The Alignment Limit in 2HDMs

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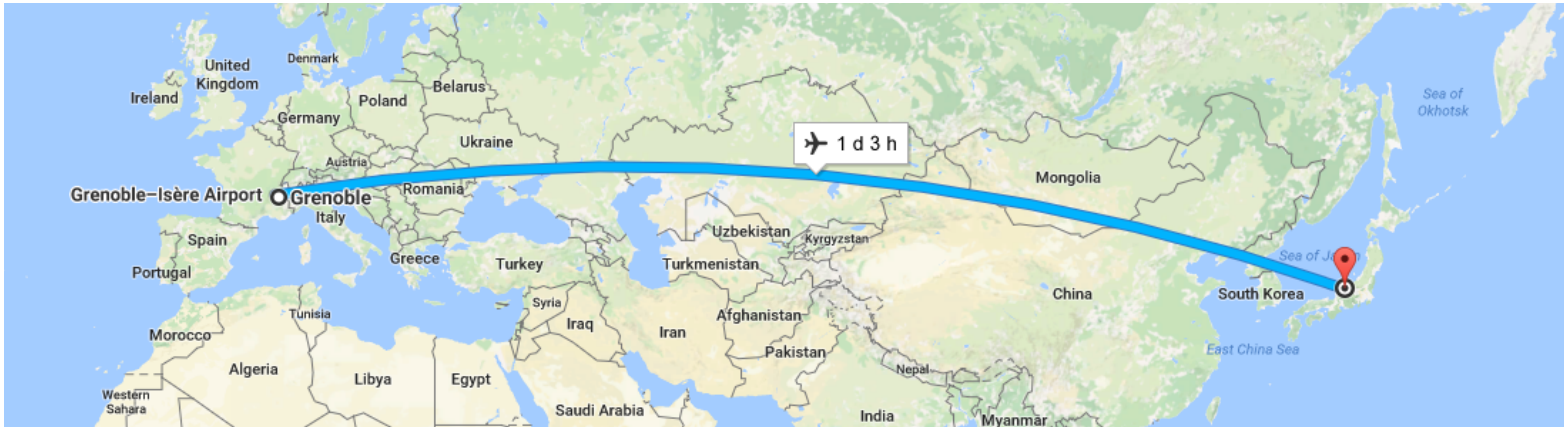
based on arXiv:1507.00933 and 1511.03682
with Jeremy Bernon, John F. Gunion, Howard E. Haber and Yun Jiang

この非常に面白い会議に私を招待してくれてありがとう

Higgs as a Probe of New Physics, 1-5 March 2017, Univ. of Toyama, Japan



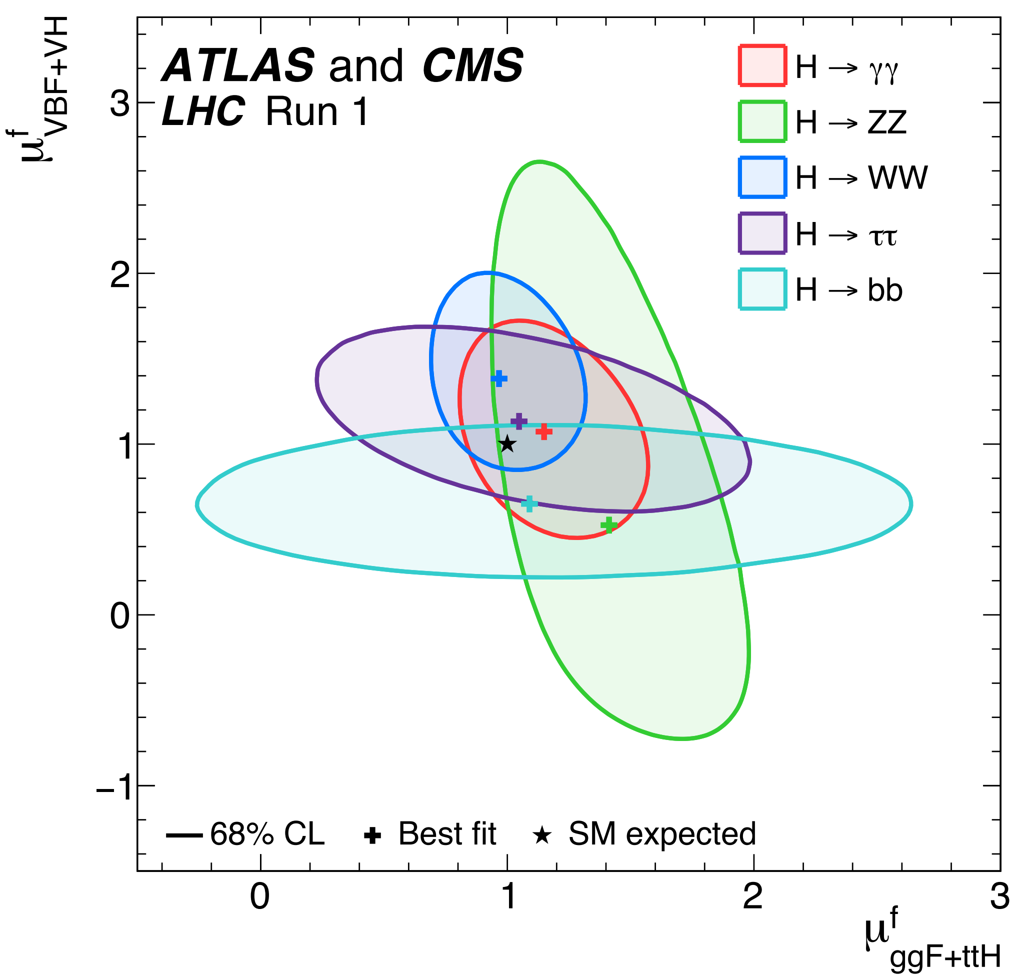
Grenoble, France

Toyama, Japan

A very SM-like Higgs boson

as a probe of new physics

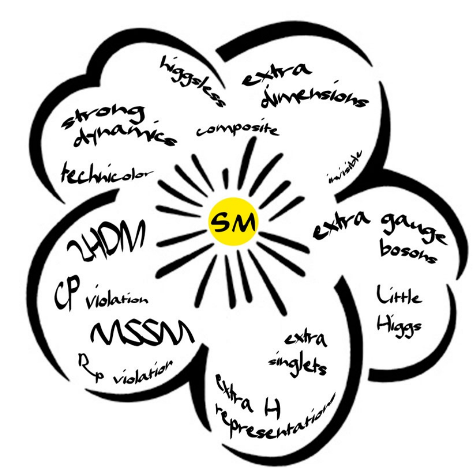
arXiv:1606.02266



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: alignment limit in 2HDMs

- 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 without 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

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

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"

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

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

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

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

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

$$H = (\sqrt{2}\text{Re}\, H_1^0 - v) c_{\beta-\alpha} - \sqrt{2}\text{Re}\, H_2^0 s_{\beta-\alpha}\,,$$
$$h = (\sqrt{2}\text{Re}\, H_1^0 - v) s_{\beta-\alpha} + \sqrt{2}\text{Re}\, H_2^0 c_{\beta-\alpha}\,.$$

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 $\cos(\beta-\alpha)=1$.

Higgs basis

Linear transformation to go to the "Higgs basis"

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

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

$$Y_1 = m_{11}^2 c_\beta^2 + m_{22}^2 s_\beta^2 - m_{12}^2 s_{2\beta}\,,$$
$$Y_2 = m_{11}^2 s_\beta^2 + m_{22}^2 c_\beta^2 + m_{12}^2 s_{2\beta}\,,$$
$$Y_3 = \tfrac{1}{2}(m_{22}^2 - m_{11}^2) s_{2\beta} - m_{12}^2 c_{2\beta}\,.$$

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

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

$$\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$$

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(β-α)≃1 or cos(β-α)≃1

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

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

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

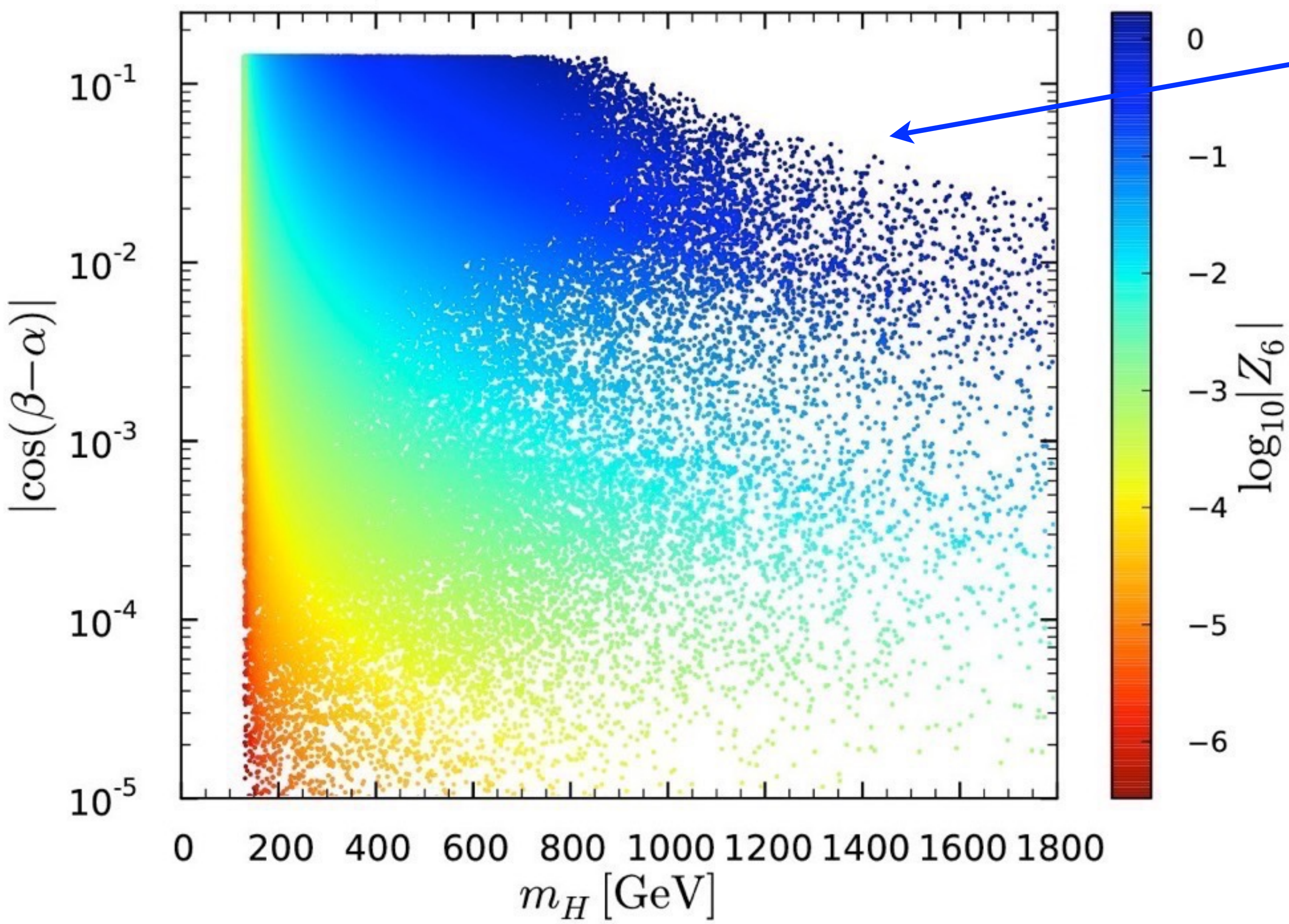
SM-like H $\quad H \simeq (\sqrt{2}\mathrm{Re}\, H_1^0 - v) c_{\beta-\alpha}\,, \quad Z_1 v^2 > m_A^2 + Z_5 v^2$

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

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 $Z_6 \to 0$.

Relation btw Z_6, cos(β-α) and $m_{h,H}$

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

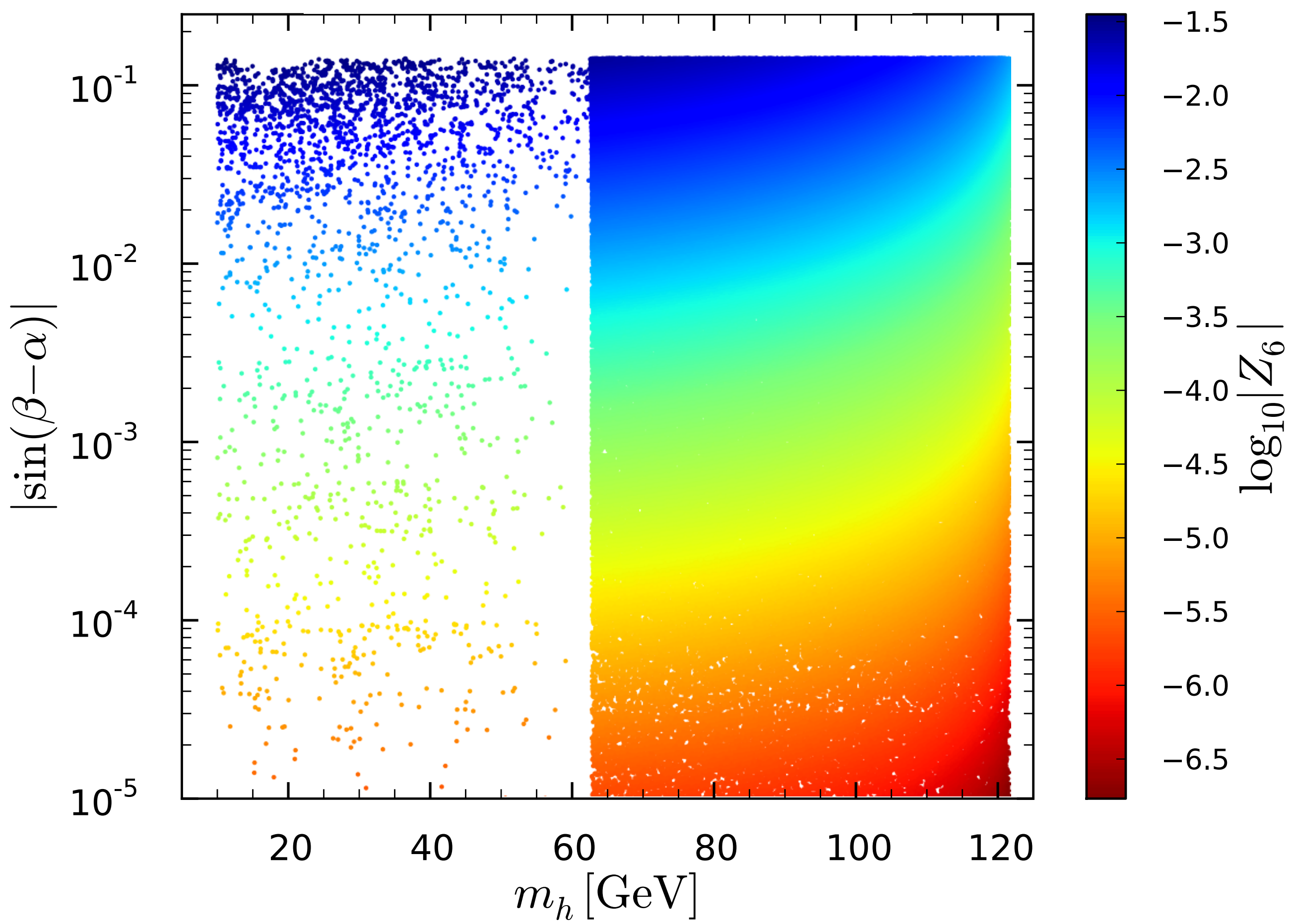
$$c_{\beta-\alpha} = \frac{-Z_6 v^2}{\sqrt{(m_H^2 - m_h^2)(m_H^2 - Z_1 v^2)}} \simeq 0$$

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 $m_{h,H}$

Different ways to achieve alignment

m_H=125 GeV, H=H_{SM}



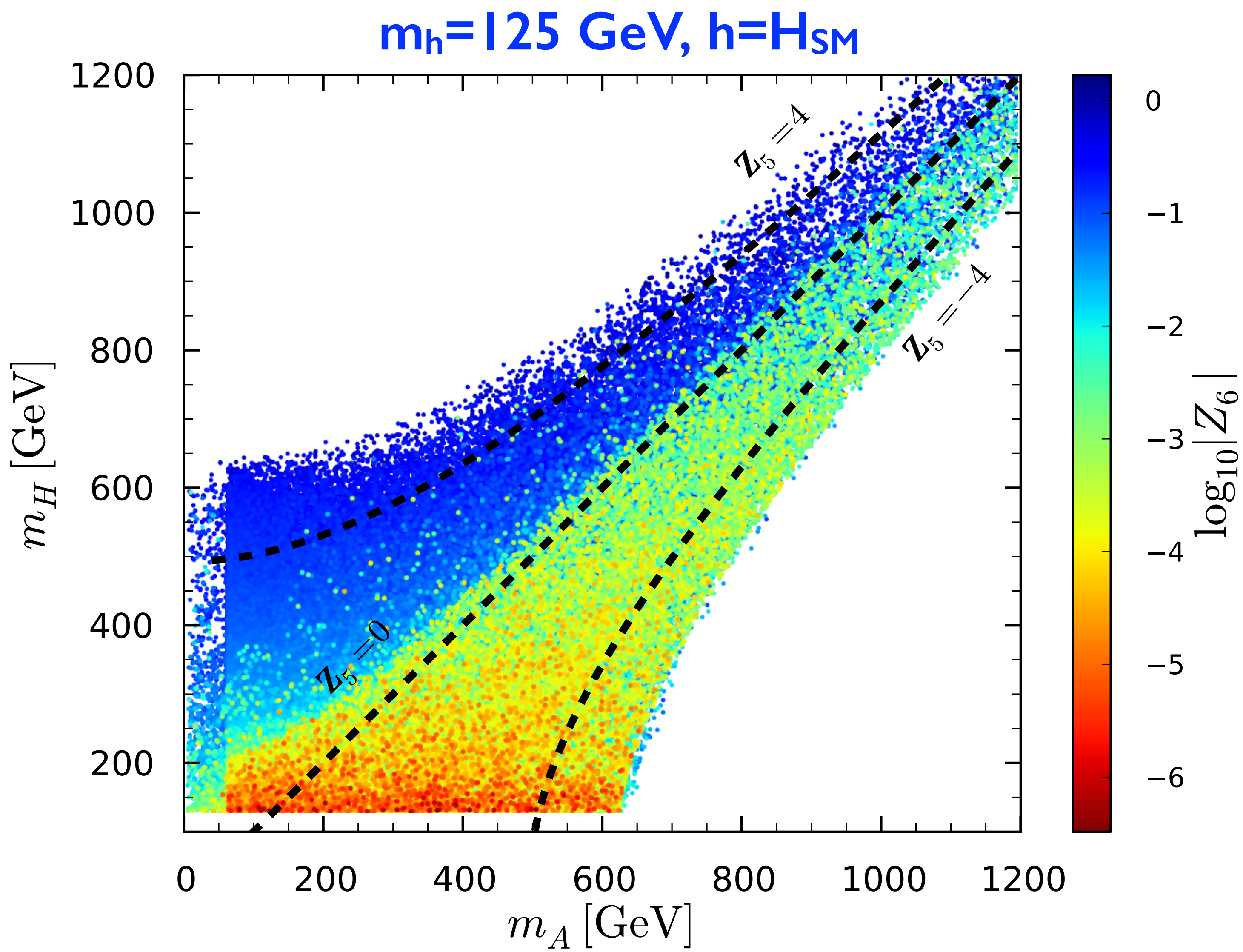
$$s_{\beta-\alpha} = \frac{-Z_6 v^2}{\sqrt{(m_H^2 - m_h^2)(Z_1 v^2 - m_h^2)}} \simeq 0$$

Fine-tuned? Note that $Z_6 = Z_7 = 0$ corresponds to an exact Z_2 symmetry in the Higgs basis.

$$Z_{6,7} = -\tfrac{1}{2} s_{2\beta}[\lambda_1 c_\beta^2 - \lambda_2 s_\beta^2 \mp \lambda_{345} c_{2\beta}] \to 0$$

- $s_{2\beta} = 0 \to$ only 1 Higgs field acquires a VEV, Z_2 unbroken
- $\lambda_1 = \lambda_2 = \lambda_{345} \to$ softly broken CP3 symmetry   Ferreira, Haber, Silva, 0902.1537
- $\lambda_1 = \lambda_2 = \lambda_{345}$ and $m_{12}^2 = 0 \to$ exact CP3 symmetry   Dev, Pilaftsis 1408.3405

Relation btw Z_6, m_H and m_A



alignment prefers
mH < mA

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 GeV or mH=125 GeV with ≥4 GeV H-h mass difference to avoid degenerate Higgs scenarios; alignment condition: $C_V \geq 0.99$ (1% deviation from exact alignment)
  - 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:

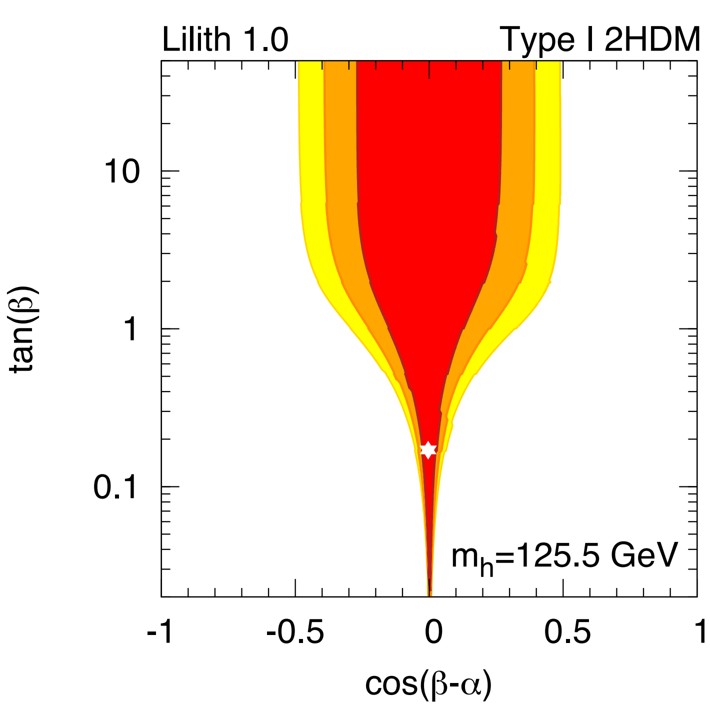
✓ S, T, U Peskin-Takeuchi parameters (→Higgs mass splitting)
✓ B-physics constraints (→ tanβ, charged Higgs mass)
✓ LEP Higgs searches (e+e-→Zh, e+e-→Z*→Ah, e+e-→H+H-)
✓ Upsilon constraints on light CP-odd states
✓ CMS light CP-odd search (A→μμ from 7 TeV dataset)
✓ ATLAS+CMS heavy Higgs searches (H→ZZ; A→Zh; H,A→ττ, μμ; …) from Run-1

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

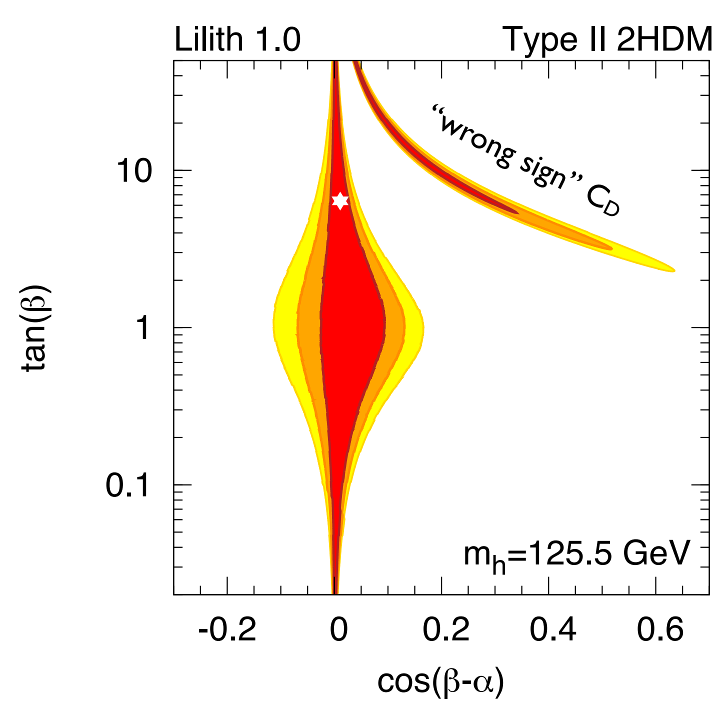
Reminder: Type I and II coupling structure

	Type I and II	Type I		Type II	
Higgs	C_V	C_U	C_D	C_U	C_D
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

Results for m_h = 125 GeV

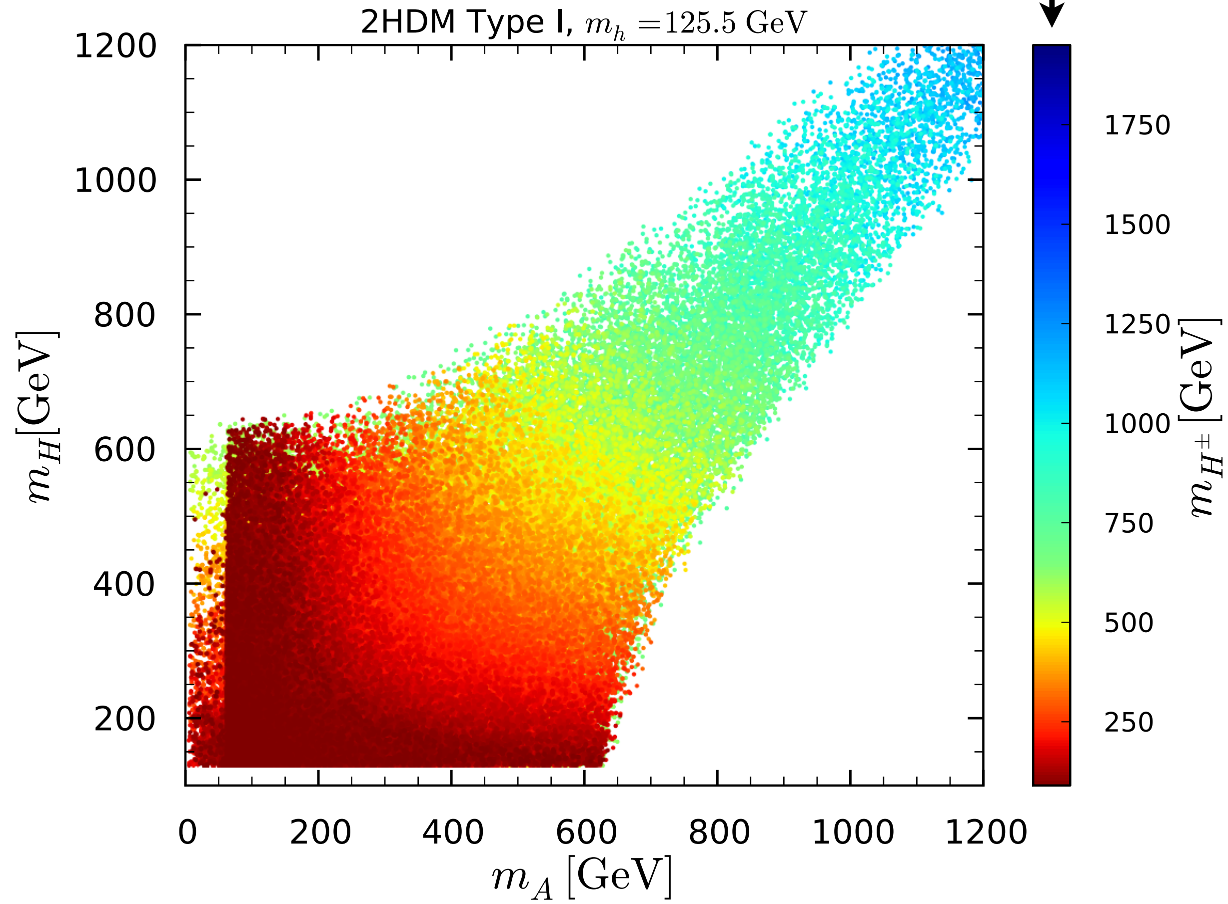
$\sin(\beta-\alpha) \geq 0.99$

arXiv:1507.00933

(mH = 125 GeV in arXiv:1511.03682 and backup slides)

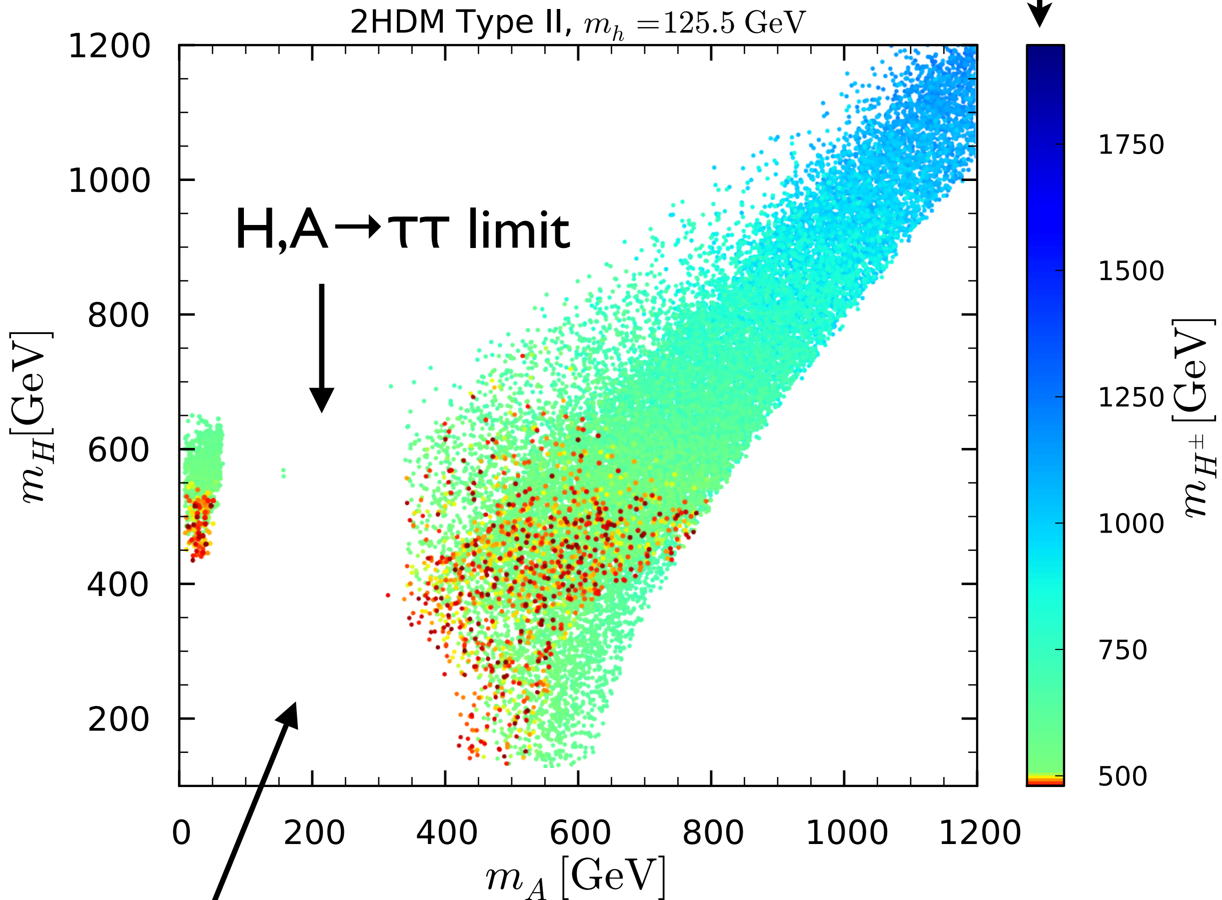
Relation between m_A, m_H and $m_{H^\pm}$

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



Type I

ordering from
high to low values



Type II

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

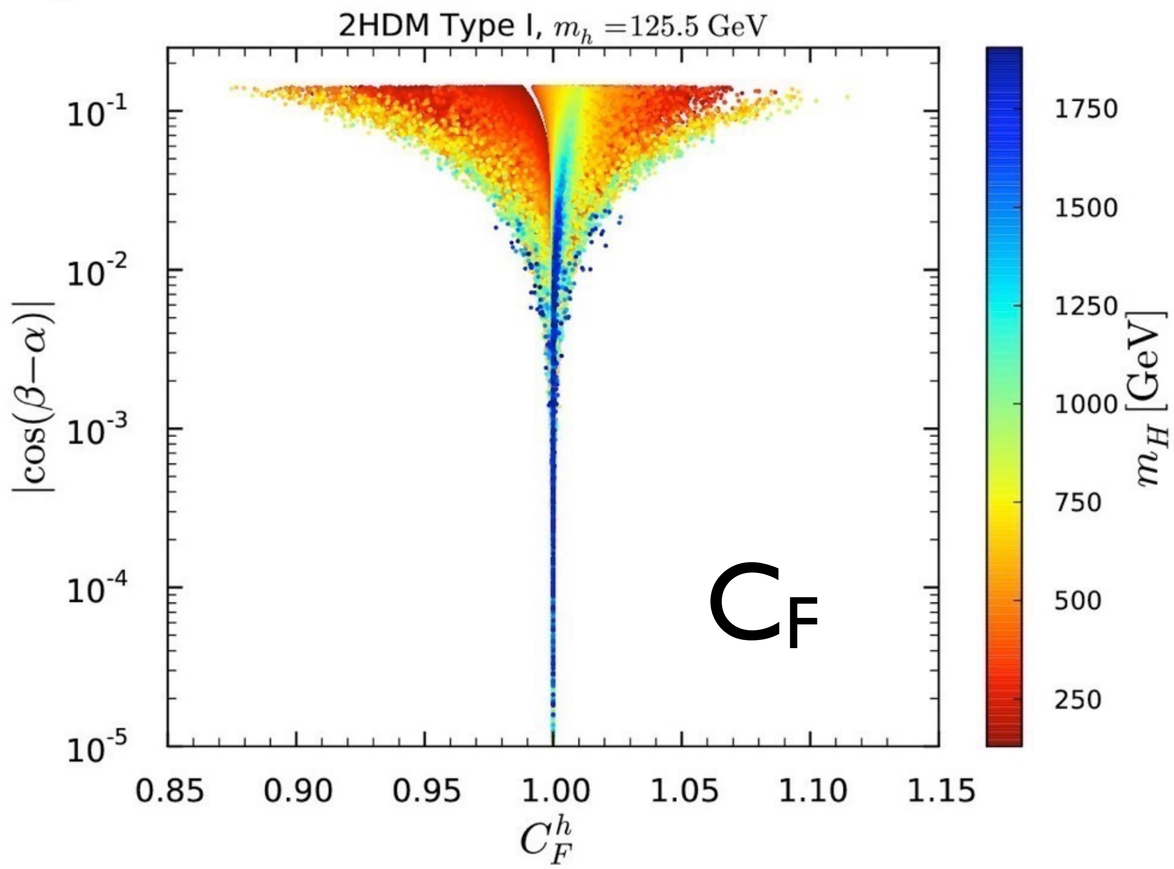
[Misiak et al.,1503.01789]

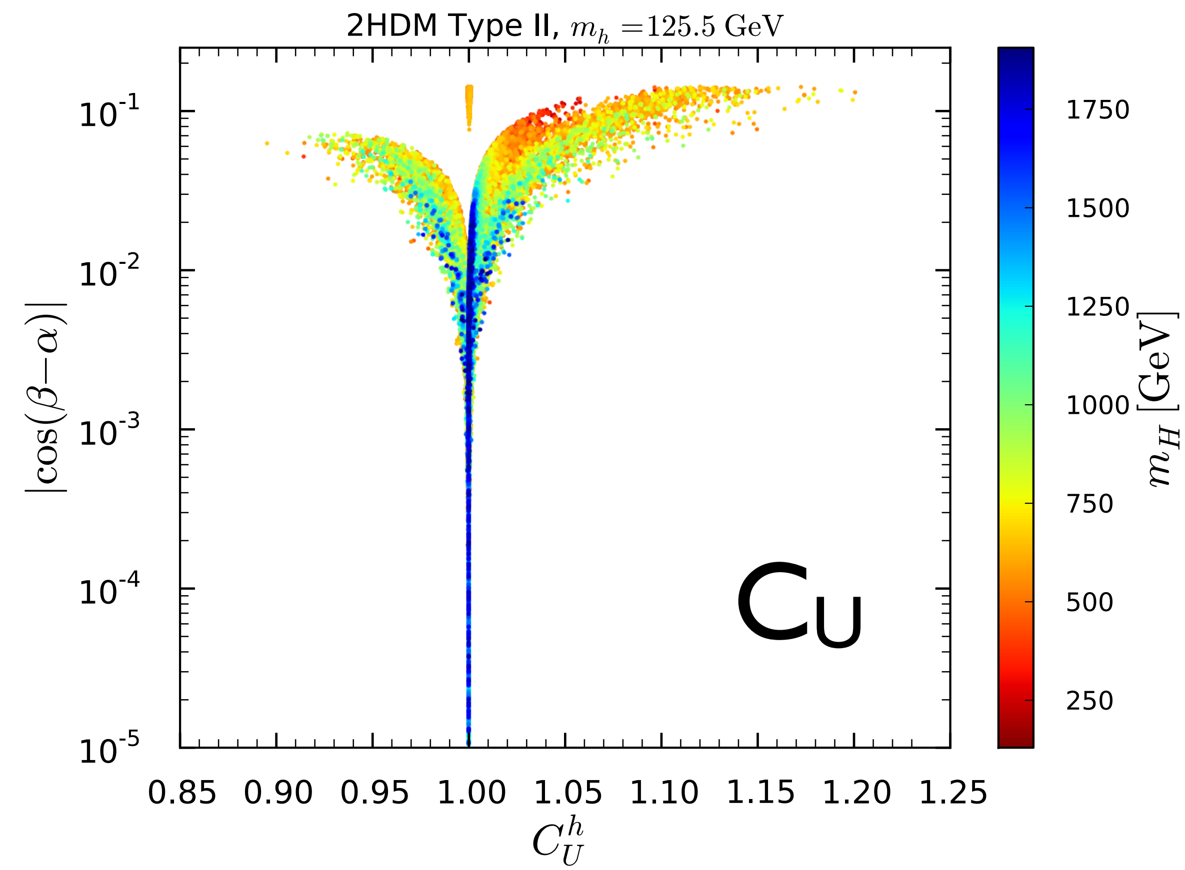
Couplings of the 125 GeV state: $C_{F,U}$

Type I

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

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%

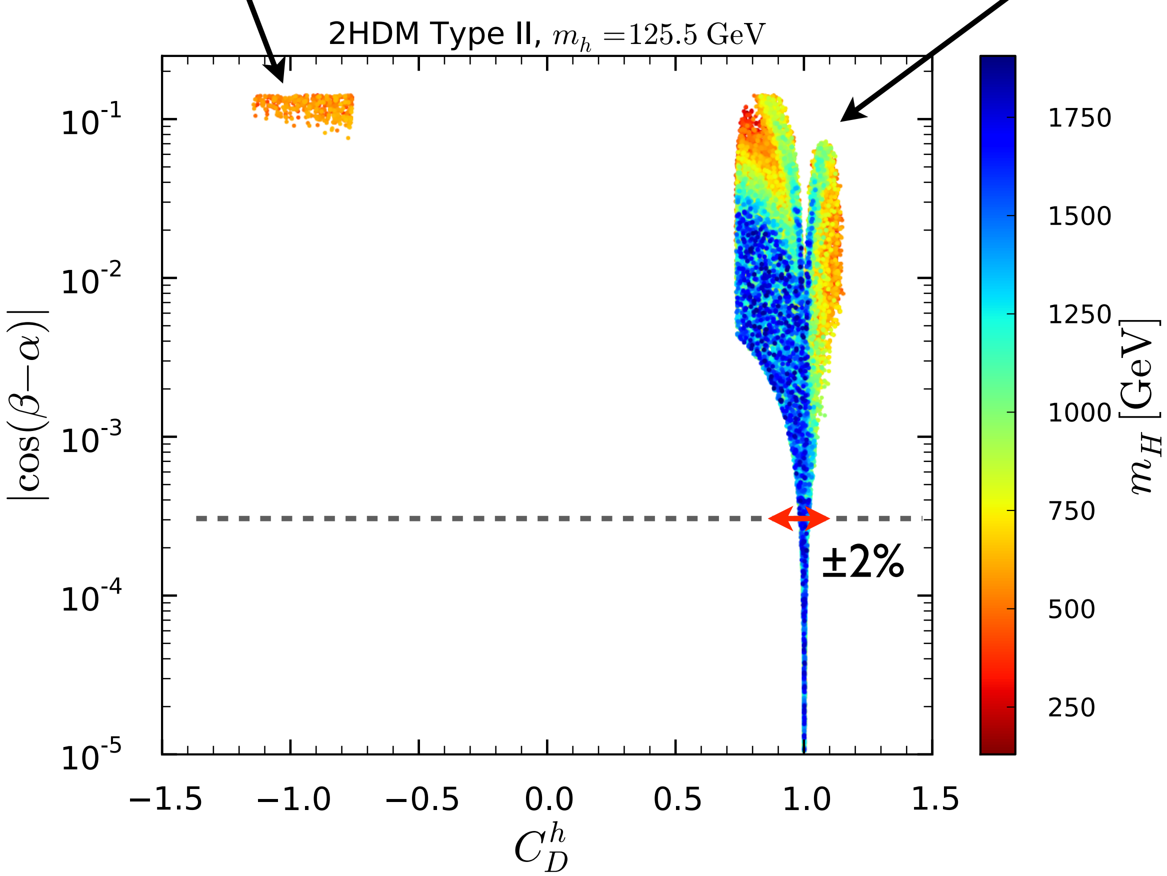
Note that C_U=C_D≡C_F in Type I

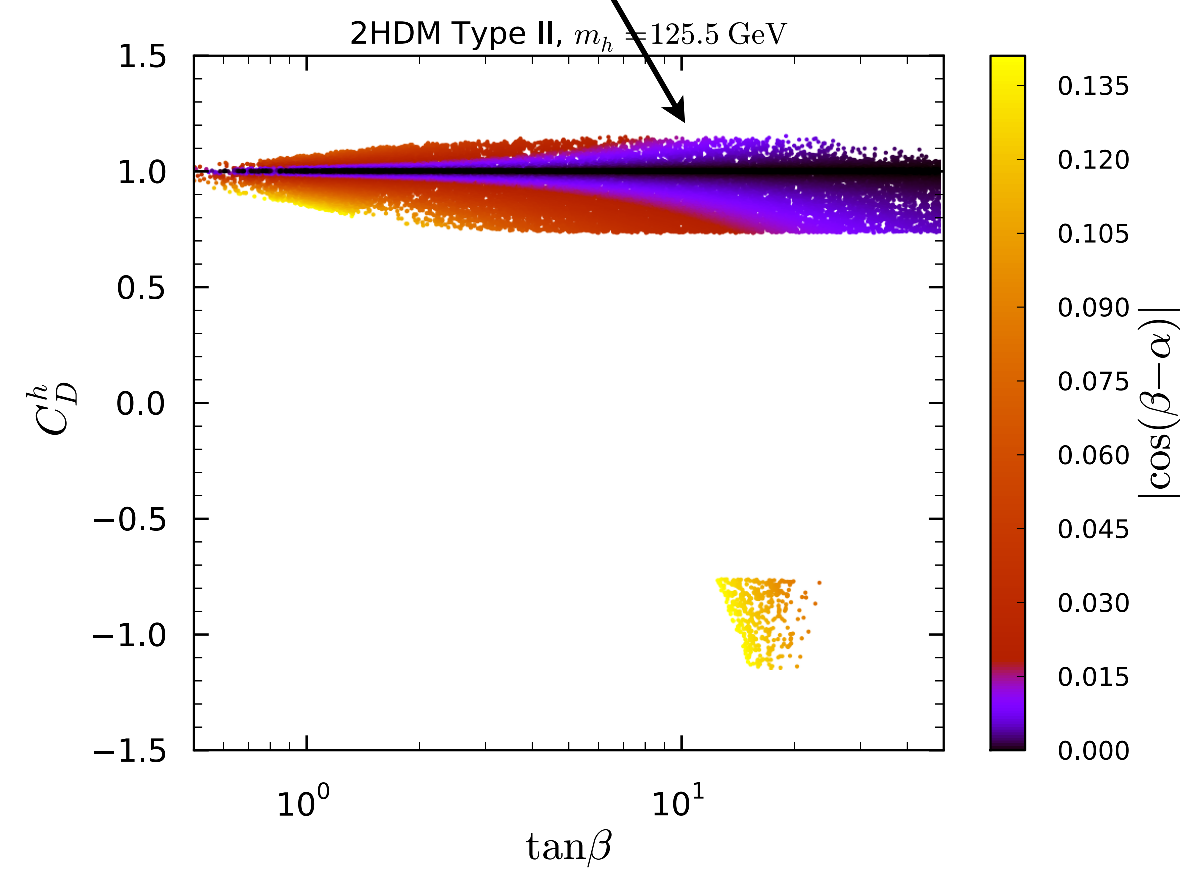
C_D in Type II

C_D = -sin α / cos β
= $s_{β-α}$ - tanβ $c_{β-α}$

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

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





* 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

Alignment of C_D is delayed for large tanβ

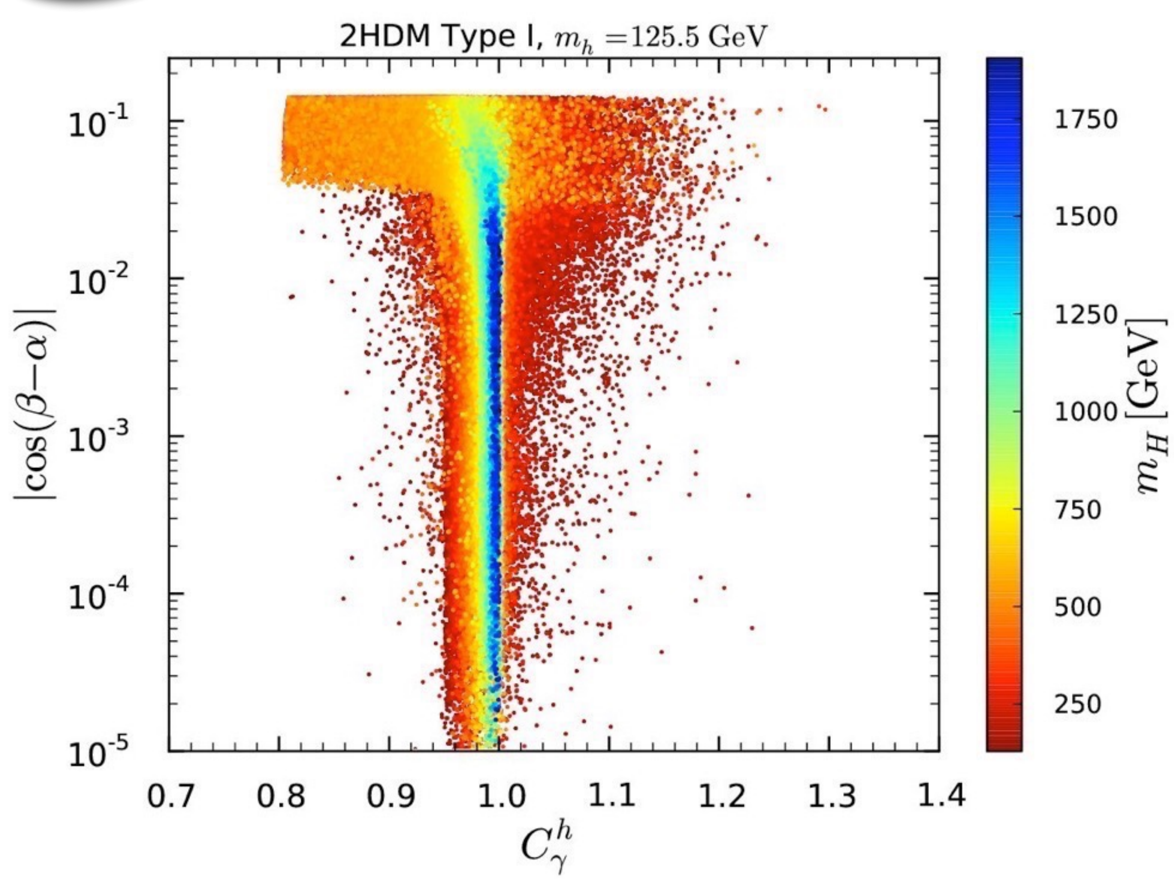
This heavily influences the signal strengths in Type II, as CD determines the h→bb branching ratio.

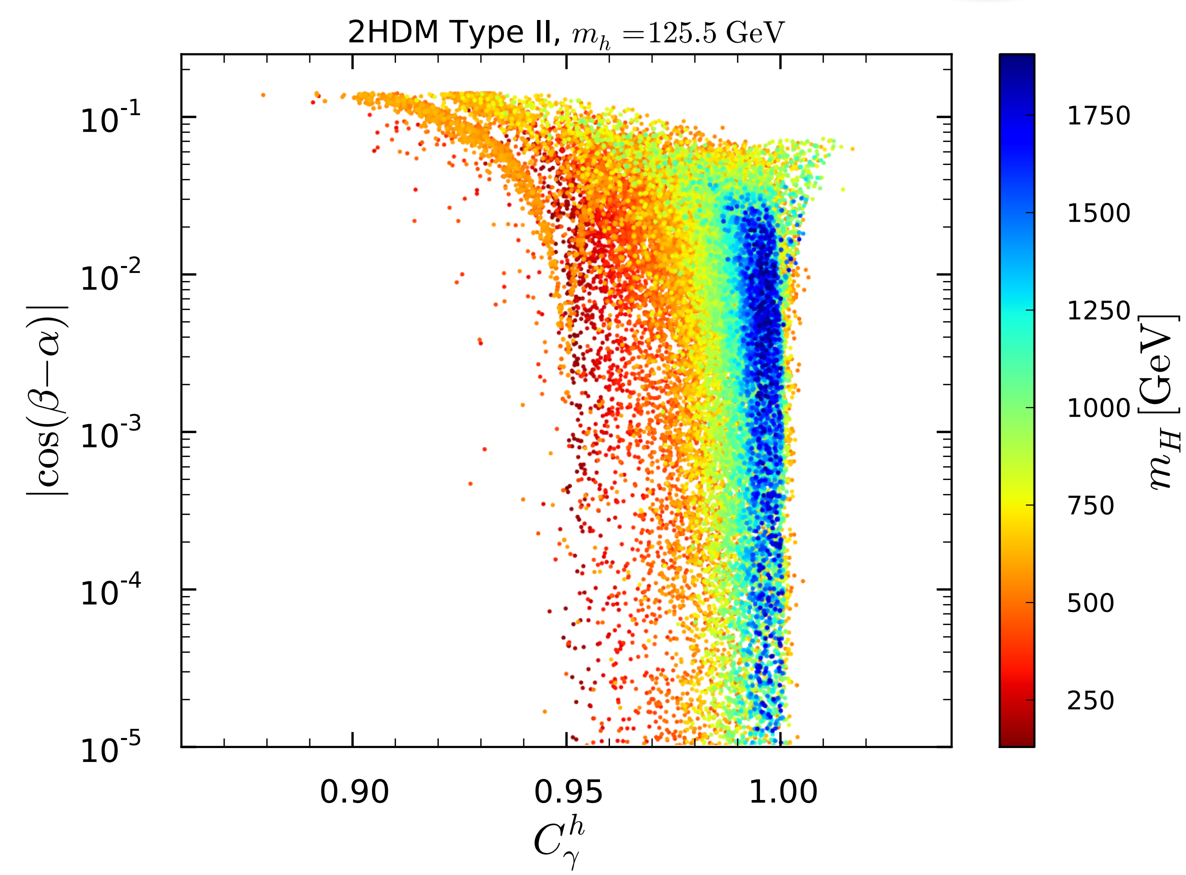
Coupling to photons: C_γ

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.

$$\mu_X^h(Y) \equiv \frac{\sigma(X)\,\mathrm{BR}(\mathrm{h}\to\mathrm{Y})}{\sigma(X_{\mathrm{SM}})\,\mathrm{BR}(\mathrm{H_{SM}}\to\mathrm{Y})}$$

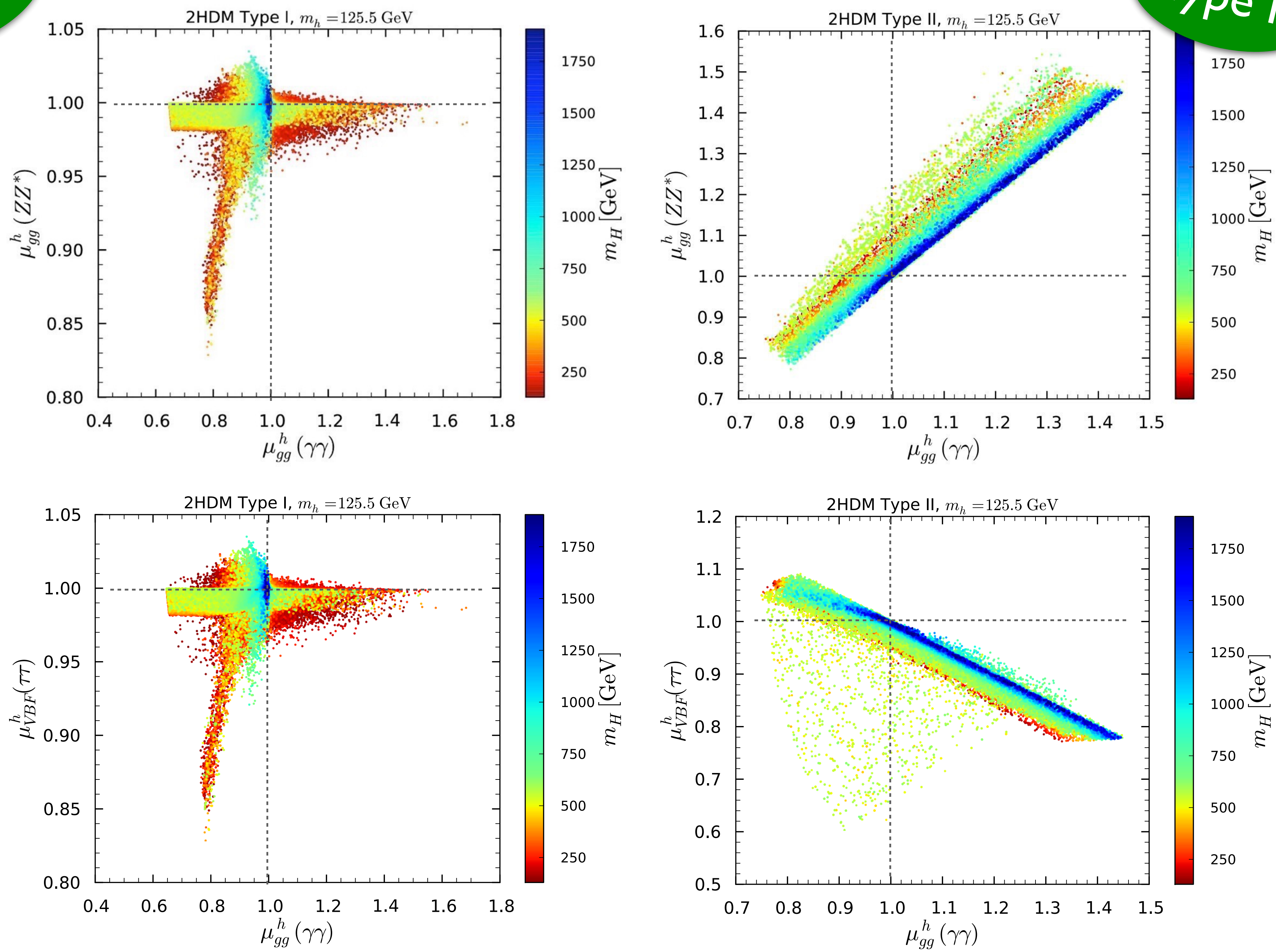
Signal strengths

Type I

Type II

ZZ

ττ



γγ γγ

Possibility to disentangle alignment with or without decoupling before the discovery of a new state

Possibility to favour Type I or Type II

E.g. $\mu_{gg}(\gamma\gamma)>1$ with $\mu_{gg}(ZZ)\sim 1$ possible in Type I but not in Type II

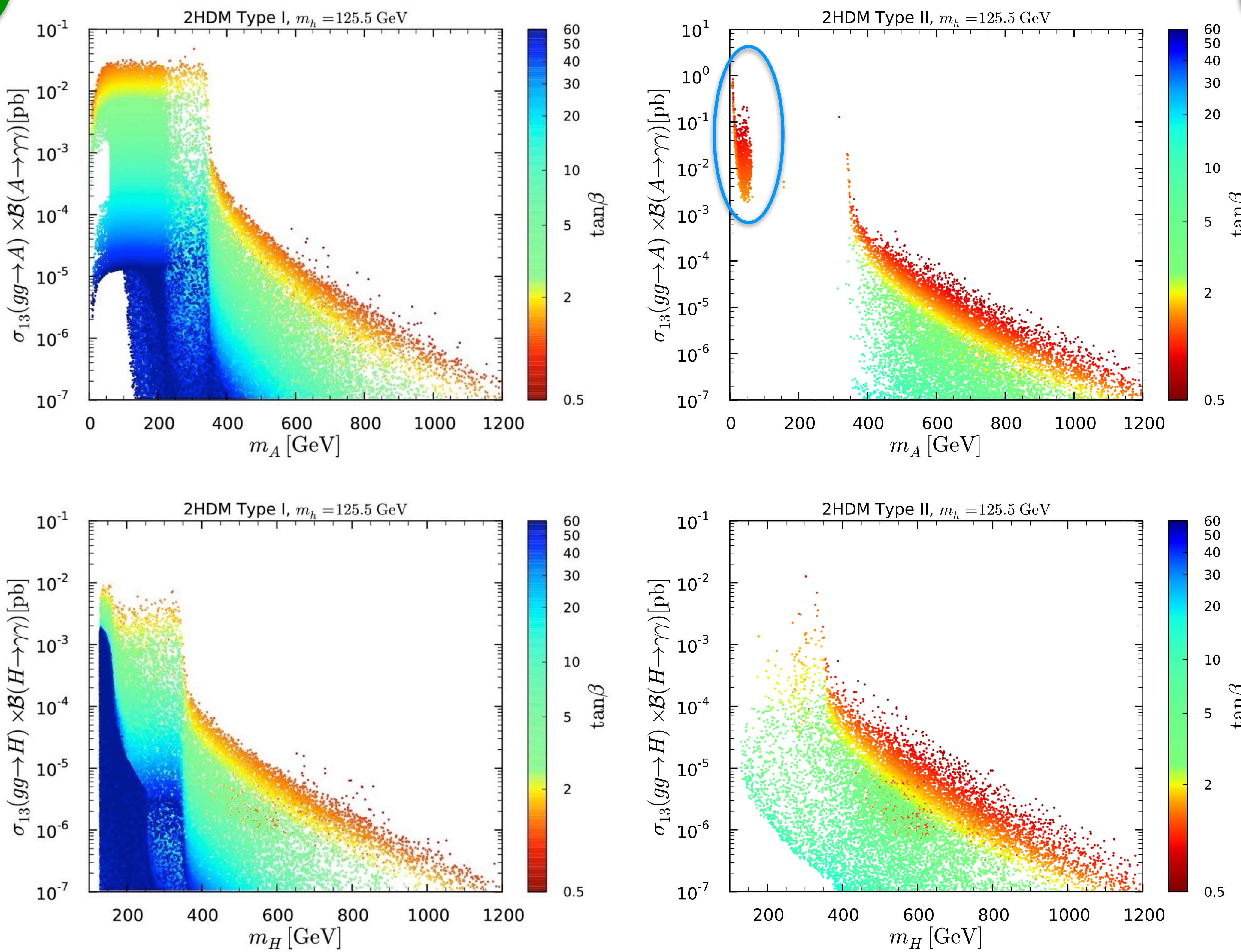
Prospects for gg→H,A→γγ at Run2

Type I

Type II

A

H

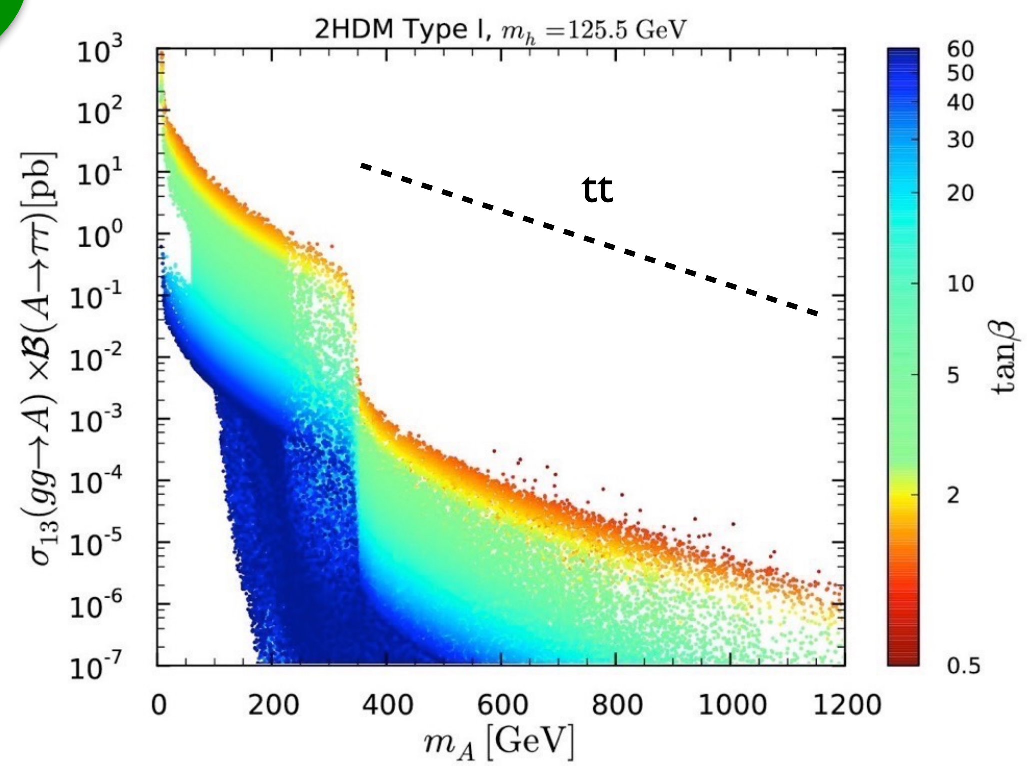


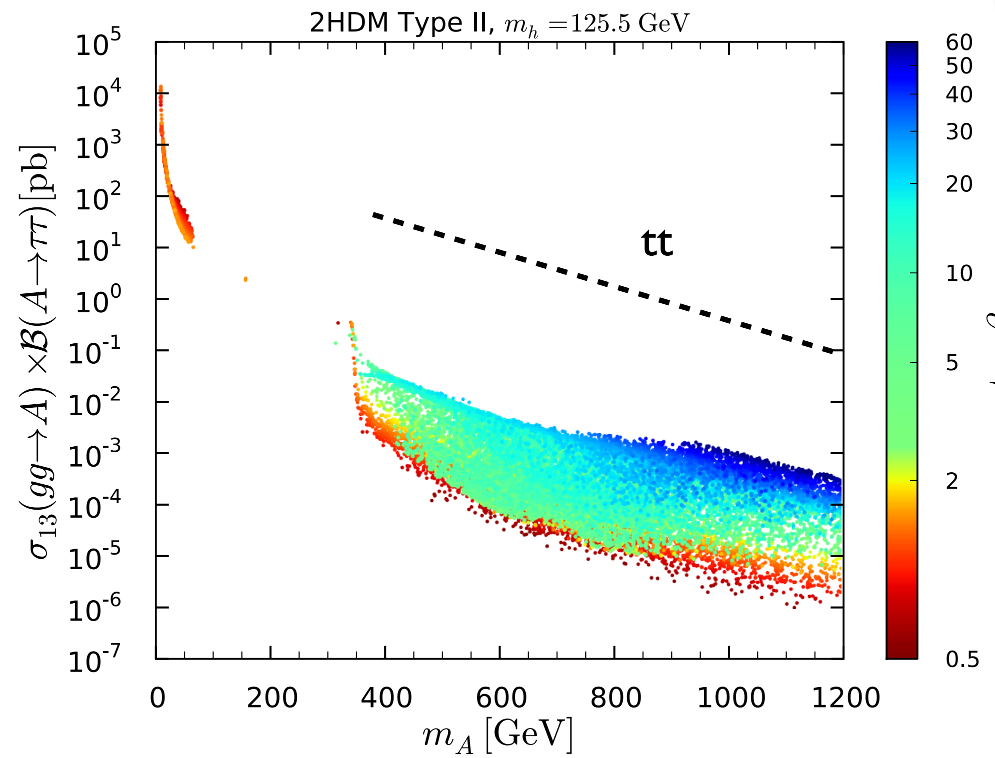
Prospects for gg→H,A→ττ

Type I

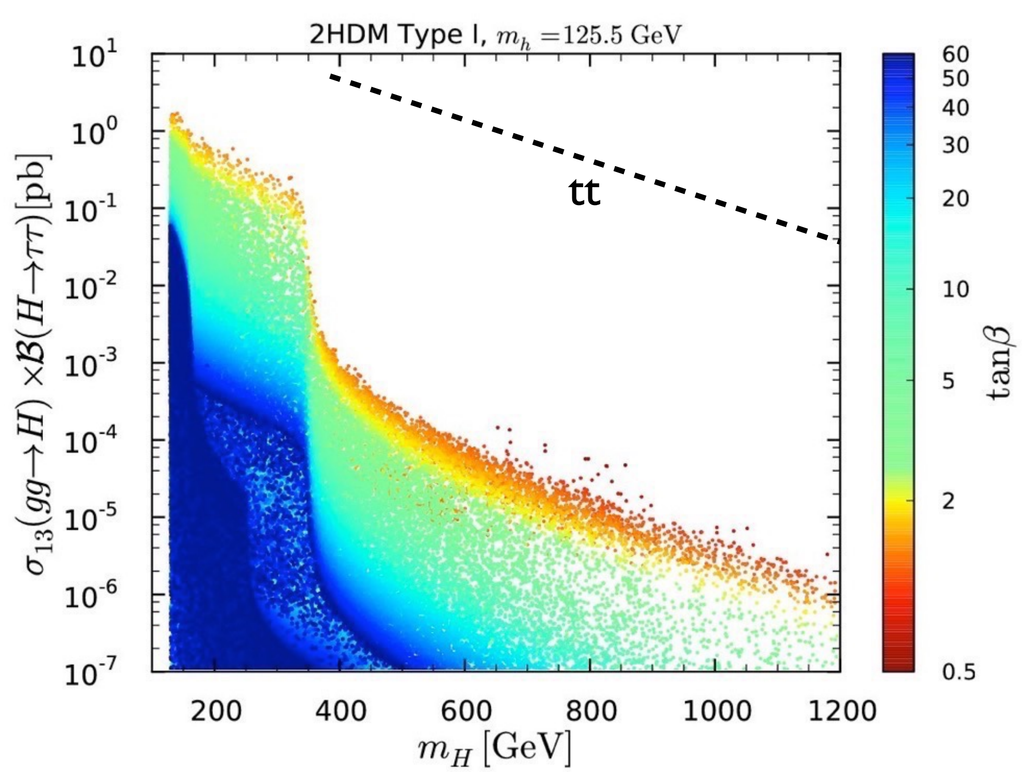
Type II

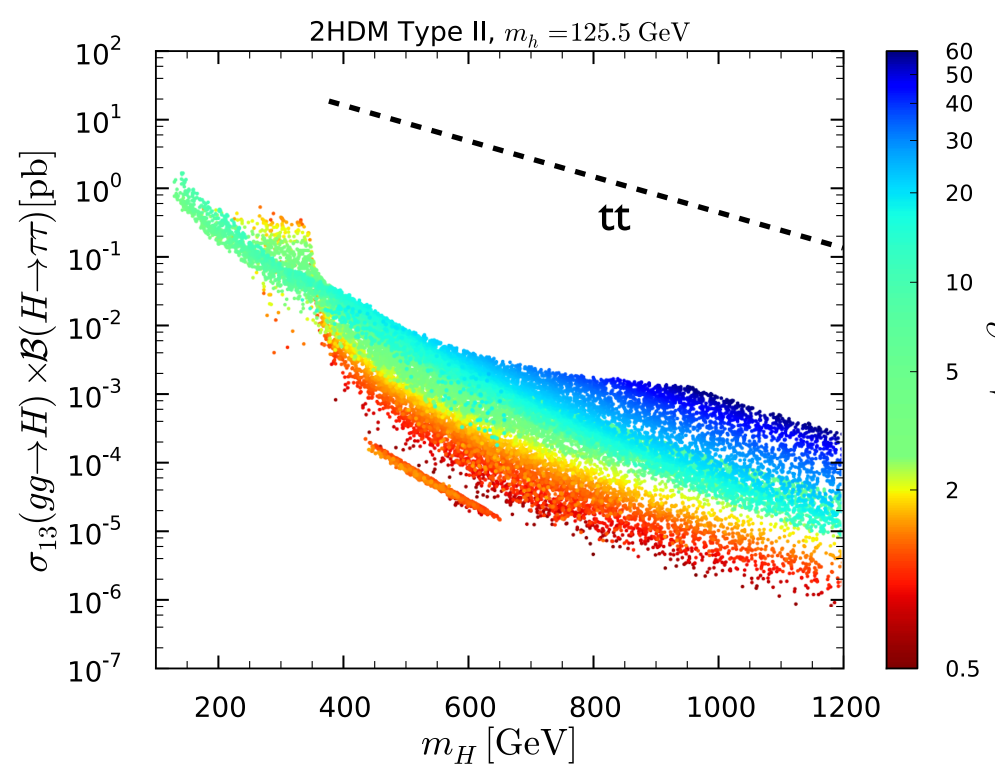
A





H



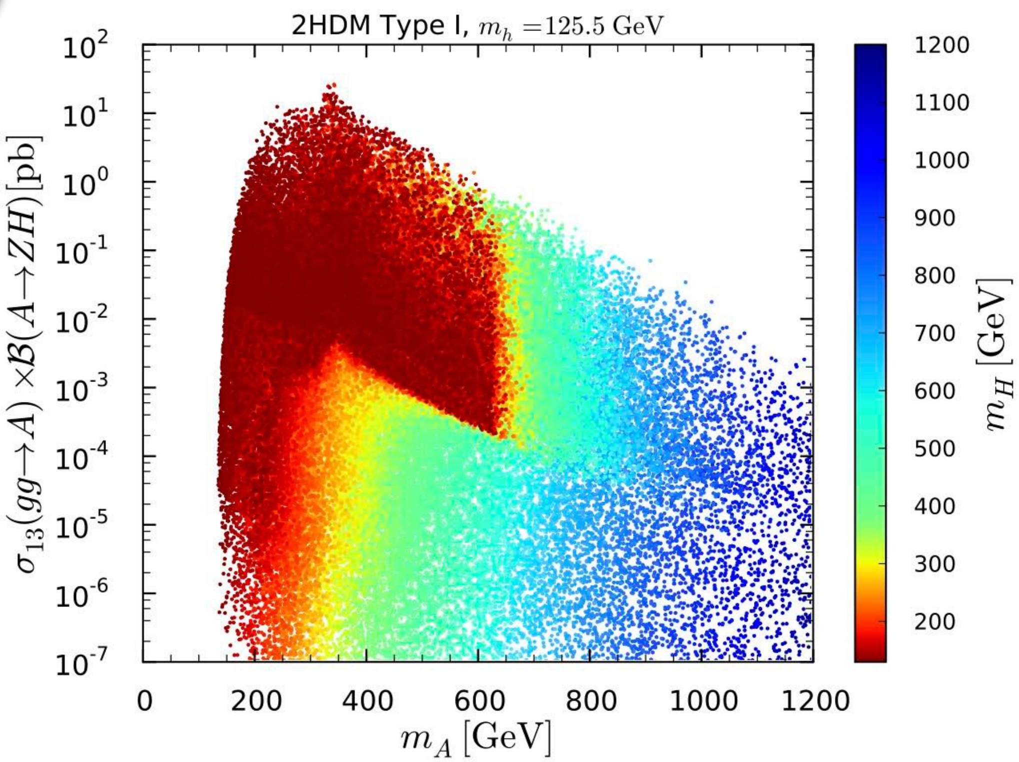


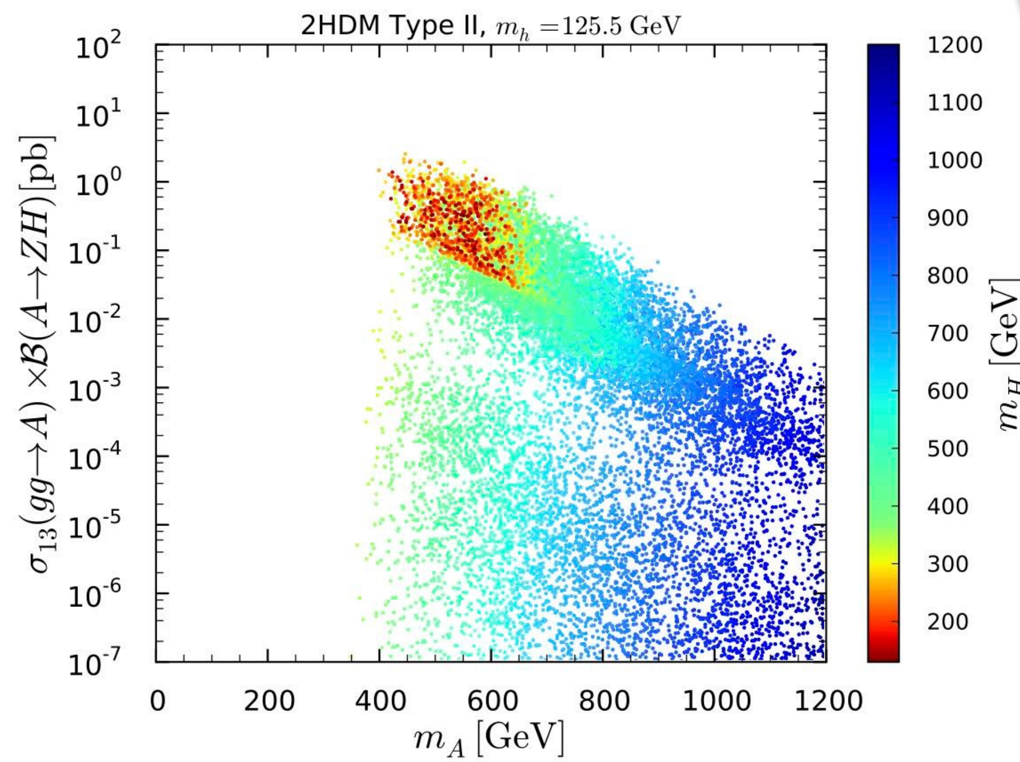
`Exotic' modes can have O(pb) XS

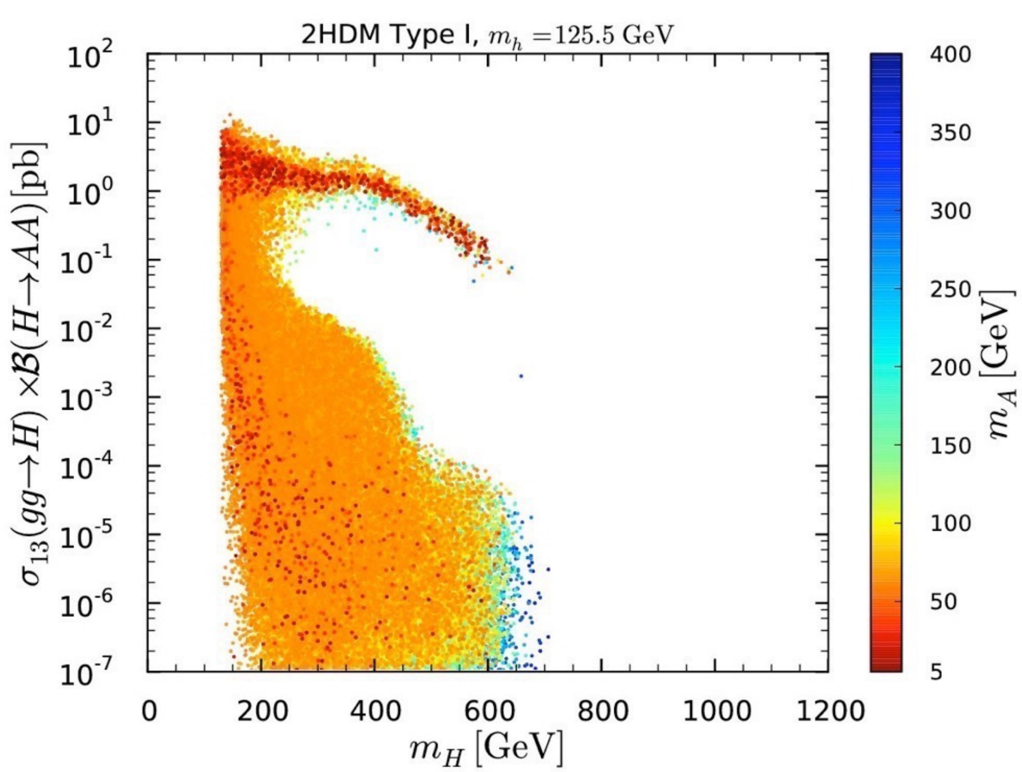
gg→A→ZH, gg→H→AA

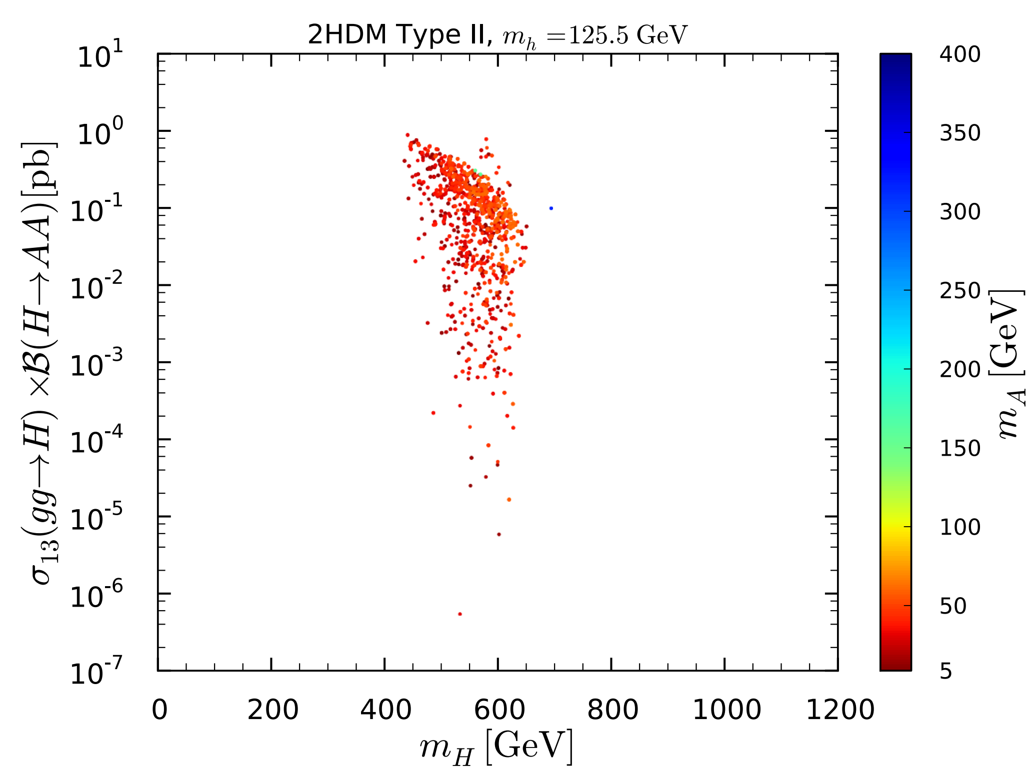
Type I

Type II





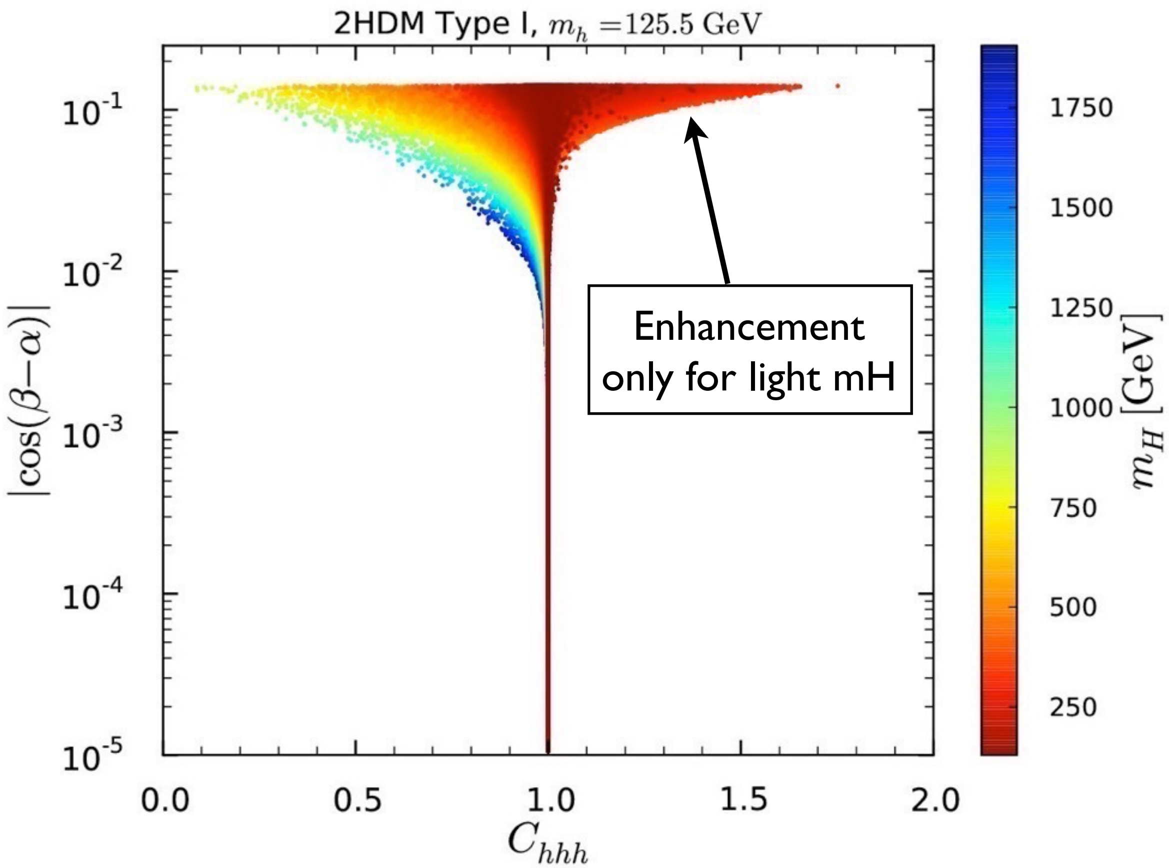




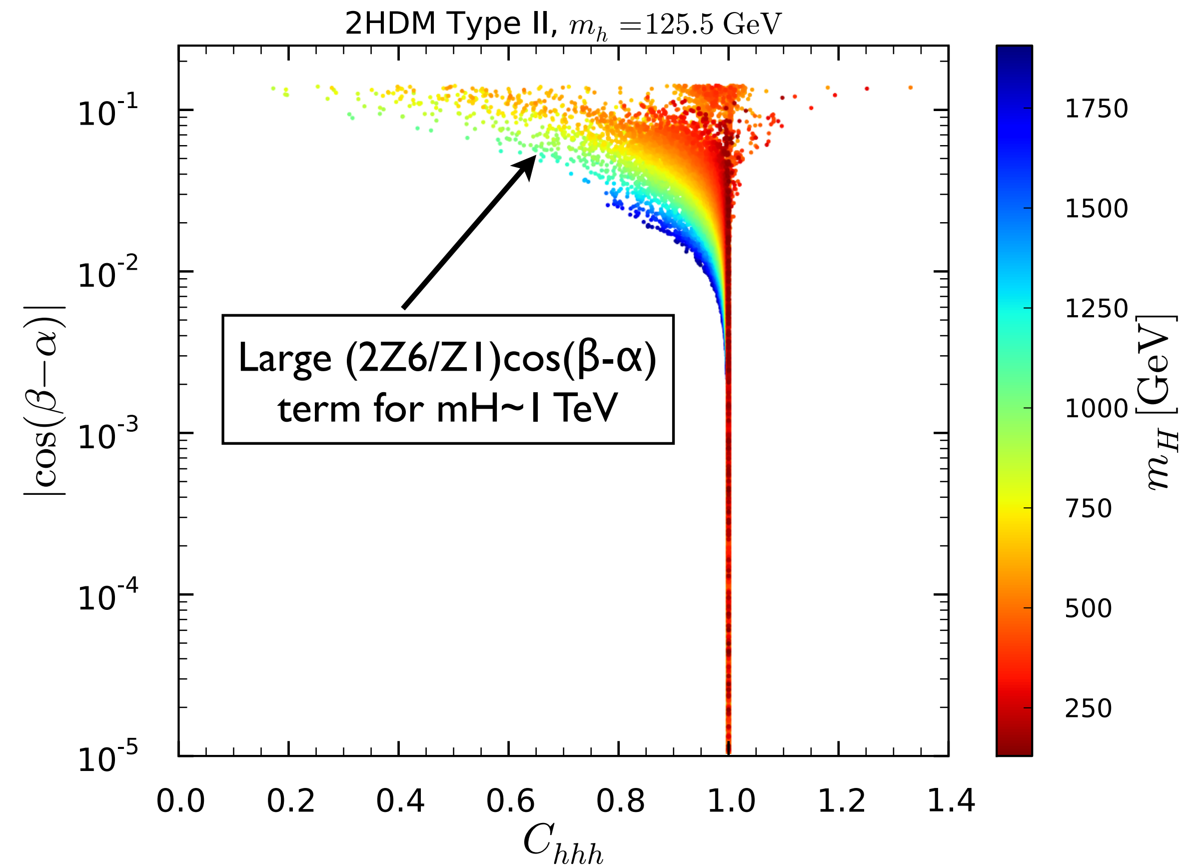
Higgs self-coupling

crucial for scrutinising the Higgs potential as well as for EW phase transition

Type I



Type II



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

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

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.

Radiative corrections and EWPT

- Large radiative corrections in particular to the trilinear couplings due to non-decoupling effects

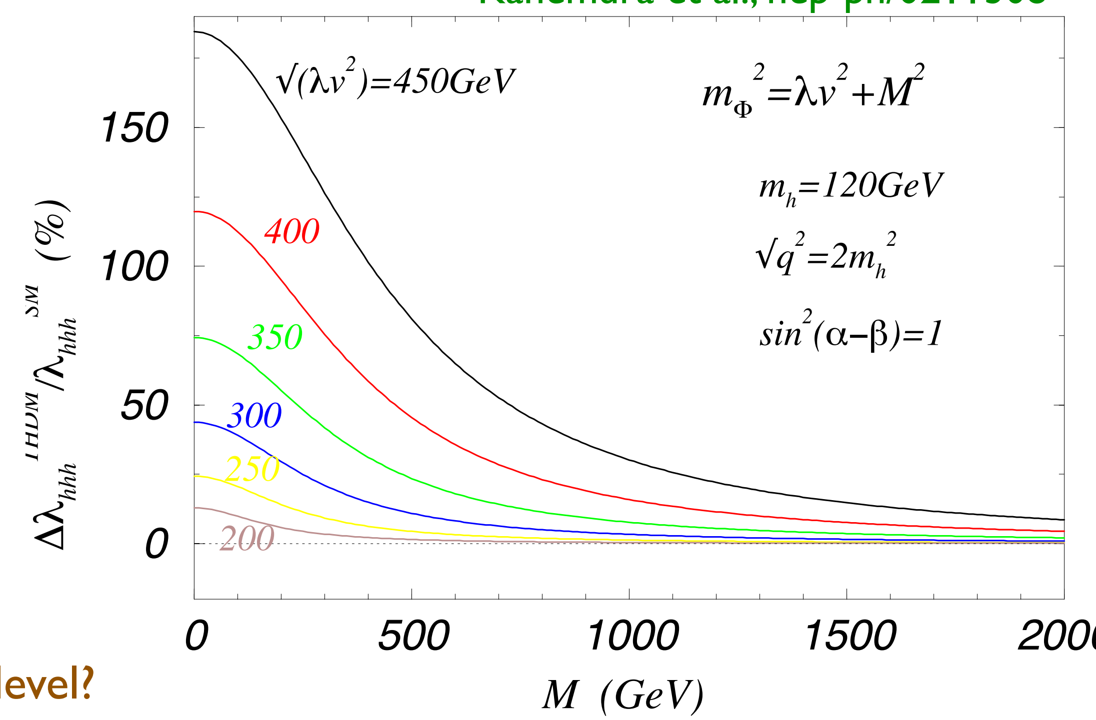
Kanemura, Kiyoura, Okada, Senaha, Yuan, 0211308
Kanemura, Okada, Senaha, Yuan, 0408364

Gauge-independent renormalization
Krause, Lorenz, Muhlleitner, Santos, Ziesche, 1605.04853

Gauge indep. MSbar renormalization
Denner, Jenniches, Lang, Sturm, 1607.07352

NB: mixing angles get renormalised; meaning of alignment beyond tree level?

Kanemura et al., hep-ph/0211308



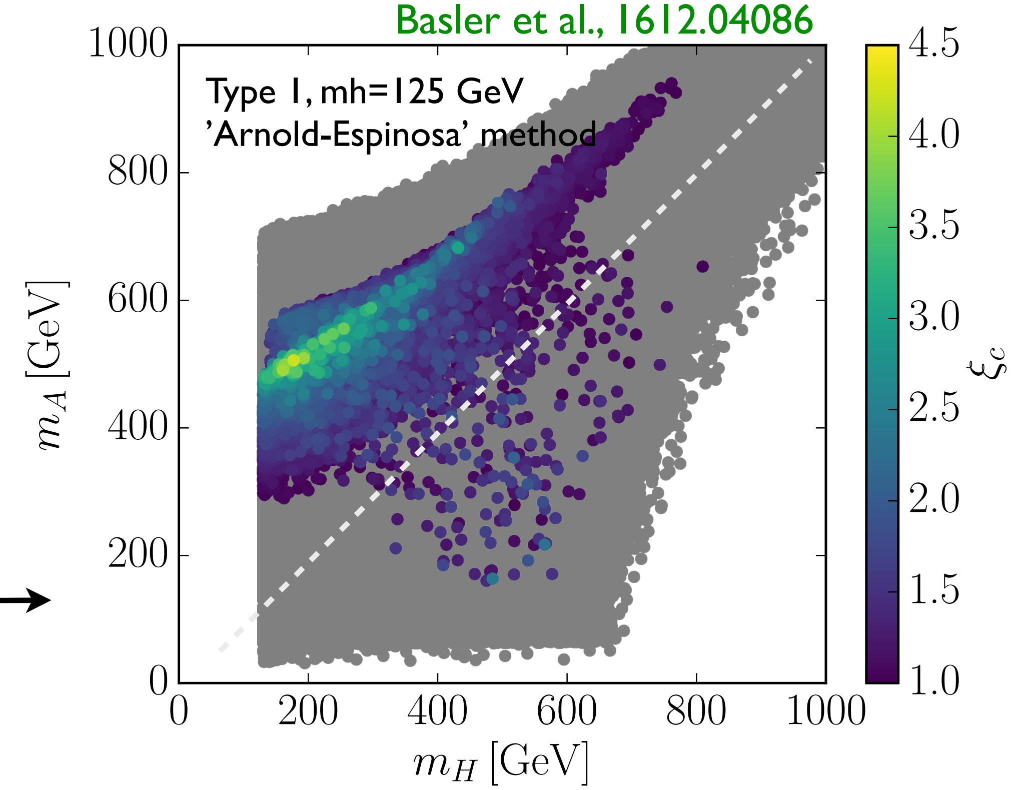
- Important for Higgs-to-Higgs decays at the LHC and for strength of electroweak phase transition

Bochkarev, Kuzmin, Shaposhnikov, 1990 […]
Dorsch, Huber, (Mimasu,) No, 1305.6610, 1405.5537

Basler, Krause, Muhlleitner, Wittbrodt, Wlotzka, 1612.04086:

Renormalisation of the loop-corrected potential such that not only the VEV and all physical Higgs boson masses, but also all mixing matrix elements remain at their tree-level values. →

Basler et al., 1612.04086



Conclusions

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 !

thank you

ありがとうございました

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N. Craig, J. Galloway, and S. Thomas, Searching for Signs of the Second Higgs Doublet, arXiv:1305.2424.

M. Carena, I. Low, N. R. Shah, and C. E. Wagner, Impersonating the Standard Model Higgs Boson: Alignment without Decoupling, JHEP 1404 (2014) 015, arXiv:1310.2248.

M. Carena, H. E. Haber, I. Low, N. R. Shah, and C. E. M. Wagner, Complementarity between nonstandard Higgs boson searches and precision Higgs boson measurements in the MSSM, Phys.Rev. D91 (2015) 035003, arXiv:1410.4969.

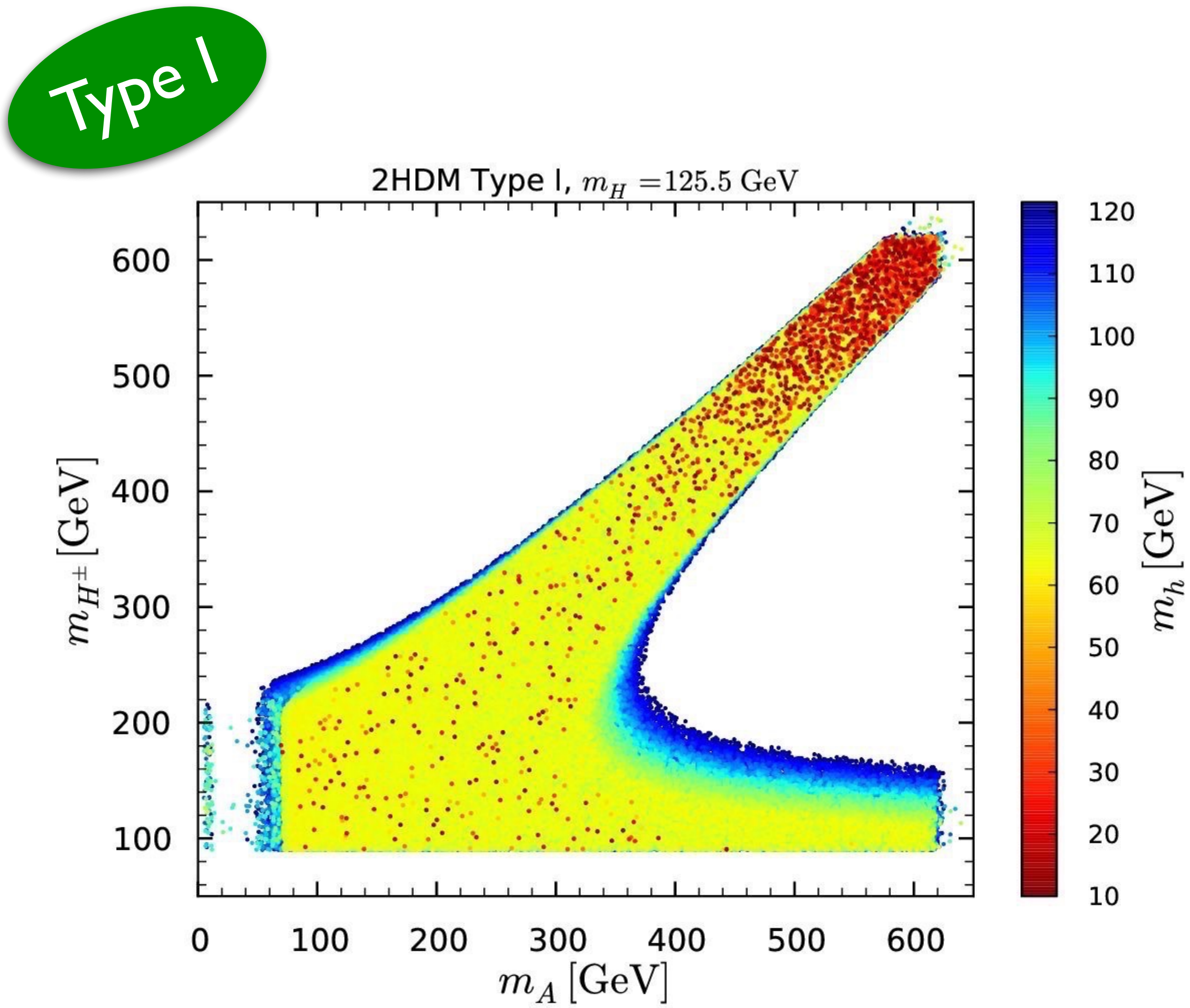
J. Bernon, J. F. Gunion, Y. Jiang, and S. Kraml, Light Higgs bosons in Two-Higgs-Doublet Models, arXiv:1412.3385.

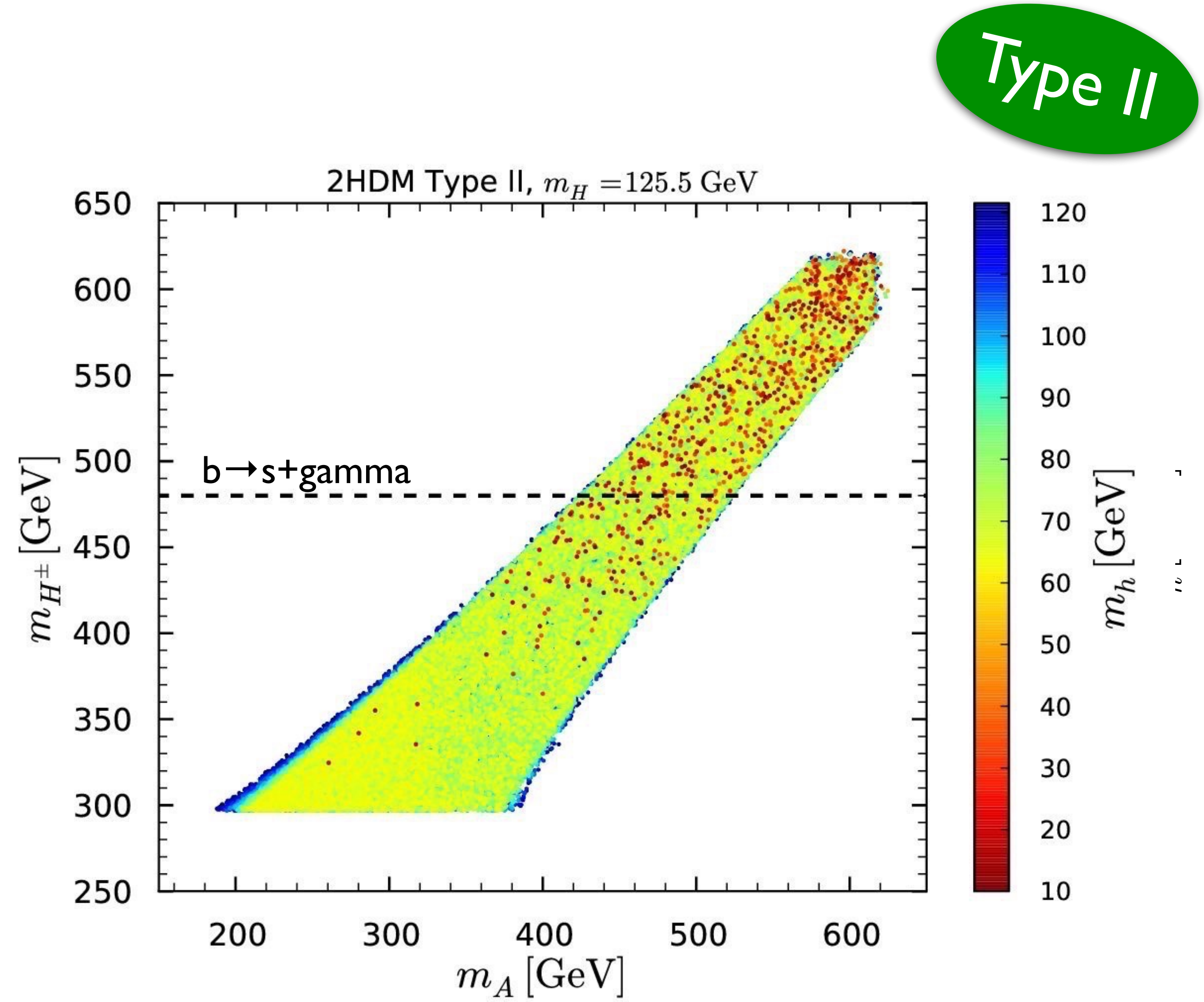
Results for m_H = 125 GeV

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

arXiv:1511.03682

Parameter space





mass splittings constrained by T parameter

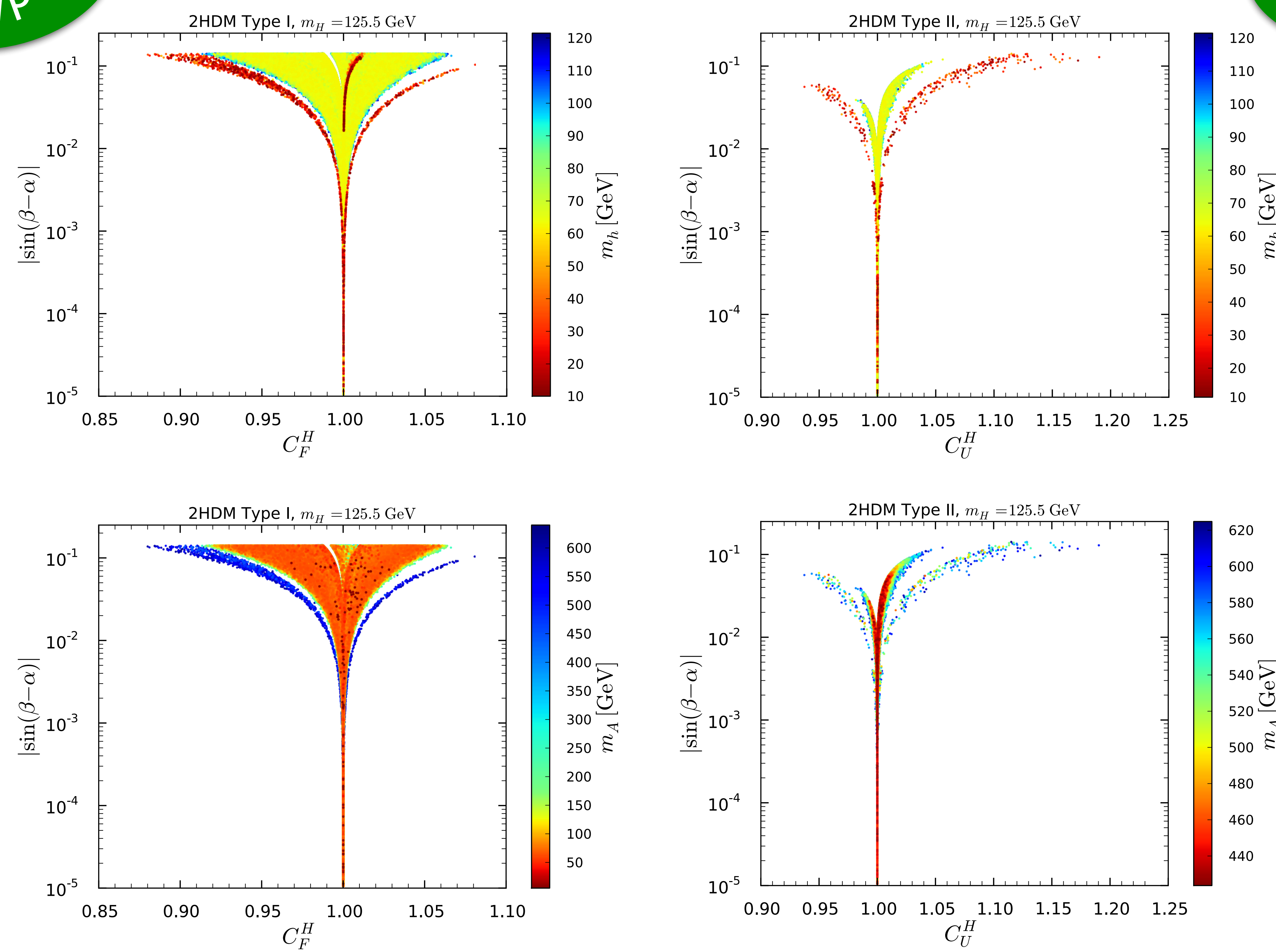
definite upper limit on A and $H^\pm$ masses of about 640 GeV

m_H=125 GeV, H=H_{SM}

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

Type I

Type II

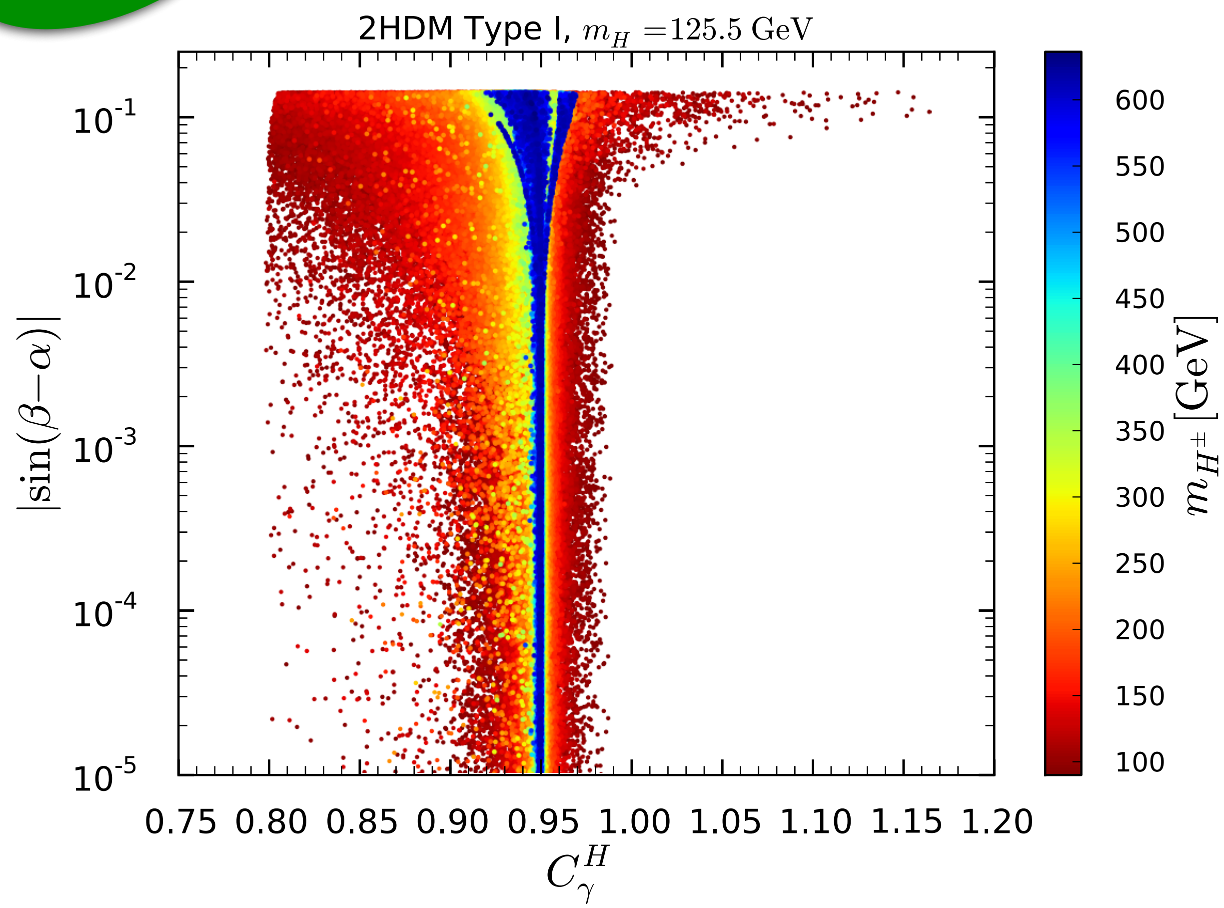


Deviations up to -15% in Type I, +20% in Type II for large h-A mass splitting (tanβ~1)

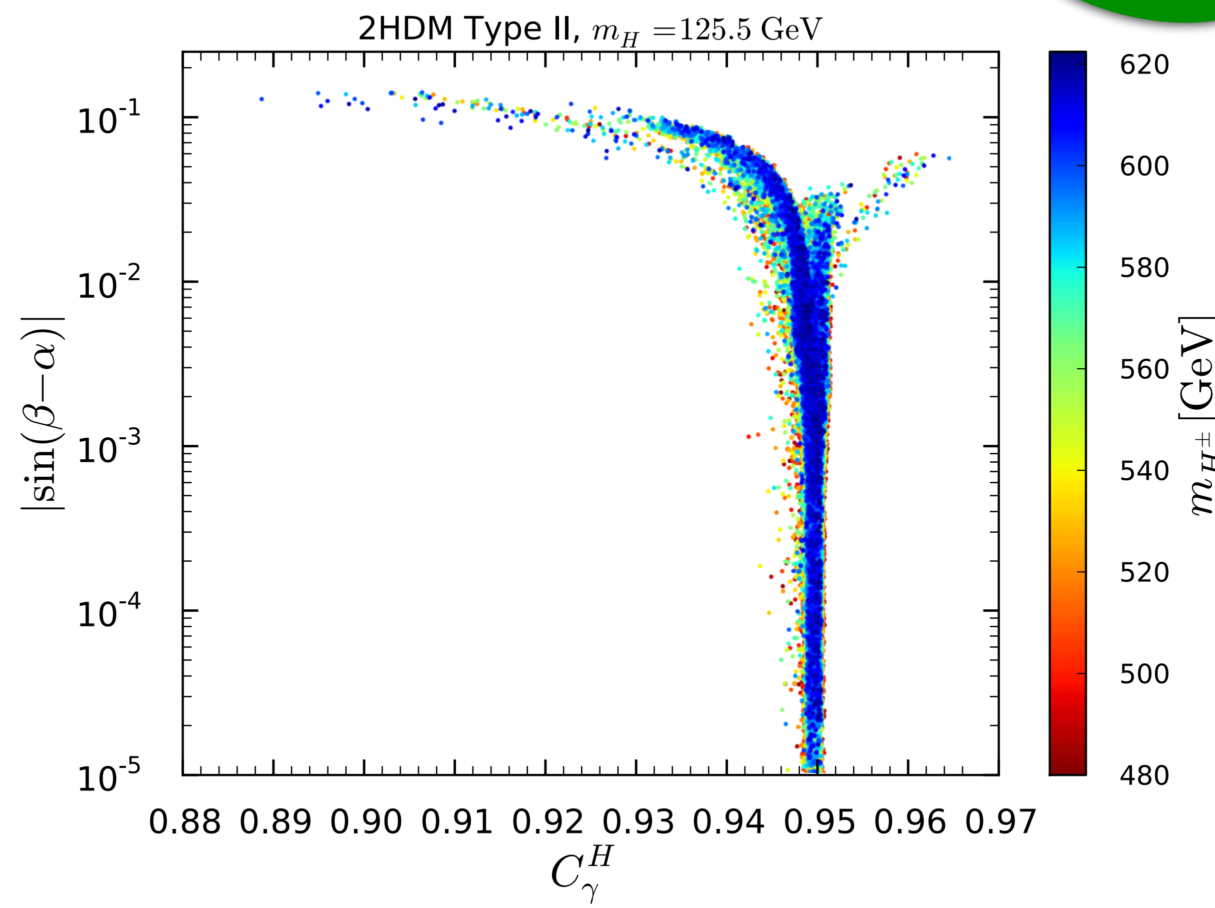
Coupling to photons: C_γ

Loop contributions from W, top and charged Higgs

Type I



Type II

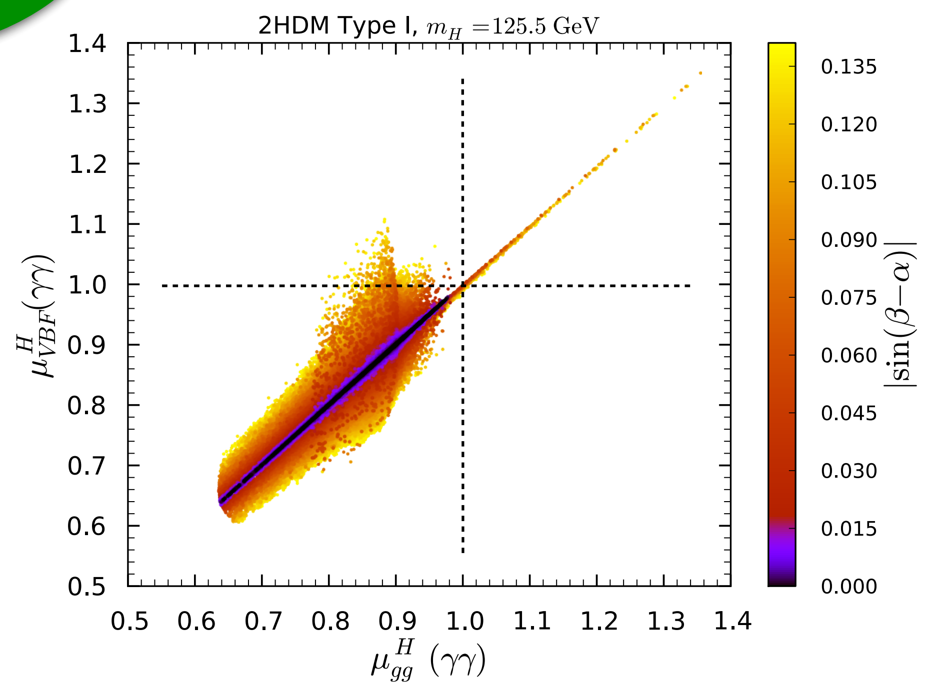


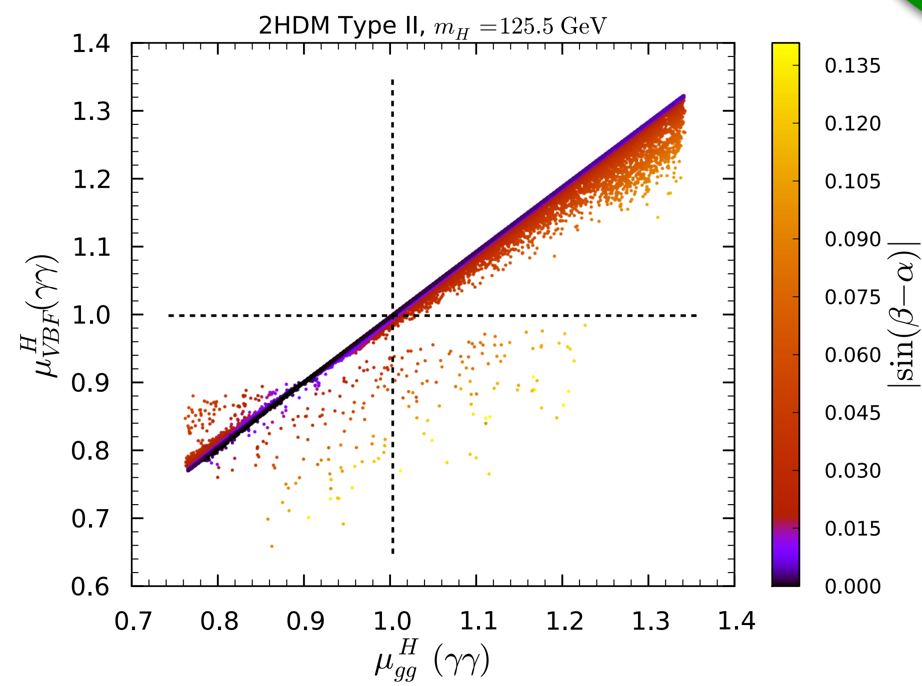
Does not align to unity:
Large deviations for a light charged Higgs even in deep alignment limit (Type I)
~5% suppression in the limit of a `heavy' charged Higgs

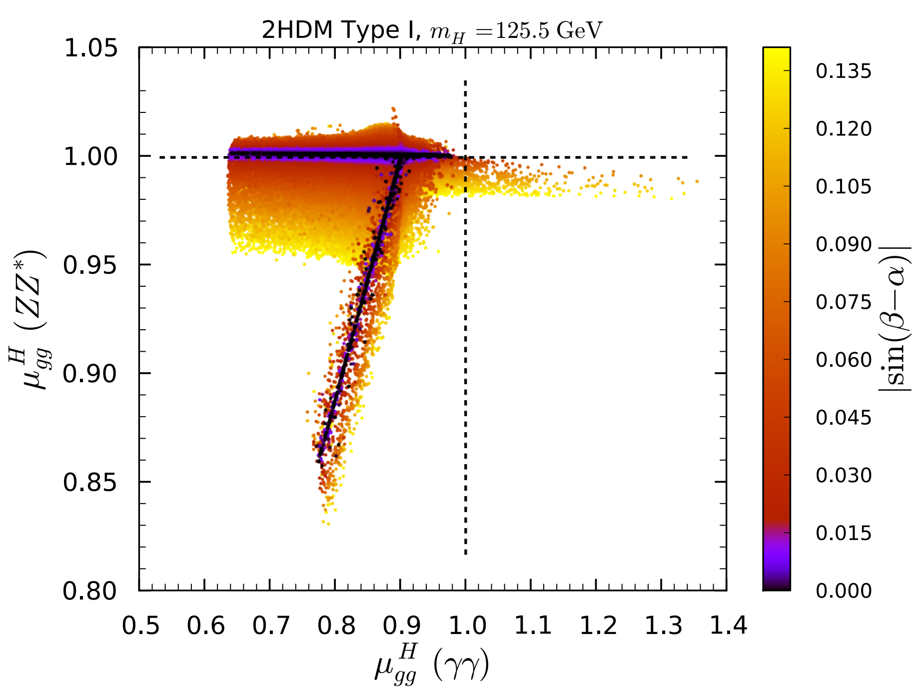
Signal strengths

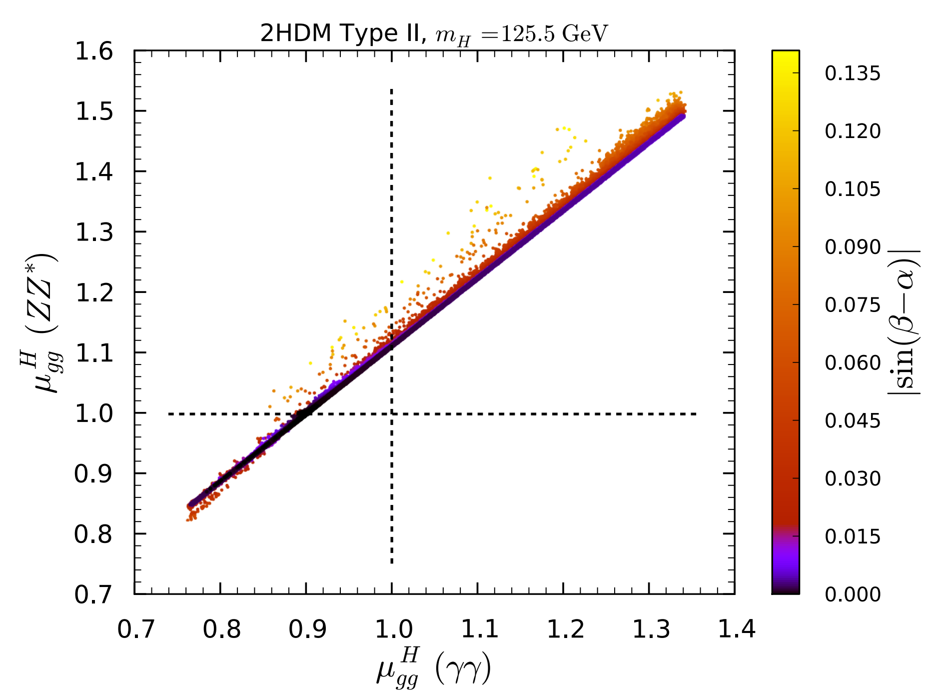
Type I

Type II









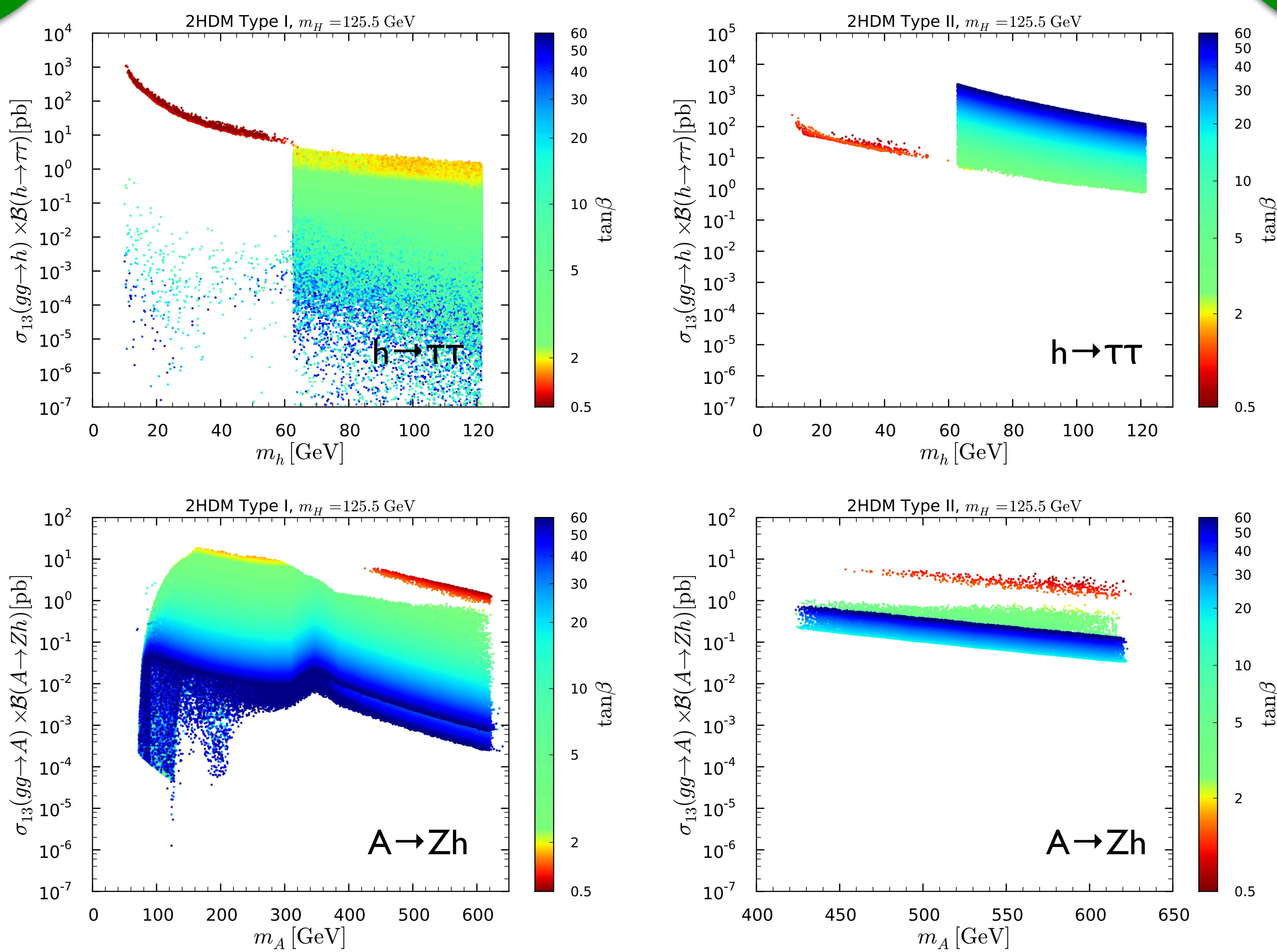
Again distinct correlations that distinguish Type I from Type II

m_H=125 GeV, H=H_{SM}

Searches at 13 TeV: $h \to \tau\tau$ and $A \to Zh$

Type I

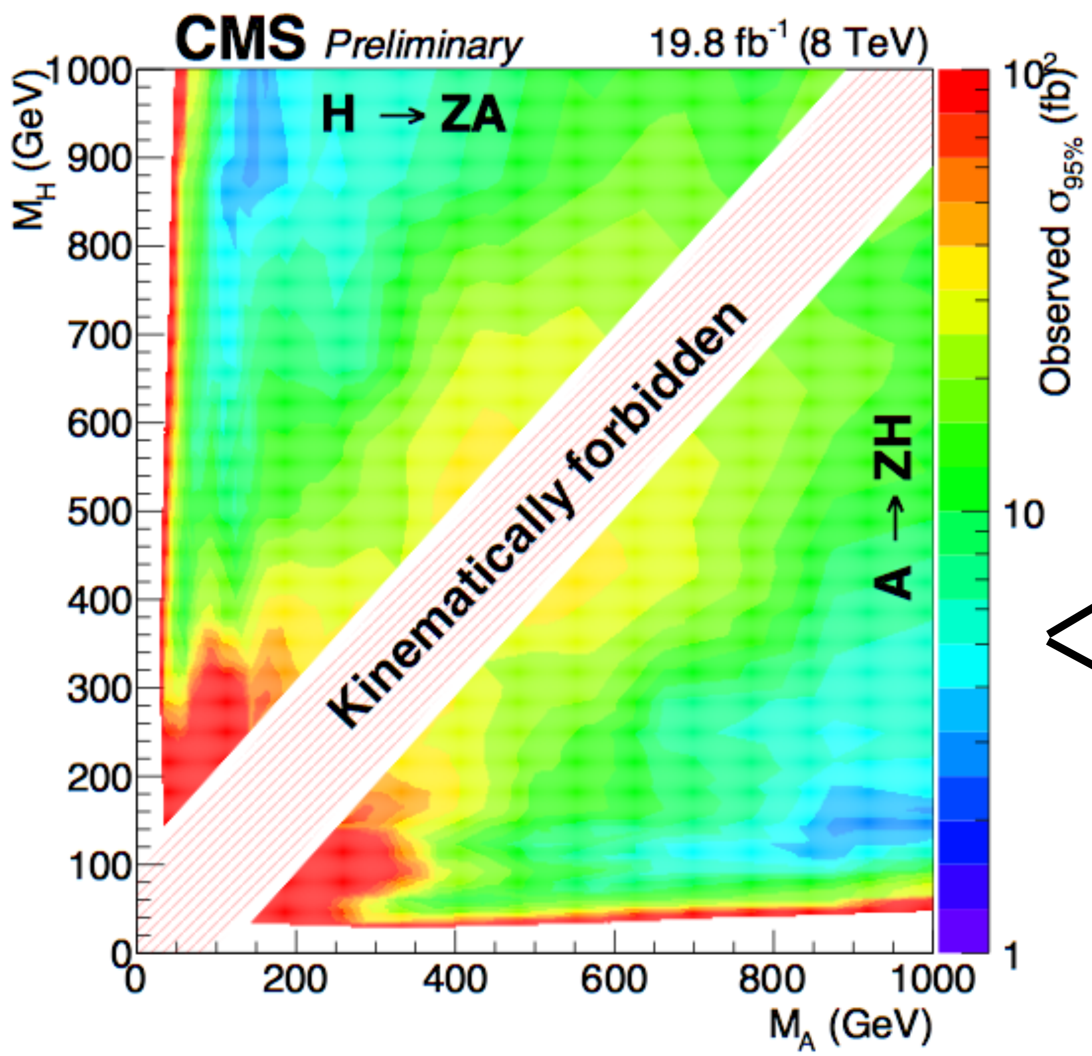
Type II



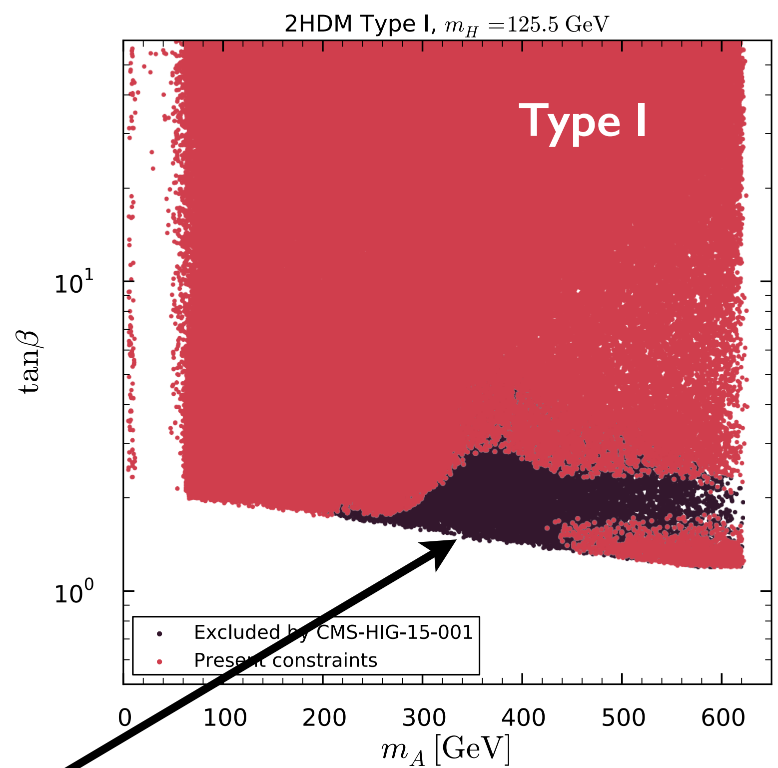
Note lower limit on cross section in Type II

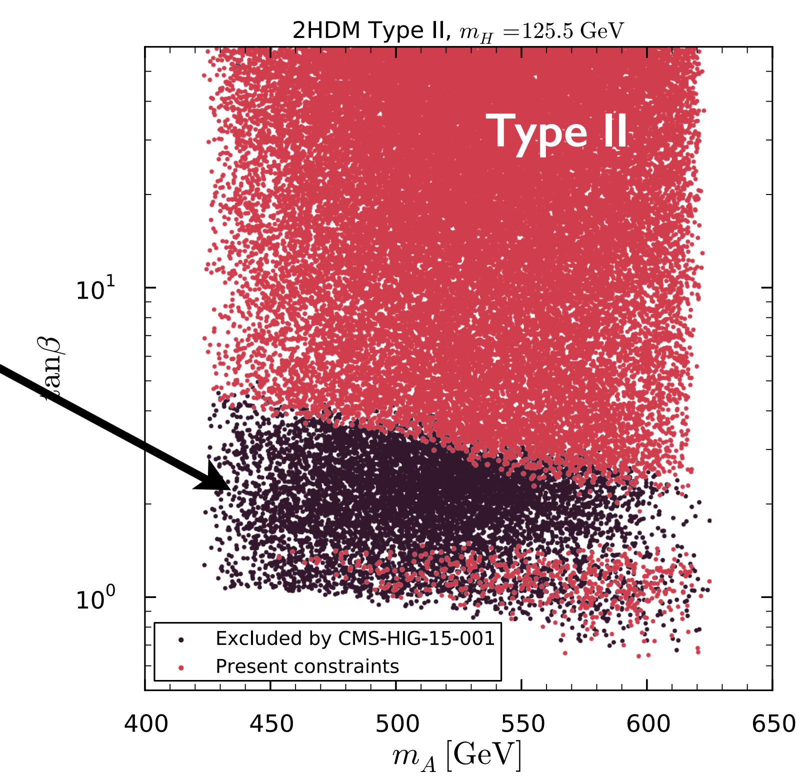
Impact of CMS limit on A→Zh

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





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 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>
```

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

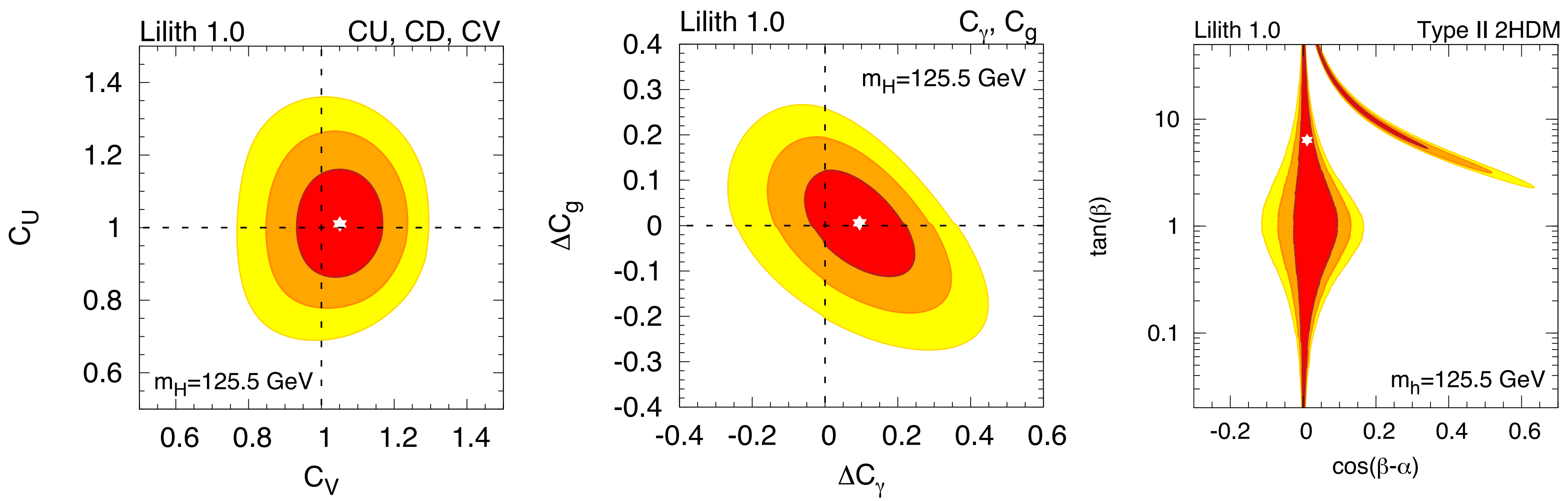
Calculation follows recommendations of LHC Higgs Cross Section Working Group

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