The Alignment Limit in Two-Higgs-Doublet Models

Sabine Kraml
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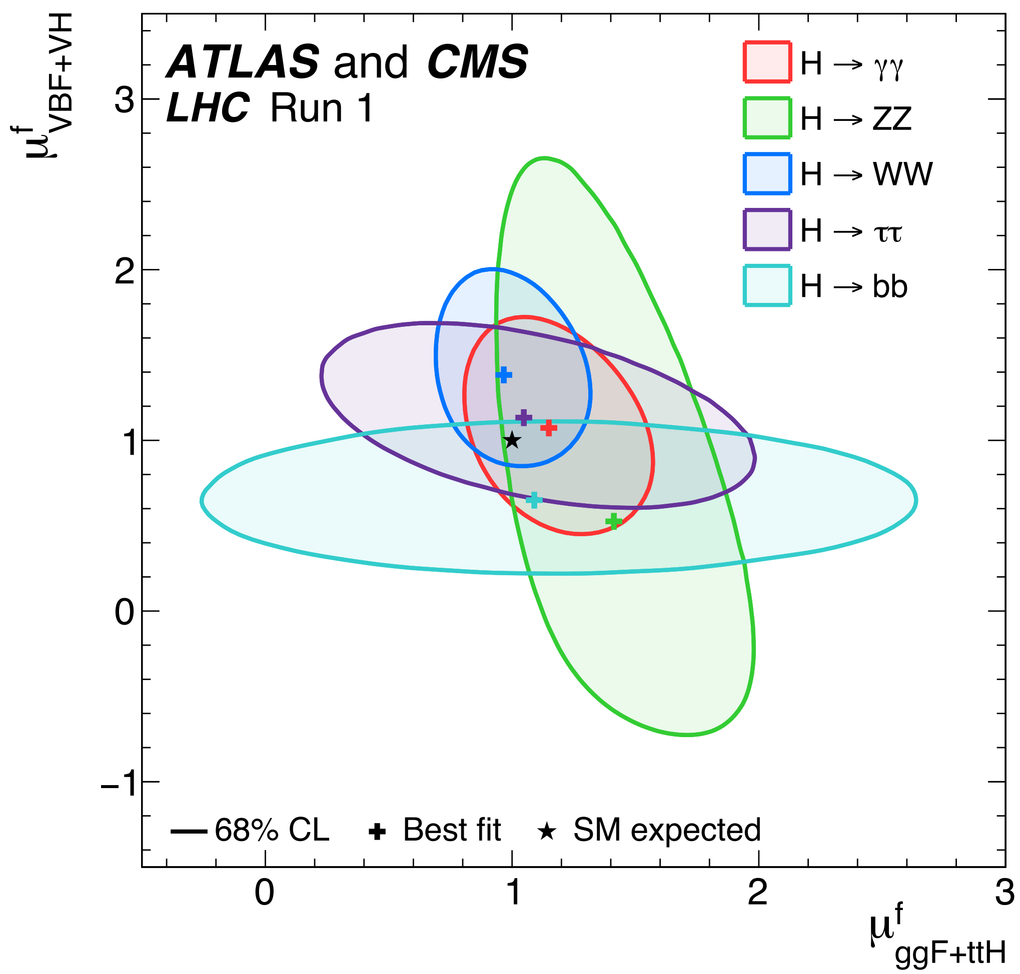
based on arXiv:1507.00933 and 1511.03682
with Jeremy Bernon*, John F. Gunion, Howard E. Haber and Yun Jiang

* detailed discussion and paper update in Jeremy's thesis (Sep. 2016)

Theorie LHC France Workshop
7-9 Nov 2016, Orsay

A very SM-like Higgs boson

arXiv:1606.02266



The current LHC measurements indicate that the 125 GeV Higgs boson is very SM like and so far show no sign of any other new particle.

Conceptually, however, there is no reason why the Higgs sector should be minimal.

Indeed a non-minimal Higgs sector is theoretically very attractive (needed by most BSM theories) and, if confirmed, would shine a new light on the mechanism of electroweak symmetry breaking dynamics.

Higgs mass:

125.09 ± 0.24 GeV

arXiv:1503.07589

This talk

- It is possible that the 125 GeV Higgs boson appears SM-like due to the alignment limit of an extended Higgs sector
- Alignment occurs automatically in the decoupling limit, but it is also possible without decoupling.
- What are the phenomenological consequences of alignment w/o decoupling ? (How) can we test it ?

theoretical framework:

CP-conserving two-Higgs doublet model (2HDM) of Type I and Type II

Two Higgs Doublet Model (*Z_2* basis)

2HDM: SM supplemented by a second Y=+1 complex scalar.

The most general gauge invariant renormalizable scalar potential is given by

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

- Softly-broken discrete Z_2 symmetry to avoid tree-level Higgs-mediated FCNCs $\Phi_1 \to +\Phi_1$ and $\Phi_2 \to -\Phi_2$. Then $\lambda_6 = \lambda_7 = 0$.
- Take m_{12}^2 and λ_5 to be real : scalar potential is CP-conserving

$$\langle \Phi_i \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_i \end{pmatrix}$$

To avoid tree-level Higgs-mediated FCNCs, we extend the Z_2 symmetry to Yukawa sector

$$-\mathcal{L}_{\text{Yuk}} = \mathcal{Y}_b^1 \bar{b}_R \Phi_1^{i\,*} Q_L^i + \mathcal{Y}_b^2 \bar{b}_R \Phi_2^{i\,*} Q_L^i + \mathcal{Y}_\tau^1 \bar{\tau}_R \Phi_1^{i\,*} L_L^i + \mathcal{Y}_\tau^2 \bar{\tau}_R \Phi_2^{i\,*} L_L^i$$
$$+ \epsilon_{ij} \big[\mathcal{Y}_t^1 \bar{t}_R Q_L^i \Phi_1^j + \mathcal{Y}_t^2 \bar{t}_R Q_L^i \Phi_2^j\big] + \text{h.c.}\,,$$

5 physical scalar states: two CP-even (h, H) with $m_h < m_H$ (mass matrix: mixing angle α), a CP-odd (A) and a pair of charged Higgs ($H^\pm$).

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Type I: $\mathcal{Y}_t^1 = \mathcal{Y}_b^1 = \mathcal{Y}_\tau^1 = 0\,,$
Type II: $\mathcal{Y}_t^1 = \mathcal{Y}_b^2 = \mathcal{Y}_\tau^2 = 0\,.$

5 physical scalar states: two CP-even (h, H) with $m_h < m_H$ (mass matrix: mixing angle α), a CP-odd (A) and a pair of charged Higgs ($H^\pm$).

Higgs basis

Linear transformation to go to the "Higgs basis"

$$\langle \Phi_i \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} \mathbf{0} \\ \boldsymbol{v_i} \end{pmatrix}$$

$$\begin{pmatrix} \boldsymbol{H_1} \\ \boldsymbol{H_2} \end{pmatrix} = \begin{pmatrix} \boldsymbol{c_\beta} & \boldsymbol{s_\beta} \\ -\boldsymbol{s_\beta} & \boldsymbol{c_\beta} \end{pmatrix} \begin{pmatrix} \boldsymbol{\Phi_1} \\ \boldsymbol{\Phi_2} \end{pmatrix} \quad \Rightarrow \quad \langle H_1^0 \rangle = v/\sqrt{2}\,, \quad \langle H_2^0 \rangle = 0\,.$$

$$\mathcal{V} = Y_1 H_1^\dagger H_1 + Y_2 H_2^\dagger H_2 + Y_3 [H_1^\dagger H_2 + \text{h.c.}] + \frac{1}{2} Z_1 (H_1^\dagger H_1)^2 + \frac{1}{2} Z_2 (H_2^\dagger H_2)^2 + Z_3 (H_1^\dagger H_1)(H_2^\dagger H_2)$$
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$$Y_1 = m_{11}^2 c_\beta^2 + m_{22}^2 s_\beta^2 - m_{12}^2 s_{2\beta}\,,$$
$$Y_2 = m_{11}^2 s_\beta^2 + m_{22}^2 c_\beta^2 + m_{12}^2 s_{2\beta}\,,$$
$$Y_3 = \tfrac{1}{2}(m_{22}^2 - m_{11}^2) s_{2\beta} - m_{12}^2 c_{2\beta}\,.$$

$$Y_1 = -Z_1 v^2/2, \quad Y_3 = -Z_6 v^2/2$$

$$Z_1 \equiv \lambda_1 c_\beta^4 + \lambda_2 s_\beta^4 + \tfrac{1}{2}\lambda_{345} s_{2\beta}^2\,,$$
$$Z_2 \equiv \lambda_1 s_\beta^4 + \lambda_2 c_\beta^4 + \tfrac{1}{2}\lambda_{345} s_{2\beta}^2\,,$$
$$Z_i \equiv \tfrac{1}{4} s_{2\beta}^2 \left[\lambda_1 + \lambda_2 - 2\lambda_{345}\right] + \lambda_i\,, \quad (\text{for } i = 3, 4 \text{ or } 5)\,,$$
$$Z_6 \equiv -\tfrac{1}{2} s_{2\beta} \left[\lambda_1 c_\beta^2 - \lambda_2 s_\beta^2 - \lambda_{345} c_{2\beta}\right],$$
$$Z_7 \equiv -\tfrac{1}{2} s_{2\beta} \left[\lambda_1 s_\beta^2 - \lambda_2 c_\beta^2 + \lambda_{345} c_{2\beta}\right].$$

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Now we get for the two neutral CP-even states (with $m_h < m_H$ per def.)

$$\mathcal{M}_H^2 = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & m_A^2 + Z_5 v^2 \end{pmatrix}, \qquad \begin{aligned} H &= (\sqrt{2}\,\text{Re}\, H_1^0 - v) c_{\beta-\alpha} - \sqrt{2}\,\text{Re}\, H_2^0 s_{\beta-\alpha}\,, \\ h &= (\sqrt{2}\,\text{Re}\, H_1^0 - v) s_{\beta-\alpha} + \sqrt{2}\,\text{Re}\, H_2^0 c_{\beta-\alpha}\,. \end{aligned}$$

One of the two CP-even mass eigenstates will be SM-like if aligned with the direction of the vacuum expectation value, i.e. if $\sin(\beta-\alpha)=1$ or $\cos(\beta-\alpha)=1$.

The alignment limit

$$\mathcal{M}_H^2 = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & m_A^2 + Z_5 v^2 \end{pmatrix},$$

$$Z_1 v^2 = m_h^2 s_{\beta-\alpha}^2 + m_H^2 c_{\beta-\alpha}^2 ,$$
$$Z_6 v^2 = (m_h^2 - m_H^2) s_{\beta-\alpha} c_{\beta-\alpha} ,$$
$$m_A^2 + Z_5 v^2 = m_H^2 s_{\beta-\alpha}^2 + m_h^2 c_{\beta-\alpha}^2 .$$

A SM-like Higgs boson exists if $(\sqrt{2}\mathrm{Re}\, H_1^0 - v)$ is an approximate mass eigenstate. Occurs for $|Z_6| \ll 1$ and/or $m_A^2 + Z_5 v^2 \gg Z_1 v^2, Z_6 v^2$ (negligible mixing of H_1^0 and H_2^0)

$\sin(\beta-\alpha) \simeq 1$ or $\cos(\beta-\alpha) \simeq 1$

SM-like h

$$h \simeq (\sqrt{2}\mathrm{Re}\, H_1^0 - v) s_{\beta-\alpha} , \quad Z_1 v^2 < m_A^2 + Z_5 v^2$$

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

- $m_H^2 \gg v^2$ ..... decoupling limit
- $|Z_6| \ll 1$ .... alignment w/o decoupling

SM-like H

$$H \simeq (\sqrt{2}\mathrm{Re}\, H_1^0 - v) c_{\beta-\alpha} , \quad Z_1 v^2 > m_A^2 + Z_5 v^2$$

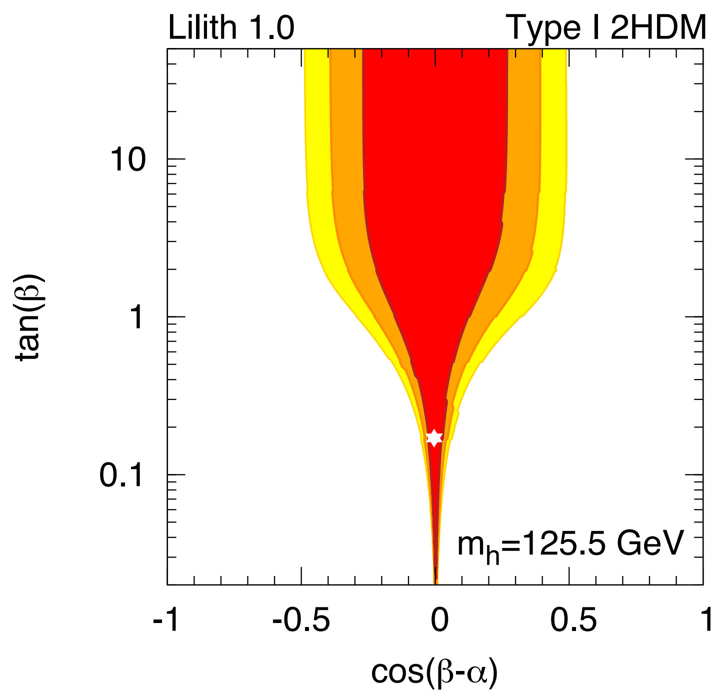
$$s_{\beta-\alpha} = \frac{-Z_6 v^2}{\sqrt{(m_H^2 - m_h^2)(Z_1 v^2 - m_h^2)}} \simeq 0$$

Since mh<mH, there is no decoupling limit as in the case of a SM-like h. However, alignment without decoupling can be achieved in the limit of $Z_6 \to 0$.

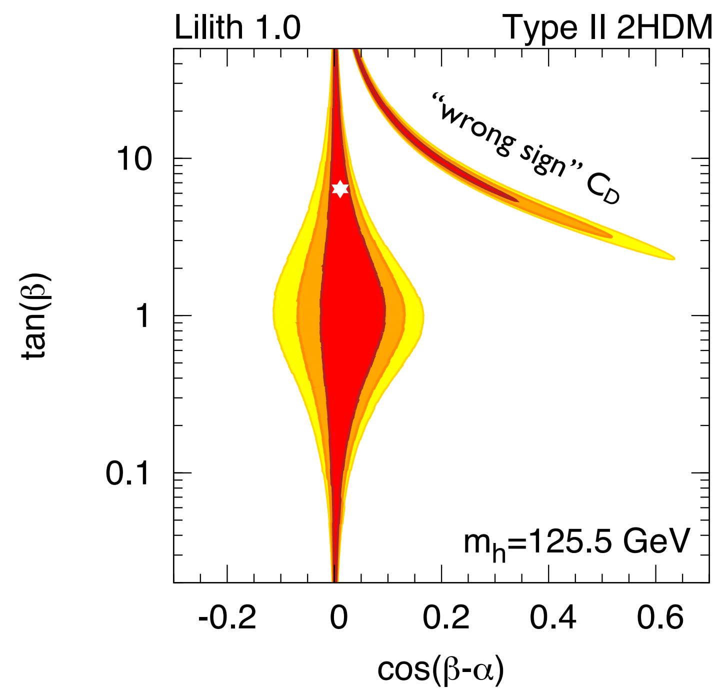
2HDMs of Types I and II

	Type I and II	Type I		Type II	
Higgs	VV	up quarks	down quarks and leptons	up quarks	down quarks and leptons
h	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
H	$\cos(\beta-\alpha)$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
A	0	$\cot\beta$	$-\cot\beta$	$\cot\beta$	$\tan\beta$

Notation of coupling scale factors, or *reduced couplings*: **C_V** (V=W,Z) for the coupling to gauge bosons, **$C_{U,D}$** for the couplings to up-type and down-type fermions and **$C_{\gamma,g}$** for the couplings to photons and gluons.



BR(h→AA) < 0.16 at 95% CL



BR(h→AA) < 0.26 at 95% CL

Fit to LHC data
assuming mh=125 GeV
(1, 2, 3 σ contours)

Bernon, Dumont, SK,
arXiv:1409.1588

2HDMs of Types I and II

Higgs	Type I and II C_V	Type I C_U	Type I C_D	Type II C_U	Type II C_D
h	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
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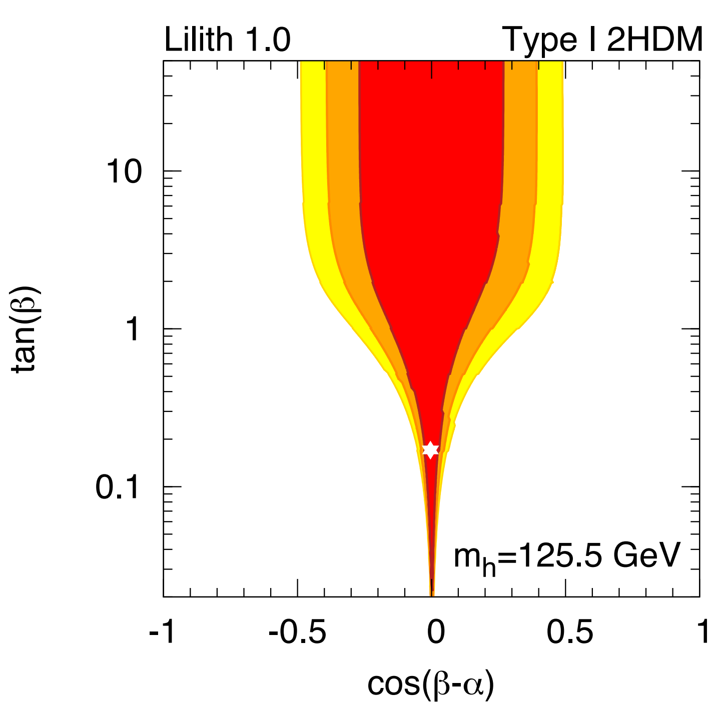

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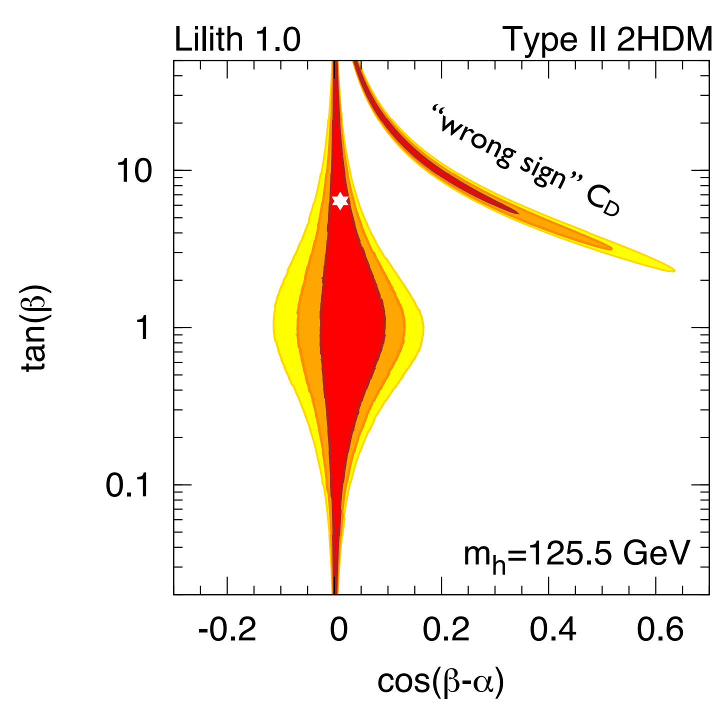

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Fit to LHC data
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Remarks

- Alignment limit means one of the Higgs mass eigenstates is approximately aligned with the direction of the scalar field vacuum expectation values.
- In this case, the W and Z gauge bosons dominantly acquire their masses from only one Higgs doublet of the Higgs basis.
- Moreover, the coupling of that CP-even Higgs boson to the gauge bosons tends towards the SM value (in terms of reduced coupling: $C_V \to 1$).
- While this is automatically the case in the decoupling limit when the extra non-SM Higgs states are very heavy, such an alignment can also occur when the extra Higgs states are light, below about 600 GeV.

Study the consequences of alignment with and w/o decoupling for

- measurements of the couplings and signal strengths of the 125 GeV state,
- ways to discover the additional Higgs states of the 2HDM.

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- measurements of the couplings and signal strengths of the 125 GeV state,
- ways to discover the additional Higgs states of the 2HDM.

In the numerical analysis we will require $C_V \geq 0.99$, i.e. we allow 1% deviation from exact alignment.

Setup of the numerical analysis

- Scan over 2HDM parameter space with **2HDMC** Eriksson, Rathsman, Stal, 0902.0851

$$m_h,\ m_H,\ m_A,\ m_{H^\pm},\ m_{12}^2,\ \tan\beta,\ \alpha$$

  - Either mh=125.5 GeV or mH=125.5 GeV with ≥4 GeV H-h mass difference to avoid degenerate Higgs scenarios; alignment condition: **$C_V \geq 0.99$**
  - Theoretical constraints: stability of the scalar potential, perturbativity of the self-couplings, tree-level unitarity of the Higgs-Higgs scattering matrices

- LHC cross sections with **SusHi** and **VBFNLO** Harlander, Liebler, Mantler, 1212.3942; Arnold et al., 0811.4559

- Experimental constraints:

  ✓ S, T, U Peskin-Takeuchi parameters (→Higgs mass splitting)
  ✓ B-physics constraints (→ tanβ, charged Higgs mass)
  ✓ LEP Higgs searches (e+e-→Zh, e+e-→Z*→Ah, e+e-→H+H-)
  ✓ Upsilon constraints on light CP-odd states
  ✓ CMS light CP-odd search (A→μμ from 7 TeV dataset)
  ✓ ATLAS and CMS heavy Higgs searches (H→ZZ; A→Zh; H,A→ττ, μμ; …)

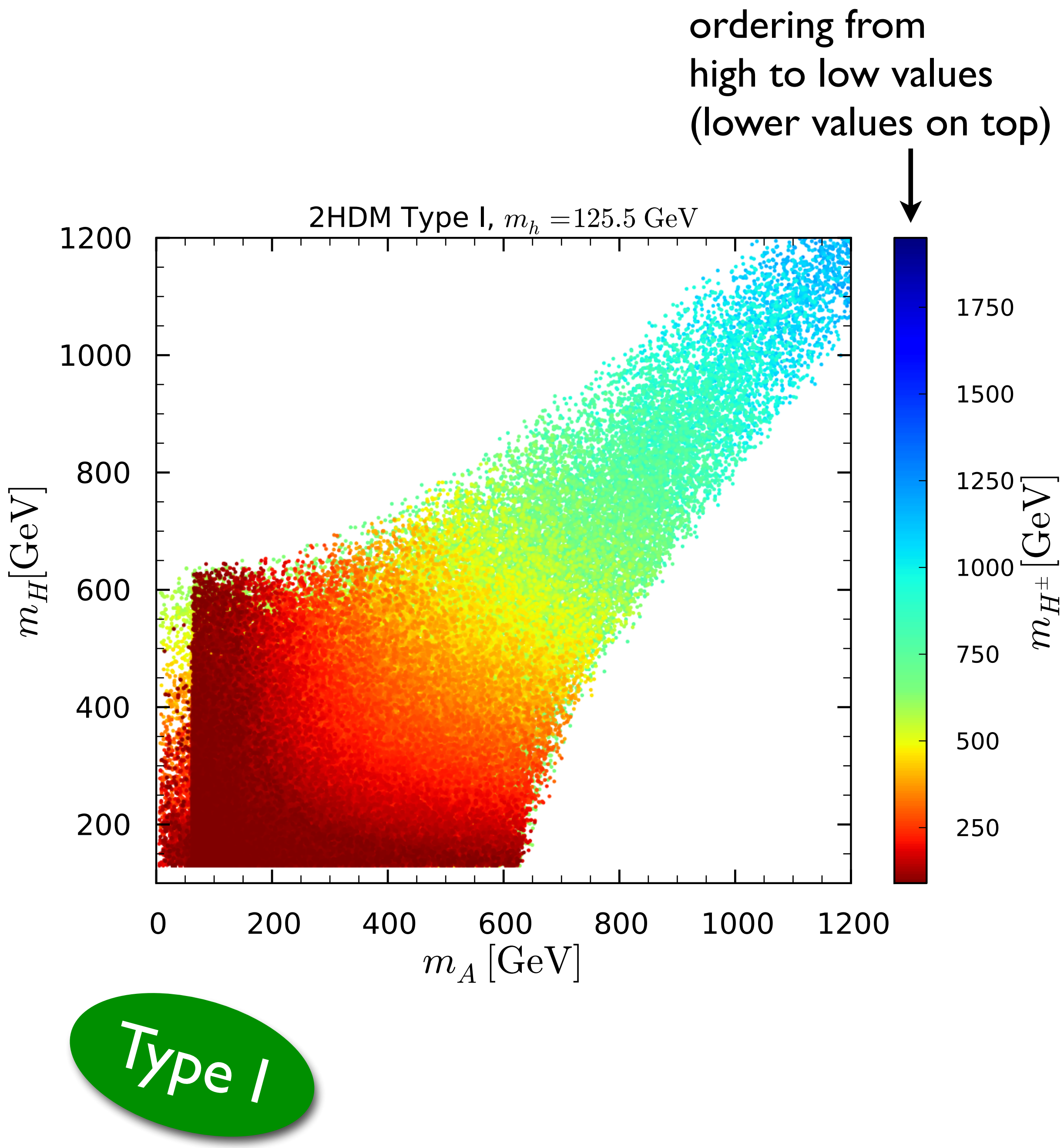
  ✓ 125 GeV Higgs signal strengths with **Lilith** Bernon, Dumont, 1502. 04138

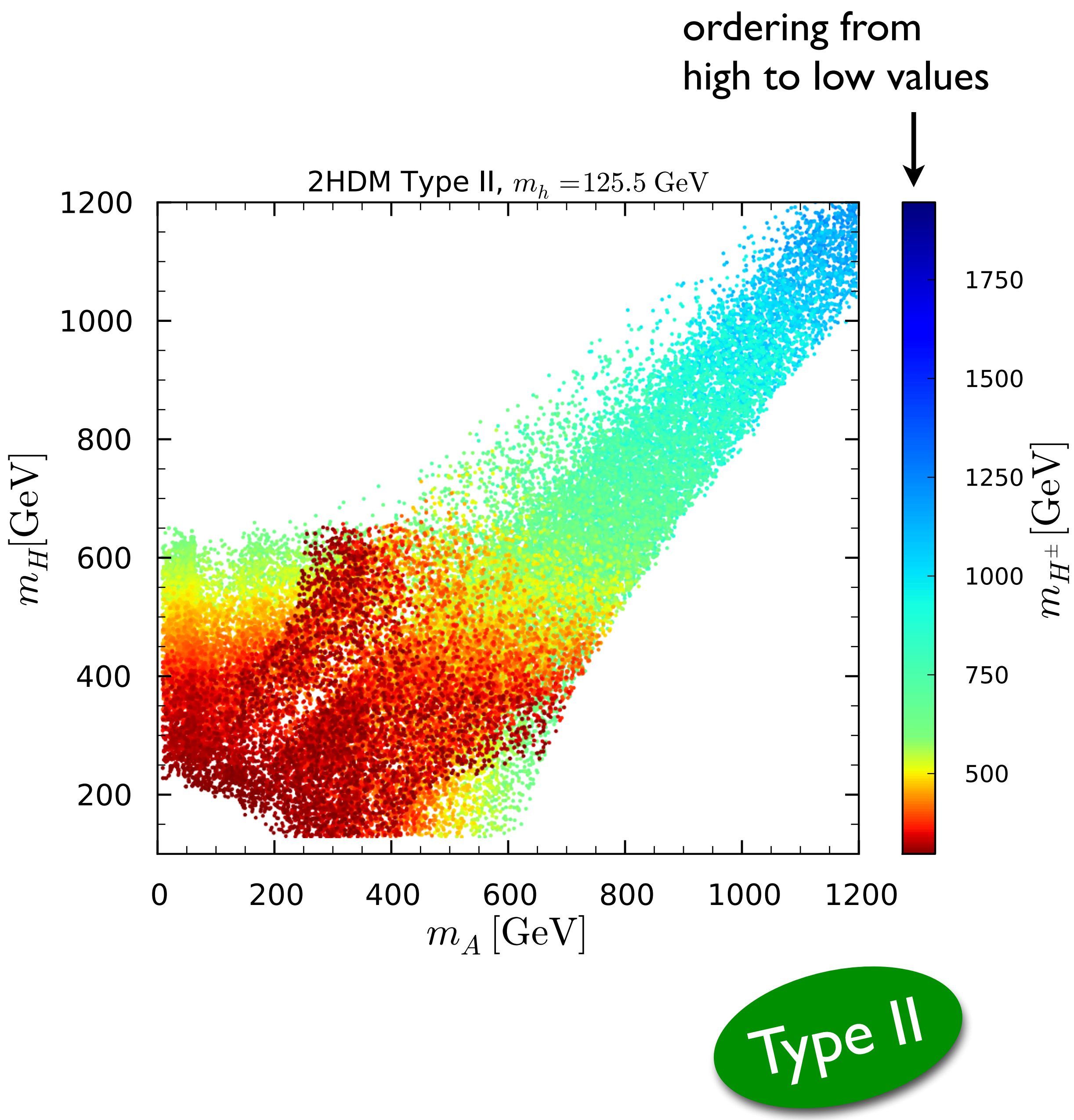
Case 1: m_h = 125 GeV

$\sin(\beta-\alpha) \geq 0.99$

arXiv:1507.00933 (updated)

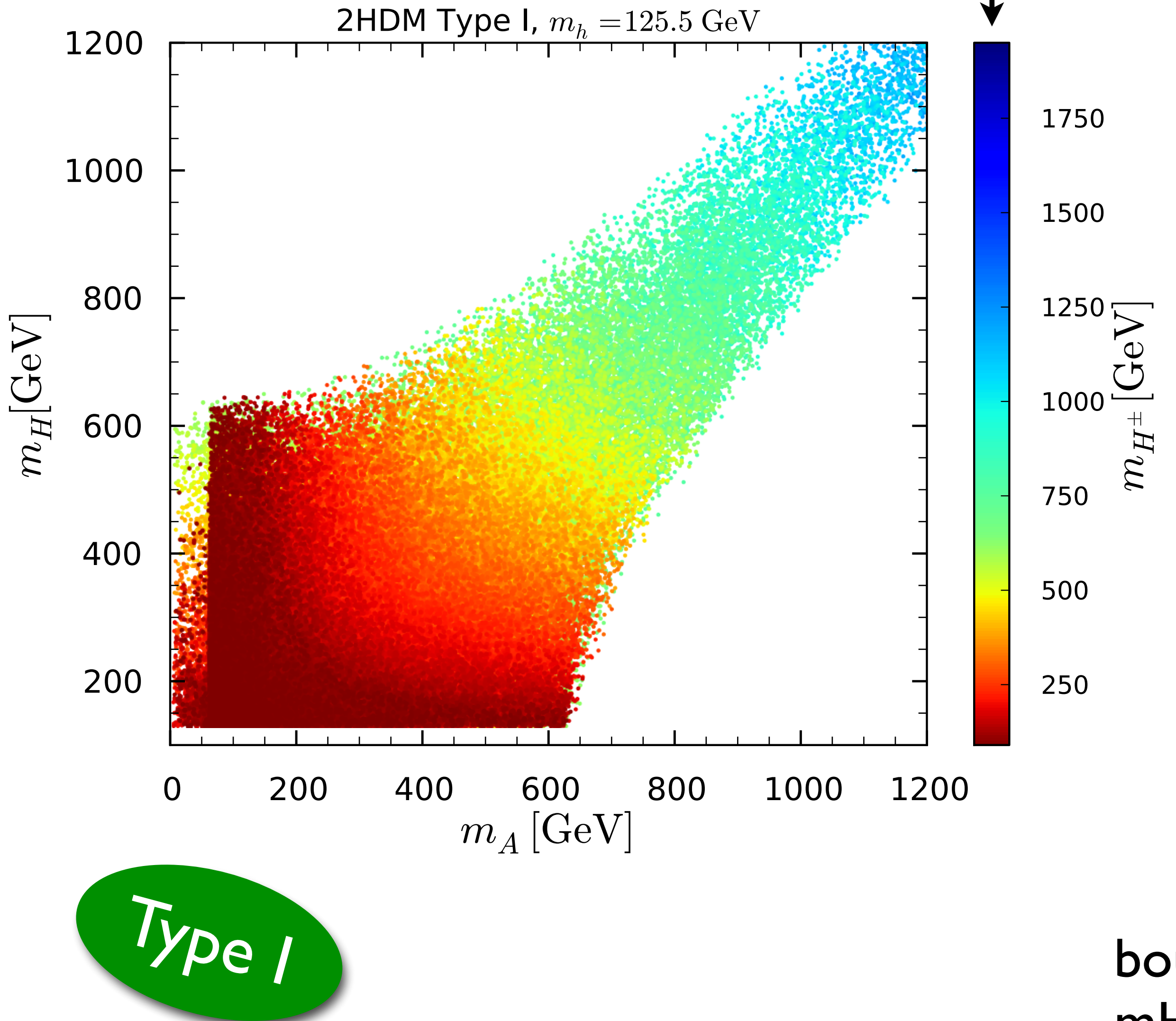
Relation btw m_A, m_H and $m_{H^\pm}$



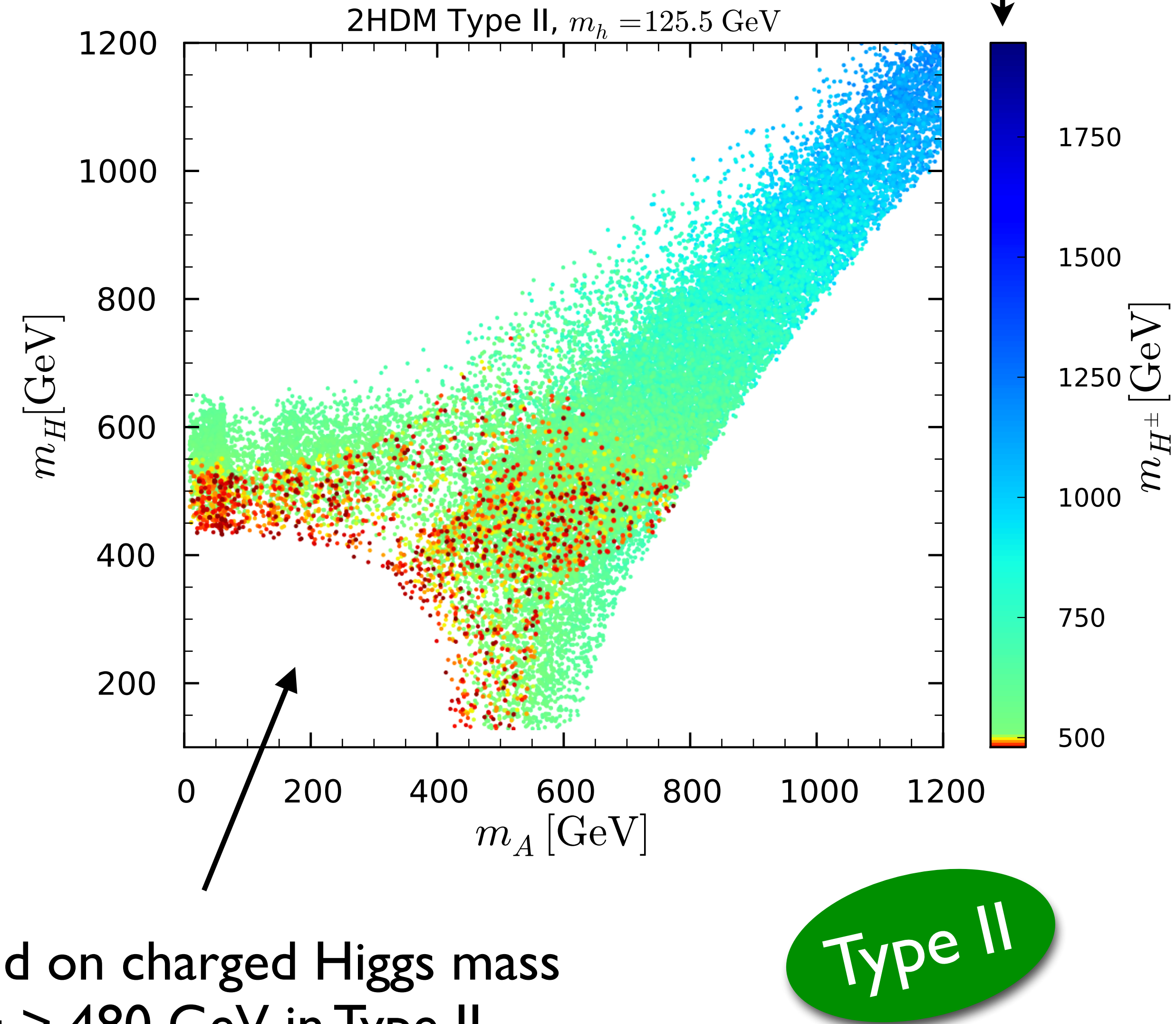


Relation btw m_A, m_H and $m_{H^\pm}$

ordering from
high to low values
(lower values on top)



ordering from
high to low values



bound on charged Higgs mass
mH± > 480 GeV in Type II

[Misiak et al.,1503.01789]

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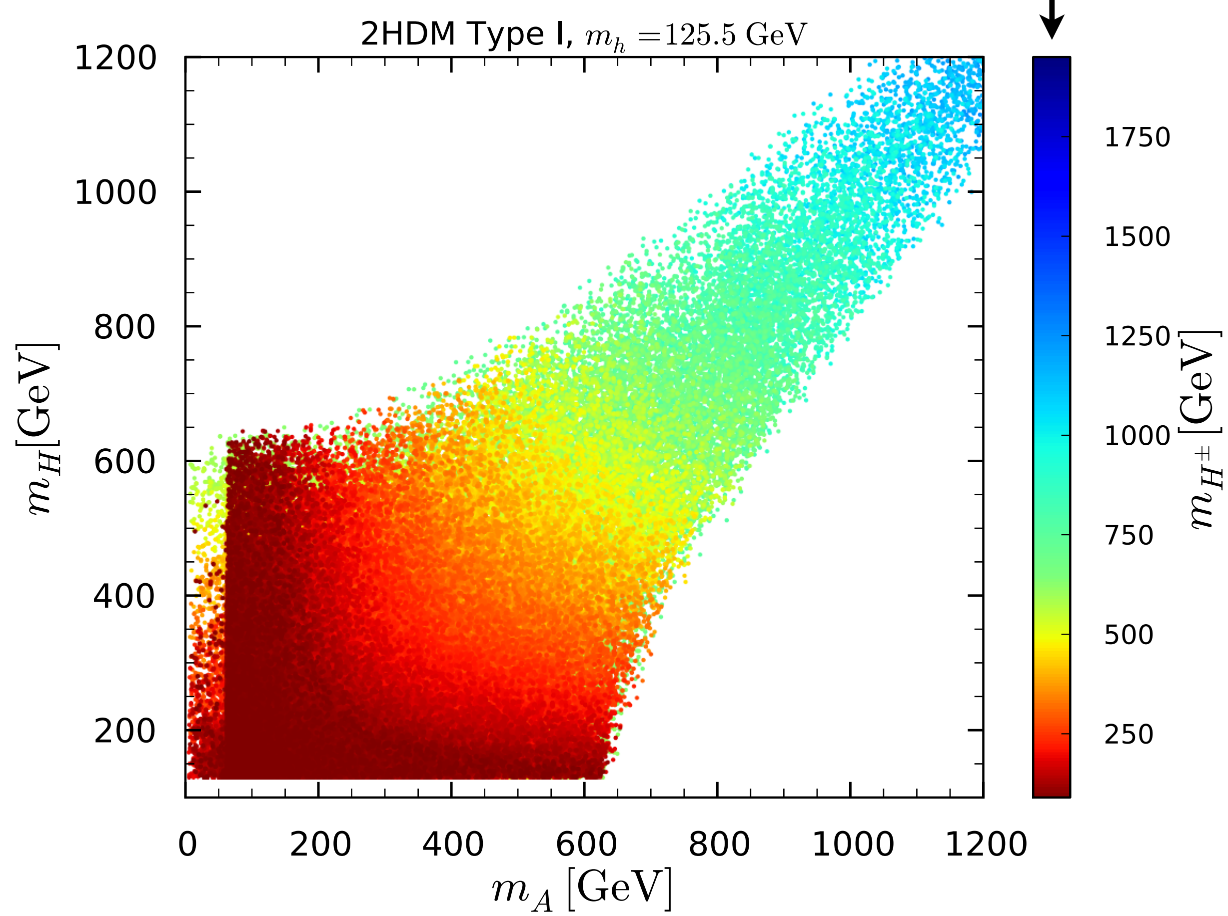
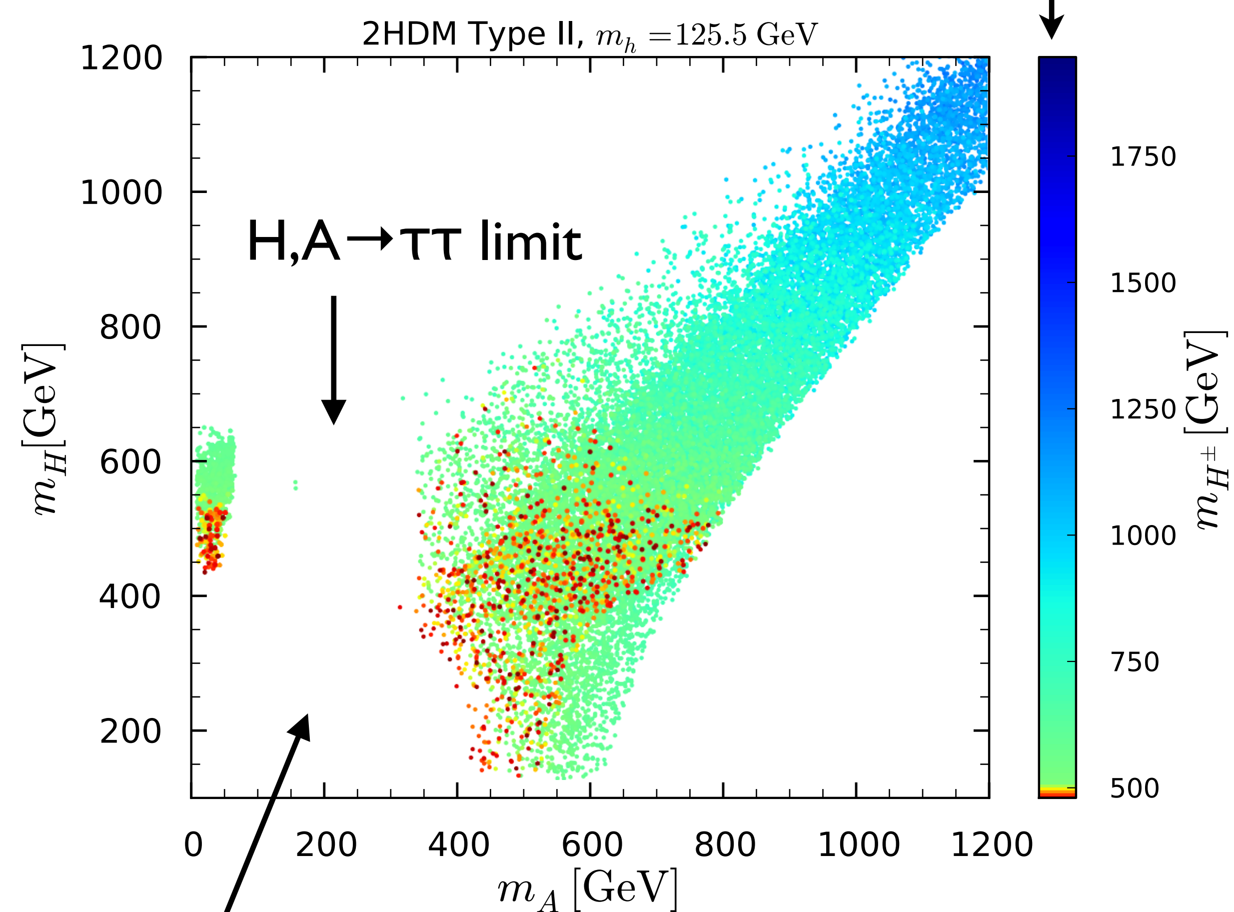


Type I

ordering from
high to low values



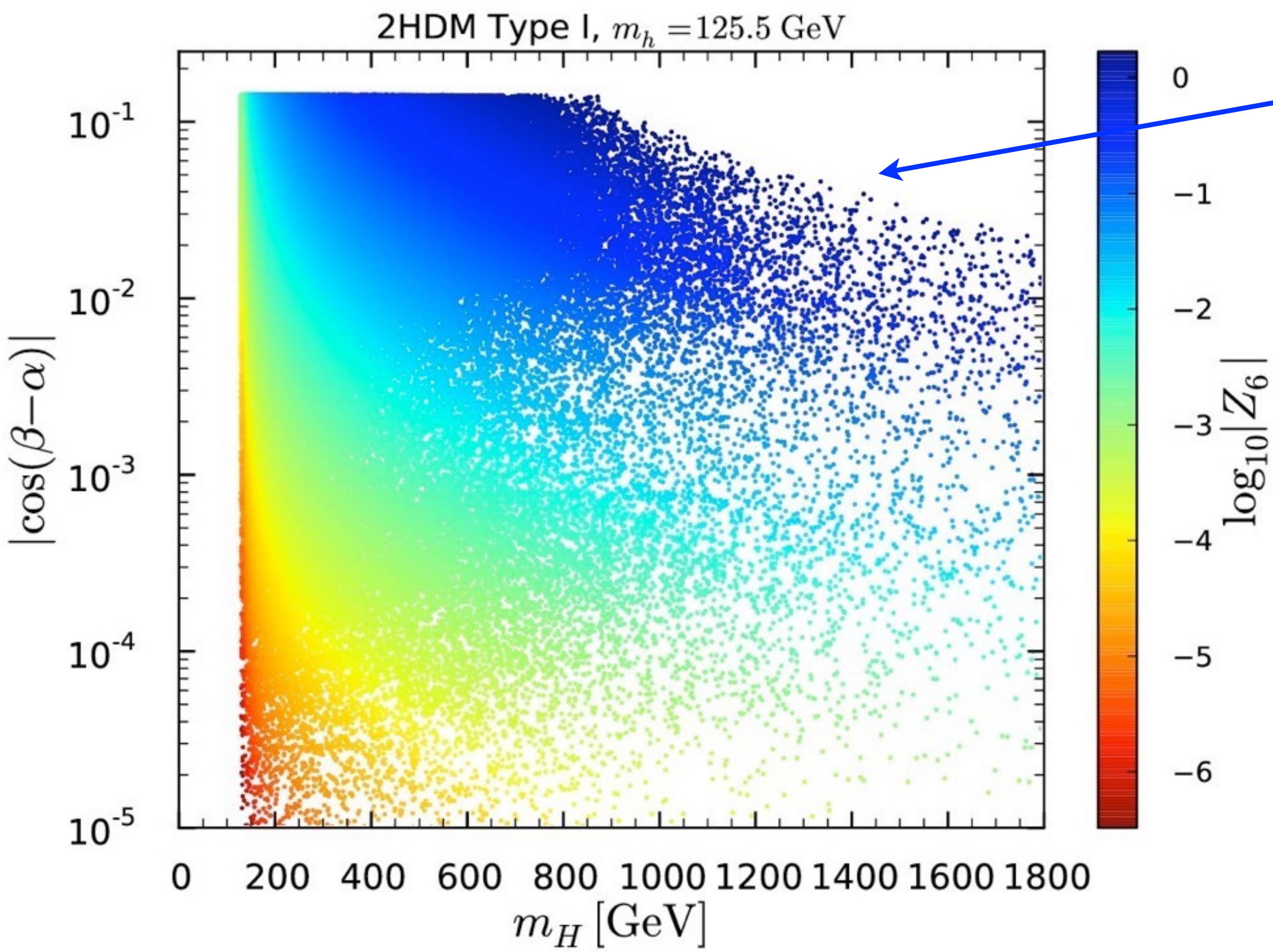
bound on charged Higgs mass
mH± > 480 GeV in Type II

Type II

[Misiak et al.,1503.01789]

Relation btw Z_6, cos(β-α) and m_H

Different ways to achieve alignment



decoupling limit implies an upper bound on cos(β-α)

indirect sub-% constraint on cos(β-α) if mH>850 GeV

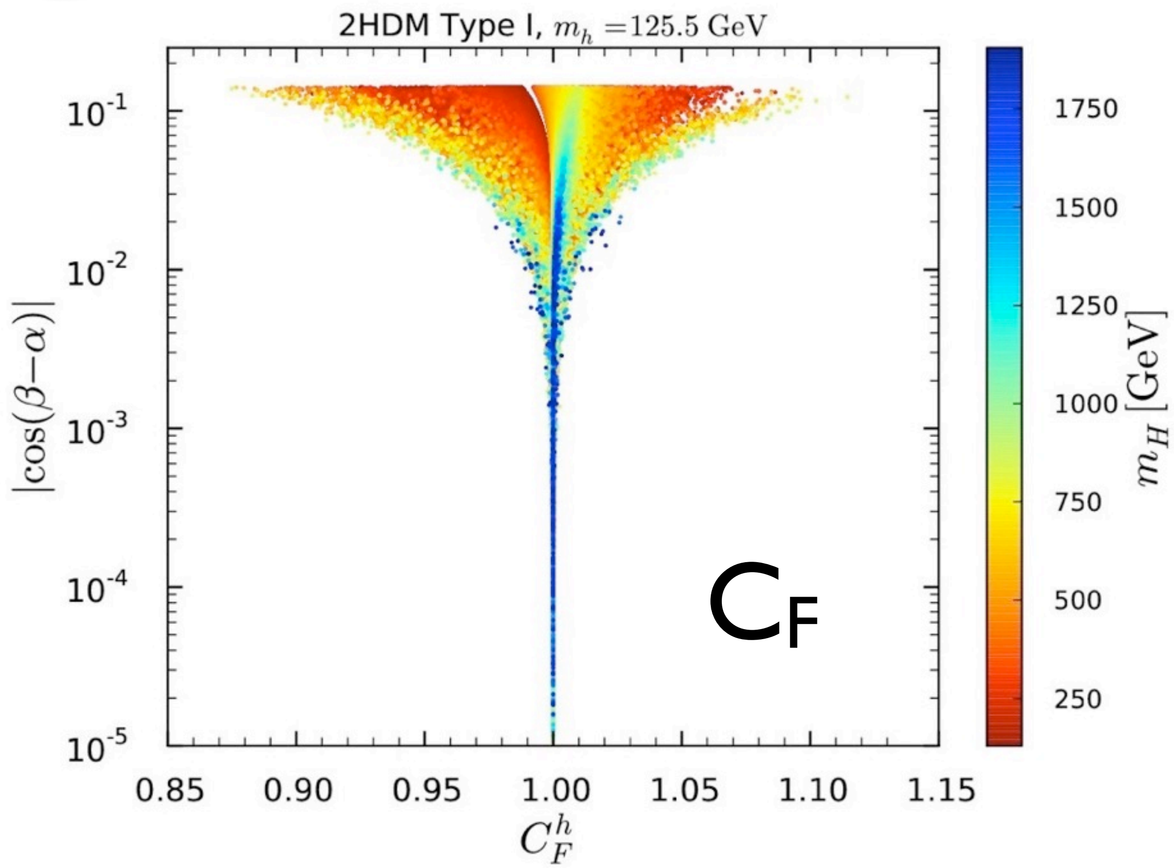
NB: in all plots, we give 3d information on a 2d plot by means of a color code in the third dimension.

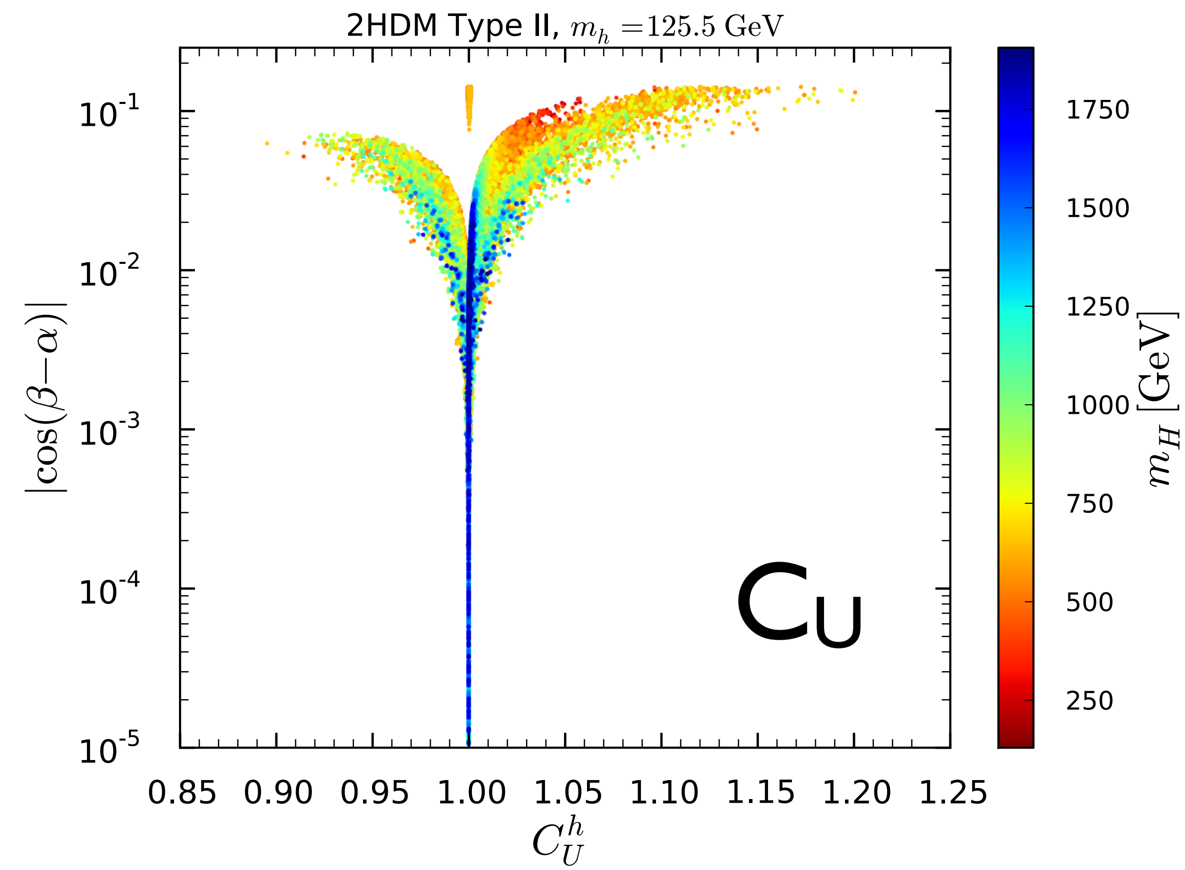
Couplings of the 125 GeV state: C_U

$C_U = \cos\alpha / \sin\beta$

Type I

Type II





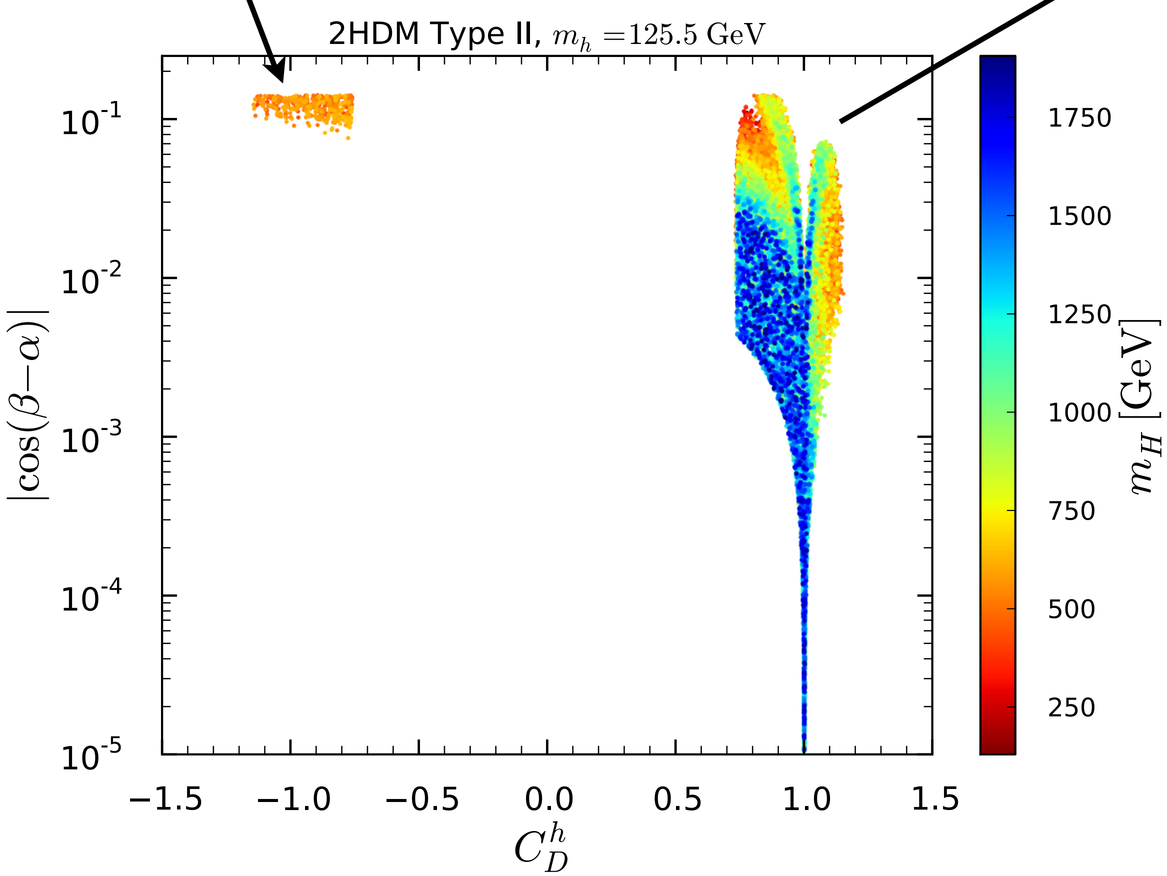
for small mH up to ±10% (-10%, +20%) deviation in Type I (Type II);
for mH in the TeV range, deviations can reach ±5%

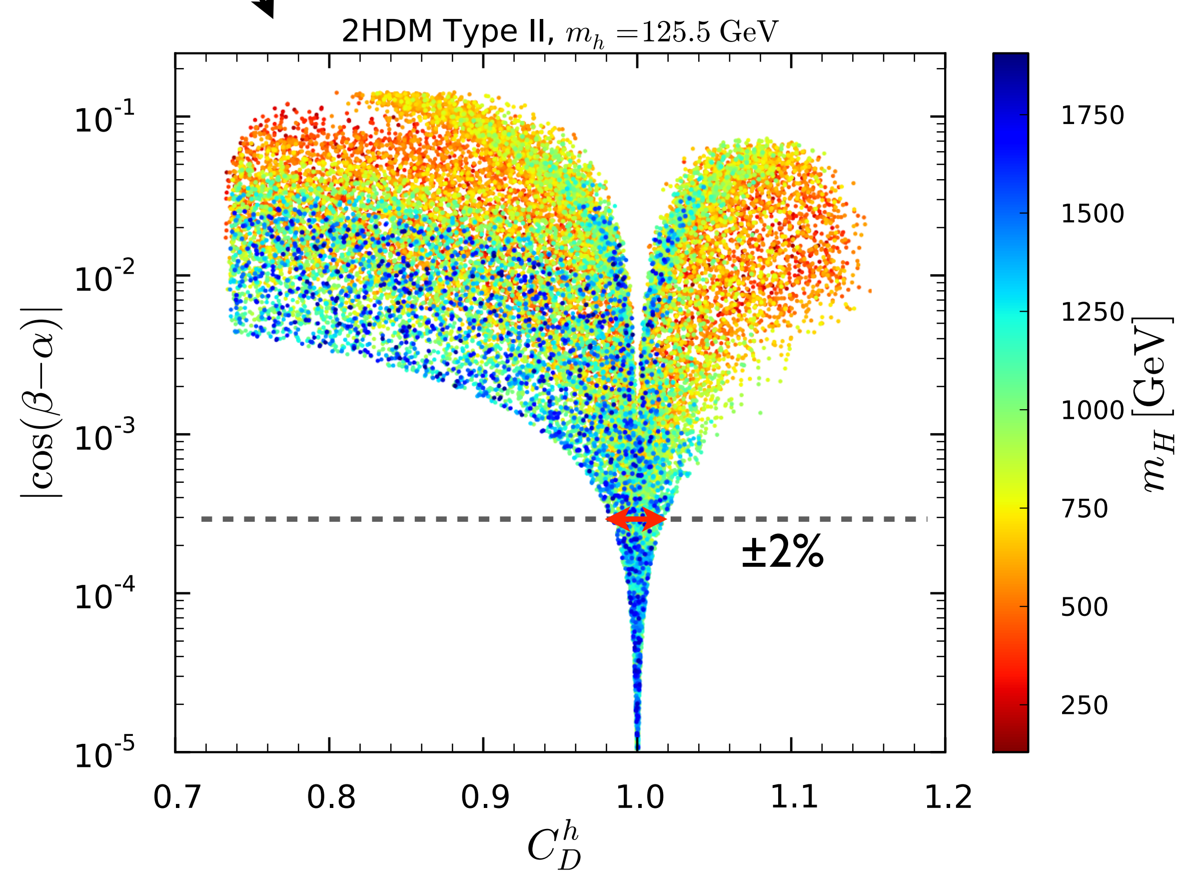
Note that C_U=C_D≡C_F in Type I

C_D in Type II

Opposite-sign C_D solution for mH=[230,665] GeV and cos(β-α)>0.06

Zoom on C_D>0: large deviations from unity even for high mH and/or very small cos(β-α)



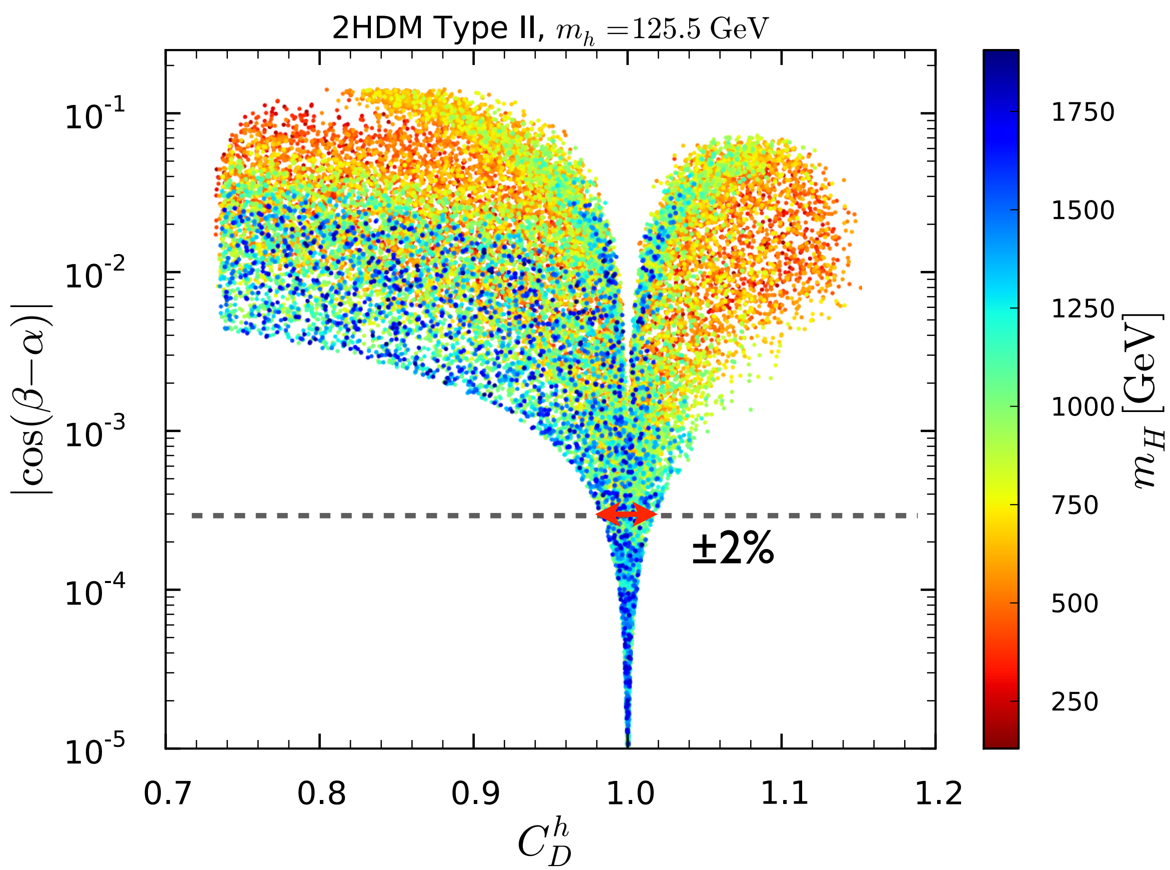


$C_U = \cos\alpha / \sin\beta$
$C_D = -\sin\alpha / \cos\beta$

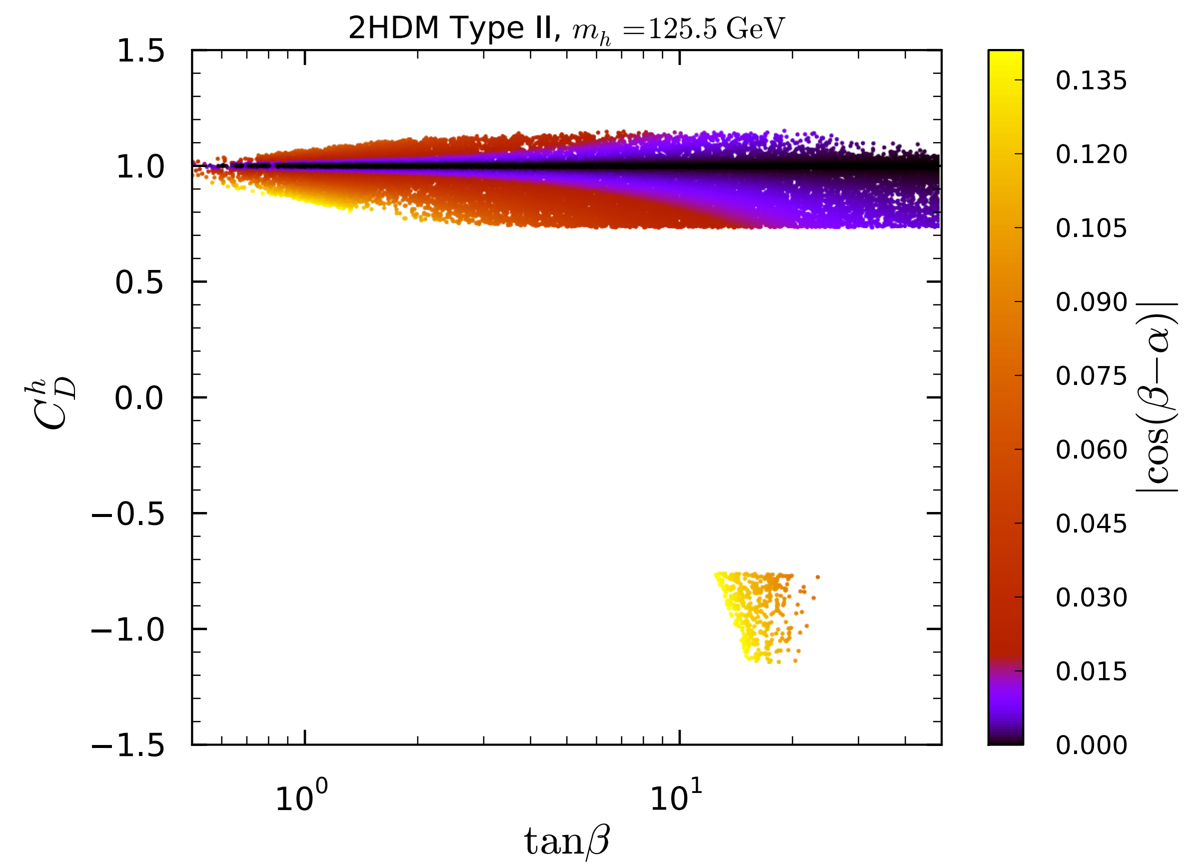
* C_D=1 only for very small cos(β-α)
* Large deviations C_D>1 need light mH
* C_D~0.8 together with mH~400 GeV would point to Type II with cos(β-α)~0.1

C_D in Type II

Zoom on C_D>0: large deviations from unity even for high mH and/or very small cos(β-α)



Alignment of C_D is delayed for large tanβ



* C_D=1 only for very small cos(β-α)

* Large deviations C_D>1 need light mH

* C_D~0.8 together with mH~400 GeV would point to Type II with cos(β-α)~0.1

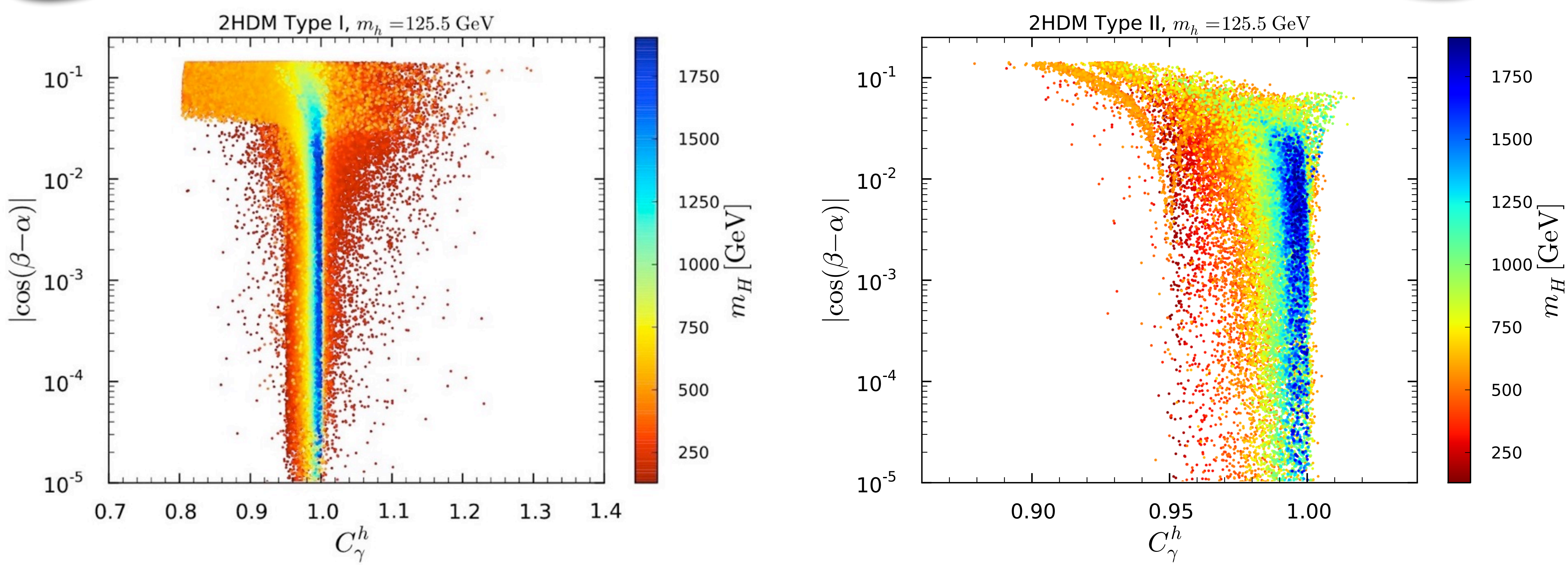
This heavily influences the signal strengths in Type II, as CD determines the h→bb branching ratio.

Coupling to photons: C_γ

Loop contributions from W, top and charged Higgs

Type I

Type II



$$g_{hH^+H^-} = -v\left[Z_3 s_{\beta-\alpha} + Z_7 c_{\beta-\alpha}\right]$$

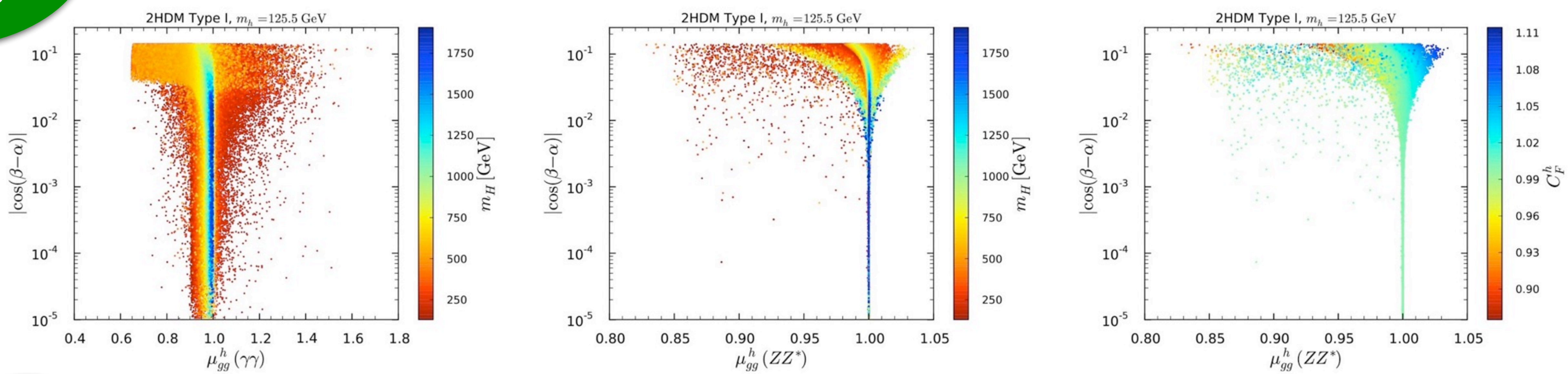
finite nonzero value in the alignment limit, with or without decoupling

In the decoupling limit, the charged Higgs loop is suppressed by a factor of $O(v^2/m^2)$ relative to the W and the top quark loop contributions. In the *alignment limit without decoupling*, the charged Higgs loop is parametrically of the same order as the corresponding SM loop contributions, thereby leading to a shift of C_γ from its SM value. This is in stark contrast to the behavior of tree-level Higgs couplings, which approach their SM values in the alignment limit with or without decoupling.

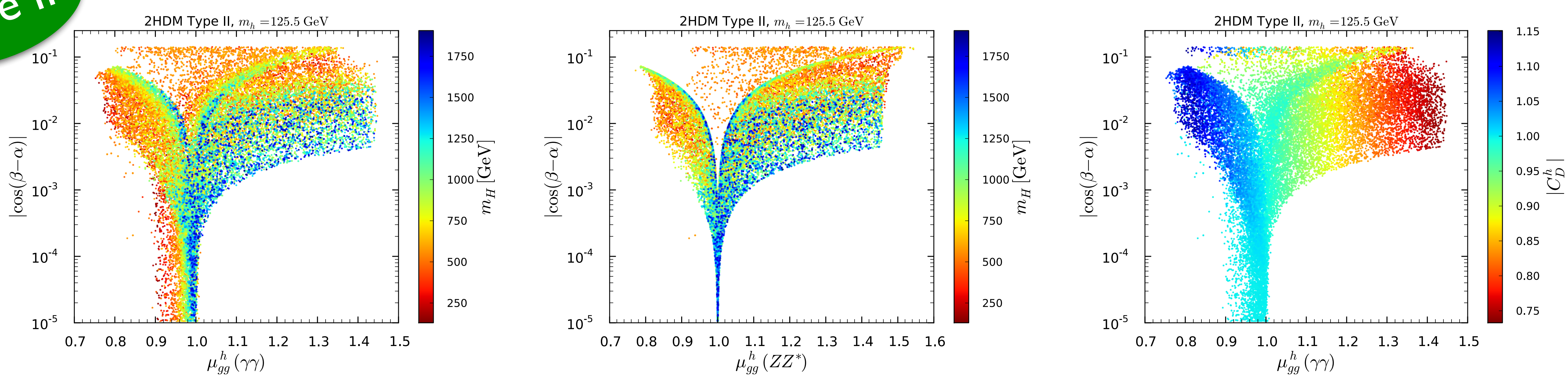
$$\mu^h_X(Y) \equiv \frac{\sigma(X)\,\mathrm{BR}(\mathrm{h}\to \mathrm{Y})}{\sigma(X_{\mathrm{SM}})\,\mathrm{BR}(\mathrm{H}_{\mathrm{SM}}\to \mathrm{Y})}$$

Signal strengths

Type I



Type II



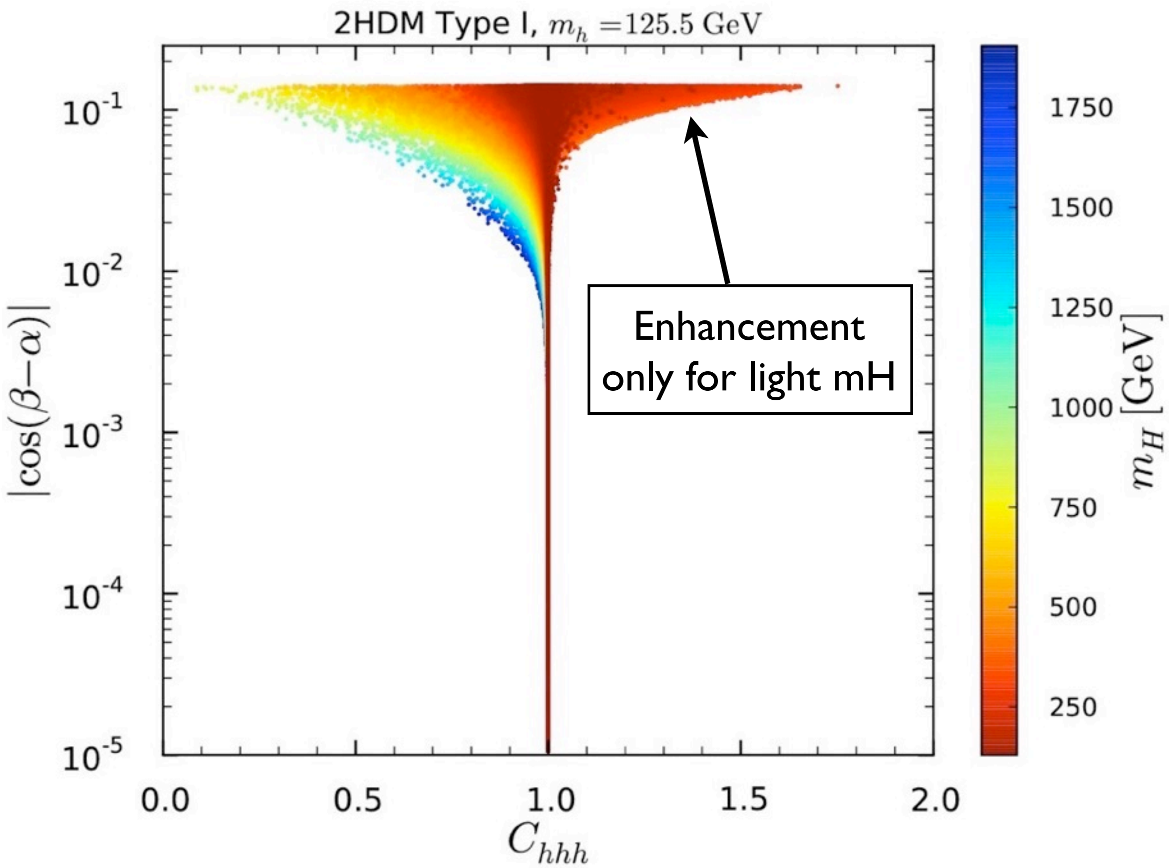
- As cos(β-α) decreases, the signal strengths in Type II converge to unity much more slowly than in Type I. This is a consequence of the delayed alignment of $C_D \to 1$ in Type II when tanβ is large.
- An additional effect arises in $\mu_{gg}(\gamma\gamma)$ due to the charged Higgs loop contribution to the h→γγ amplitude.
- Precision measurements might reveal non-decoupling regime before the discovery of other new states.

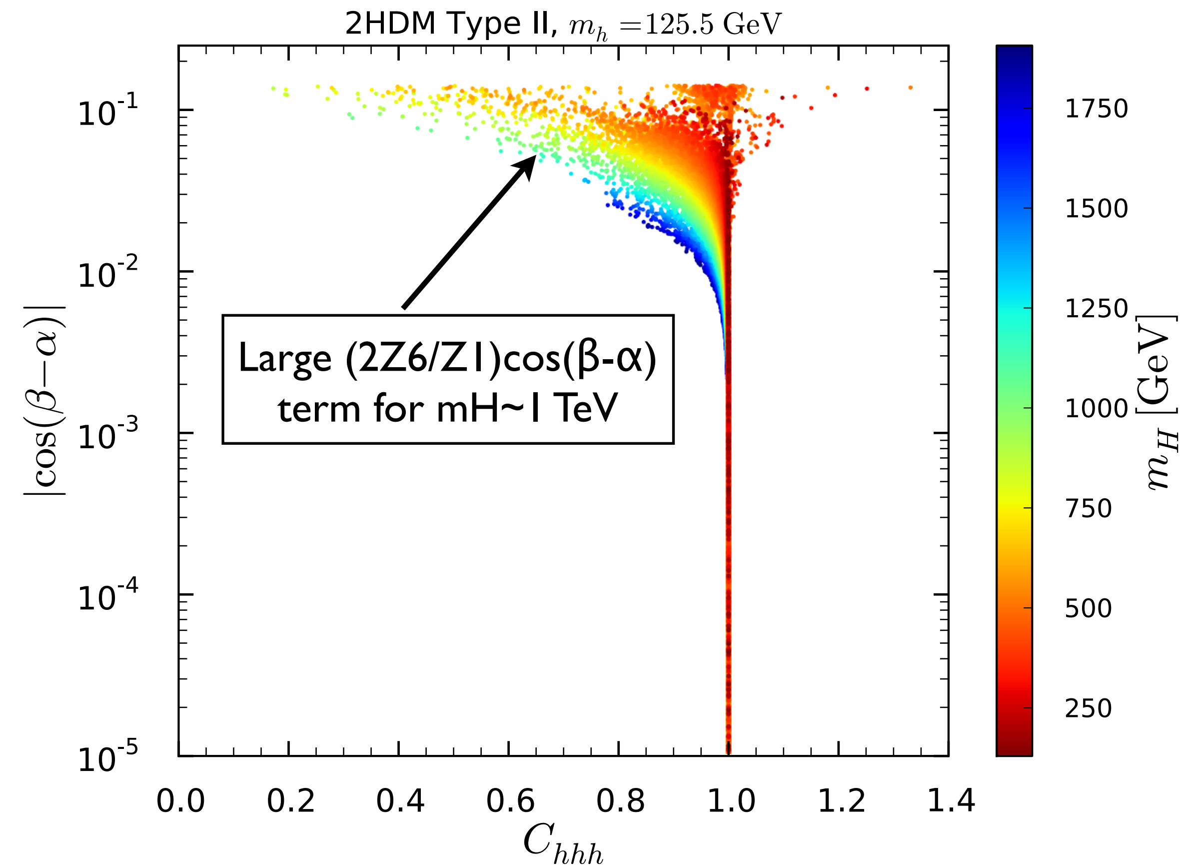
Higgs self-coupling

crucial for scrutinising the Higgs potential
see also talk by J. Baglio this morning

Type I

Type II





$$g_{hhh} = g_{hhh}^{SM}\left[1 + \frac{2Z_6}{Z_1}c_{\beta-\alpha} + \left(\frac{Z_{345}}{Z_1} - \frac{2Z_6^2}{Z_1^2} - \frac{3}{2}\right)c_{\beta-\alpha}^2 + \mathcal{O}(c_{\beta-\alpha}^3)\right]$$

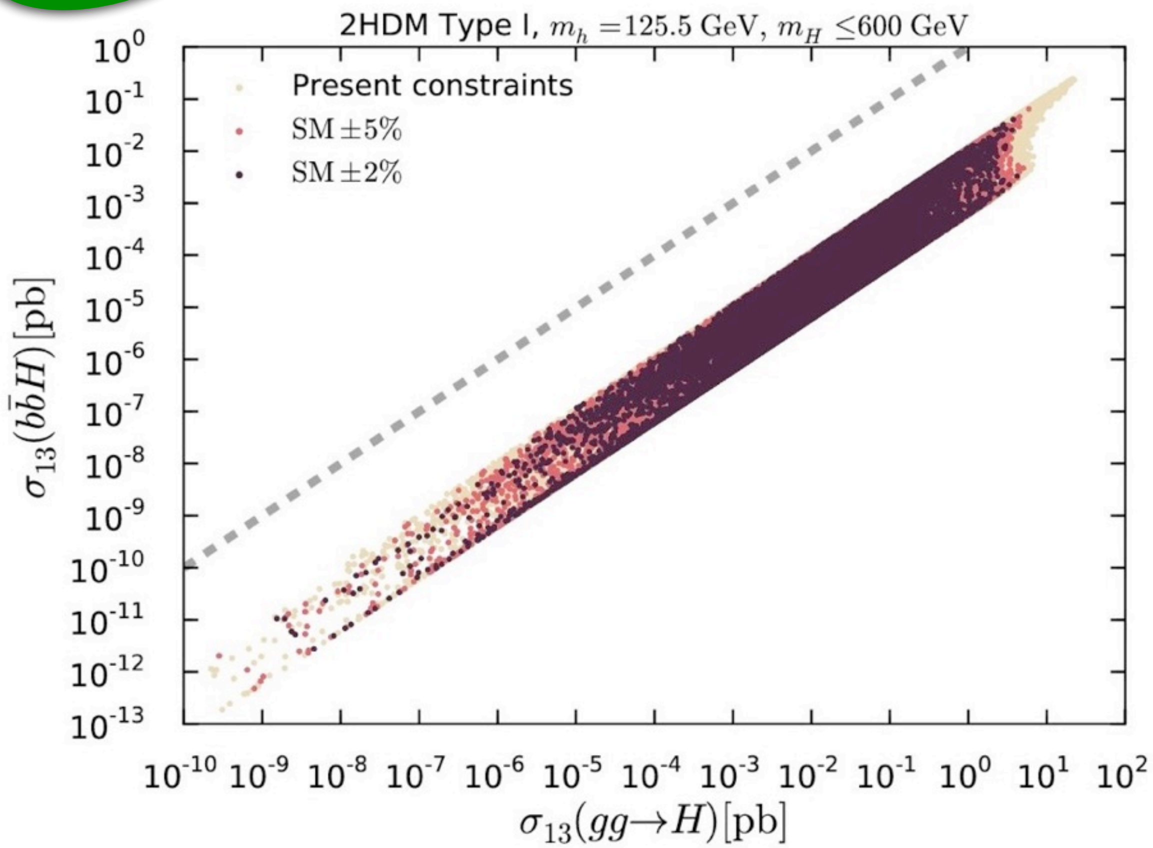
$$g_{hhh}^{SM} = -\frac{3m_h^2}{v}$$

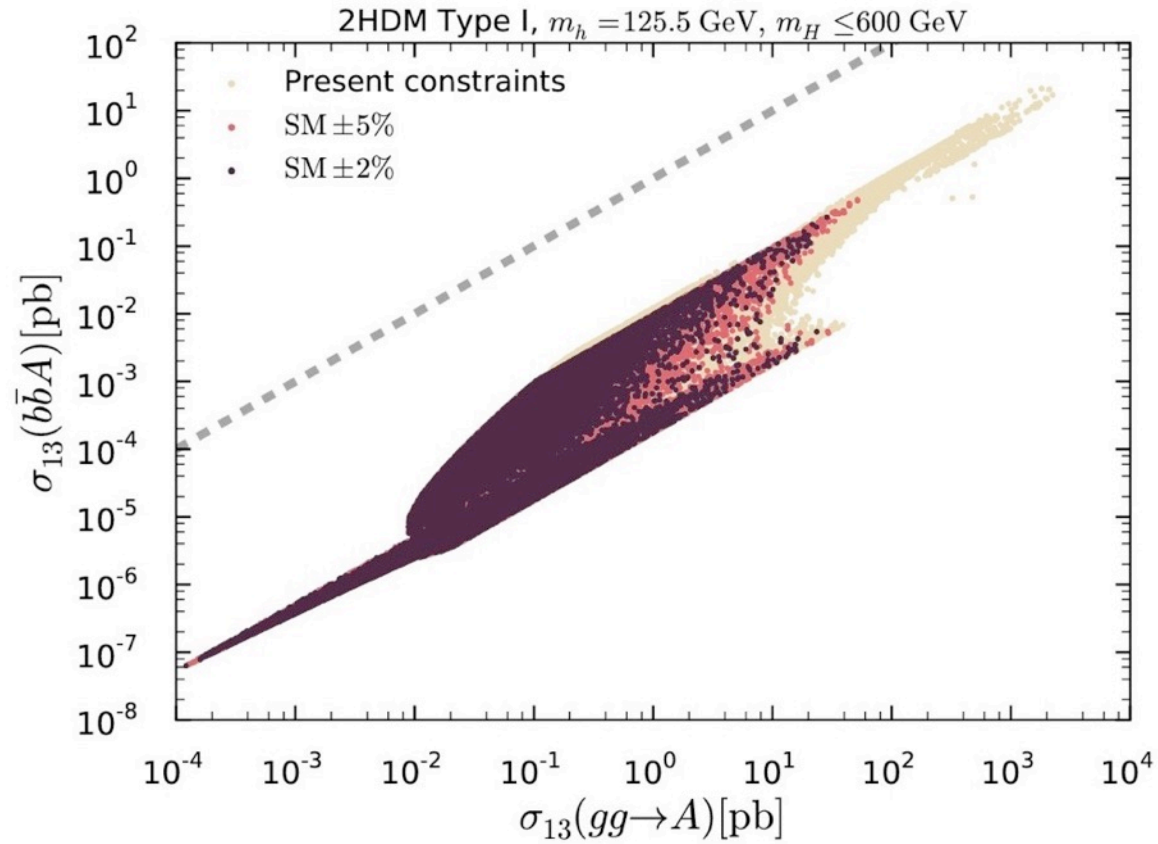
Large values of $C_{hhh} > 1$ (up to C_{hhh}~1.7 in Type I and up to C_{hhh}~1.4 in Type II) can be achieved in the non-decoupling regime, roughly mH < 600 GeV, for cos(β-α) values of the order of 0.1, whereas for heavier mH, C_{hhh} is always suppressed as compared to its SM prediction.

H and A production at 13 TeV

most important channels:
gluon-gluon fusion and bb associated production

Type I





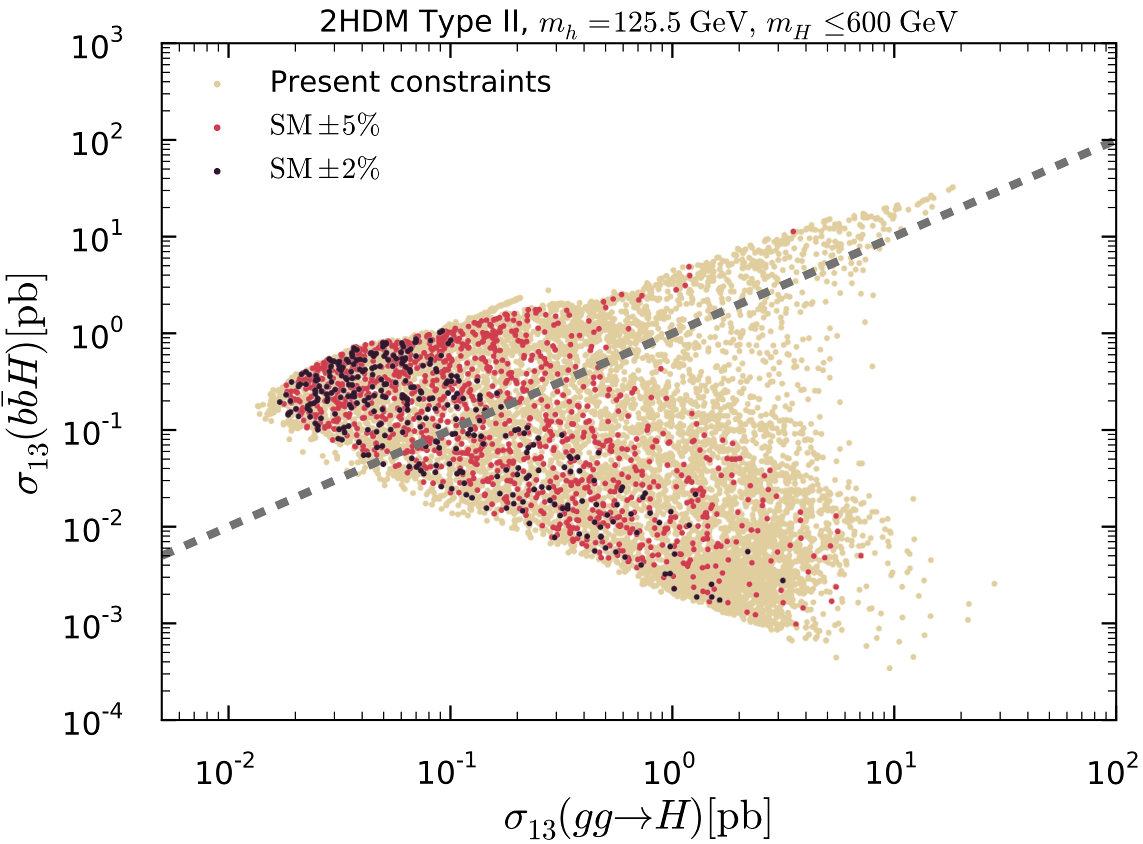
- Strong correlation btw. gg→X and bbX (X=H,A) production modes because the relevant couplings are the same*): $C_F(H)=\sin\alpha/\sin\beta$, $C_U(A)=-C_D(A)=\cot\beta$
- Overall, gg→X is always at least two orders of magnitude larger than bbX

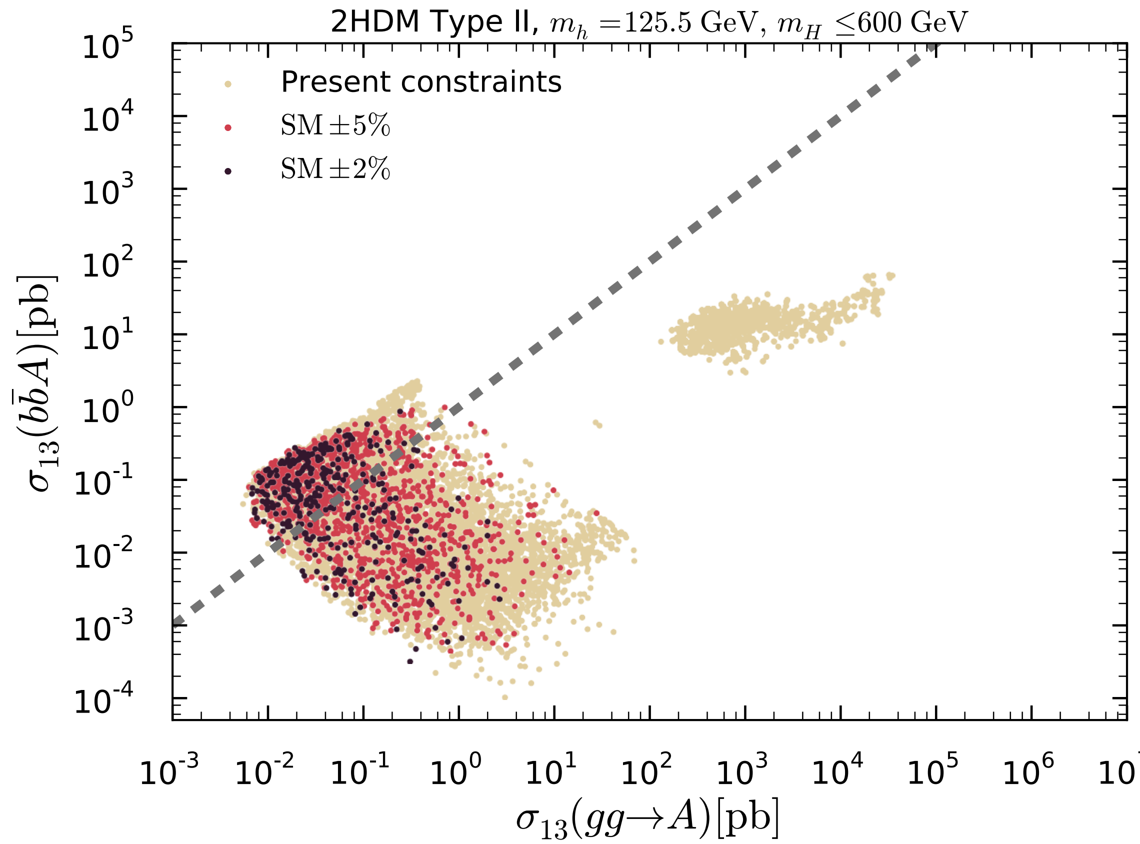
*) up to a sign in case of the A

H and A production at 13 TeV

most important channels:
gluon-gluon fusion and bb associated production

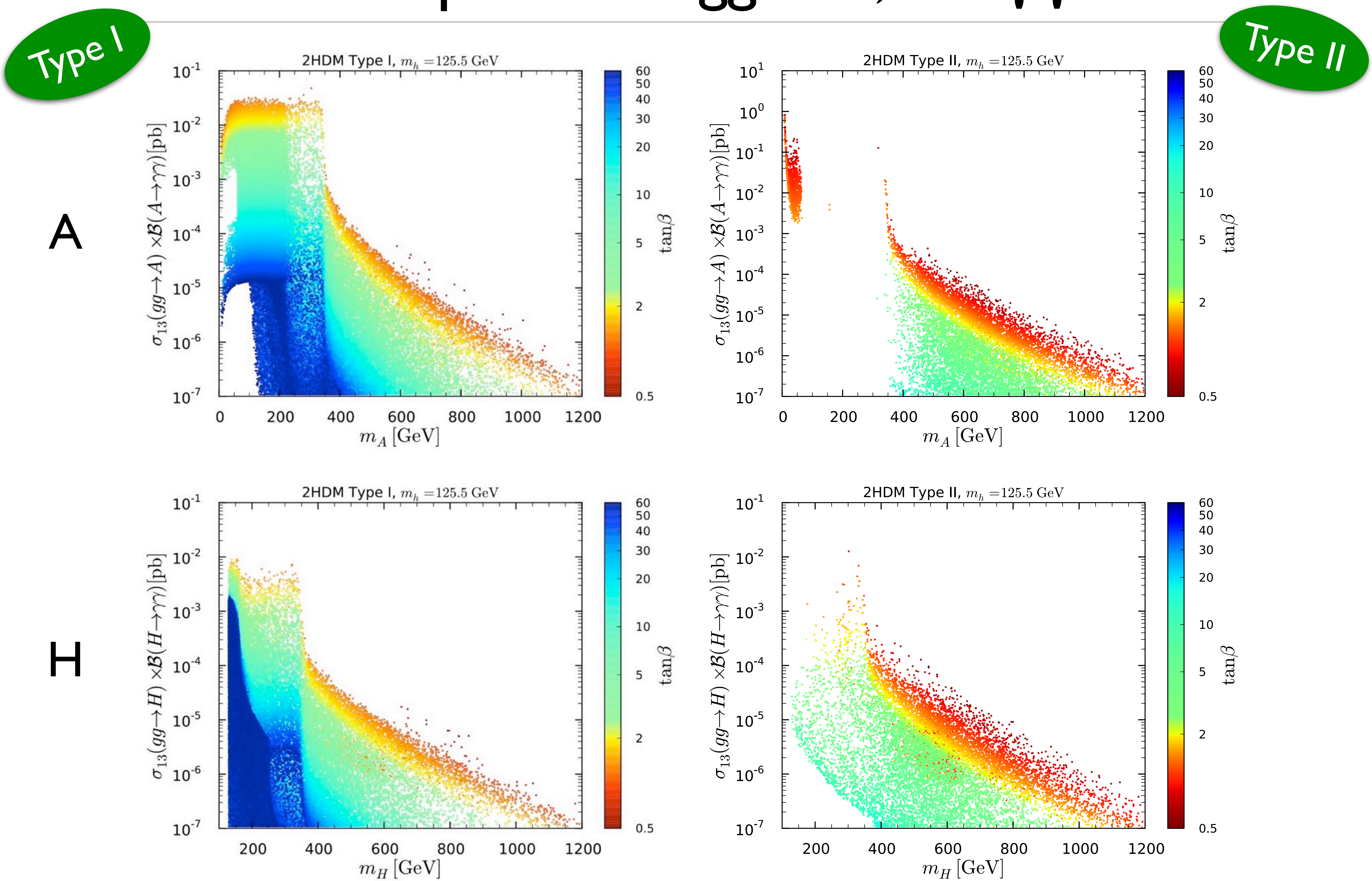
Type II





- Either gg→X or bbX (X=H,A) production can be dominant in different regions of the parameter space.
- Reason is the structure of couplings to fermions, e.g. $C_U(A)$= cotβ=1/$C_D(A)$.
- Minimal cross sections much larger than in Type I, quite promising for direct search.

Prospects for gg→H,A→γγ

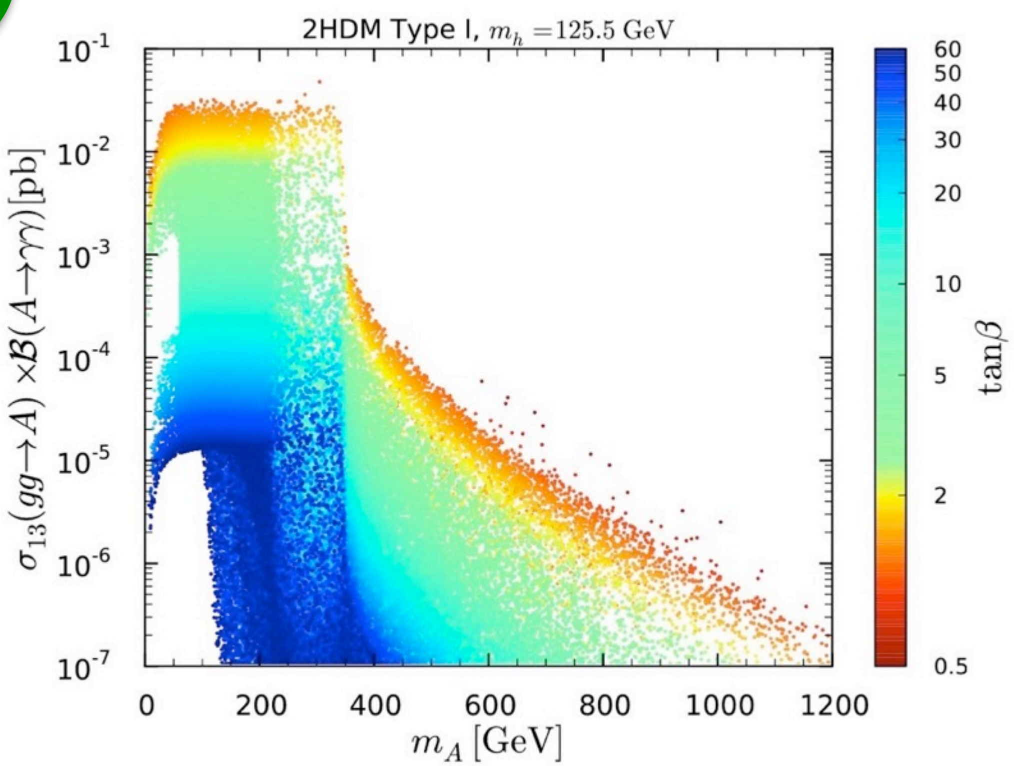


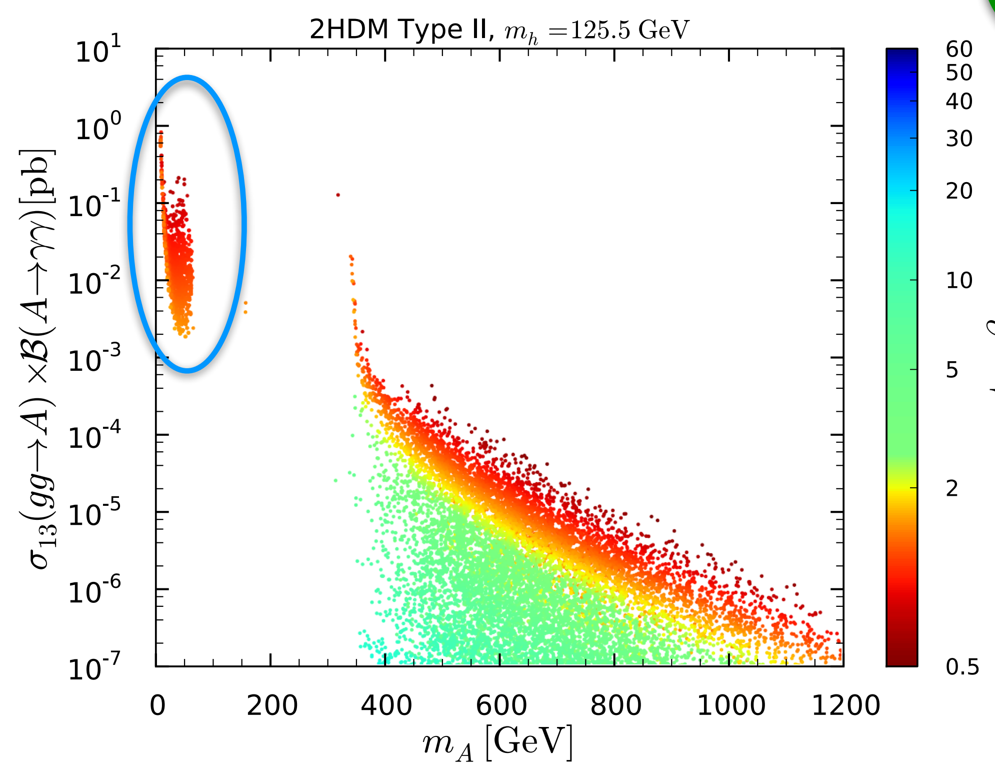
Prospects for gg→H,A→γγ

Type I

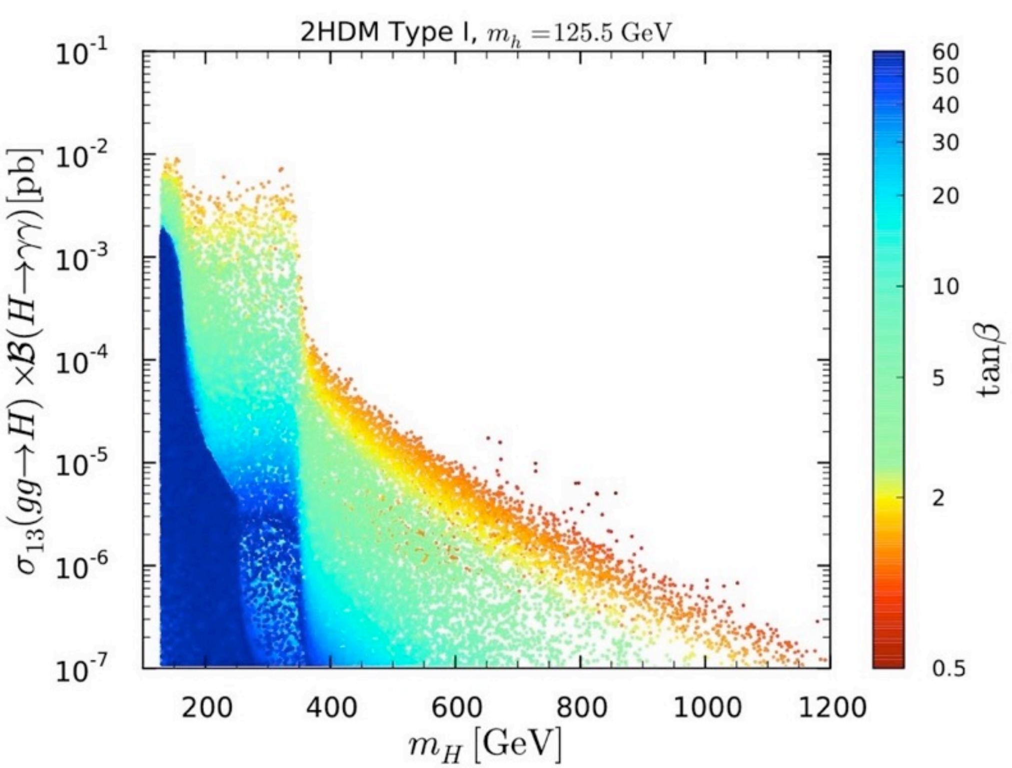
Type II

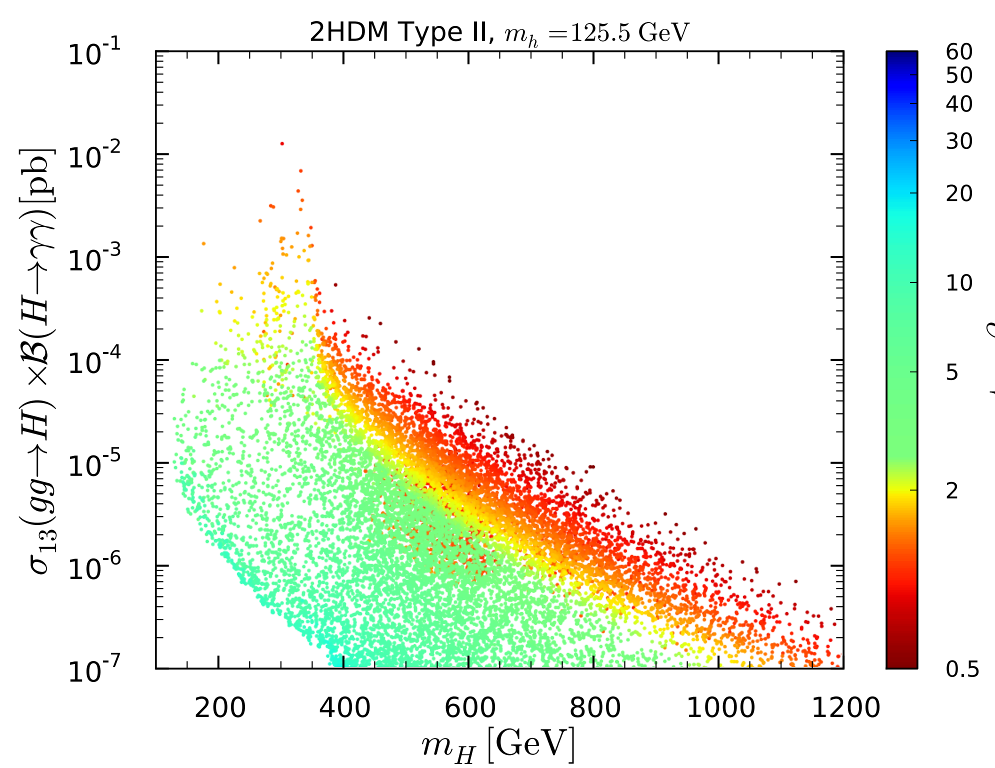
A





H



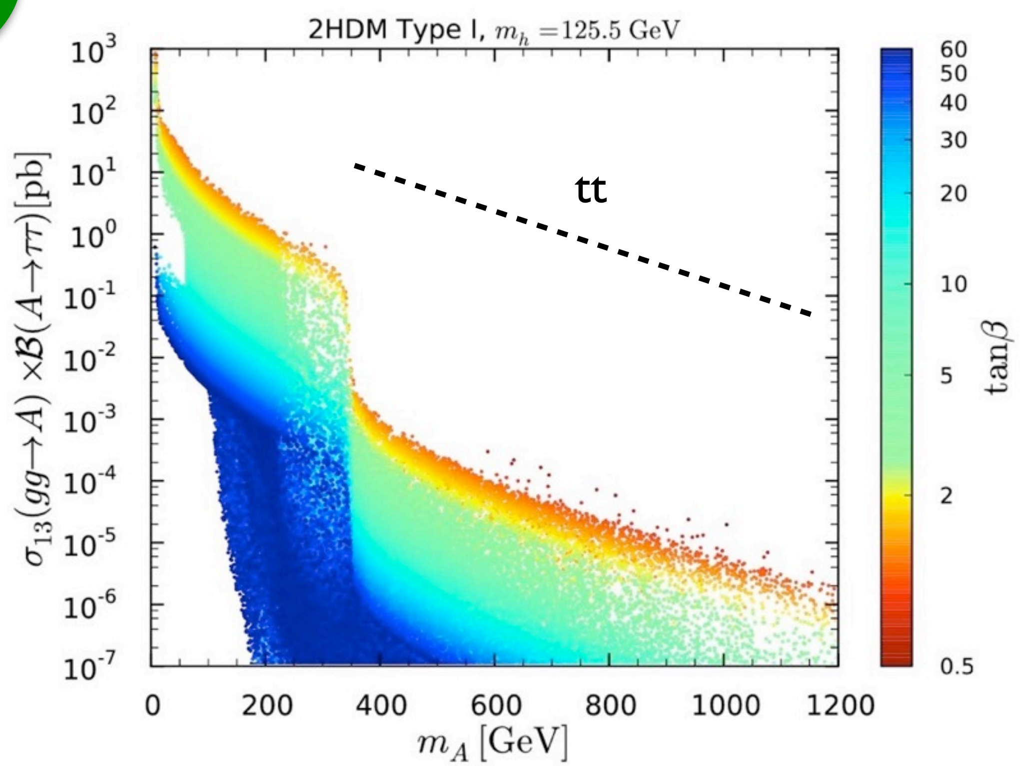


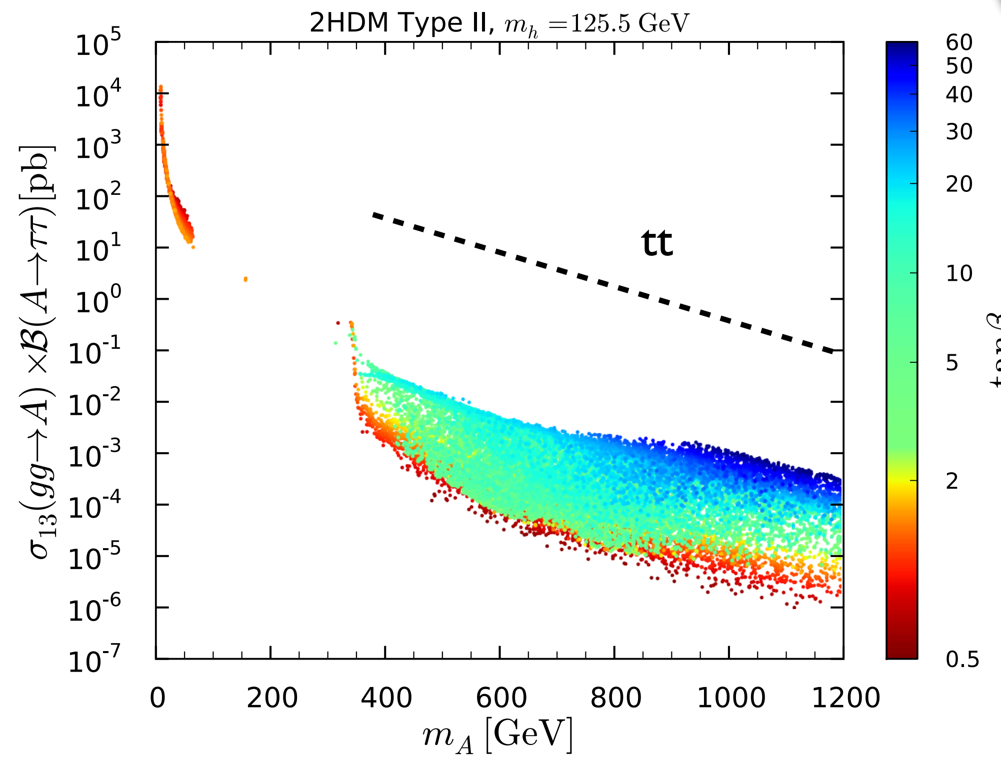
Prospects for gg→H,A→ττ

Type I

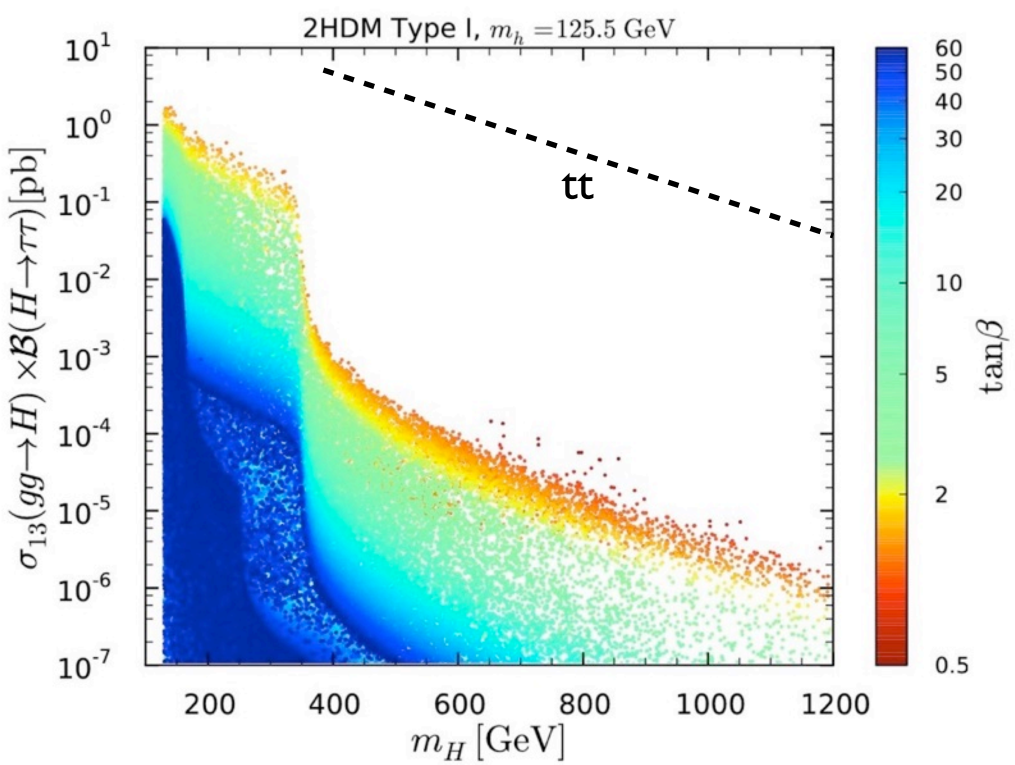
Type II

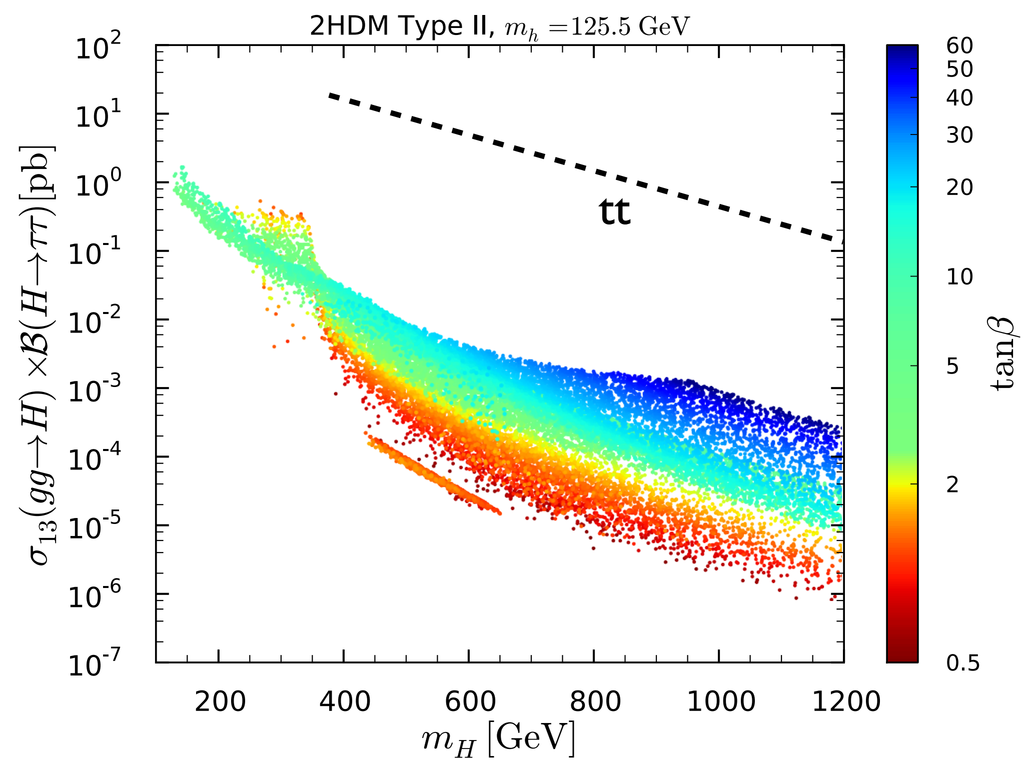
A





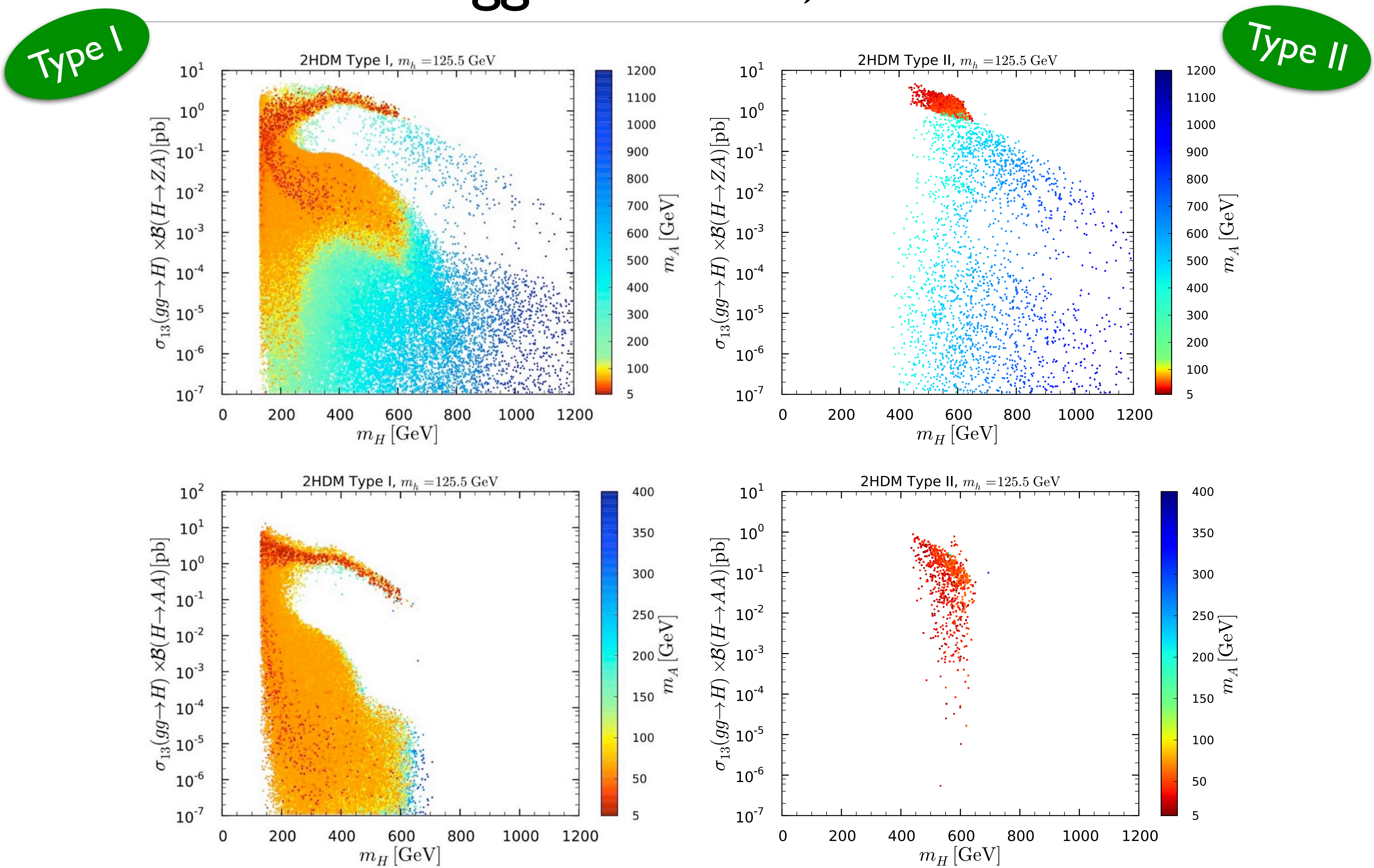
H





`Exotic' modes can have O(pb) XS

gg→H→ZA, AA

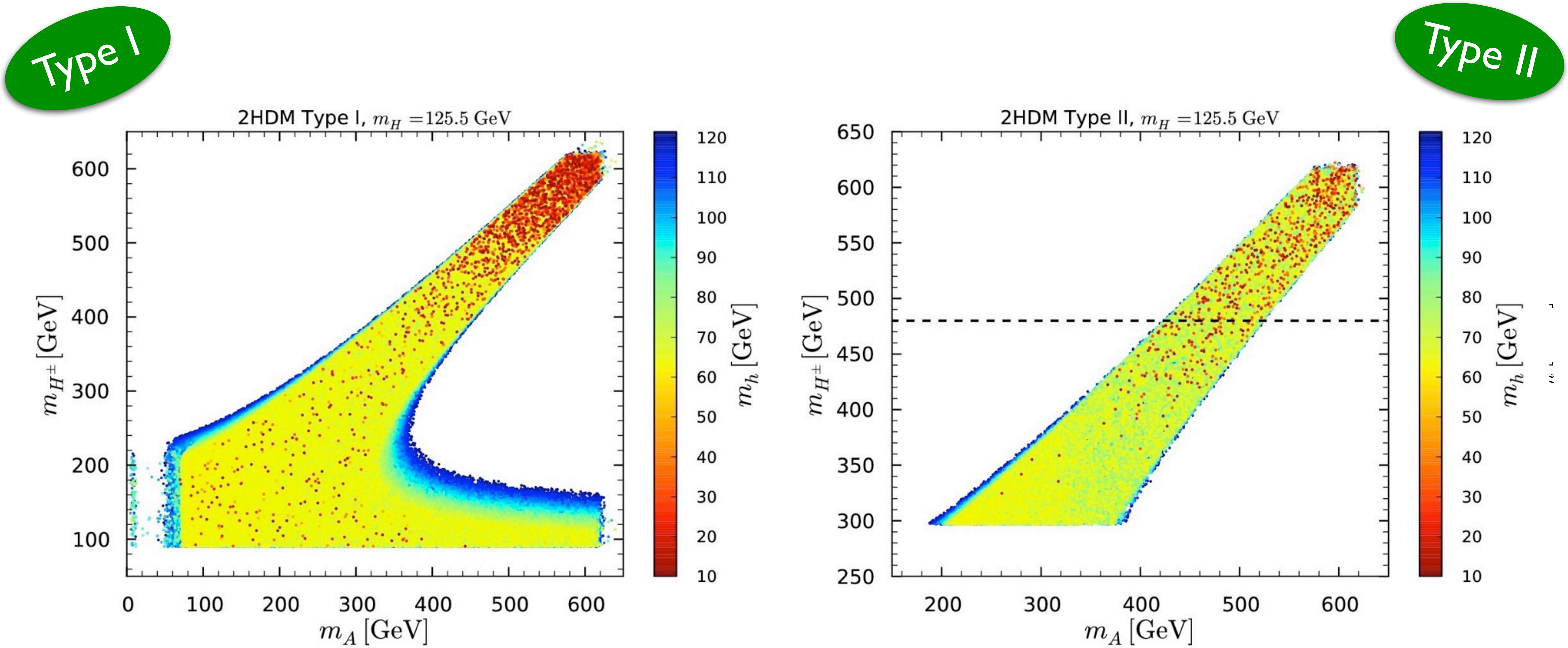


Case 2: m_H = 125 GeV

$\cos(\beta-\alpha) \geq 0.99$

arXiv:1511.03682

Parameter space



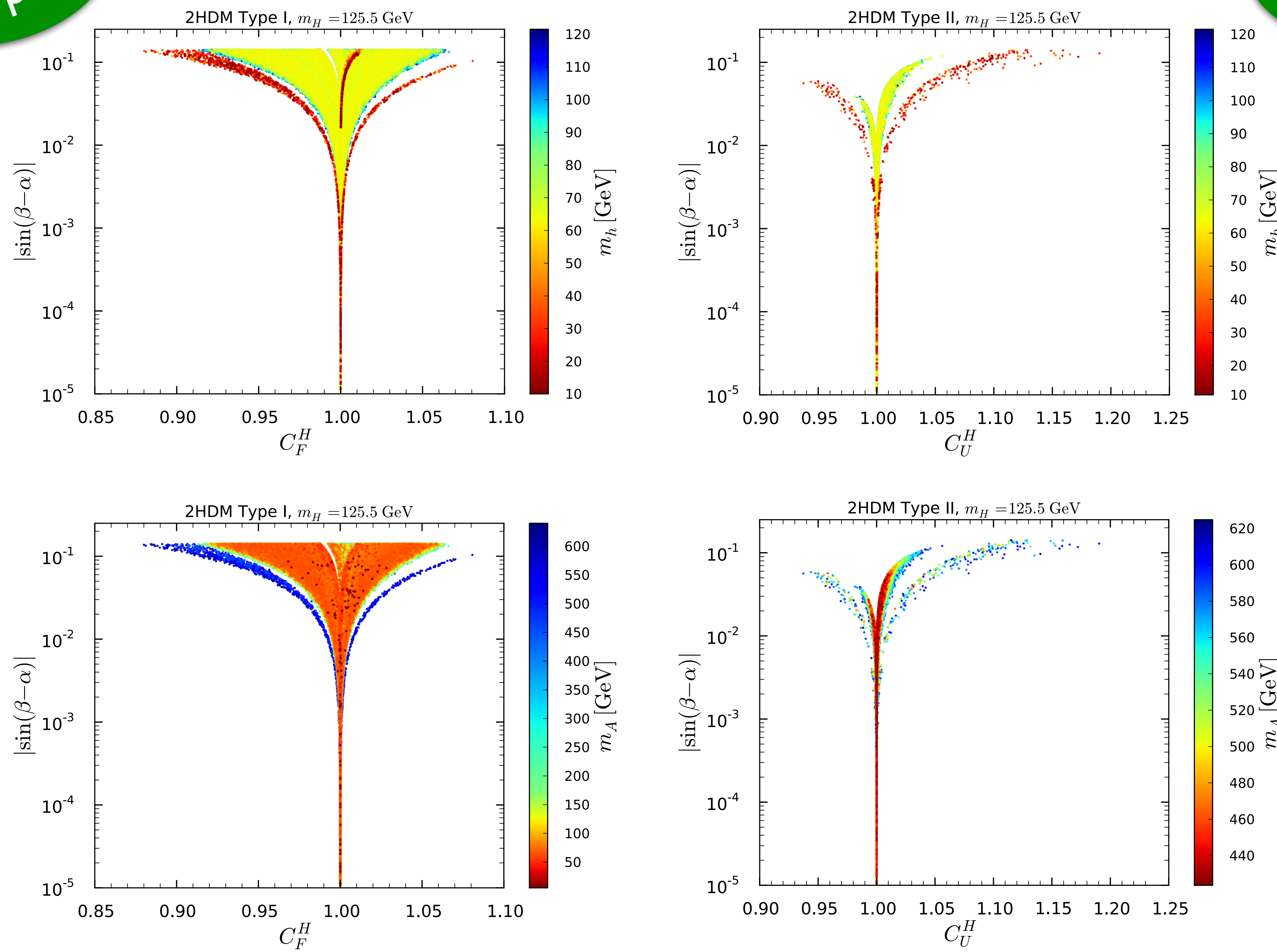
mass splittings constrained by T parameter

definite upper limit on A and $H^{\pm}$ masses of about 640 GeV

Couplings of the 125 GeV state: $C_{F,U}$

Type I

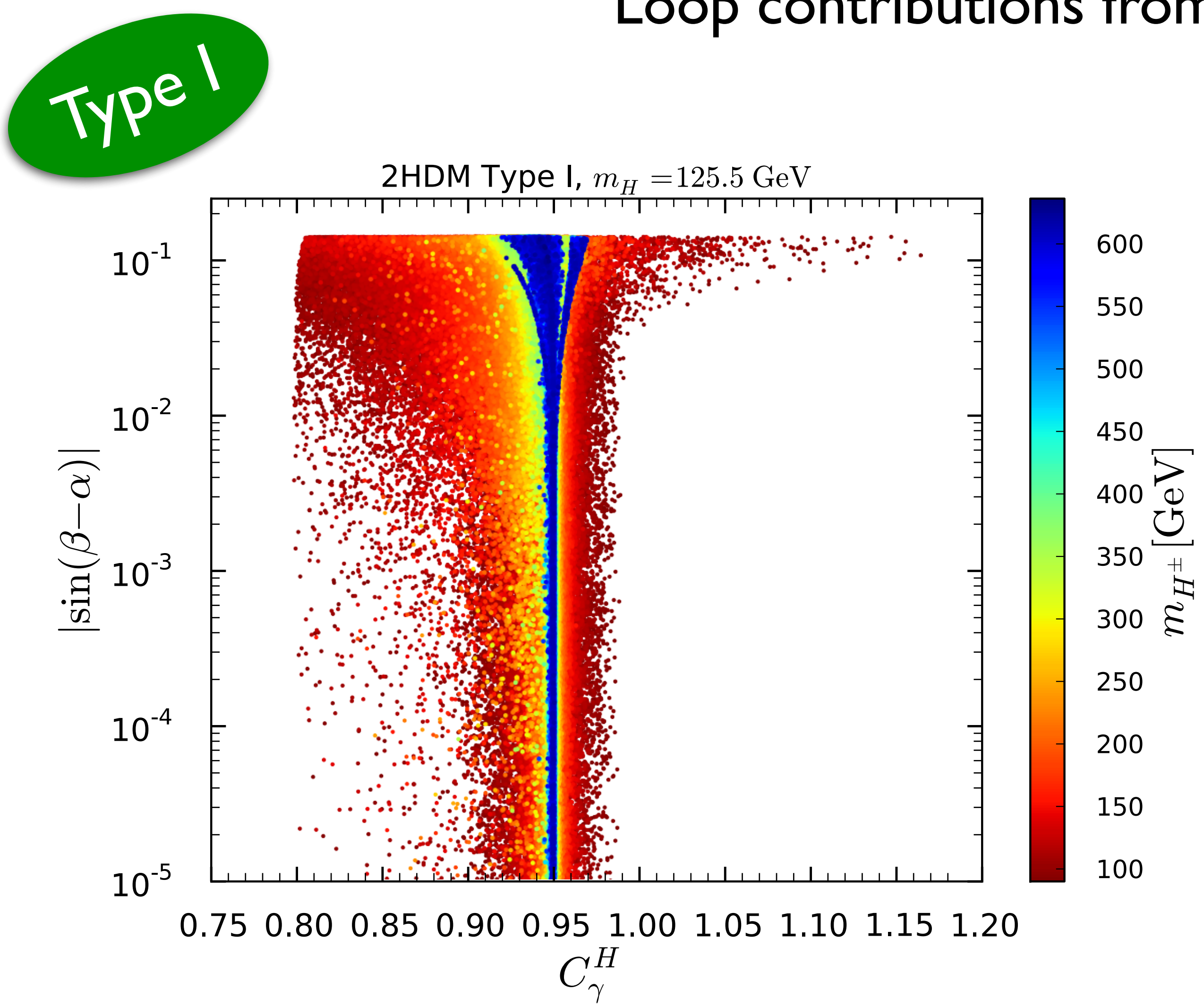
Type II

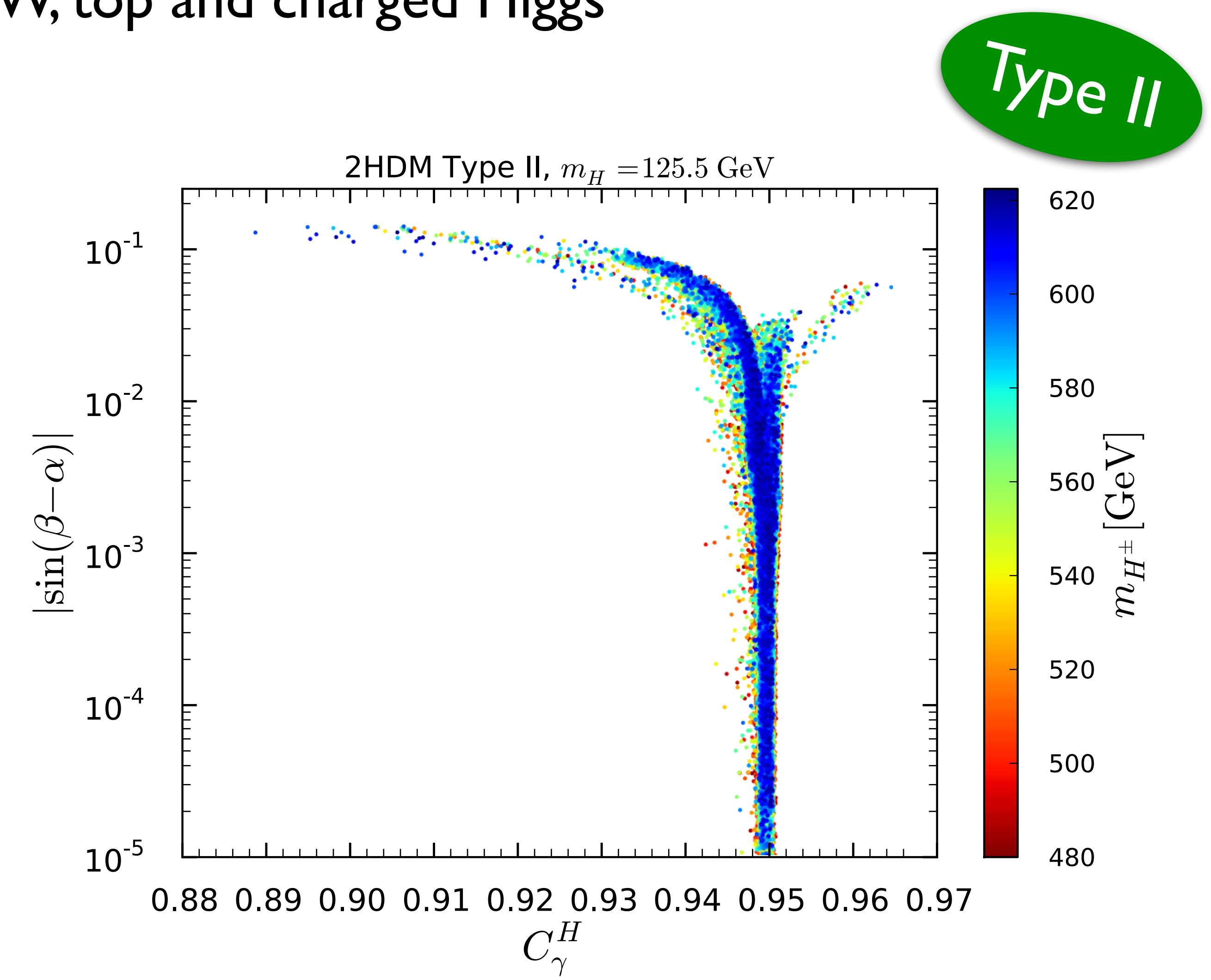


Deviations up to -15% in Type I, +20% in Type II for large h-A mass splitting (tanβ~1)

Coupling to photons: C_γ

Loop contributions from W, top and charged Higgs



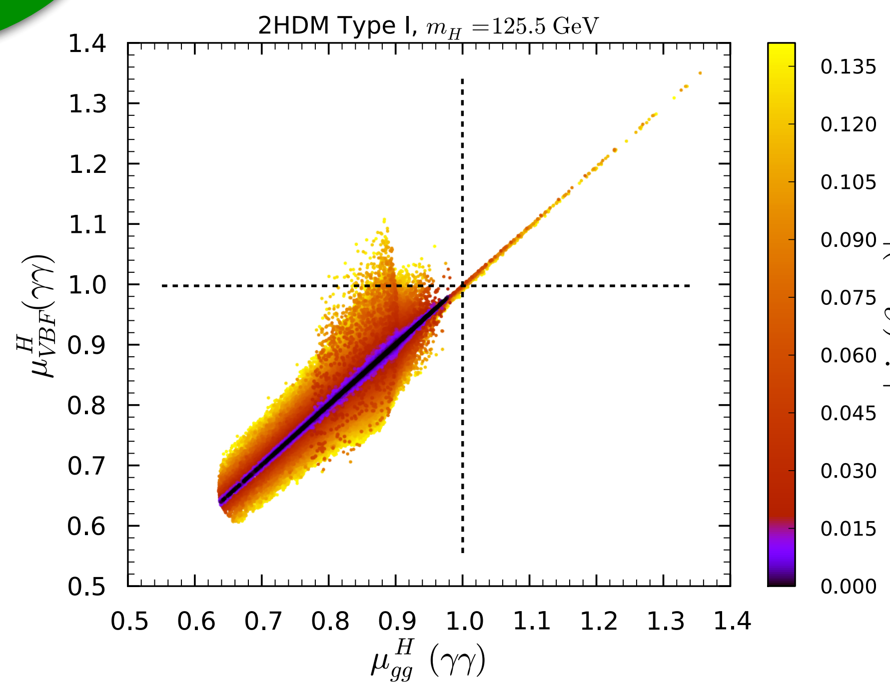


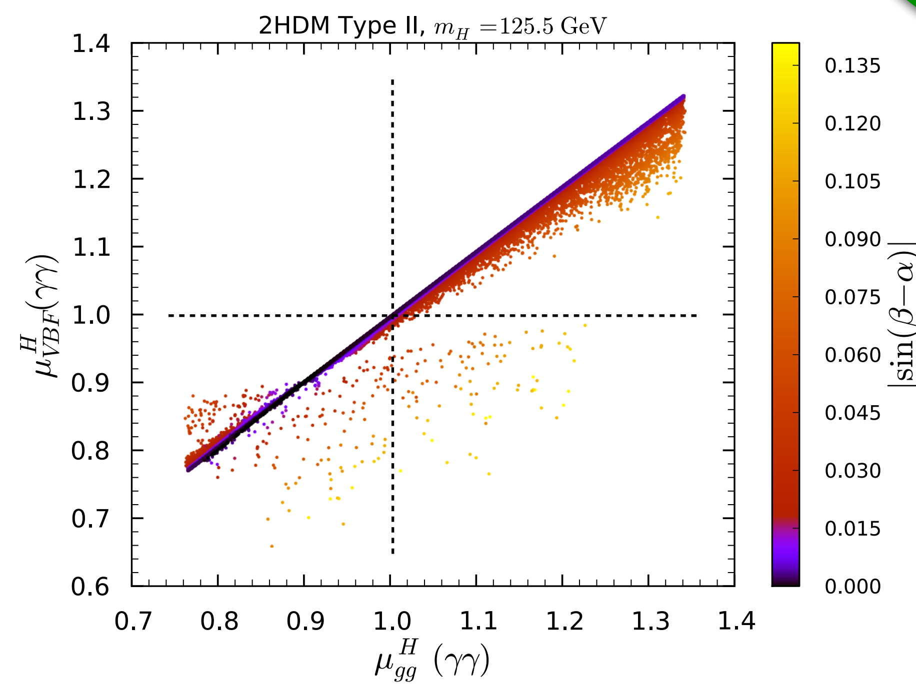
Does not align to unity:
Large deviations for a light charged Higgs even in deep alignment limit (Type I)
~5% suppression in the limit of a `heavy' charged Higgs

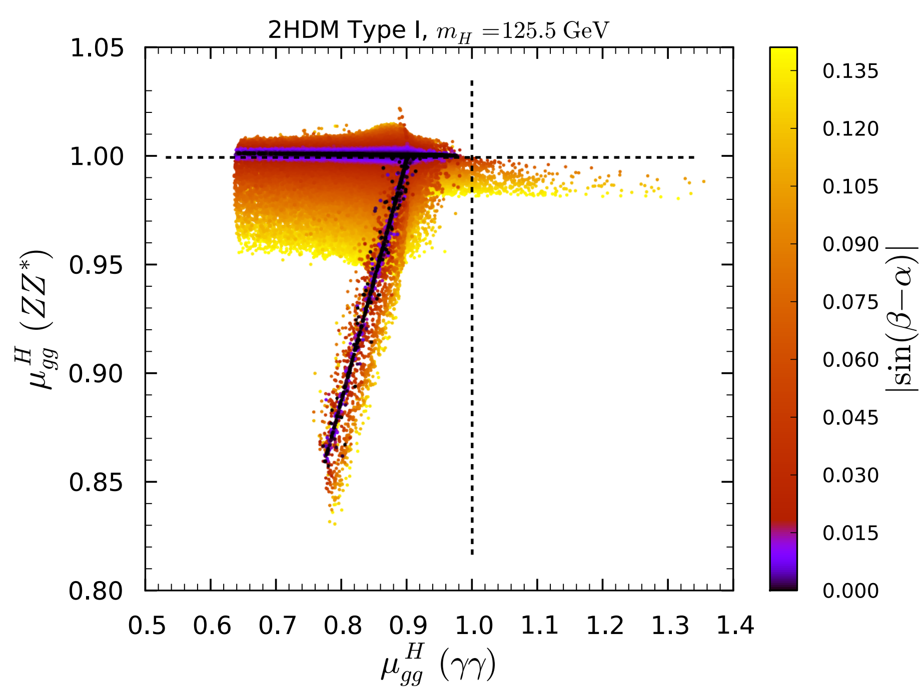
Signal strengths

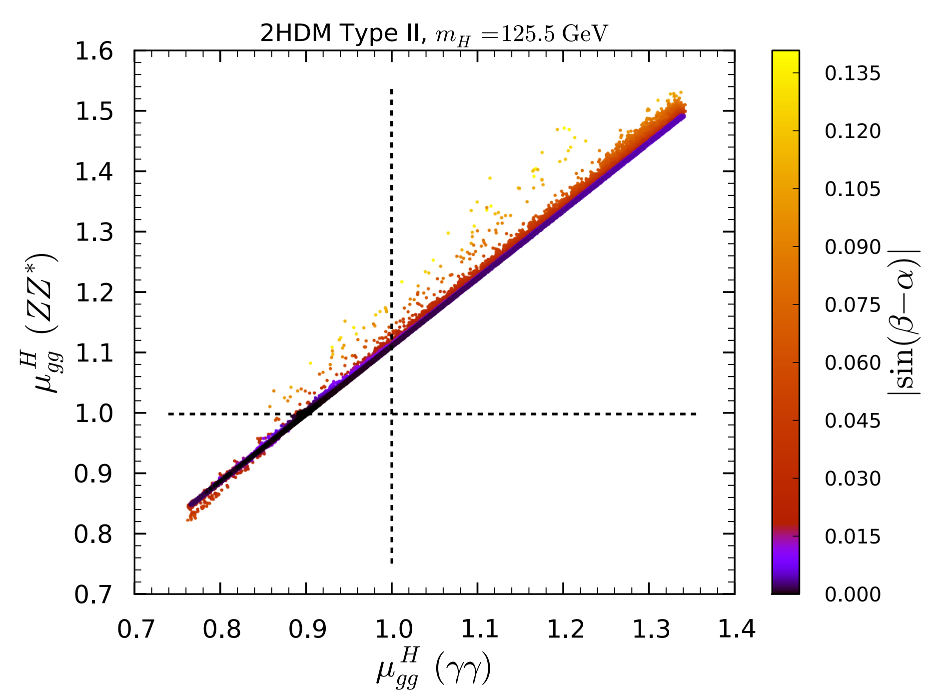
Type I

Type II







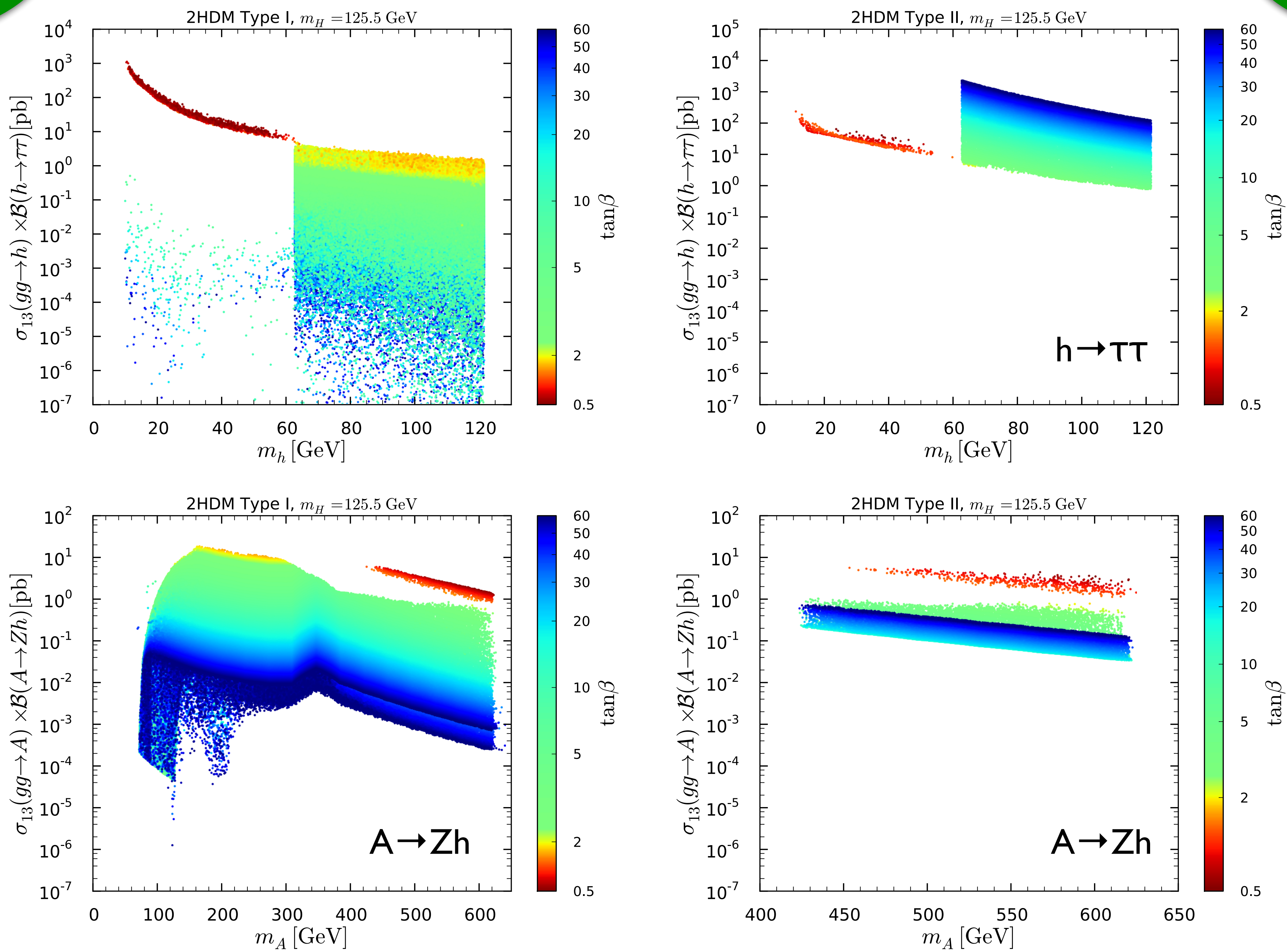


Again distinct correlations that distinguish Type I from Type II

Searches at 13 TeV: h→ττ and A→Zh

Type I

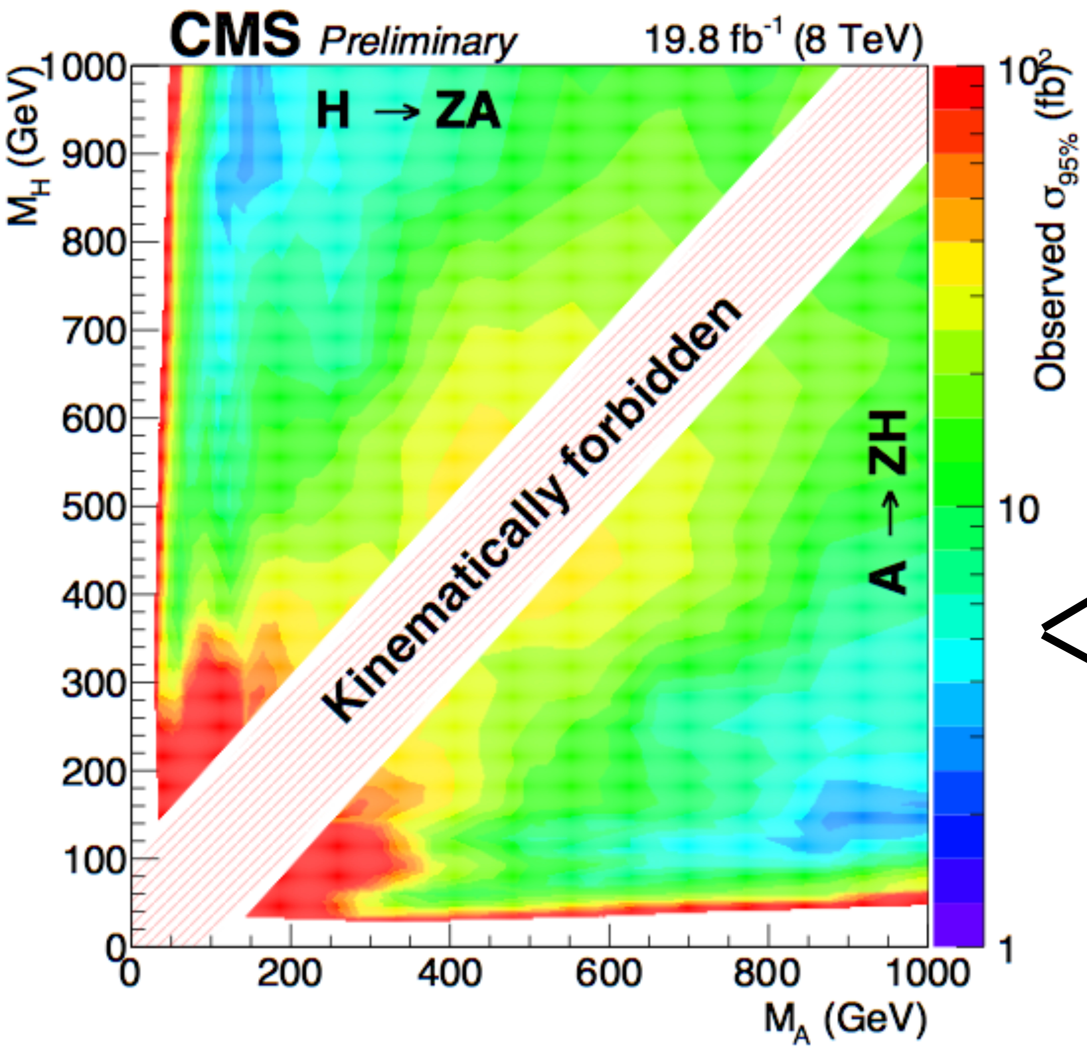
Type II



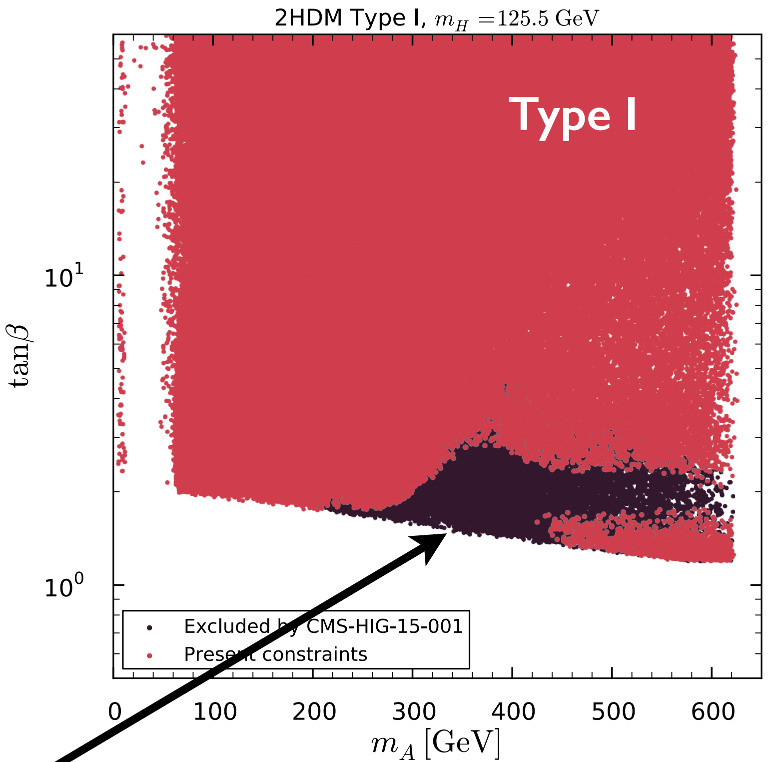
Note lower limit on cross section in Type II

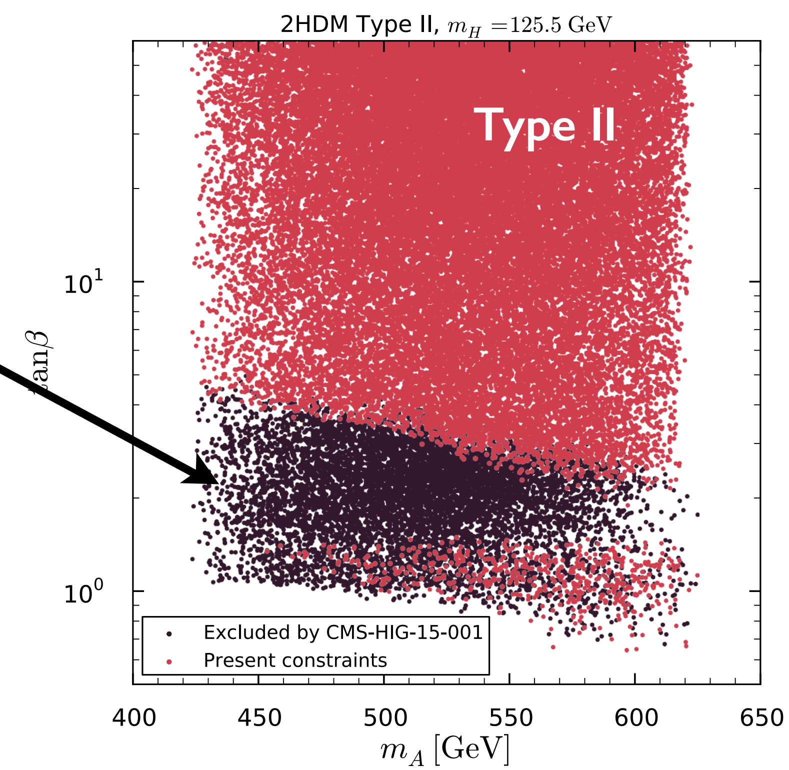
Impact of CMS limit on A→Zh

Search for H/A decaying into Z and A/H, with Z → ll and A/H → bb or A/H → τ τ

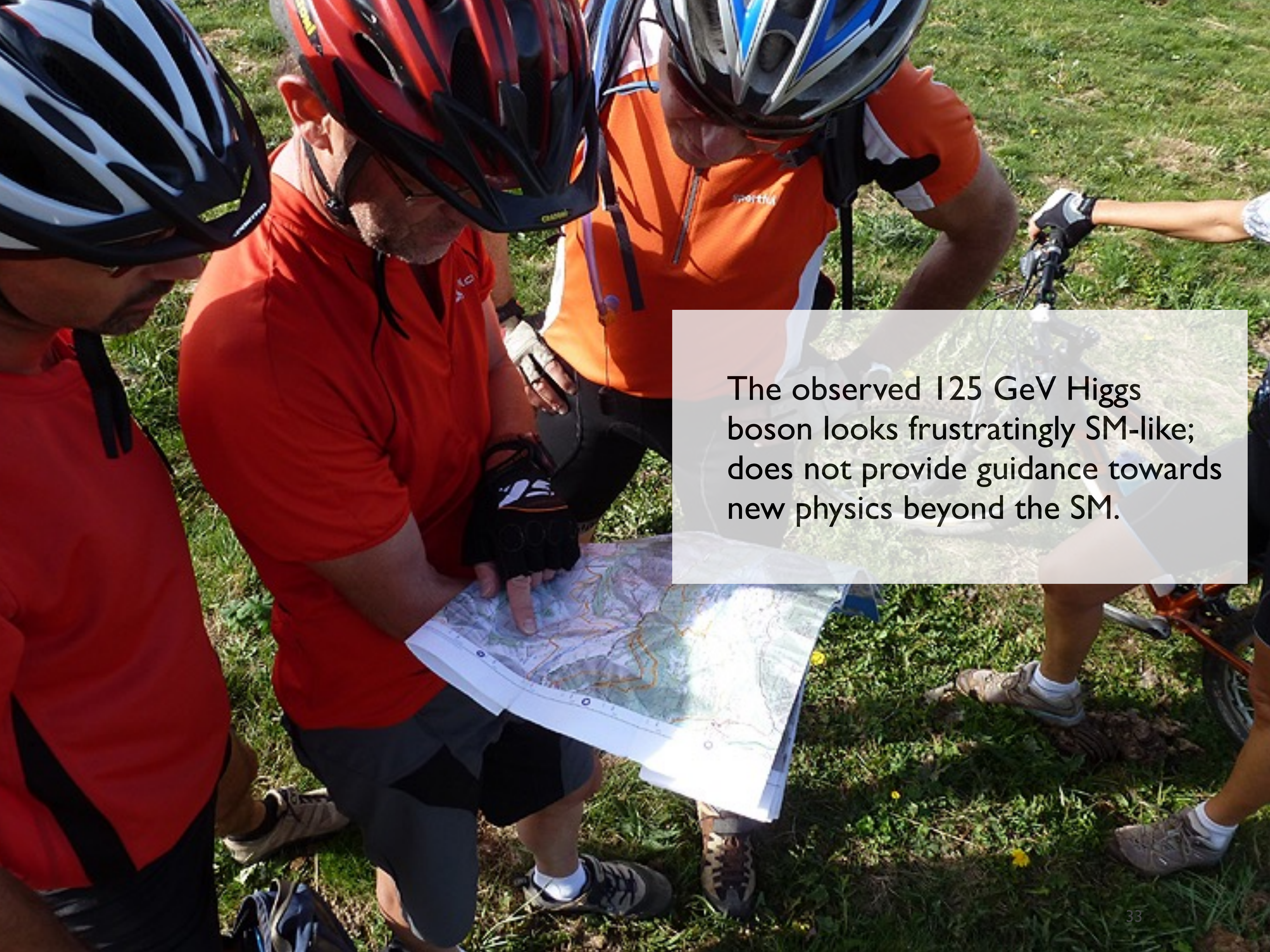


CMS-PAS-HIG-15-001

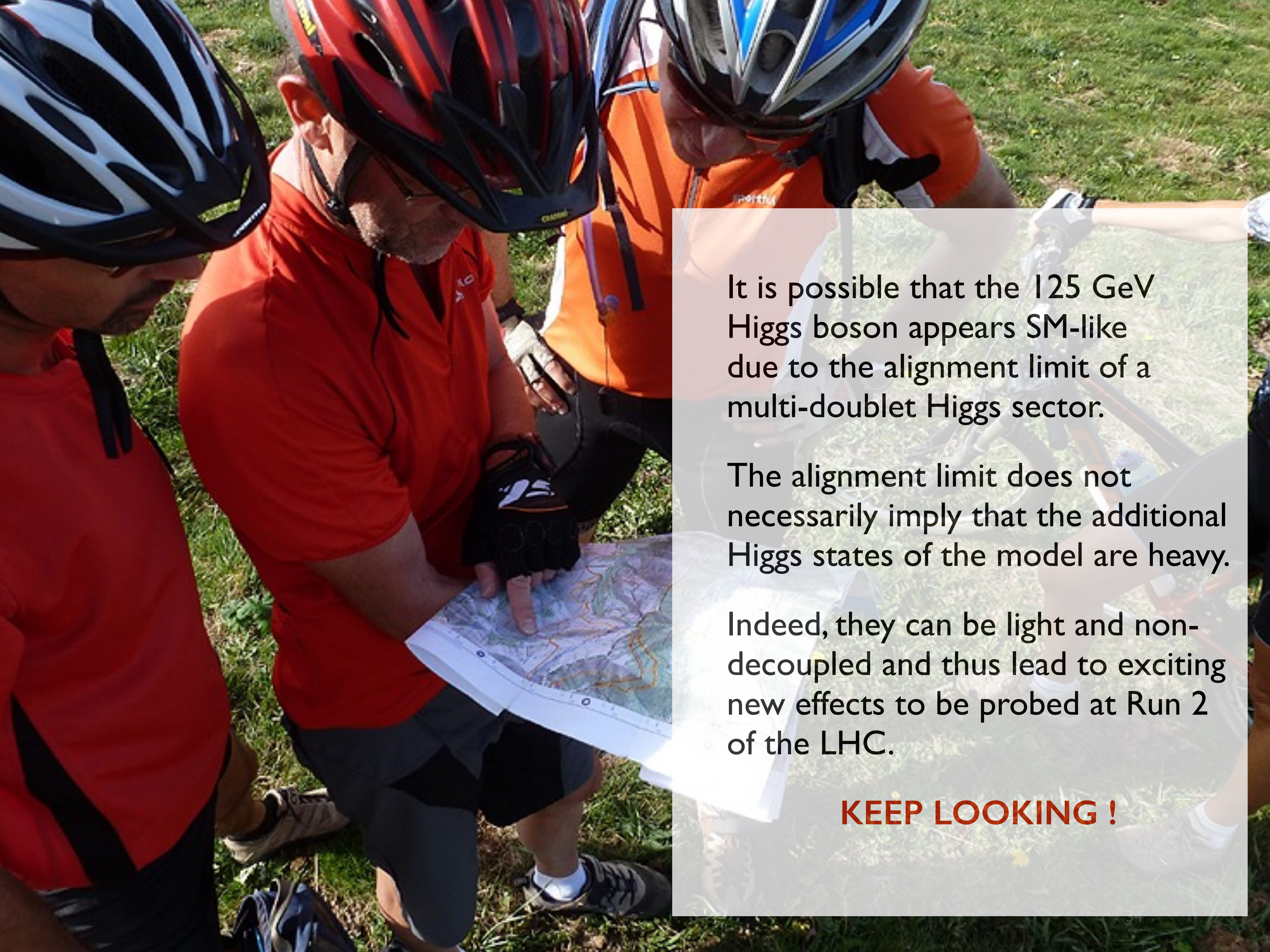




conclusions



The observed 125 GeV Higgs boson looks frustratingly SM-like; does not provide guidance towards new physics beyond the SM.



It is possible that the 125 GeV Higgs boson appears SM-like due to the alignment limit of a multi-doublet Higgs sector.

The alignment limit does not necessarily imply that the additional Higgs states of the model are heavy.

Indeed, they can be light and non-decoupled and thus lead to exciting new effects to be probed at Run 2 of the LHC.

KEEP LOOKING !

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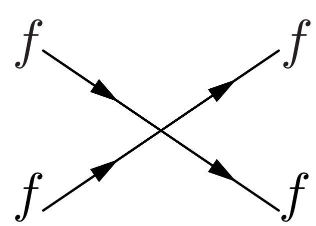
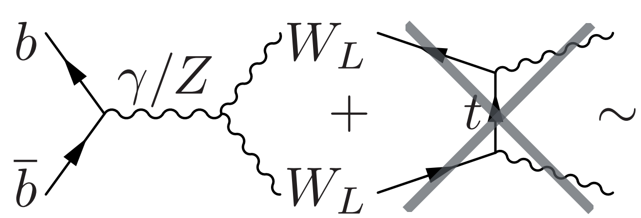
No more no-loose theorem

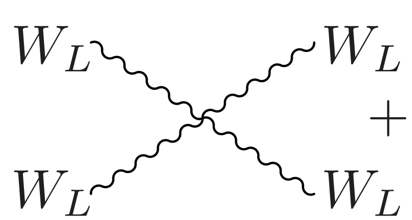
Guaranteed discoveries in the history of HEP (unitarity of scattering amplitudes):



$\sim G_F E^2 \simeq E^2/v^2 < 16\pi^2 \longrightarrow m_W < 4\pi v$



$\sim g_W^2 E^2/m_W^2 < 16\pi^2 \longrightarrow m_t < 4\pi v$



$+ \ldots \sim g_W^2 E^2/m_W^2 < 16\pi^2 \longrightarrow m_H < 4\pi v$

from A. Wulzer, 1510.05159

The Higgs discovery completes the SM — and leaves us without any no-loose theorem to exploit for future discoveries.

Two Higgs Doublet Model (*Z_2* basis)

2HDM: SM supplemented by a second Y=+1 complex scalar.

The most general gauge invariant renormalizable scalar potential is given by

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

- Softly-broken discrete Z_2 symmetry to avoid tree-level Higgs-mediated FCNCs $\Phi_1 \to +\Phi_1$ and $\Phi_2 \to -\Phi_2$. Then $\lambda_6=\lambda_7=0$.
- Take m_{12}^2 and λ_5 to be real : scalar potential is CP-conserving

$$\langle\Phi_i\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} \mathbf{0} \\ \boldsymbol{v_i} \end{pmatrix}$$

<u>Minimum conditions</u>

$$m_{11}^2 = m_{12}^2 \tan\beta - \frac{1}{2}v^2\left(\lambda_1\cos^2\beta + \lambda_{345}\sin^2\beta\right) ,$$

$$m_{22}^2 = m_{12}^2 \cot\beta - \frac{1}{2}v^2\left(\lambda_2\sin^2\beta + \lambda_{345}\cos^2\beta\right) ,$$

$$\lambda_{345} \equiv \lambda_3 + \lambda_4 + \lambda_5 , \qquad \tan\beta \equiv \frac{v_2}{v_1} , \qquad v^2 \equiv v_1^2 + v_2^2 = \frac{4M_W^2}{g^2} = (246\ \mathrm{GeV})^2 .$$

Physical Higgs states

Of originally eight scalar degrees of freedom, three Goldstone bosons ($G^\pm$ and G^0) are absorbed by the $W^\pm$ and Z^0. Thus remain five physical Higgs particles:

h, H, A, H$^\pm$

CP-even (h, H) CP-odd (A) charged ($H^\pm$)

with

$$m_A^2 = 2\, m_{12}^2/\sin 2\beta - \lambda_5 v^2\,, \qquad m_{H^\pm}^2 = m_A^2 + \frac{1}{2}v^2(\lambda_5 - \lambda_4)\,,$$

and the mass^2 matrix for the two neutral CP-even states

$$\mathcal{M}^2 \equiv \begin{pmatrix} \lambda_1 v^2 c_\beta^2 + (m_A^2 + \lambda_5 v^2) s_\beta^2 & \left[\lambda_{345} v^2 - (m_A^2 + \lambda_5 v^2)\right] s_\beta c_\beta \\ \left[\lambda_{345} v^2 - (m_A^2 + \lambda_5 v^2)\right] s_\beta c_\beta & \lambda_2 v^2 s_\beta^2 + (m_A^2 + \lambda_5 v^2) c_\beta^2 \end{pmatrix}$$

$$H = (\sqrt{2}\mathrm{Re}\,\Phi_1^0 - v_1)c_\alpha + (\sqrt{2}\mathrm{Re}\,\Phi_2^0 - v_2)s_\alpha\,,$$
$$h = -(\sqrt{2}\mathrm{Re}\,\Phi_1^0 - v_1)s_\alpha + (\sqrt{2}\mathrm{Re}\,\Phi_2^0 - v_2)c_\alpha\,,$$

$$\begin{pmatrix} m_H^2 & 0 \\ 0 & m_h^2 \end{pmatrix} = \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} \mathcal{M}_{11}^2 & \mathcal{M}_{12}^2 \\ \mathcal{M}_{12}^2 & \mathcal{M}_{22}^2 \end{pmatrix} \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix}$$

with $m_h < m_H$ per def.

Couplings to fermions

The most general renormalizable Yukawa couplings for the 2HDM are

$$-\mathcal{L}_{\text{Yuk}} = \mathcal{Y}_b^1 \bar{b}_R \Phi_1^{i\,*} Q_L^i + \mathcal{Y}_b^2 \bar{b}_R \Phi_2^{i\,*} Q_L^i + \mathcal{Y}_\tau^1 \bar{\tau}_R \Phi_1^{i\,*} L_L^i + \mathcal{Y}_\tau^2 \bar{\tau}_R \Phi_2^{i\,*} L_L^i \\ + \epsilon_{ij} \left[\mathcal{Y}_t^1 \bar{t}_R Q_L^i \Phi_1^j + \mathcal{Y}_t^2 \bar{t}_R Q_L^i \Phi_2^j \right] + \text{h.c.}\,,$$

where $\boldsymbol{\epsilon_{12} = -\epsilon_{21} = 1}$, $\boldsymbol{\epsilon_{11} = \epsilon_{22} = 0}$, $\boldsymbol{Q_L = (t_L\,,\, b_L)}$ and $\boldsymbol{L_L = (\nu_L\,,\, e_L)}$

To avoid tree-level Higgs-mediated FCNCs, we extend the Z_2 symmetry to Yukawa sector

Four possible Z_2 charge assignments

	Φ_1	Φ_2	t_R	b_R	τ_R	t_L, b_L, ν_L, e_L
Type I	+	−	−	−	−	+
Type II	+	−	−	+	+	+
Type X (lepton specific)	+	−	−	−	+	+
Type Y (flipped)	+	−	−	+	−	+

Couplings to fermions

The most general renormalizable Yukawa couplings for the 2HDM are

$$-\mathcal{L}_{\rm Yuk} = \mathcal{Y}_b^1 \overline{b}_R \Phi_1^{i\,*} Q_L^i + \mathcal{Y}_b^2 \overline{b}_R \Phi_2^{i\,*} Q_L^i + \mathcal{Y}_\tau^1 \overline{\tau}_R \Phi_1^{i\,*} L_L^i + \mathcal{Y}_\tau^2 \overline{\tau}_R \Phi_2^{i\,*} L_L^i$$
$$+ \epsilon_{ij} \left[\mathcal{Y}_t^1 \overline{t}_R Q_L^i \Phi_1^j + \mathcal{Y}_t^2 \overline{t}_R Q_L^i \Phi_2^j \right] + \text{h.c.}\,,$$

where $\boldsymbol{\epsilon_{12} = -\epsilon_{21} = 1}$, $\boldsymbol{\epsilon_{11} = \epsilon_{22} = 0}$, $\boldsymbol{Q_L = (t_L\,,\, b_L)}$ and $\boldsymbol{L_L = (\nu_L\,,\, e_L)}$

To avoid tree-level Higgs-mediated FCNCs, we extend the Z_2 symmetry to Yukawa sector

Four possible Z_2 charge assignments

	Φ_1	Φ_2	t_R	b_R	τ_R	t_L, b_L, ν_L, e_L
Type I	$+$	$-$	$-$	$-$	$-$	$+$
Type II	$+$	$-$	$-$	$+$	$+$	$+$
Type X (lepton specific)	$+$	$-$	$-$	$-$	$+$	$+$
Type Y (flipped)	$+$	$-$	$-$	$+$	$-$	$+$

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$$\text{Type I:} \quad \mathcal{Y}_t^1 = \mathcal{Y}_b^1 = \mathcal{Y}_\tau^1 = 0\,,$$
$$\text{Type II:} \quad \mathcal{Y}_t^1 = \mathcal{Y}_b^2 = \mathcal{Y}_\tau^2 = 0\,.$$

(

Lilith

a tool for constraining new physics from Higgs measurements
(**Li**ght **Li**kelihood Fi**t** for the **H**iggs)

J. Bernon, B. Dumont, 1502.04138

http://lpsc.in2p3.fr/projects-th/lilith

About Lilith

- Lilith is a light and easy to use Python tool to determine the likelihood of a generic 125 GeV Higgs boson from the latest experimental data.

- Written by my students **Beranger Dumont** and **Jeremy Bernon** based on our work on fitting the Higgs data.
    - *Higgs couplings at the end of 2012*, G. Belanger et al., arXiv:1212.5244
    - *Global fit to Higgs signal strengths and couplings and implications for extended Higgs sectors*, G. Belanger et al., arXiv:1306.2941
    - *Phenomenological MSSM in view of the 125 GeV Higgs data*, B. Dumont, J.F. Gunion, SK, arXiv:1312.7027
    - *Status of Higgs couplings after Run 1 of the LHC*, J. Bernon, B. Dumont, SK, arXiv:1409.1588 ← **Lilith**

old-fashioned Fortran code

- The experimental results used are the the signal strenghts in the pure Higgs production modes as published by ATLAS and CMS (and Tevatron exp's).

- All experimental data are stored in a flexible XML database (easy to maintain); Lilith-1.0.1 includes the latest ATLAS $H \to \tau\tau$, $H \to WW$, $VH \to Vbb$ results.

- Public tool; can conveniently be used to fit the Higgs couplings and/or put constraints on theories beyond the Standard Model.

Usage: reduced couplings mode

```xml
<?xml version="1.0"?>

<lilithinput>

<mh>125.5</mh>

<reducedcouplings>
  <C to="tt">1.0</C> <!-- top quarks -->
  <C to="cc">1.0</C> <!-- charm quarks -->
  <C to="bb">1.0</C> <!-- bottom quarks -->
  <C to="tautau">1.0</C> <!-- tau leptons -->

  <C to="WW">1.0</C> <!-- vector bosons -->
  <C to="ZZ">1.0</C>

  <!-- optionnal: if not specified: SM contributions -->
  <C to="gammagamma">1.0</C>
  <C to="Zgamma">1.0</C>
  <C to="gg">1.0</C>
  <C to="VBF">1.0</C>

  <precision>BEST-QCD</precision>

</reducedcouplings>

<!-- optionnal: if not specified: SM -->
<extraBR>
  <BR type="invisible">0.0</BR>
  <BR type="undetected">0.0</BR>
</extraBR>

</lilithinput>
```

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  <BR type="undetected">0.0</BR>
</extraBR>

</lilithinput>
```

← precision of the calculation of gg→H, H→gg, H→gamma gamma and H→Zgamma

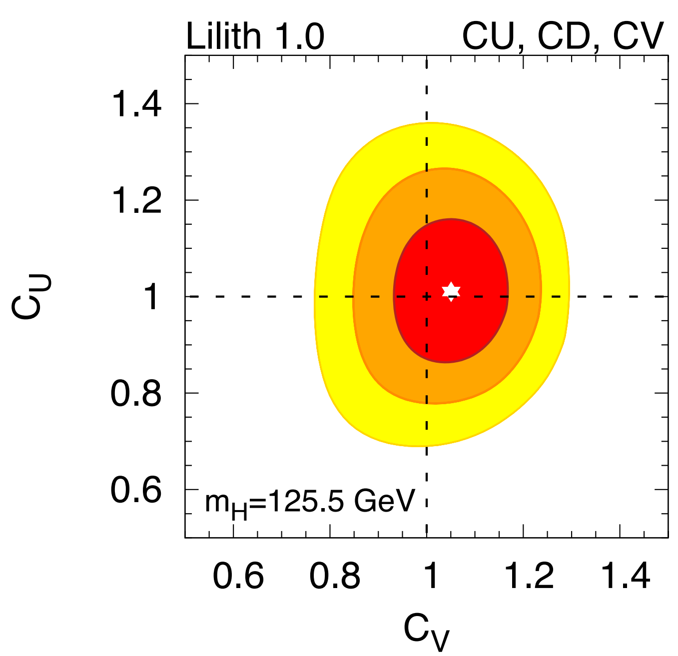
Calculation follows recommendations of LHC Higgs Cross Section Working Group

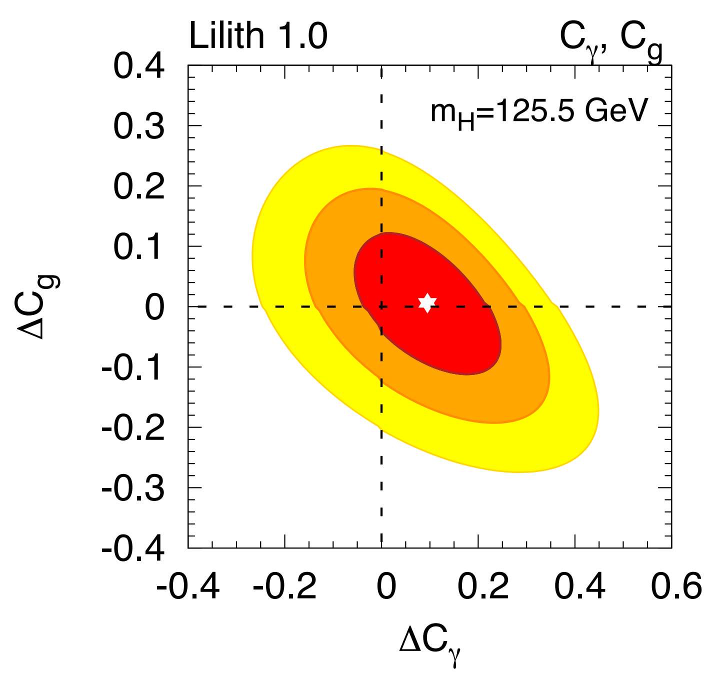
Output

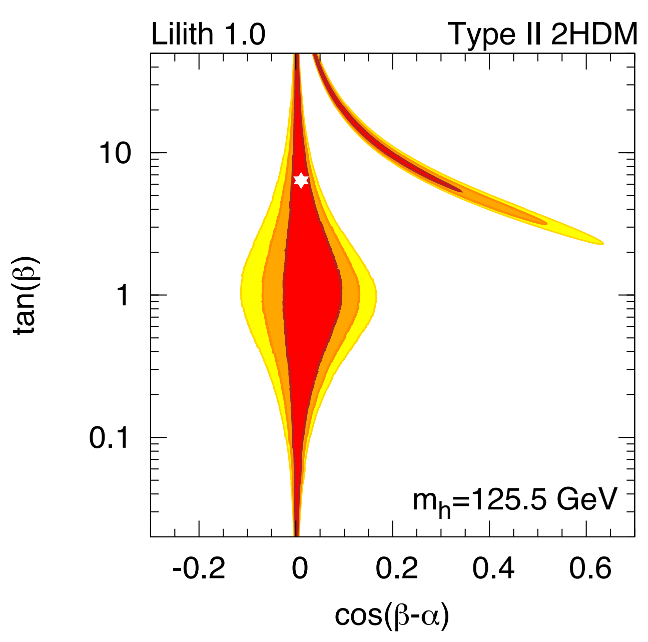
- Lilith returns the values of -2*Log(likelihood) and the number of degrees of freedom (=number of experimental results used) :

Running Lilith in a shell `<python lilith.py user_input_file>`

```
-----------------------
Lilith version 1.0.1
-----------------------
-2*log(L) = 13.111668
ndf = 26
```





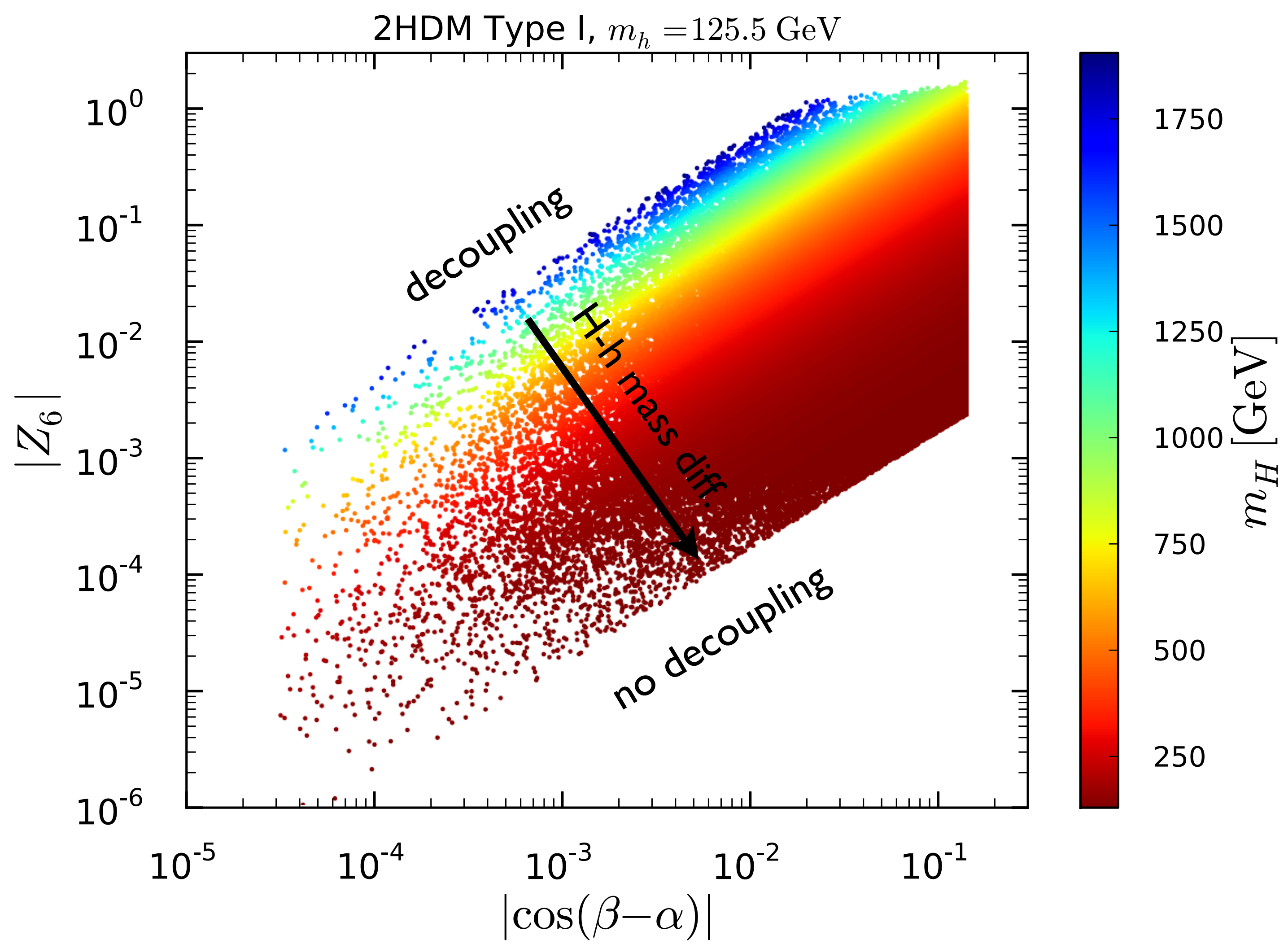


arXiv:1409.1588

)

Relation btw Z_6, cos(β-α) and m_H

Different ways to achieve alignment

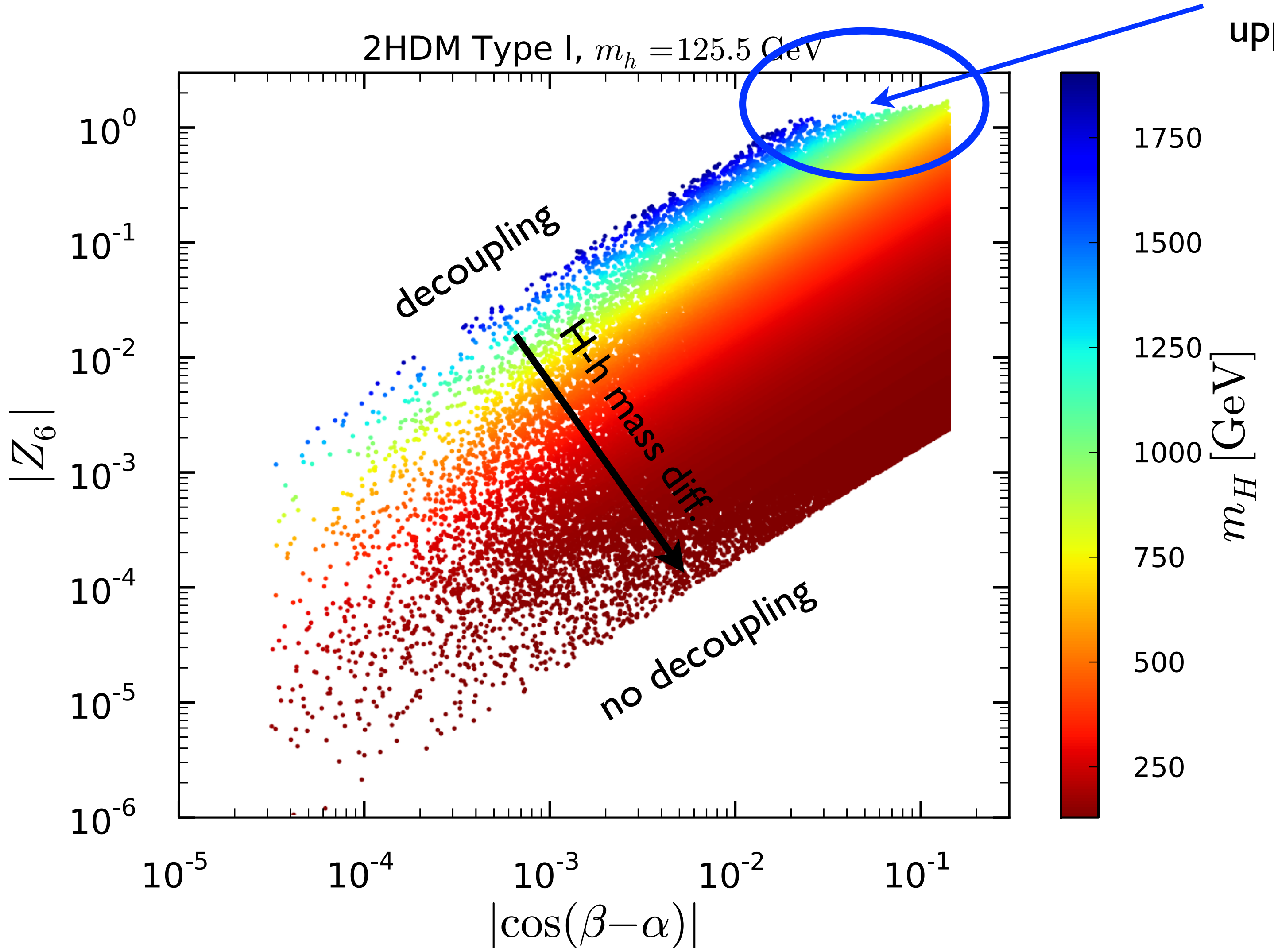


NB: in all plots, we give 3d information on a 2d plot by means of a color code in the third dimension.

Relation btw Z_6, cos(β-α) and m_H

Different ways to achieve alignment

decoupling limit implies an upper bound on cos(β-α)



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