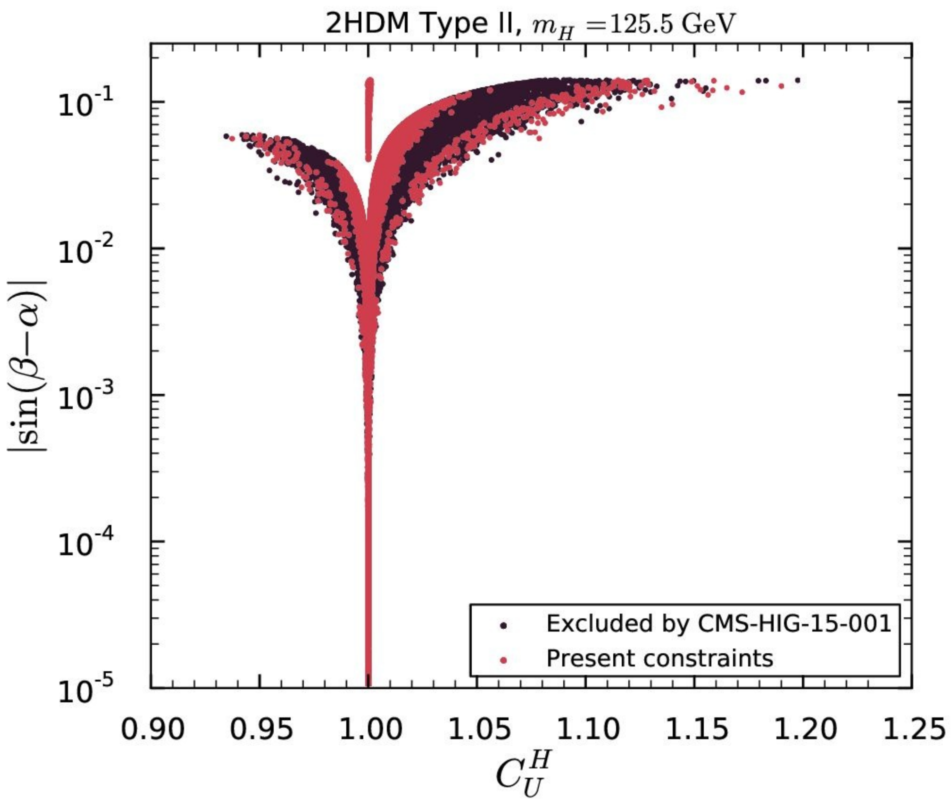


Fermion couplings of the 125 GeV state

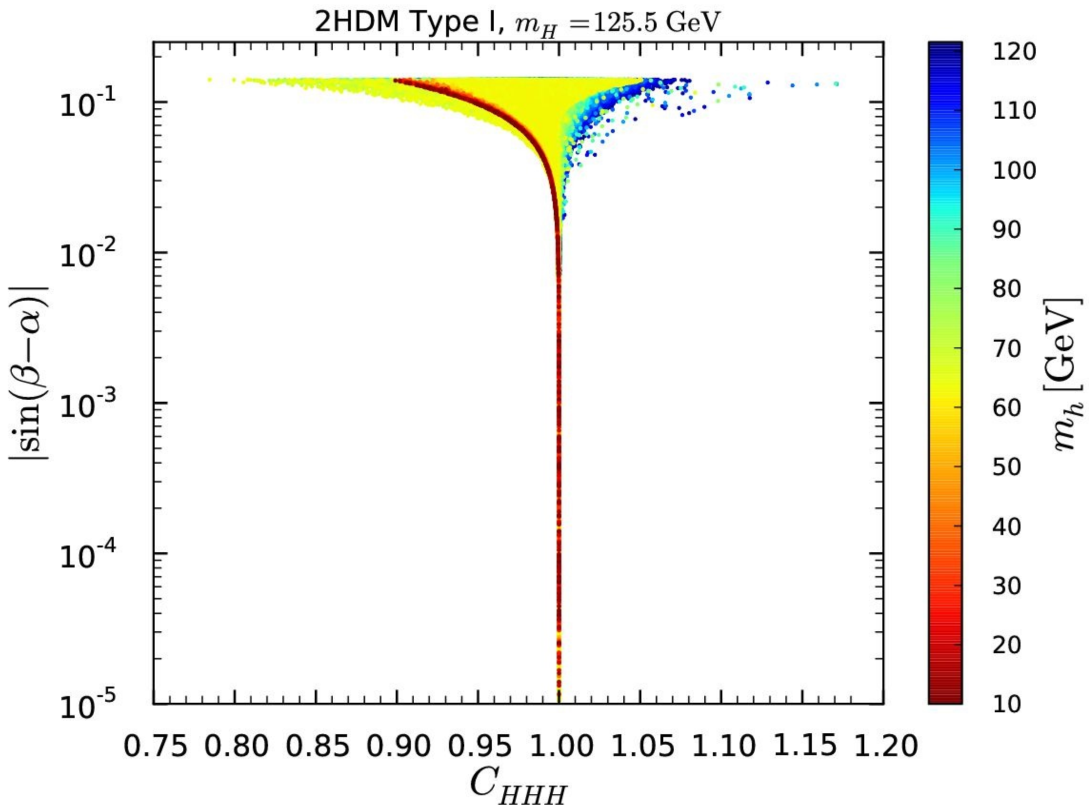


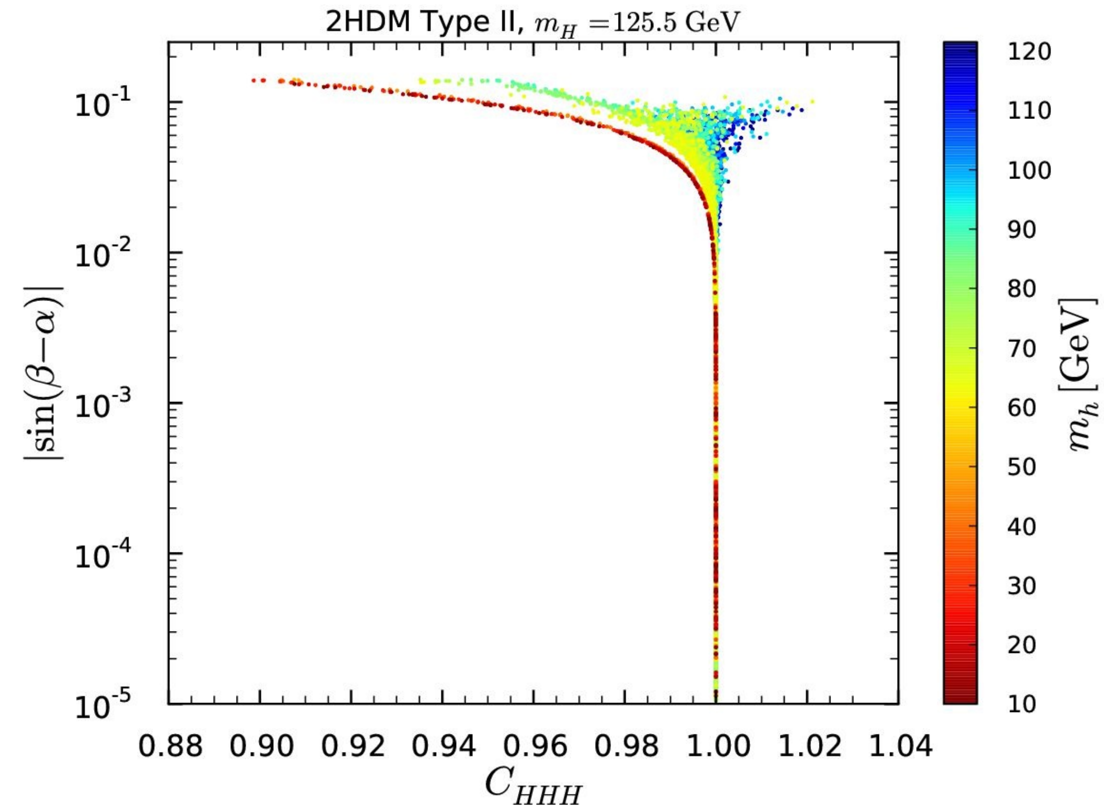


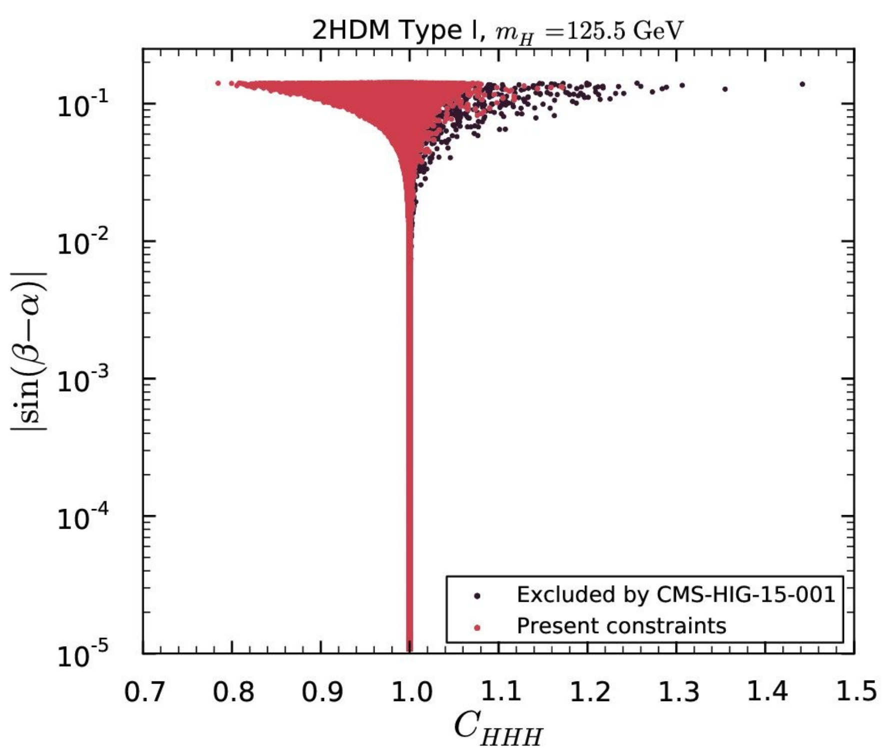


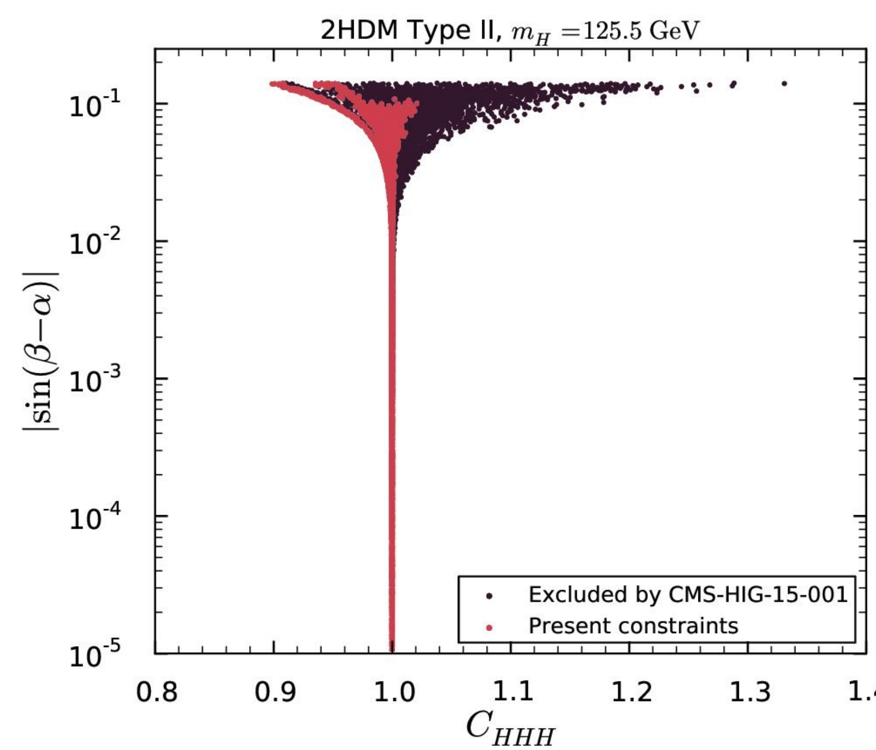


Trilinear Higgs coupling

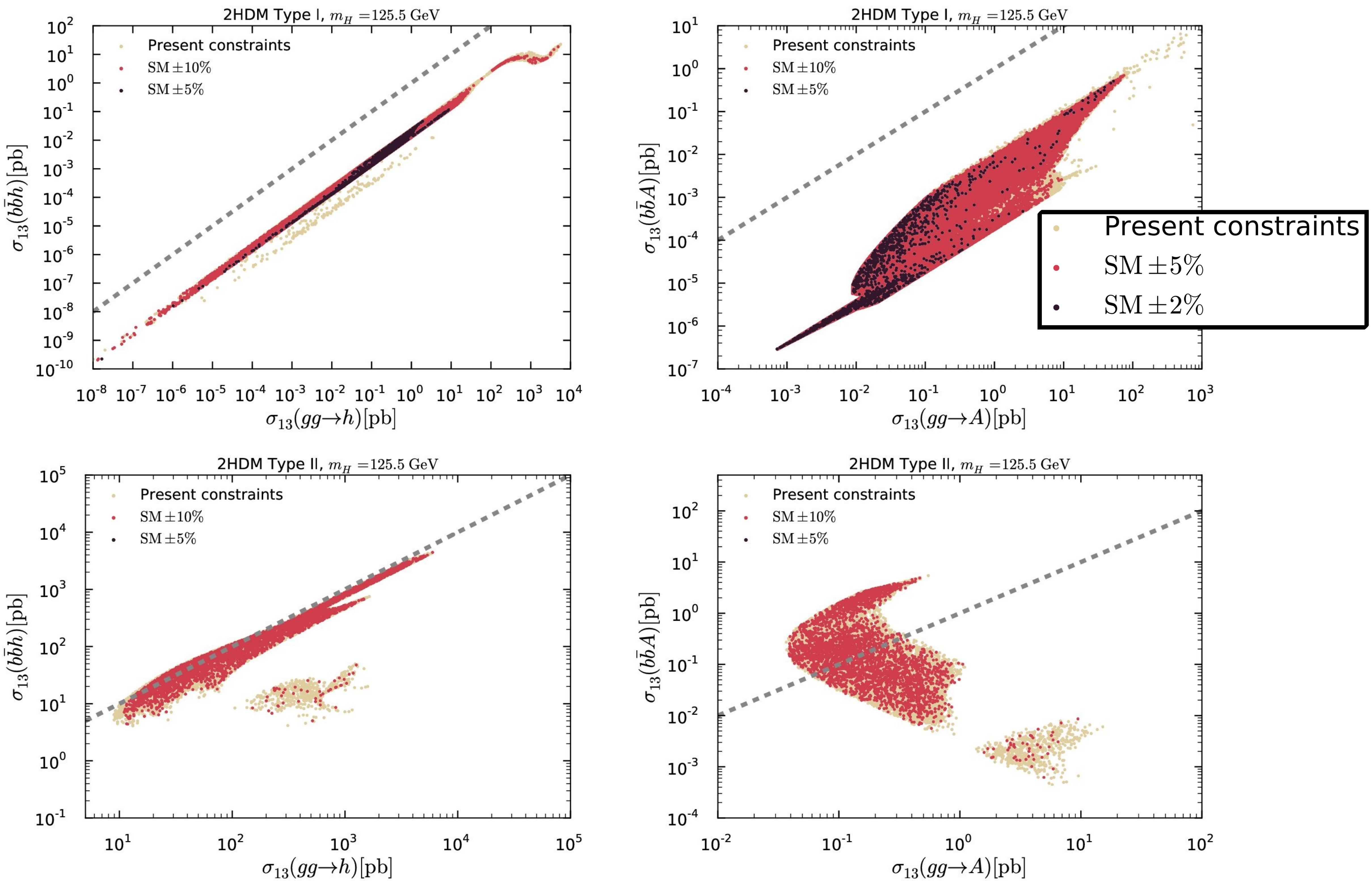








h, A production cross sections at the LHC 13 TeV



A→γγ, tt at the LHC 13 TeV