Status of 2HDM and C2HDM after run1

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24 February 2015

Higgs Cross Section Working Group
WG3: Extended Scalars

CP-conserving and explicit CP-violating (softly broken Z_2 symmetric)

$$V(\Phi_1,\Phi_2) = m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - (m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c}) + \frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}]$$

- m^2_{12} and λ_5 real, vacuum configuration (CP-conserving)

$$\langle\phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_1\end{pmatrix};\quad \langle\phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_2\end{pmatrix}$$

7 free parameters + M_W: $m_h,\ m_H,\ m_A,\ m_{H\pm},\ \tan\beta,\ \alpha,\ M^2 = \frac{m_{12}^2}{\sin\beta\ \cos\beta}$

- m^2_{12} and λ_5 complex, vacuum configuration (explicit CP-violating)

$$\langle\phi_1\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_1\end{pmatrix};\quad \langle\phi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\ v_2\end{pmatrix}$$

I. Ginzburg, M. Krawczyk and P. Osland, hep-ph/ 0211371.

8 free parameters + M_W: $m_1,\ m_2,\ m_3,\ m_{H\pm},\ \tan\beta,\ \alpha_{1,2,3},\ Re(m_{12}^2)$

Lightest Higgs couplings

$$\alpha_1 = \alpha + \pi / 2$$

to gauge bosons

$$g_{2HDM}^{hVV} = \sin(\beta - \alpha)\ g_{SM}^{hVV}$$

$$V = W, Z$$

CP-CONSERVING

$$g_{C2HDM}^{hVV} = C\ g_{SM}^{hVV} = (c_\beta R_{11} + s_\beta R_{12})\ g_{SM}^{hVV} = \cos(\alpha_2)\cos(\beta - \alpha_1)\ g_{SM}^{hVV}$$

CP-VIOLATING

$$g_{C2HDM}^{hVV} = \cos(\alpha_2)\ g_{2HDM}^{hVV}$$

$$C \equiv c_\beta R_{11} + s_\beta R_{12}$$

$$|s_2| = 0 \ \Rightarrow \ h_1 \text{ is a pure scalar,}$$
$$|s_2| = 1 \ \Rightarrow \ h_1 \text{ is a pure pseudoscalar}$$

$$R = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 s_3 \end{pmatrix}$$

Lightest Higgs couplings

Yukawa couplings

$$Y_{C2HDM} \equiv c_2 Y_{2HDM} \pm i\gamma_5 s_2 \begin{cases} t_\beta \\ 1/t_\beta \end{cases}$$

$$R = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 s_3 \end{pmatrix}$$

CP-CONSERVING

	Type I	Type II	Lepton Specific	Flipped
Up	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$
Down	$\frac{c_\alpha}{s_\beta}$	$-\frac{s_\alpha}{c_\beta}$	$\frac{c_\alpha}{s_\beta}$	$-\frac{s_\alpha}{c_\beta}$
Leptons	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$	$-\frac{s_\alpha}{c_\beta}$	$\frac{c_\alpha}{s_\beta}$

$$\alpha_1 = \alpha + \pi / 2$$

CP-VIOLATING

	Type I	Type II	Lepton Specific	Flipped
Up	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta}\gamma_5$	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta}\gamma_5$	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta}\gamma_5$	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta}\gamma_5$
Down	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}\gamma_5$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}\gamma_5$	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}\gamma_5$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}\gamma_5$
Leptons	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}\gamma_5$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}\gamma_5$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}\gamma_5$	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}\gamma_5$

Free parameters

Parameter	2HDM	C2HDM
masses	$m_h,\, m_H,\, m_A,\, m_{H^\pm}$	$m_{h_1},\, m_{h_2},\, m_{H^\pm}$
v_2/v_1	$\tan\beta$	$\tan\beta$
angles (neutral)	α	$\alpha_1,\, \alpha_2,\, \alpha_3$
soft breaking	m_{12}^2	$Re(m_{12}^2)$

$\alpha_1 = \alpha + \pi / 2$

- Set m_h/m_{h1} = 125 GeV.

- Generate random values for the parameters subject to

    - Pre-LHC constraints
    - Theoretical bounds
    - LHC (Tevatron and LEP) results via HiggsBounds and HiggsSignals

ScannerS (Scan "R" Us)

- Tool to **Scan** parameter space of **Scalar** sectors.
- **Automatise** scans for tree level renormalisable V_{scalar}.
- **Generic** routines, **flexible** user analysis & **interfaces**.

COIMBRA, SAMPAIO, RS, (2013).

THOR FERREIRA, RS (????)

interfaced with

Higlu SPIRA (1995).

SuShi – Higgs production at NNLO in gg and bb HARLANDER, LIEBLER, MANTLER, (2013).

HDECAY – Higgs decays DJOUADI, KALINOWSKI, SPIRA (1997) + MÜHLLEITNER (2013).

Superiso – Some of the flavour physics observables MAHMOUDI (2007).

HiggsBounds – Limits from Higgs searches at LEP, Tevatron and LHC

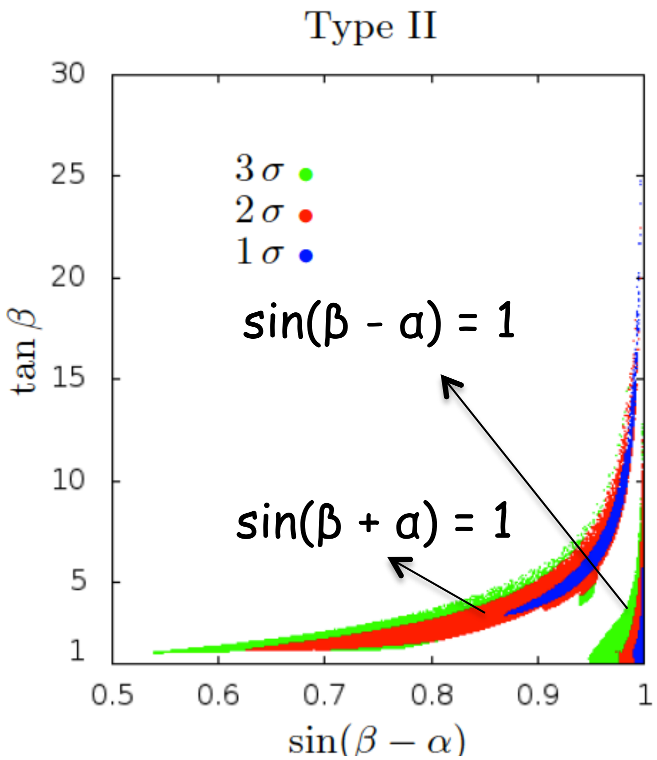
HiggsSignals – Signal rates at the Tevatron and LHC

BECHTLE, BREIN, HEINEMEYER, STÅL, STEFANIAK, WEIGLEIN, WILLIAMS (2010-2015)

and ScannerS has the remaining constraints/cross sections

- Global minimum, perturbative unitarity, potential bounded from below, electroweak precision and some alternative sources for B-physics constraints.

http://www.hepforge.org/archive/scanners/ScannerSmanual-1.0.2.pdf



Results after run 1 for the CP-conserving case

The SM-like limit (alignment)

all tree-level couplings to fermions
and massive gauge bosons are the SM ones.

$$\kappa_i = \frac{g_{2HDM}}{g_{SM}}$$

at tree-level

$$\kappa_i^2 = \frac{\Gamma^{2HDM}(h \to i)}{\Gamma^{SM}(h \to i)}$$

$$\sin(\beta-\alpha) = 1 \quad \Rightarrow \quad \kappa_F = 1; \quad \kappa_V = 1$$

Ginzburg, Krawczyk, Osland 2001

Ferreira, Gunion, Haber, RS 2014

Ferreira, Guedes, Sampaio, RS 2014

Wrong-sign limit

$$\kappa_D \kappa_V < 0 \quad \text{or} \quad \kappa_U \kappa_V < 0$$

$$\sin(\beta+\alpha) = 1 \quad \Rightarrow \quad \kappa_D = -1 \quad (\kappa_U = 1)$$

$$\sin(\beta-\alpha) = \frac{\tan^2\beta - 1}{\tan^2\beta + 1} \quad \Rightarrow \quad \kappa_V \geq 0 \ \text{ if } \ \tan\beta \geq 1$$

Shape comes primarily from μ_{VV}

Assuming that the cross section is **gluon fusion via top** and $\Gamma_T \approx \Gamma\,(h \to b\bar{b})$

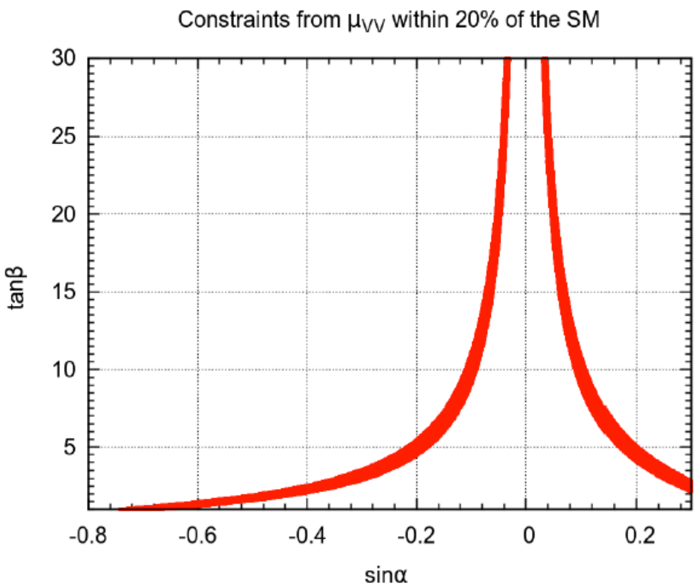
$$\mu_{VV} \approx \kappa_V^2 \frac{\kappa_U^2}{\kappa_D^2}$$

Type II

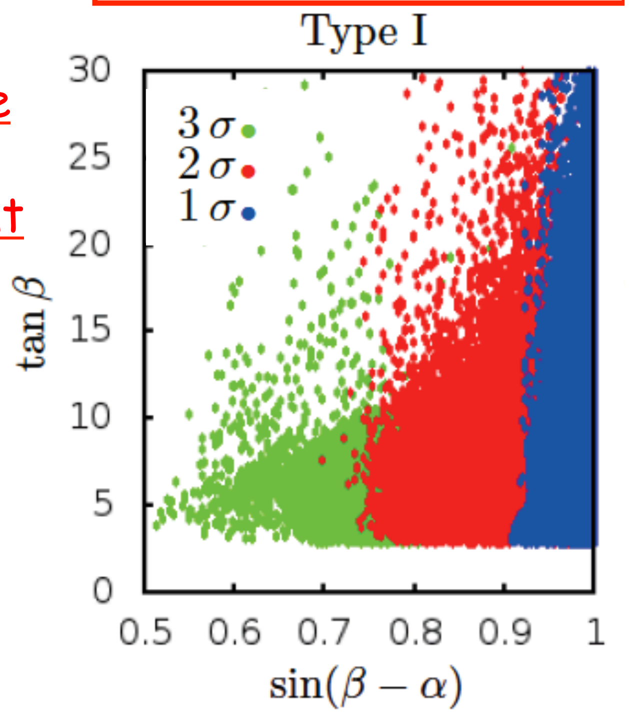
$$\mu_{VV} \approx \frac{\sin^2(\beta-\alpha)}{\tan^2\alpha\,\tan^2\beta}$$

Type I

$$\mu_{VV} \approx \mu_{\tau\tau} \approx \sin^2(\beta-\alpha)$$

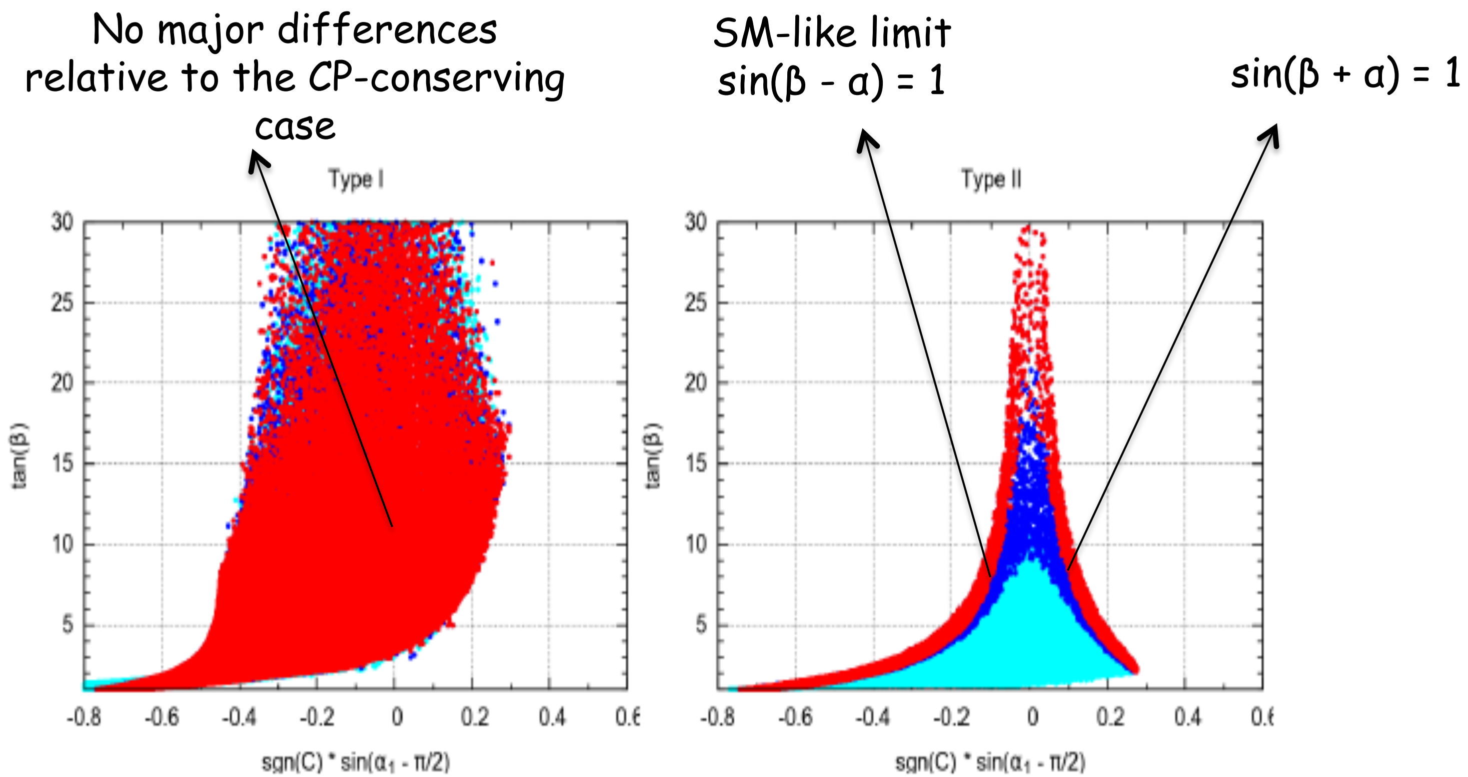


Bounds are almost independent of tanβ



Plot from: Fontes, Romão, Silva, 1406.6081

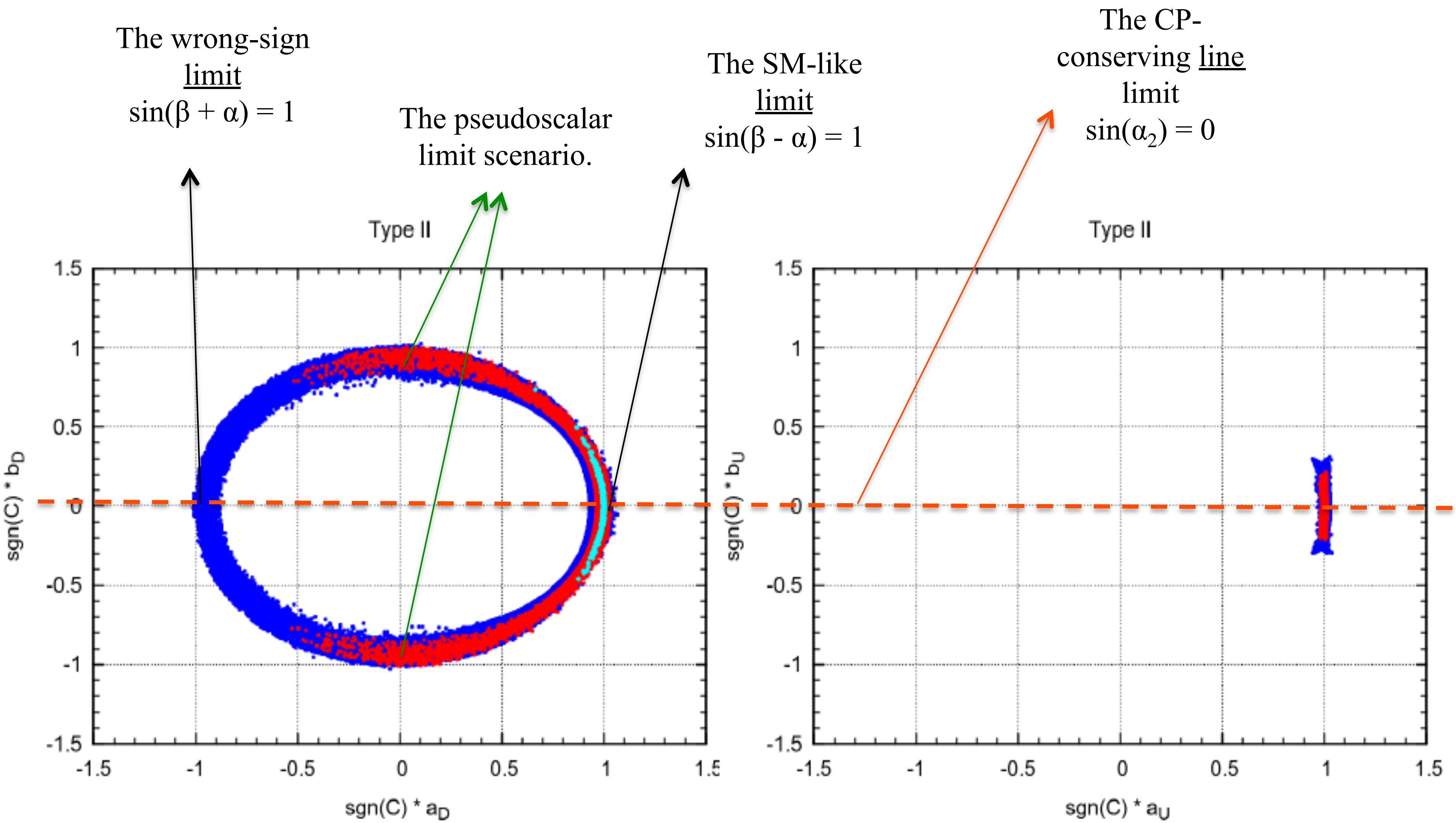
Results after run 1 for C2HDM



tanβ as a function of $\sin(\alpha_1 - \pi/2)$ for Type I and Type II. Full range (cyan), $s_2 < 0.1$ (blue) and $s_2 < 0.05$ (red).

Fontes, Romão, Silva, RS, 2015

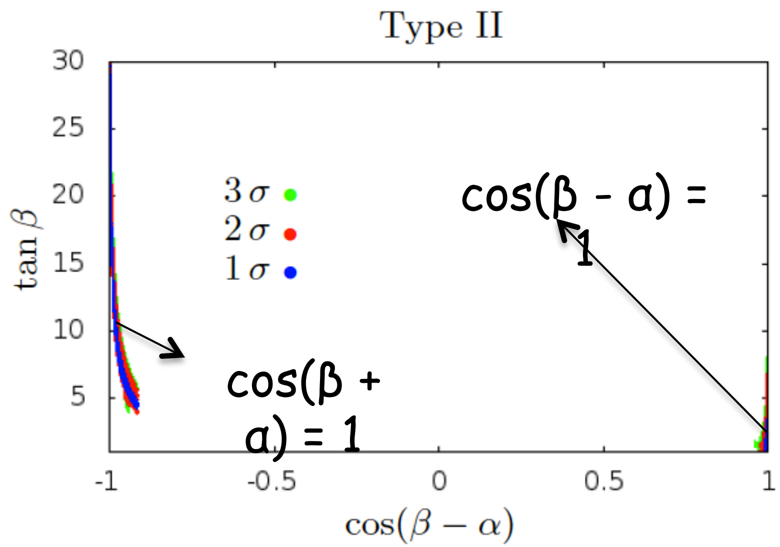
The future at the LHC



Left: sgn(C) b_D (or b_L) as a function of sgn(C) a_D (or a_L) for Type II, 13 TeV, with rates at 10% (blue), 5% (red) and 1% (cyan) of the SM prediction.

Right: same but for up-type quarks.

Heaviest CP-even scalar as the SM-like Higgs

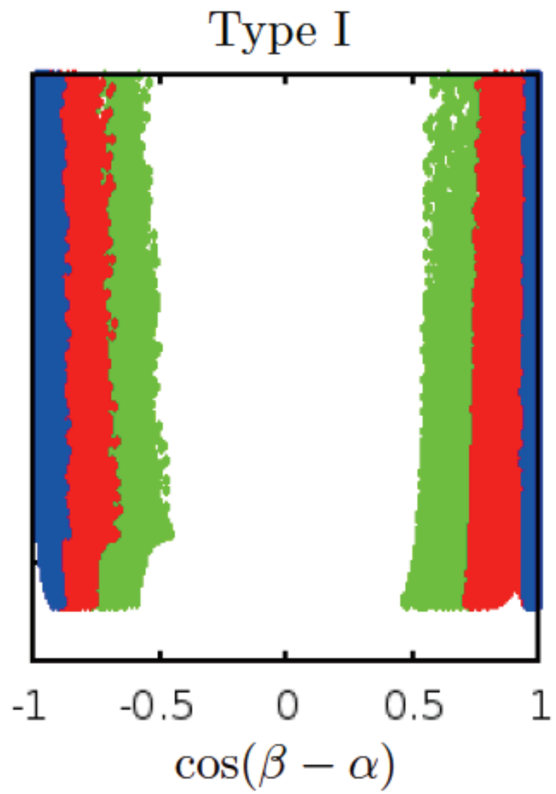


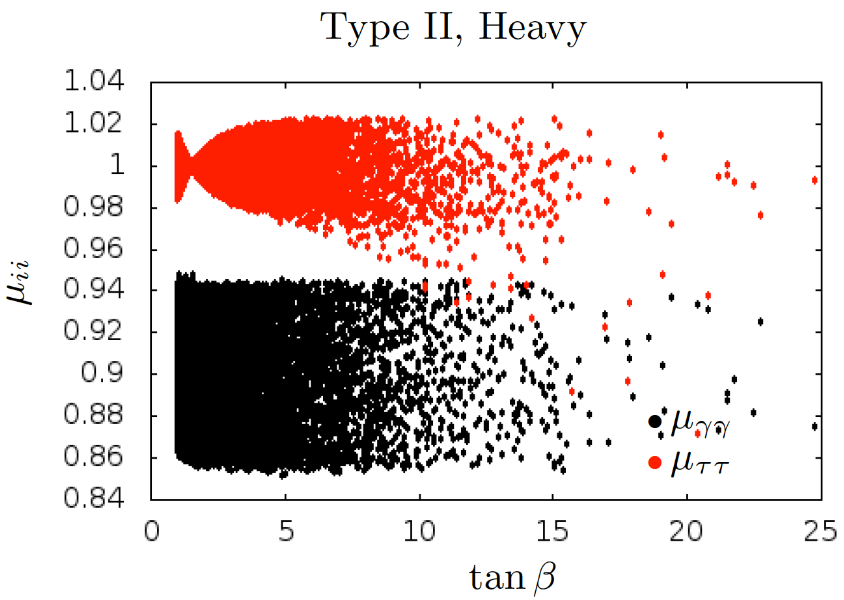
The SM-like limit

$$\cos(\beta-\alpha)=1 \Rightarrow$$
$$\Rightarrow \kappa_F=1;\ \kappa_V=1$$

The reasons for the exclusion can be easily rephrased in terms of tanβ and cos(β-α).

Wrong-sign limit $\kappa_D\kappa_V<0$



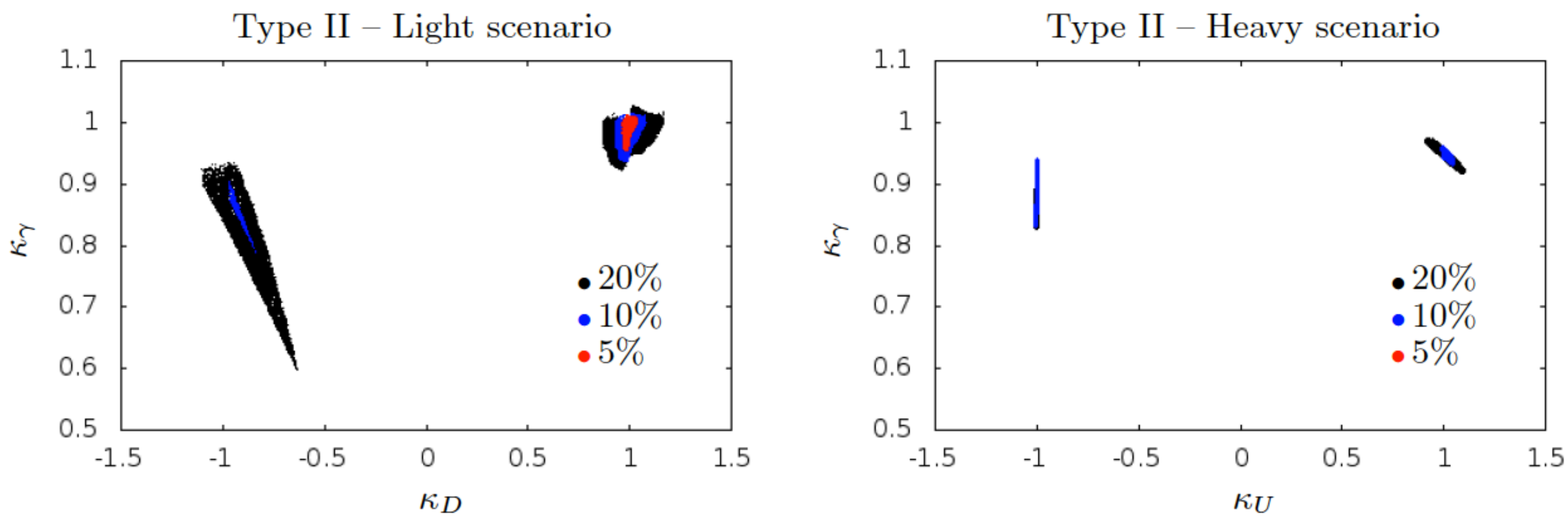


However $\mu_{\gamma\gamma}$ is always below 0.95.

The SM-like limit could be probed due to the non-decoupling nature of this scenario.

Two scenarios that could be probed at run2 with high luminosity

For the 2HDM - Accuracy in h-> γγ



5% would exclude the wrong sign in both scenarios but also the heavy scenario in the SM-like limit due to the effect of charged Higgs loops + theoretical and experimental constraints. In fact, the heavy scenario is completely excluded with a 5 % accuracy in h -> γγ.

Scenarios that could be probed at run2 with high luminosity

For the C2HDM

• To probe all four versions of the model we need three independent measurements

$$\tan\phi_i = \frac{b_i}{a_i}; \qquad i = U, D, L$$

Ratio of pseudoscalar to scalar components in Yukawa couplings.

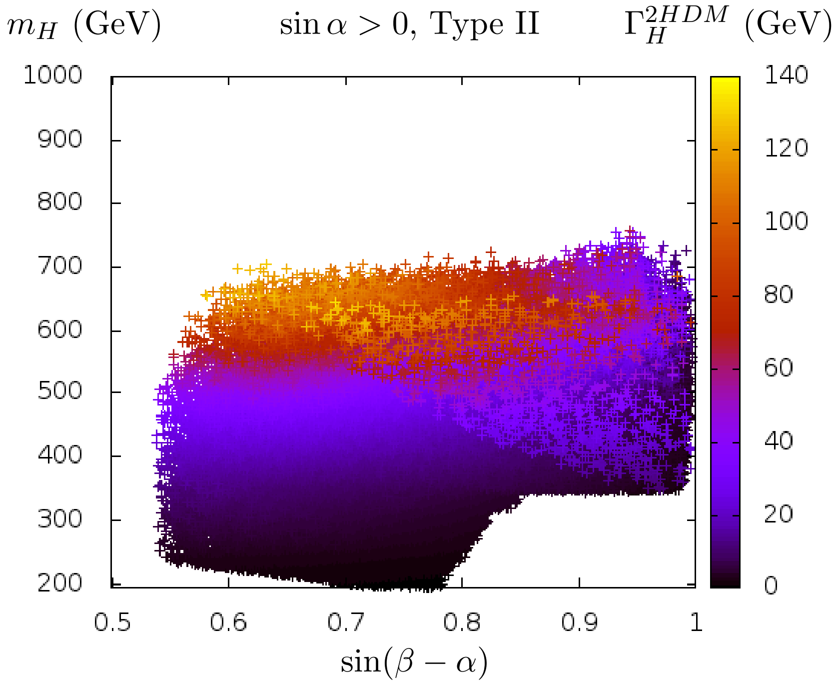
• Just one measurement for type I (U=D=L), two for the other three types. At the moment there are studies for tth and ττh. We also need bbh.

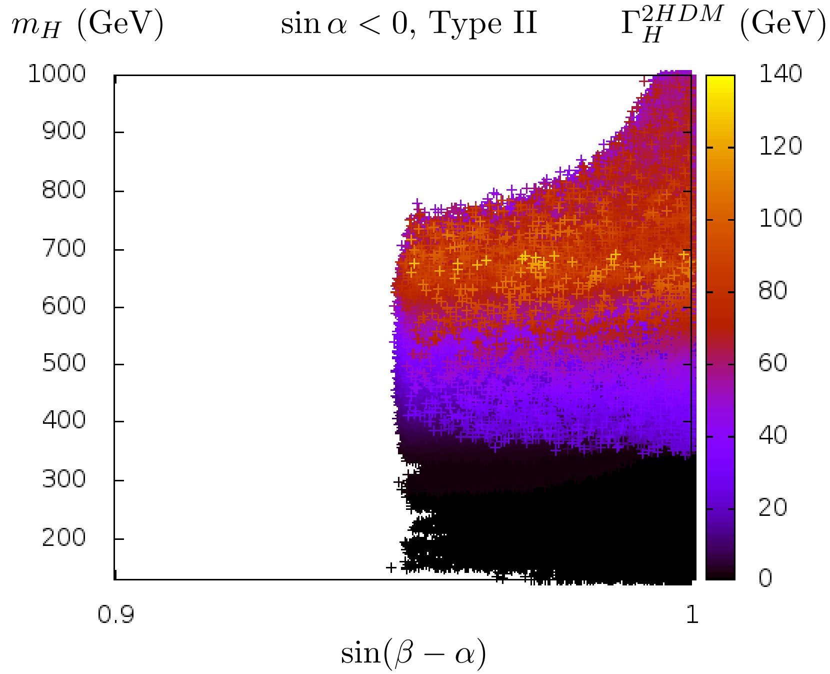
Berge, Bernreuther, Ziethe 2008
Berge, Bernreuther, Niepelt, Spiesberger, 2011
Berge, Bernreuther, Kirchner 2014

Dolan, Harris, Jankowski, Spannowsky, 2014

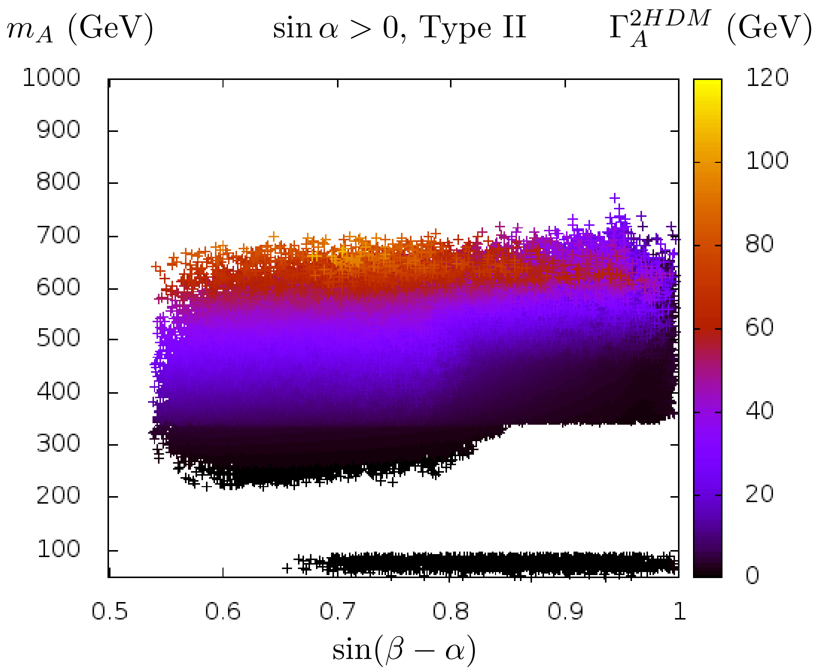
Boudjema, Godbole, Guadagnoli, Mohan, 2015

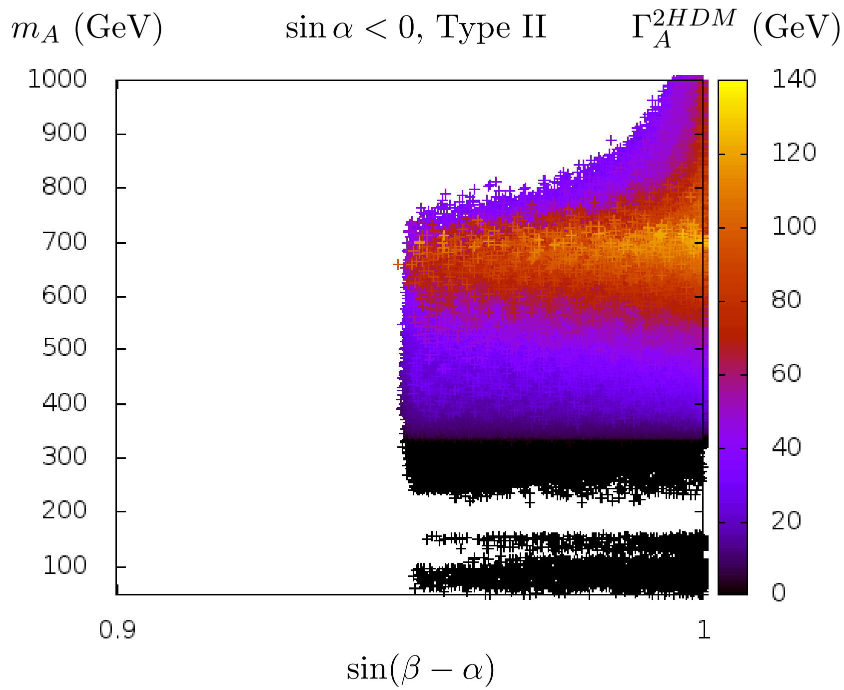
Discussion





Heavy Higgs mass and width

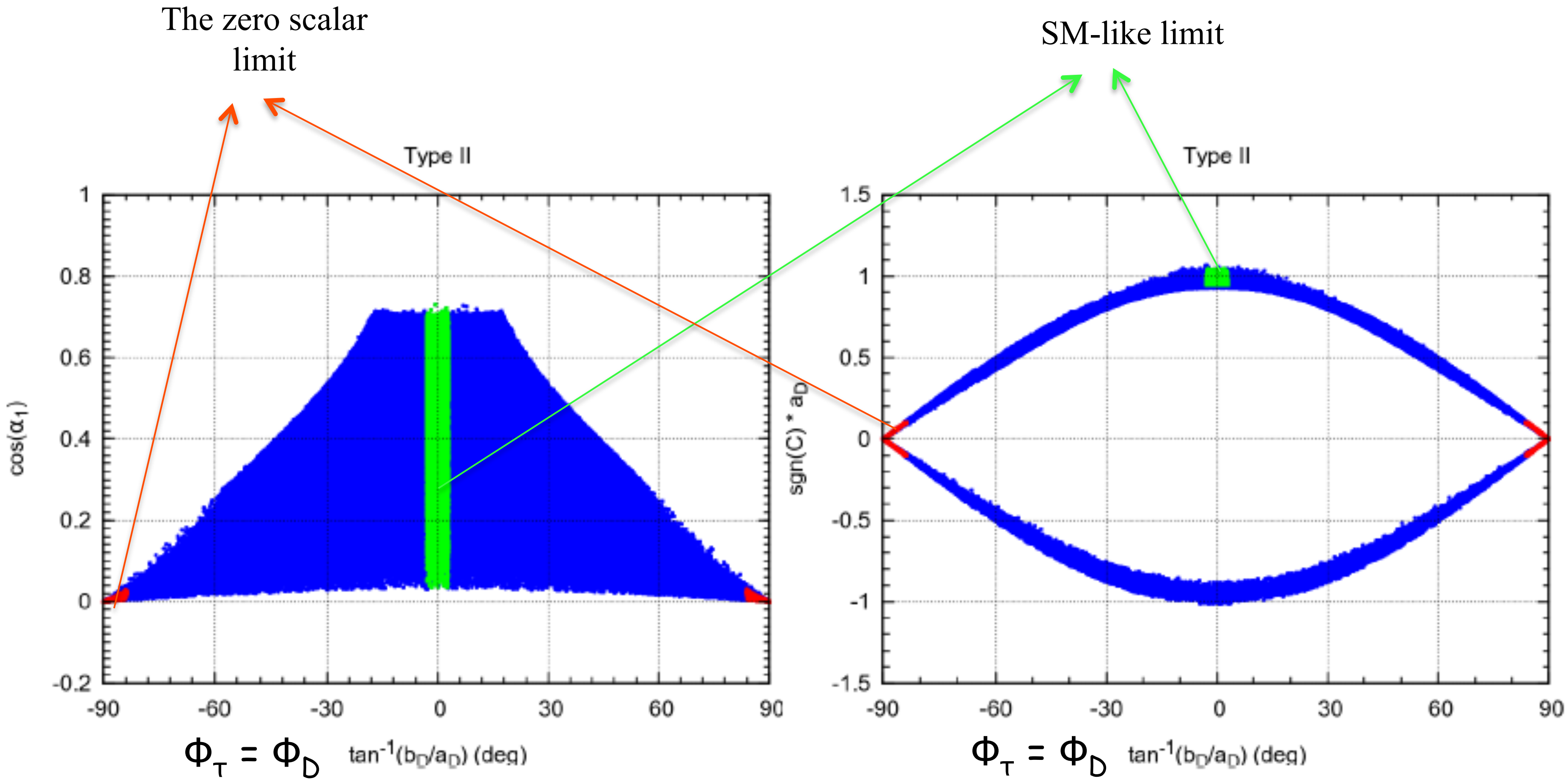




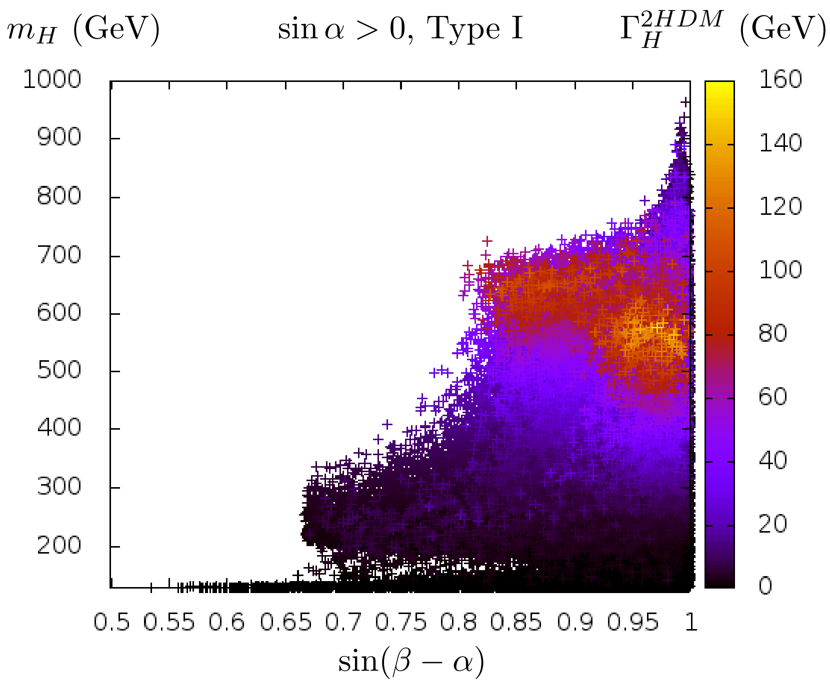
A mass and width

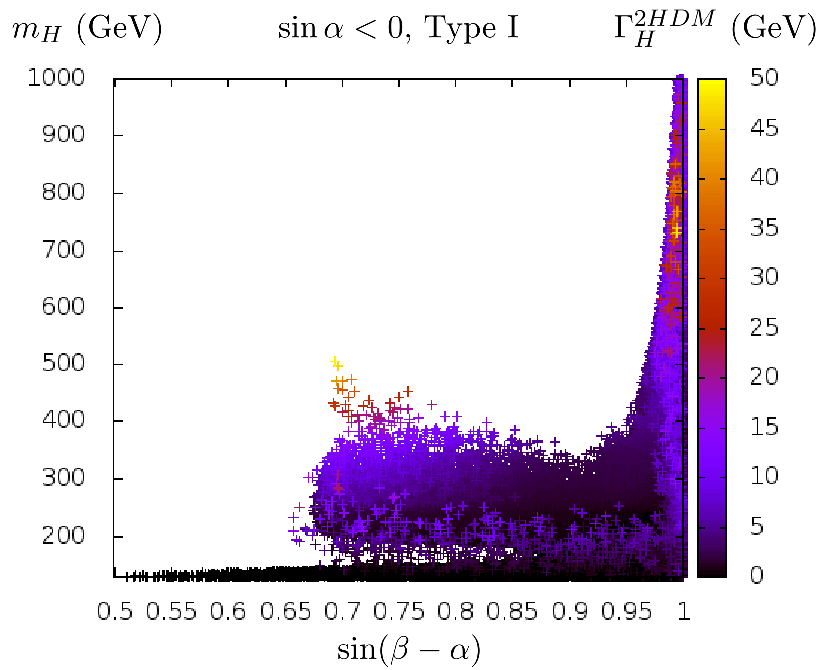
BACKUP

Direct probing at the LHC

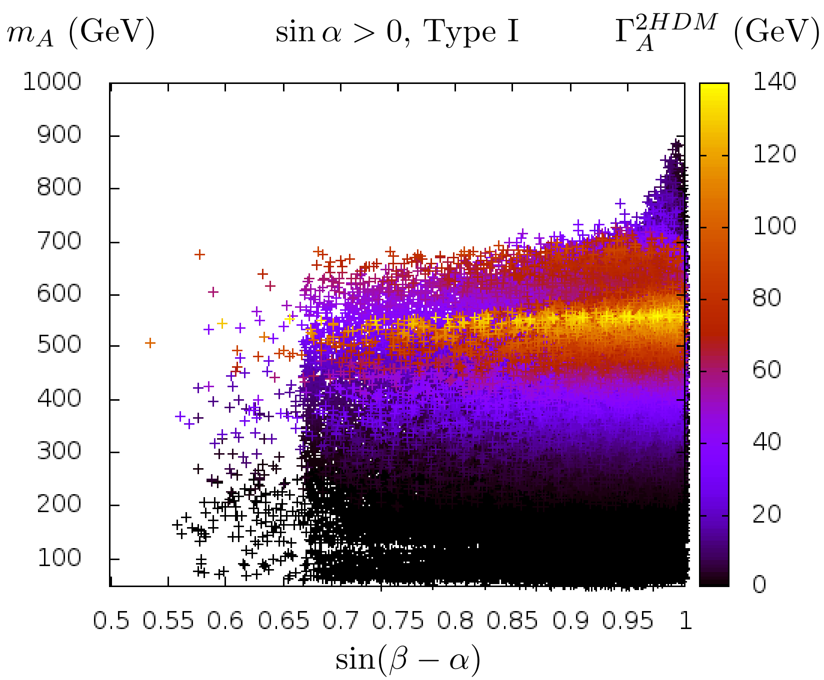


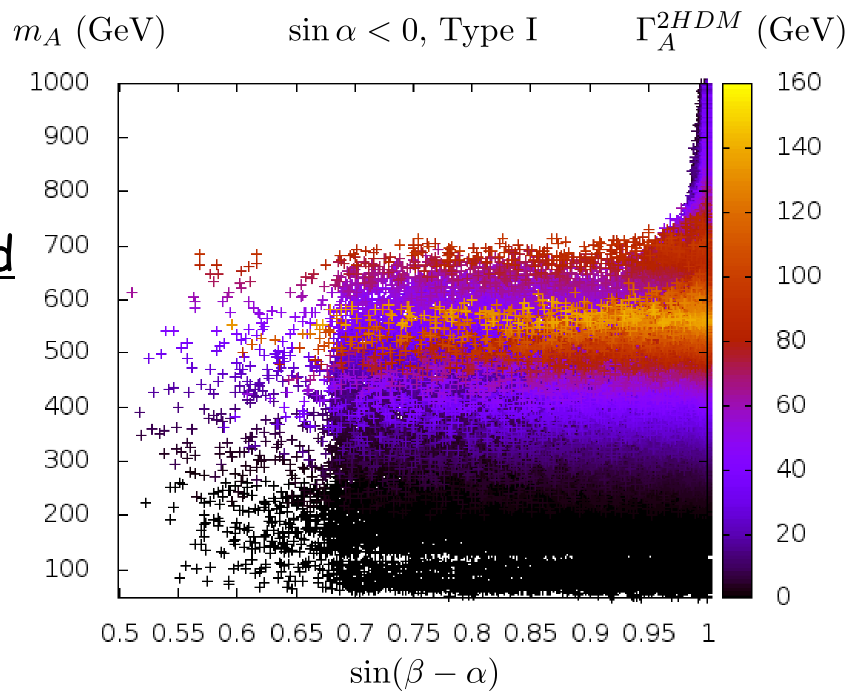
Left: $\cos\alpha_1$ as a function of Φ_D for Type II, 13 TeV, with all rates at 10% (blue); $|a_D| < 0.1$ $||b_D|-1| < 0.1$ (green); $|b_D| < 0.05$ $||a_D|-1| < 0.05$ (red).
Right: same with $\tan\beta$ replaced by $\mathrm{sgn}(C)\, a_D$.





Heavy Higgs mass and width





A mass and width

SM-like limit (alignment)
vs
Decoupling

The decoupling limit of 2HDM

$M_{12}^2 \to \infty$, $\cos(\alpha - \beta) \to 0$

- In this limit, the masses of Φ=H, $H^\pm$, A:

$$m_\Phi^2 = M_{12}^2 + \sum_i \lambda_i v^2 + \mathcal{O}(v^4/M_{12}^2), \quad , \quad m_h^2 = \sum_i \lambda_i v^2$$

- When $M_{12}^2 \gg \lambda_i v^2$, $m_{H,A,H\pm}^2$ are determined by M_{12}^2, and are independent of λ_i. In this case $\alpha \to \beta - \pi/2$, The effective theory below M_{12} is described by one Higgs doublet. In this limit:

$$h^0VV/(h_{SM}VV) = \sin(\beta - \alpha) \to 1$$

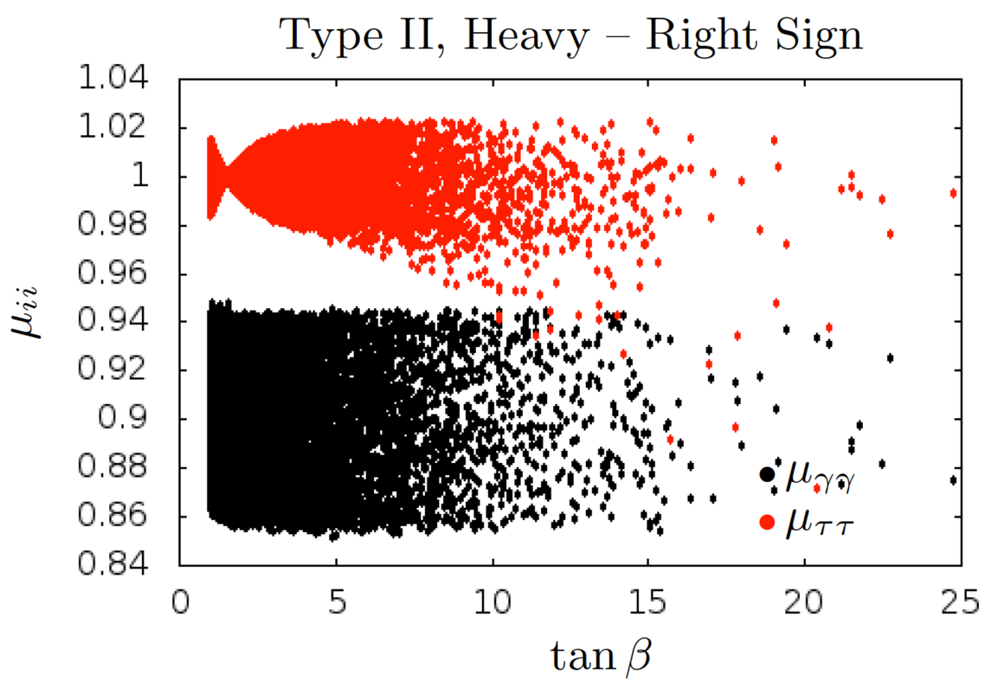
$$h^0 b\bar{b}/h_{SM} b\bar{b} = -\frac{\sin\alpha}{\cos\beta} \to 1 \ , \ (h^0 \bar{t}t)/h_{SM} t\bar{t} = \frac{\cos\alpha}{\sin\beta} \to 1$$

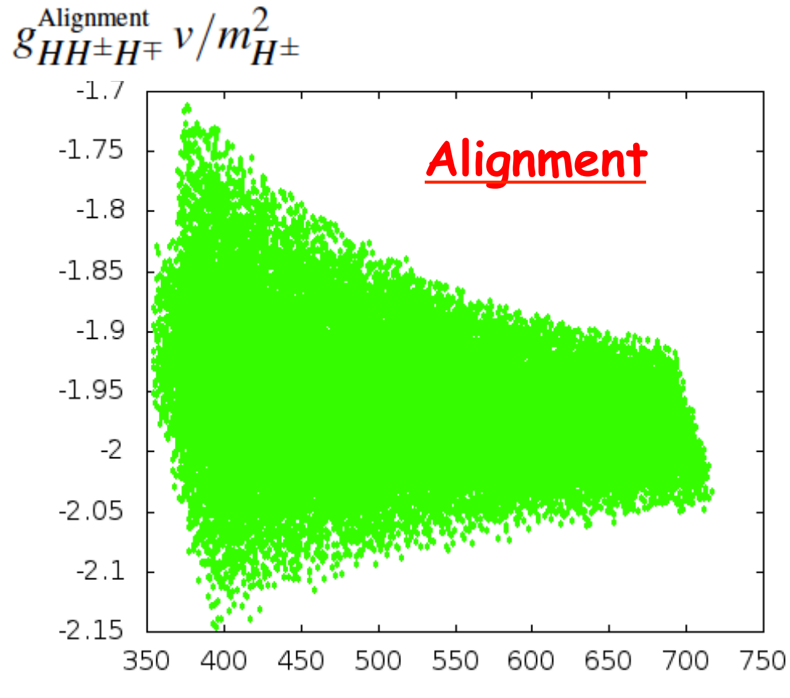
$$H^0VV \propto \cos(\beta - \alpha) \to 0 \ , \ (hhh)/(hhh)_{SM} \to 1$$

$$h^0H^+H^-, h^0A^0A^0, h^0H^0H^0, H^\pm t\bar{b} ... \neq 0$$

Gunion, Haber (2003)

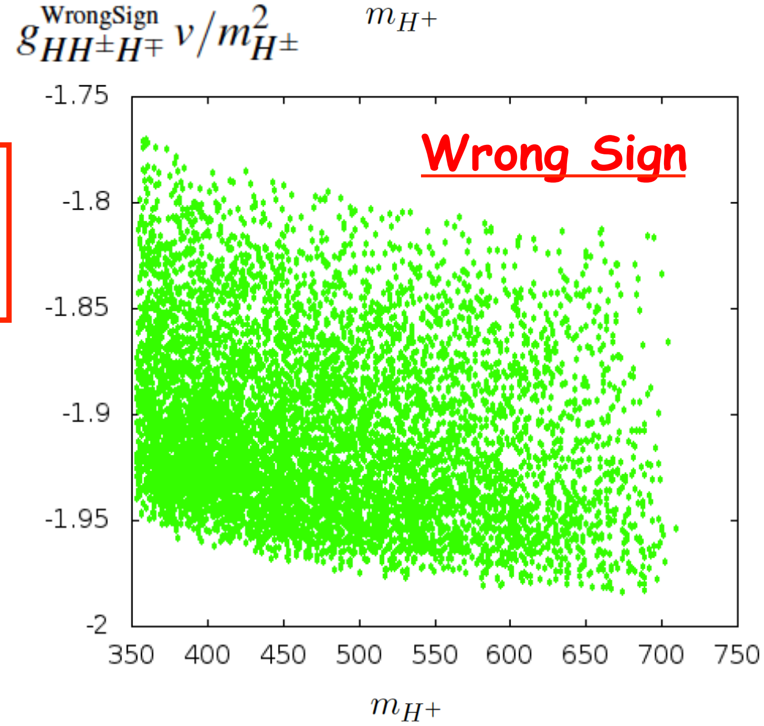
Heavy scenario and boundness from below





$$g^{SM-like}_{HH^+H^-} \approx -\frac{2m^2_{H^\pm} - m^2_H - 2M^2}{v^2}$$

$$g^{Wrong\ Sign}_{HH^+H^-} \approx -\frac{2m^2_{H^\pm} - m^2_H}{v^2}$$



Boundness from below

$$M < \sqrt{m^2_H + m^2_h/\tan^2\beta}$$

b -> s γ

$$m^2_{H^\pm} > 340 \ \text{GeV}$$

Parametrisation (8)

W. Khater and P. Osland, Nucl. Phys. B 661, 209 (2003).

- 2 charged, $H^{\pm}$, and 3 neutral, h_1, h_2 and h_3 **3 masses**

- $$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \end{pmatrix} \qquad R\,\mathcal{M}^2\,R^T = \mathrm{diag}\left(m_1^2, m_2^2, m_3^2\right)$$

$$R = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{pmatrix}$$ **3 angles**

- $\mathrm{Re}\left[m_{12}^2\right]$ **real part of the soft breaking term**

- $\tan\beta$ **ratio of vacuum expectation values**

- $$m_3^2 = \frac{m_1^2\, R_{13}(R_{12}\tan\beta - R_{11}) + m_2^2\, R_{23}(R_{22}\tan\beta - R_{21})}{R_{33}(R_{31} - R_{32}\tan\beta)}$$

- There are 3 neutral scalars. The CP nature of h_1 is determined by s_2

$$|s_2| = 0 \;\Rightarrow\; h_1 \text{ is a pure scalar,}$$
$$|s_2| = 1 \;\Rightarrow\; h_1 \text{ is a pure pseudoscalar}$$

$$g_{CPV} = g_{CPC} = g_{SM}\cos(\beta - \alpha_1)$$

but we can still have CP-violation (the two heavier scalars can mix).

- However if

$$\alpha_2 = 0;\; \beta - \alpha_1 = 0 \qquad R_{11} = c_\beta;\; R_{12} = s_\beta;\; R_{13} = 0$$

that is, the h_1WW vertex is the SM one

$$g_{CPV} = g_{SM}\cos(\alpha_2)\cos(\beta - \alpha_1) = g_{SM}$$

the model is CP-conserving.

Grzadkowski, Ogreid, Osland, 2014.

Scan 2HDM

- Set m_h = 125.9 GeV

- Generate random values for potential's parameters such that

$$50 \text{ GeV} \le m_{H^+} \le 1 \text{ TeV}$$

$$m_h + 5 \text{ GeV} \le m_A, m_H \le 1 \text{ TeV}$$

$$-900^2 \text{ GeV}^2 \le m_{12}^2 \le 900^2 \text{ GeV}^2$$

$$0.5 \le \tan\beta \le 50$$

$$-\frac{\pi}{2} \le \alpha \le \frac{\pi}{2}$$

- Impose theoretical and pre-LHC experimental constraints

- Calculate all branching ratios and production rates at the LHC

- Use collider constraints via HiggsBounds and HiggsSignals

Scan C2HDM

- Set m_{h1} = 125 GeV.
- Generate random values for potential's parameters such that,

$$-\pi/2 < \alpha_{1,2,3} \leq \pi/2$$

$$1 \leq \tan\beta \leq 30$$

$$m_1 \leq m_2 \leq 900\,\mathrm{GeV}$$

$$-(900\,\mathrm{GeV})^2 \leq Re[m_{12}^2] \leq (900\,\mathrm{GeV})^2$$

$$100\,\mathrm{GeV} \leq m_{H^\pm} \leq 900\,\mathrm{GeV}$$

$$m_{H^\pm} \gtrsim 340\ \mathrm{GeV}$$

- Impose pre-LHC experimental constraints,
- Impose theoretical constraints: perturbative unitarity, potential bounded from below.

Predictions:

Same as before except no HiggsBounds and HiggsSignals:

- Calculate all branching ratios and production rates at the LHC

$$\mu_{XX} = \frac{\sigma^{2HDM}(pp \to h) \times BR^{2HDM}(h \to XX)}{\sigma^{SM}(pp \to h) \times BR^{SM}(h \to XX)}$$

- Ask for $\mu_{WW}, \mu_{ZZ}, \mu_{\gamma\gamma}, \mu_{\tau\tau}$

  to be within 5, 10 and 20 % of the SM predictions (at 13 TeV)

- Sum over all production cross sections

The zero scalar scenarios

- There is only one way to make the pseudoscalar component to vanish

$$R_{13} = 0 \quad \Rightarrow \quad s_2 = 0$$

and they all vanish (for all types and all fermions).

- There are two ways of making the scalar component to vanish

$$R_{11} = 0 \quad \Rightarrow \quad c_1 c_2 = 0$$

$$\rightarrow \quad c_2 = 0 \quad \Rightarrow \quad g_{h1VV} = 0$$ **excluded**

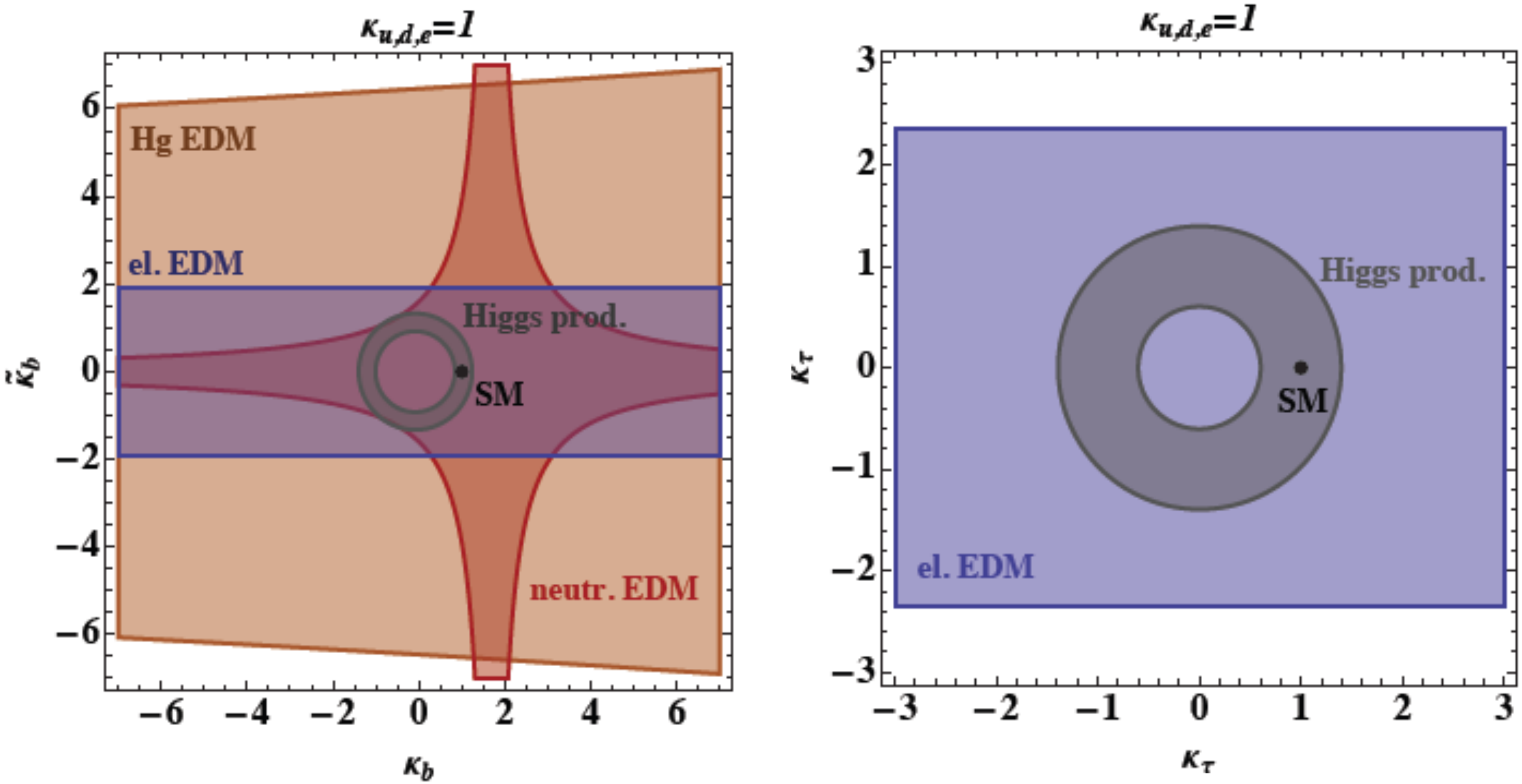
$$\searrow \quad c_1 = 0$$ **allowed**

$$R_{12} = 0 \quad \Rightarrow \quad s_1 c_2 = 0$$

excluded

	Type I	Type II	Lepton Specific	Flipped
Up	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta}$
Down	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}$	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}$
Leptons	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}$	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}$

EDMs



Plot from: Brod, Haisch, Zupan, JHEP 1311 (2013) 180.

See also

Inoue, Ramsey-Musolf, Zhang, 2014

Cheung, Lee, Senaha, Tseng, 2014