Interpretation of the LHC run-1 Higgs results (2HDM)

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“The 2HDM” (2013)

SPIRES ($\sim 10^3$)

- 105 with 2HDM
- 652 with two(-)Higgs doublet
- 11 with THDM
- 102 with inert
- 42 with 2(-)Higgs doublet
- ? unidentifiable

Outlook

Introduction

- Yukawa Lagrangian and FCNC
- Higgs potential

8-parameter CP-conserving 2HDM

- Lightest CP-even scalar as the SM-like Higgs
- Heaviest CP-even scalar as the SM-like Higgs
- Comment on the Charged Higgs

Other 2HDMs

- Aligned model

9-parameter CP-violating 2HDM

- Mixing

SM Yukawa Lagrangian

$$L_Y = \begin{bmatrix}\bar{U} & \bar{D}\end{bmatrix}_L \Phi Y_d \, D_R + \begin{bmatrix}\bar{U} & \bar{D}\end{bmatrix}_L \tilde{\Phi} \, Y_u U_R + \begin{bmatrix}\bar{N} & \bar{E}\end{bmatrix}_L \Phi \, Y_e E_R + h.c.$$

where the gauge eigenstates are

$$U = \begin{bmatrix}u_g & c_g & t_g\end{bmatrix}; \; D = \begin{bmatrix}d_g & s_g & b_g\end{bmatrix}; \; N = \begin{bmatrix}\nu_e & \nu_\mu & \nu_\tau\end{bmatrix}; \; E = \begin{bmatrix}e & \mu & \tau\end{bmatrix}$$

and Y are matrices in flavour space. To get the mass terms we just need the vacuum expectation values of the scalar fields

$$L_Y^{mass} = \frac{v}{\sqrt{2}} \, \bar{U}_L Y_u U_R + \frac{v}{\sqrt{2}} \, \bar{D}_L Y_d D_R + \frac{v}{\sqrt{2}} \, \bar{E}_L Y_e E_R + h.c.$$

which have to be diagonalised.

SM Yukawa Lagrangian

So we define

$$D_R \to N_R^{-1} D_R \, ; D_L \to N_L^{-1} D_L \, ; U_R \to K_R^{-1} U_R \, ; U_L \to K_L^{-1} U_L$$

and the mass matrices are

$$-\frac{v}{\sqrt{2}} N_L^{\dagger} Y_d N_R = M_d \, ; \qquad -\frac{v}{\sqrt{2}} K_L^{\dagger} Y_u K_R = M_u$$

and the interaction term is proportional to the mass term (just D terms)

$$L_Y^{interactions} = \frac{h}{\sqrt{2}} \bar{D}_L Y_d D_R \propto \frac{v}{\sqrt{2}} \bar{D}_L Y_d D_R$$

<u>**No scalar induced tree-level FCNCs**</u>

2HDM Yukawa Lagrangian

However in 2HDMs

$$\Phi_1 = \begin{pmatrix} - \\ (h_1 + v_1)/\sqrt{2} \end{pmatrix}; \quad \Phi_2 = \begin{pmatrix} - \\ (h_2 + v_2)/\sqrt{2} \end{pmatrix}$$

$$L_Y^{mass} = \frac{v_1}{\sqrt{2}} \bar{U}_L Y_u^1 U_R + \frac{v_1}{\sqrt{2}} \bar{D}_L Y_d^1 D_R + \frac{v_2}{\sqrt{2}} \bar{U}_L Y_u^2 U_R + \frac{v_2}{\sqrt{2}} \bar{D}_L Y_d^2 D_R + \dots$$

$$= \frac{1}{\sqrt{2}} \bar{U}_L \left(v_1 Y_u^1 + v_2 Y_u^2\right) U_R + \frac{1}{\sqrt{2}} \bar{D}_L \boxed{\left(v_1 Y_d^1 + v_2 Y_d^2\right)} D_R + \dots$$

$$-\frac{1}{\sqrt{2}} N_L^\dagger \boxed{\left(v_1 Y_d^1 + v_2 Y_d^2\right)} N_R = M_d; \qquad -\frac{1}{\sqrt{2}} K_L^\dagger \left(v_1 Y_u^1 + v_2 Y_u^2\right) K_R = M_u$$

$$L_Y^{interactions} = \frac{h_1}{\sqrt{2}} \bar{U}_L Y_u^1 U_R + \frac{h_1}{\sqrt{2}} \bar{D}_L Y_d^1 D_R + \frac{h_2}{\sqrt{2}} \bar{U}_L Y_u^2 U_R + \frac{h_2}{\sqrt{2}} \bar{D}_L Y_d^2 D_R + \dots$$

$$= \frac{h}{\sqrt{2}} \bar{U}_L \left(\cos\alpha Y_u^1 + \sin\alpha Y_u^2\right) U_R + \frac{H}{\sqrt{2}} \bar{D}_L \boxed{\left(-\sin\alpha Y_d^1 + \cos\alpha Y_d^2\right)} D_R + \dots$$

h, H are the mass eigenstates (α is the rotation angle in the CP-even sector)

2HDM Yukawa Lagrangian

How can we avoid large tree-level FCNCs?

1. **Fine tuning** – for some reason the parameters that give rise to tree-level FCNC are small

Example: Type III models CHENG, SHER (1987)

2. **Flavour alignment** – for some reason we are able to diagonalise simultaneously both the mass term and the interaction term

Example: Aligned models PICH, TUZON (2009)

$$Y_d^2 \propto Y_d^1$$ (for down type)

2HDM Yukawa Lagrangian

3. Use symmetries- for some reason the L is invariant under some symmetry

3.1 Naturally small tree-level FCNCs

Example: BGL Models BRANCO, GRIMUS, LAVOURA (2009)

3.2 No tree-level FCNCs

Example: Type I 2HDM Z_2 symmetries GLASHOW, WEINBERG; PASCHOS (1977) BARGER, HEWETT, PHILLIPS (1990)

$$L_Y = \sum_i \left[\bar{U} \quad \bar{D}\right]_L \Phi_i Y_d^i D_R + \left[\bar{U} \quad \bar{D}\right]_L \tilde{\Phi}_i Y_u^i U_R + \left[\bar{N} \quad \bar{E}\right]_L \Phi_i Y_e^i E_R + \text{h.c.}$$

$$\Phi_1 \to \Phi_1 ; \Phi_2 \to -\Phi_2 \qquad D_R \to -D_R ; E_R \to -E_R ; U_R \to -U_R$$

$$L_Y^I = \left[\bar{U} \quad \bar{D}\right]_L \Phi_2 Y_d^2 D_R + \left[\bar{U} \quad \bar{D}\right]_L \tilde{\Phi}_2 Y_u^2 U_R + \left[\bar{N} \quad \bar{E}\right]_L \Phi_2 Y_e^2 E_R + \text{h.c.}$$

2HDM Potential

$$V(\phi_1, \phi_2) = m_{11}^2\ \phi_1^+\phi_1 + m_{22}^2\ \phi_2^+\phi_2 - \left(m_{12}^2\ \phi_1^+\phi_2 + \text{h.c.}\right) + \frac{1}{2}\lambda_1\ \left(\phi_1^+\phi_1\right)^2 + \frac{1}{2}\lambda_2\ \left(\phi_2^+\phi_2\right)^2$$
$$+\ \lambda_3\ \left(\phi_1^+\phi_1\right)\left(\phi_2^+\phi_2\right) +\ \lambda_4\ \left(\phi_1^+\phi_2\right)\left(\phi_2^+\phi_1\right) + \left[\frac{1}{2}\lambda_5\left(\phi_1^+\phi_2\right)^2 + \text{h.c.}\right]$$
$$+\ \left[\lambda_6\ \left(\phi_1^+\phi_2\right)\left(\phi_1^+\phi_1\right) +\ \lambda_7\ \left(\phi_1^+\phi_2\right)\left(\phi_2^+\phi_2\right) + \text{h.c.}\right]$$

In general m_{12}^2, λ_5, λ_6 and λ_7 can be complex

Three possible minimum field configurations (doublets with same hypercharge – no inert model)

- **CP conserving** $\langle\Phi_1\rangle = \begin{pmatrix} 0 \\ v_1 \end{pmatrix}$; $\langle\Phi_2\rangle = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$

- **Charge Breaking** $\langle\Phi_1\rangle = \begin{pmatrix} 0 \\ v'_1 \end{pmatrix}$; $\langle\Phi_2\rangle = \begin{pmatrix} \alpha \\ v'_2 \end{pmatrix}$

- **CP Breaking** $\langle\Phi_1\rangle = \begin{pmatrix} 0 \\ v'_1 + i\delta \end{pmatrix}$; $\langle\Phi_2\rangle = \begin{pmatrix} 0 \\ v'_2 \end{pmatrix}$

2HDM Potential

The 2HDM parameters can be chosen so that we have a CP-conserving, a spontaneously CP-breaking or an explicit CP-breaking potential.

They are all stable at tree-level except[1]. For instance, once we are in a CP-conserving minimum the other (different nature) stationary points are saddle points above it.

Barroso, Ferreira, RS (2006)

[1]Two CP-conserving minima can coexist but we can force the potential to be in the global one by using a simple condition.

Ivanov (2007)

$$\mathrm{D} = m_{12}^2 \left(m_{11}^2 - k^2 m_{22}^2\right) \left(\tan\beta - k\right) \qquad k = \left(\frac{\lambda_1}{\lambda_2}\right)^{1/4}$$

Our vacuum is the global minimum of the potential if and only if D > 0.

Barroso, Ferreira, Ivanov, RS (2012)

8-parameter CP-conserving 2HDM after the 8 TeV run

Lightest CP-even scalar as the SM-like Higgs

P.M. Ferreira, R. Santos, M. Sher and J.P. Silva, Phys. Rev. D **85**, 077703 (2012) [arXiv:1112.3277 [hep-ph]]; D. Carmi, A. Falkowski, E. Kuflik and T. Volansky, JHEP **1207** (2012) 136 [arXiv:1202.3144 [hep-ph]]; H.S. Cheon and S.K. Kang, JHEP **1309**, 085 (2013) [arXiv:1207.1083 [hep-ph]]; W. Altmannshofer, S. Gori and G.D. Kribs, Phys. Rev. D **86**, 115009 (2012) [arXiv:1210.2465 [hep-ph]]; Y. Bai, V. Barger, L.L. Everett and G. Shaughnessy, Phys. Rev. D **87**, 115013 (2013) [arXiv:1210.4922 [hep-ph]]; C.-Y. Chen and S. Dawson, Phys. Rev. D **87**, 055016 (2013) [arXiv:1301.0309 [hep-ph]]; A. Celis, V. Ilisie and A. Pich, JHEP **1307**, 053 (2013) [arXiv:1302.4022 [hep-ph]]; C-W. Chiang and K. Yagyu, JHEP **1307**, 160 (2013) [arXiv:1303.0168 [hep-ph]]; M. Krawczyk, D. Sokolowska and B. Swiezewska, J. Phys. Conf. Ser. **447**, 012050 (2013) [arXiv:1303.7102 [hep-ph]]; B. Grinstein and P. Uttayarat, JHEP **1306**, 094 (2013) [Erratum-ibid. **1309**, 110 (2013)] [arXiv:1304.0028 [hep-ph]]; A. Barroso, P.M. Ferreira, R. Santos, M. Sher and J.P. Silva, arXiv:1304.5225 [hep-ph]; B. Coleppa, F. Kling and S. Su, JHEP **1401**, 161 (2014) [arXiv:1305.0002 [hep-ph]]; P.M. Ferreira, R. Santos, M. Sher and J.P. Silva, arXiv:1305.4587 [hep-ph]; O. Eberhardt, U. Nierste and M. Wiebusch, JHEP **1307**, 118 (2013) [arXiv:1305.1649 [hep-ph]]; S. Choi, S. Jung and P. Ko, JHEP **1310** (2013) 225 [arXiv:1307.3948 [hep-ph]]. V. Barger, L.L. Everett, H.E. Logan and G. Shaughnessy, Phys. Rev. D **88** (2013) 115003 [arXiv:1308.0052 [hep-ph]]; D. López-Val, T. Plehn and M. Rauch, JHEP **1310** (2013) 134 [arXiv:1308.1979 [hep-ph]]; S. Chang, S.K. Kang, J.-P. Lee, K.Y. Lee, S.C. Park and J. Song, arXiv:1310.3374 [hep-ph]; K. Cheung, J. S. Lee and P. -Y. Tseng, JHEP **1401**, 085 (2014) [arXiv:1310.3937 [hep-ph]]; A. Celis, V. Ilisie and A. Pich, JHEP **1312**, 095 (2013) [arXiv:1310.7941 [hep-ph]]; G. Cacciapaglia, A. Deandrea, G.D. La Rochelle and J.-B. Flament, arXiv:1311.5132 [hep-ph]; L. Wang and X. F. Han, JHEP **1404**, 128 (2014) [arXiv:1312.4759 [hep-ph]]; K. Cranmer, S. Kreiss, D. López-Val and T. Plehn, arXiv:1401.0080 [hep-ph]; F. J. Botella, G. C. Branco, A. Carmona, M. Nebot, L. Pedro and M. N. Rebelo, JHEP **1407**, 078 (2014) [arXiv:1401.6147 [hep-ph]]; S. Kanemura, K. Tsumura, K. Yagyu and H. Yokoya, arXiv:1406.3294 [hep-ph]; P. M. Ferreira, R. Guedes, J. F. Gunion, H. E. Haber, M. O. P. Sampaio and R. Santos, arXiv:1407.4396 [hep-ph].

Z_2 symmetric CP-conserving 2HDM (softly broken)

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

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

All parameters including vevs real

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

- ➡ $\tan\beta = \frac{v_2}{v_1}$ ratio of vacuum expectation values
- ➡ α rotation angle neutral CP-even sector

2HDM Lagrangian

Scalars - gauge bosons couplings

$$\kappa_V^h = \sin(\beta-\alpha)$$ for the light CP-even Higgs

$$\kappa_V^H = \cos(\beta-\alpha)$$ for the heavy CP-even Higgs

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

at tree-level

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

Yukawa couplings (lightest scalar)

(no FCNC at tree-level)

Type I $$\kappa_U^I = \kappa_D^I = \kappa_L^I = \frac{\cos\alpha}{\sin\beta}$$

Type II $$\kappa_U^{II} = \frac{\cos\alpha}{\sin\beta} \qquad \kappa_D^{II} = \kappa_L^{II} = -\frac{\sin\alpha}{\cos\beta}$$

Type F $$\kappa_U^F = \kappa_L^F = \frac{\cos\alpha}{\sin\beta} \qquad \kappa_D^F = -\frac{\sin\alpha}{\cos\beta}$$

Type LS $$\kappa_U^{LS} = \kappa_D^{LS} = \frac{\cos\alpha}{\sin\beta} \qquad \kappa_L^{LS} = -\frac{\sin\alpha}{\cos\beta}$$

III = I' = Y = Flipped = 4… **IV = II' = X = Lepton Specific= 3…**

ScannerS (Scan "R" Us)

- Tool to **Scan** parameter space of **Scalar** sectors. Coimbra, Sampaio, RS, (2013).
- **Automatise** scans for tree level renormalisable V_{scalar}.
- **Generic** routines, **flexible** user analysis & **interfaces**.

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 (2010-2014)

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

2HDM allowed parameter space in September 2014

- 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

Predictions:

Same as before except no HiggsBounds and HiggsSignals:

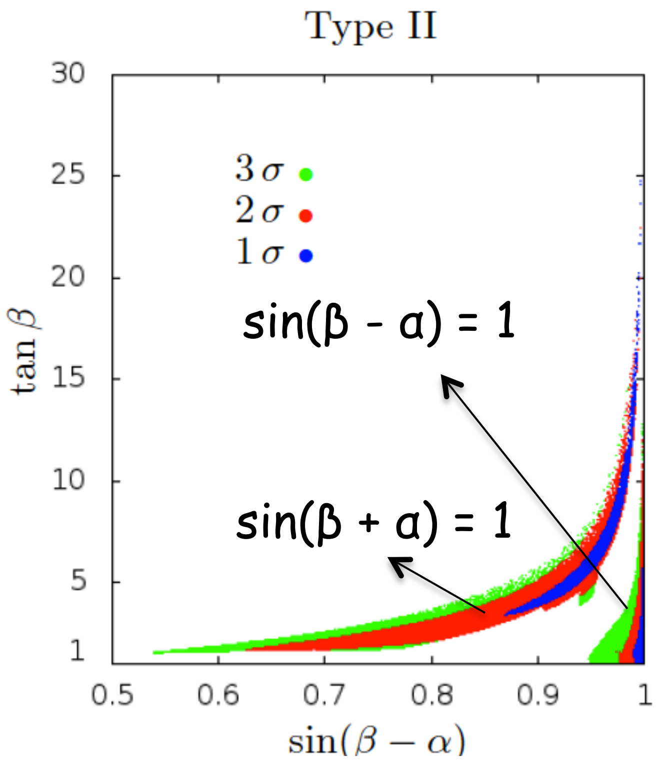
- Calculate all branching ratios and production rates at the LHC

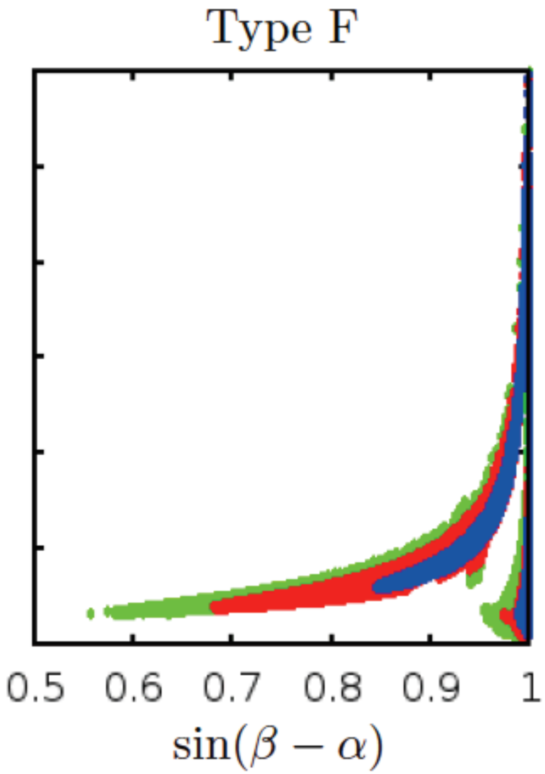
$$\mu_{XX} = \frac{\sigma^{2HDM}(pp \to h) \times BR^{2HDM}(h \to XX)}{\sigma^{SM}(pp \to h) \times BR^{SM}(h \to XX)}$$

- 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 SM-like limit (alignment)

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

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

Wrong-sign limit

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

Ginzburg, Krawczyk, Osland 2001

Ferreira, Gunion, Haber, RS 2014

$$\kappa_D=-\frac{\sin\alpha}{\cos\beta}=-\sin(\beta+\alpha)+\cos(\beta+\alpha)\tan\beta \qquad \kappa_U=\frac{\cos\alpha}{\sin\beta}=\sin(\beta+\alpha)+\cos(\beta+\alpha)\cot\beta$$

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

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

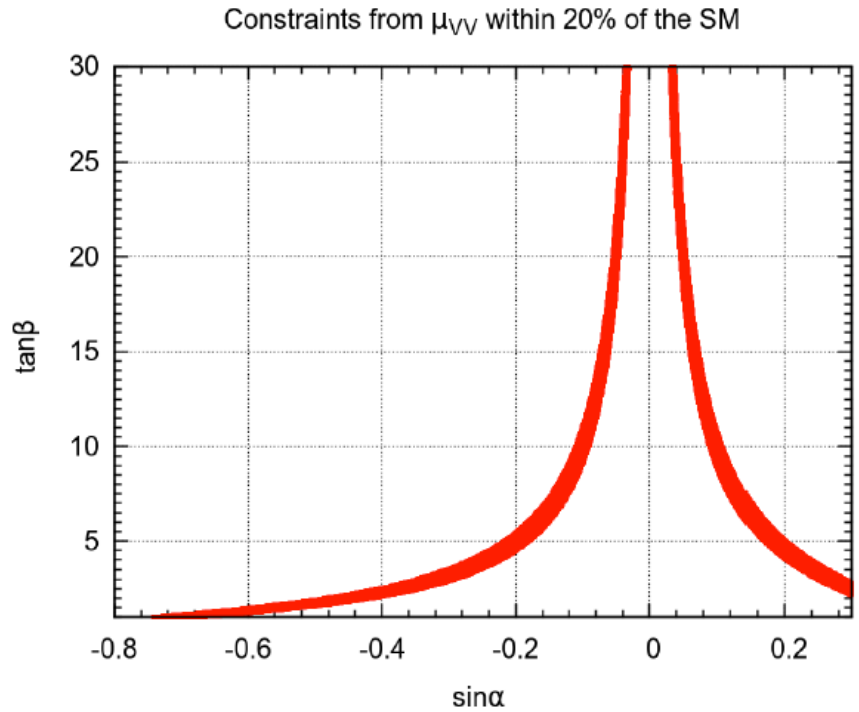
Why the shape? Shape comes primarily from μ_{VV}

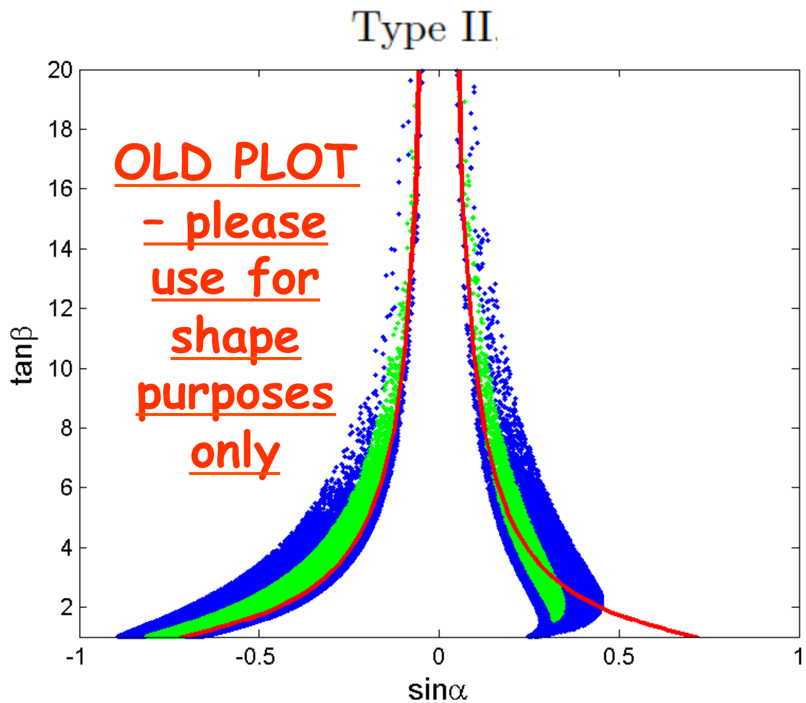
Assuming that the cross section is **gluon fusion via top**

$$\Gamma_T \approx \Gamma\,(h \to b\bar{b}) \qquad \mu_{VV} \approx \frac{\sin^2(\beta-\alpha)}{\tan^2\alpha\,\tan^2\beta} \qquad \mu_{VV} \approx \kappa_V^2 \frac{\kappa_U^2}{\kappa_D^2}$$

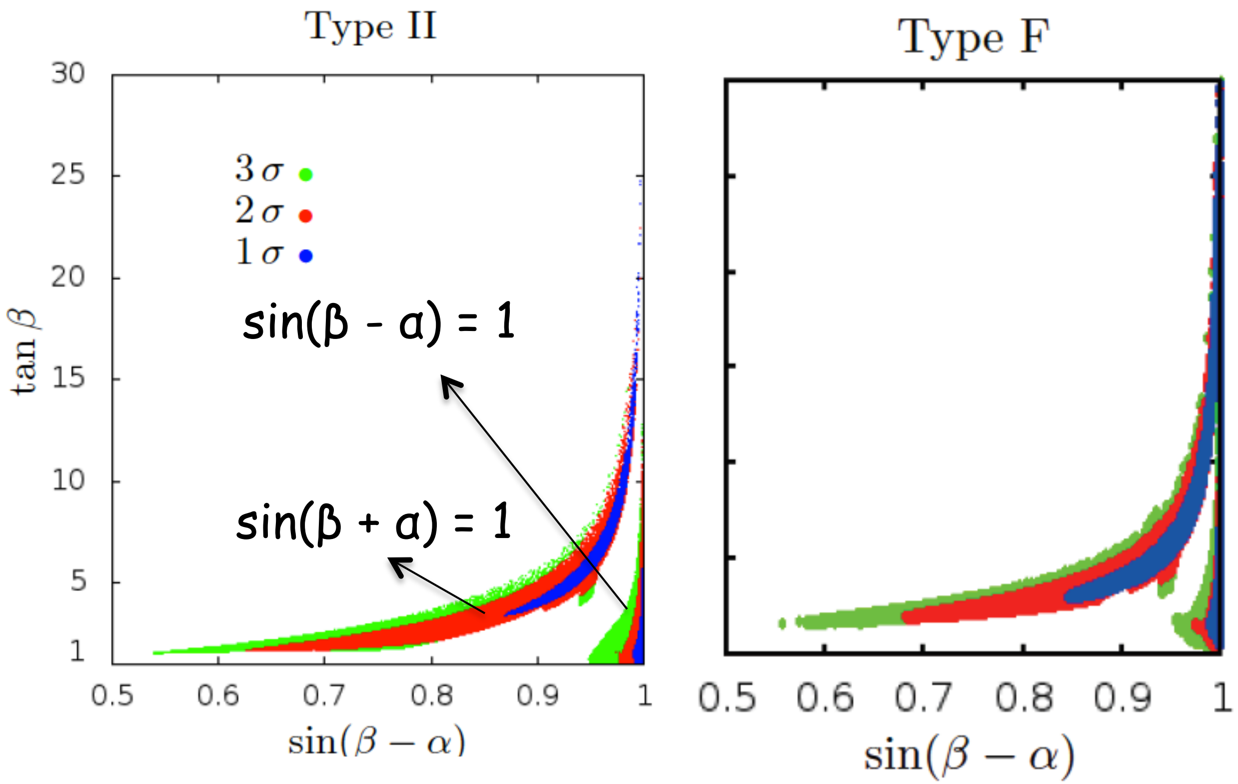
Once you impose μ_{VV} you are nearly there

Ferreira, Haber, RS, Silva, (2012).





Plot from: Fontes, Romão, Silva, 1406.6081



Why is the SM-like (but not the wrong sign) region so close to sin(β−α) = 1? Again the same reason.

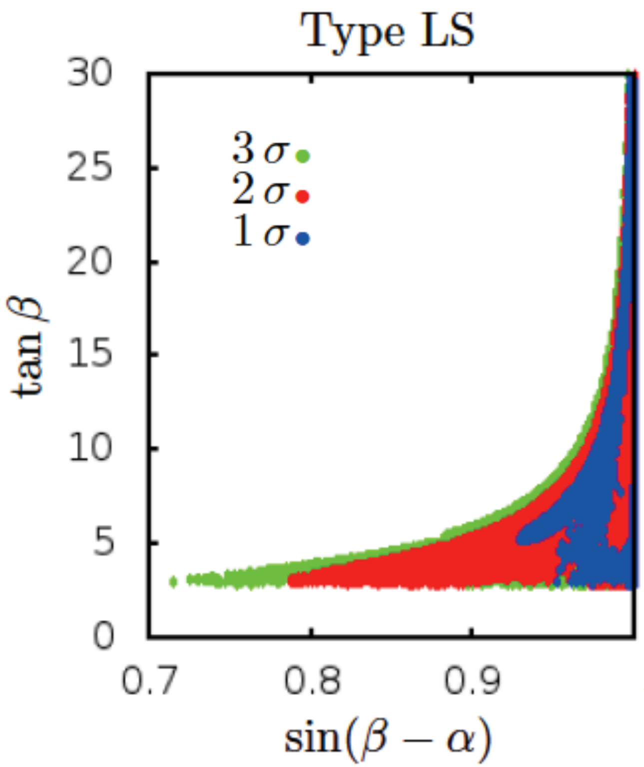
$$\mu_{VV} \approx \frac{\sin^2(\beta-\alpha)}{\tan^2\alpha \tan^2\beta}$$

$$\sin(\beta-\alpha) = 0.8;\ \tan\beta = 2.5 \qquad \begin{cases} \alpha = -0.26 \;\Rightarrow\; \mu_{VV} = 2.2 \\ \alpha = 0.26 \;\Rightarrow\; \mu_{VV} = 1.4 \end{cases}$$

What is the effect of the b-loops? Exclude the high tanβ region.

$$\frac{\sin^2\alpha}{\cos^2\beta} = (\sin(\beta-\alpha) - \cos(\beta-\alpha)\tan\beta)^2$$

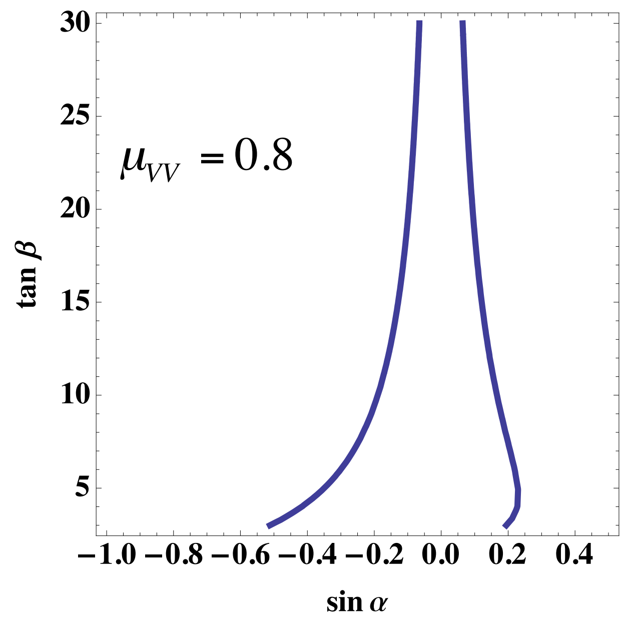
$$\sin(\beta-\alpha) = 0.8;\ \tan\beta = 10 \Rightarrow \kappa_D \approx 27$$

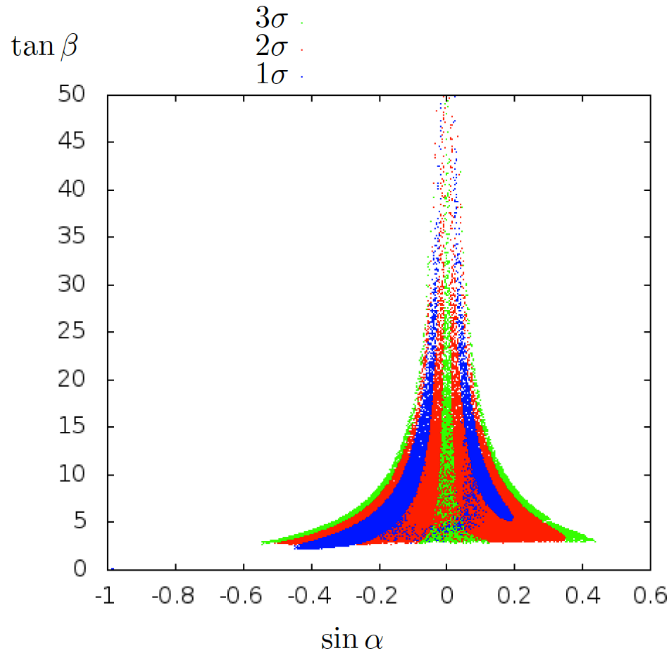


The shape of type LS

$$\mu_{VV} \approx \sin^2(\beta-\alpha)\ \kappa_U^2 \frac{\Gamma_{bb}^{SM} + \Gamma_{\tau\tau}^{SM}}{\Gamma_{bb}^{2HDM} + \Gamma_{\tau\tau}^{2HDM}}$$

$$\mu_{VV} \approx \sin^2(\beta-\alpha)\ \frac{9m_b^2/m_\tau^2 + 1}{9m_b^2/m_\tau^2 + \tan^2\alpha\ \tan^2\beta}$$

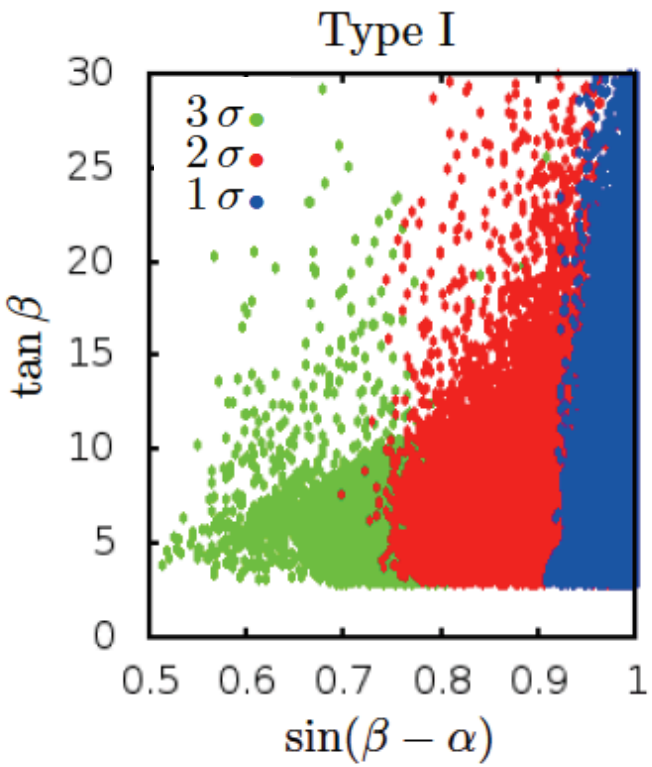




Two legs? Wrong Sign scenario? But

$\kappa_D\kappa_V > 0;\ \kappa_U\kappa_V > 0;\ \kappa_U\kappa_D > 0;$

More later



The shape of type I

$$\kappa_F \approx \kappa_V = \sin(\beta - \alpha)$$

Cross sections and widths are like in the SM +singlet for "large" tanβ. Only Higgs self-couplings are different.

Using the same approx as in type II

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

$$\sin^2(\beta - \alpha) = 0.8 \Rightarrow$$

$$\sin(\beta - \alpha) = 0.89$$

Except for h -> γγ

$$\mu_{\gamma\gamma} \approx \kappa_\gamma^2$$

Which is close to 1.

Therefore bounds are almost independent of tanβ

Also there is just one "leg" (next slide).

$$\kappa_U = \kappa_D = \kappa_L = \frac{\cos\alpha}{\sin\beta} = \sin(\beta - \alpha) + \cos(\beta - \alpha)\cot\beta$$

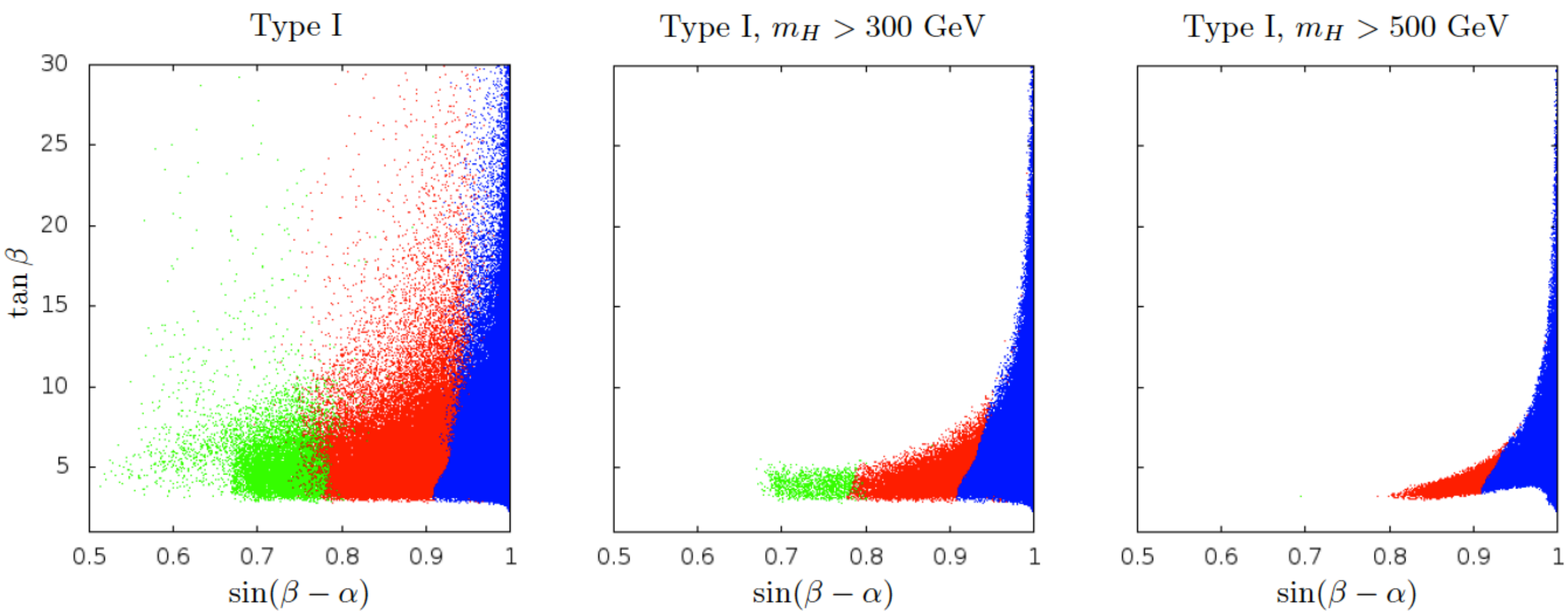
Type I

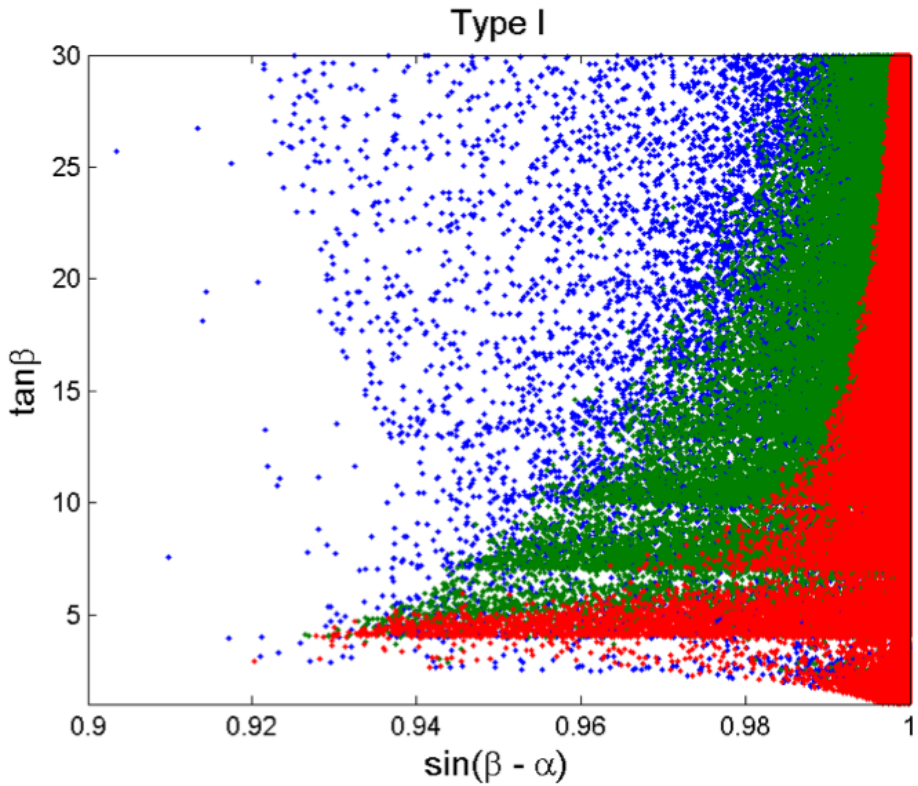
$$\kappa_U = \kappa_D = \frac{\cos\alpha}{\sin\beta} = \sin(\beta+\alpha) + \cos(\beta+\alpha)\cot\beta$$

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

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

Because constraints force tanβ to be order 1 or larger, “there is no wrong-sign Yukawa coupling” in Type I (more about this later).



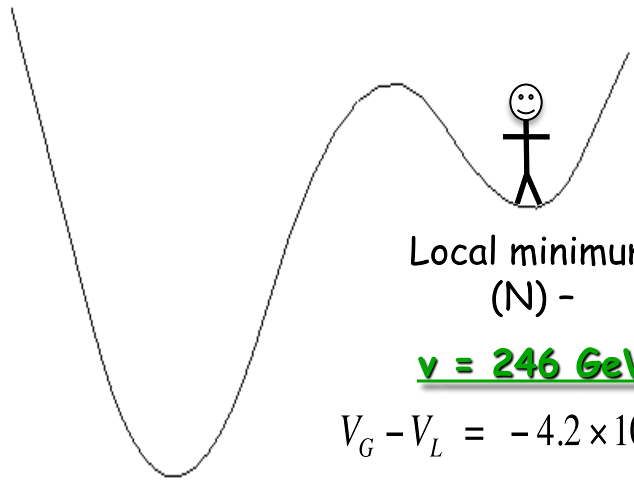


blue - 20% all rates

green - + m_H > 300 GeV

red - + discriminant

Plot from THOR



Local minimum (N) - $m_W = 80.4$ GeV

v = 246 GeV

$V_G - V_L = -4.2 \times 10^8$ GeV

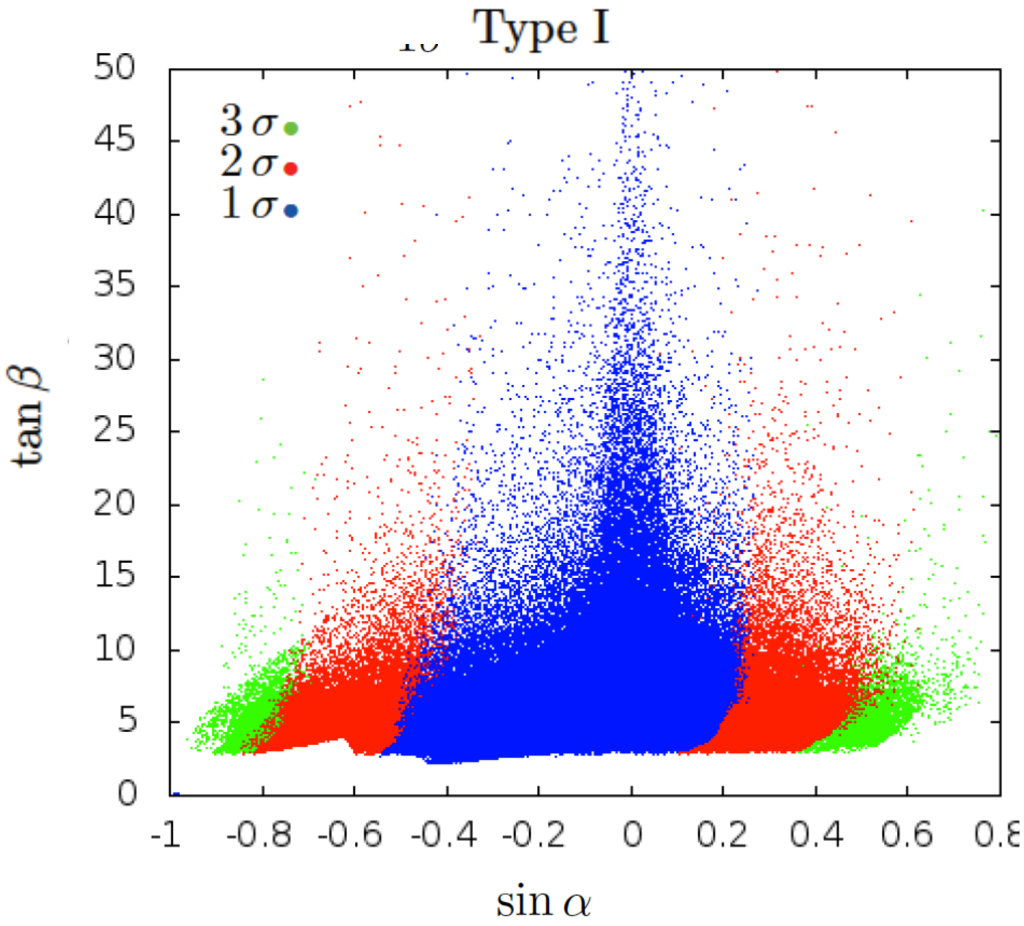
Global minimum (N) - $m_W = 107.5$ GeV

v = 329 GeV

While usually forcing the minimum to be the global one does not add much to constrain the parameter space, this is a case where it excludes part of the large tanβ region.

$$\mathrm{D} = m_{12}^2 \left(m_{11}^2 - k^2 m_{22}^2\right) \left(\tan\beta - k\right)$$

Our vacuum is the global minimum of the potential if and only if D > 0.



The fermiophobic limit (**type I**)

$$\alpha = \frac{\pi}{2}$$

$$\kappa_U = \kappa_D = \kappa_L = \frac{\cos\alpha}{\sin\beta} = 0$$

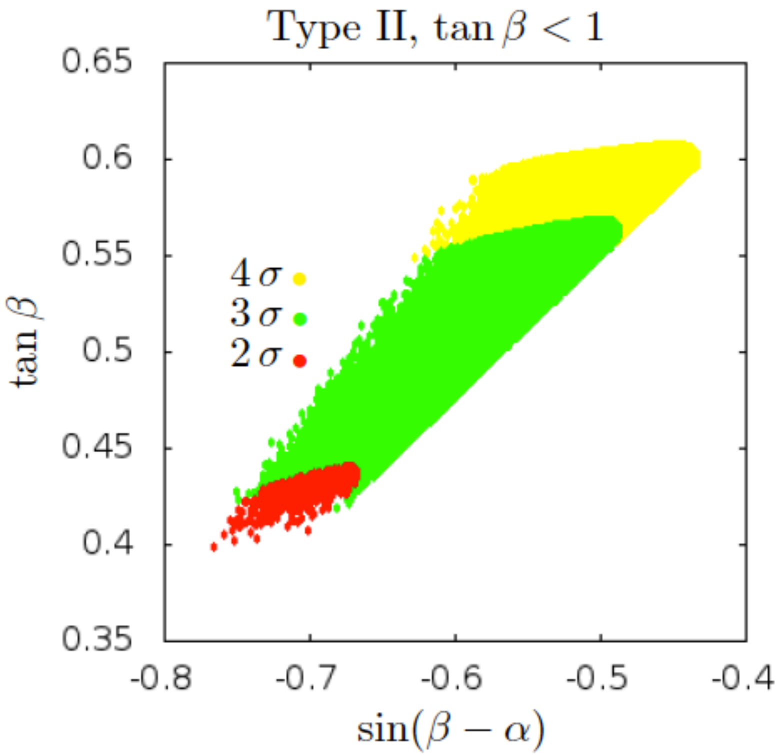
sinα =1 is excluded at 3 sigma.

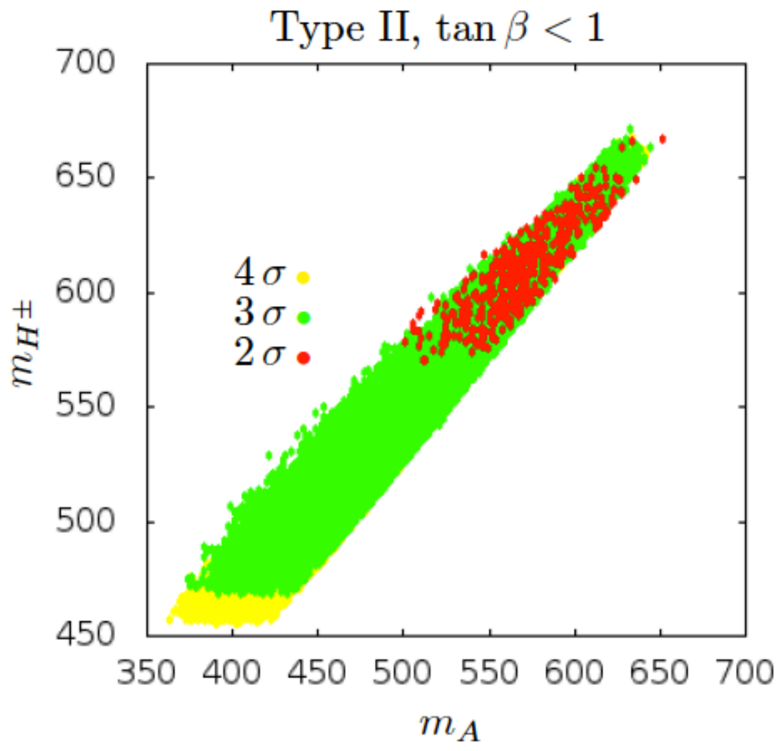
The dark side of the wrong sign scenario

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

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

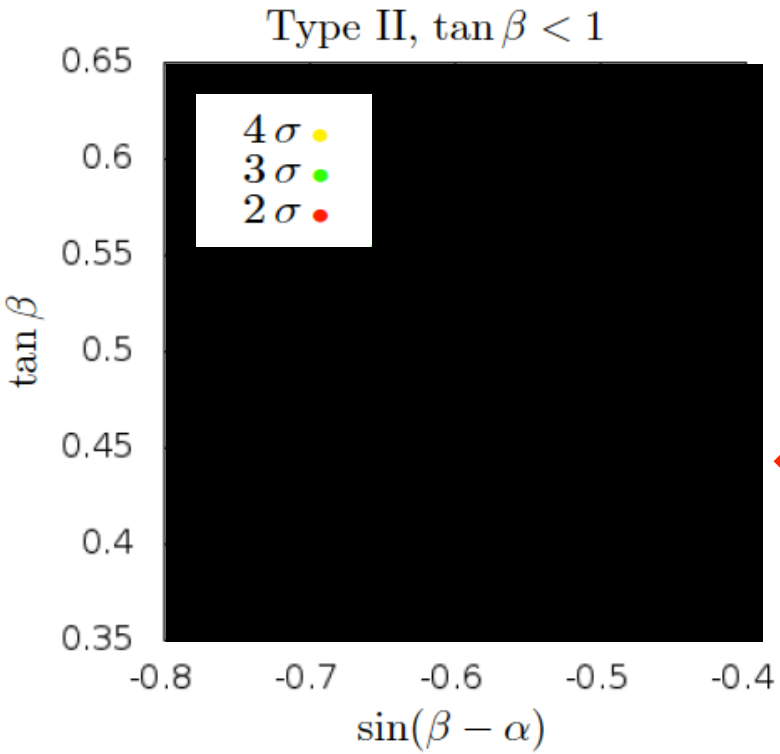
Possible in all types.

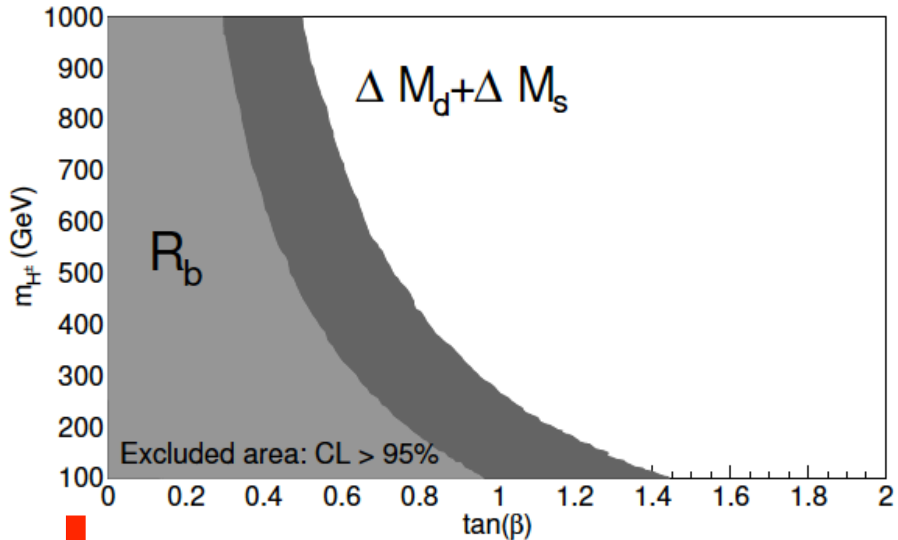




Z-> bb and b -> s γ included.

The dark side of the wrong sign scenario





Deschamps, Descotes-Genon, Monteil, Niess, T'Jampens, Tisserand, 2010

Final results when the limits from BB mixing are included.

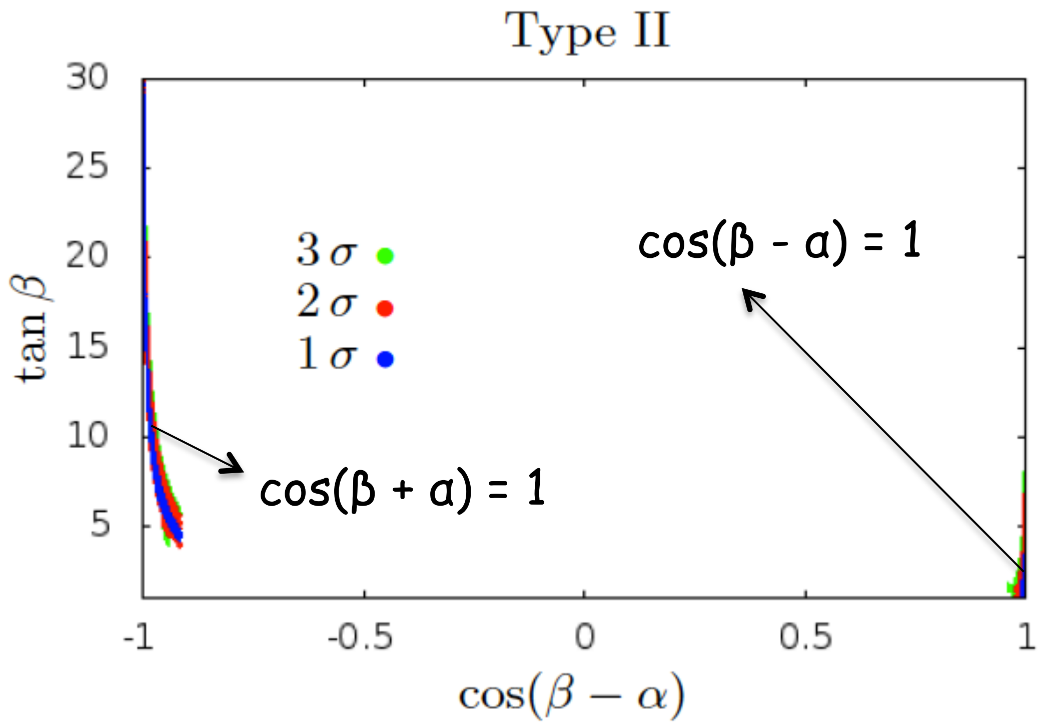
The 8-parameter CP-conserving 2HDM after the 8 TeV run

Heaviest CP-even scalar as the SM-like Higgs

P. M. Ferreira, R. Santos, M. Sher and J. P. Silva, Phys. Rev. D **85**, 035020 (2012) [arXiv:1201.0019 [hep-ph]]
L. Wang and X. F. Han, arXiv:1404.7437 [hep-ph].

$$\begin{cases} \sin(\beta-\alpha) \to \mathrm{sign}(\alpha)\cos(\beta-\alpha) \\ \cos(\beta-\alpha) \to -\mathrm{sign}(\alpha)\sin(\beta-\alpha) \end{cases}$$

This is true in our convention. The reasons for the exclusion can be easily rephrased in terms of $\tan\beta$ and $\cos(\beta-\alpha)$.



The SM-like limit

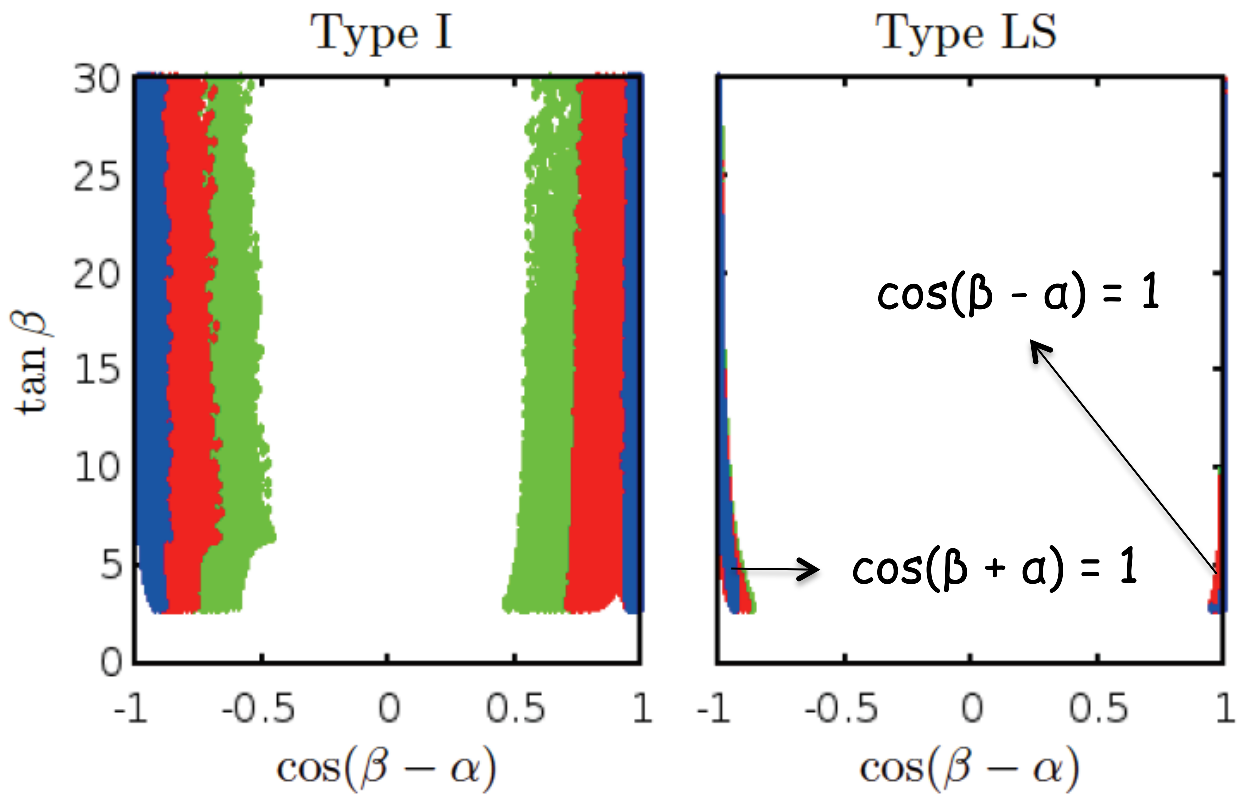
$$\cos(\beta-\alpha)=1 \;\Rightarrow\; \Rightarrow\; \kappa_F=1;\; \kappa_V=1$$

Wrong-sign limit

$$\kappa_D\kappa_V<0$$

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

$$\cos(\beta-\alpha)=-\frac{\tan^2\beta-1}{\tan^2\beta+1} \;\Rightarrow\; \kappa_V\le 0 \;\text{ if }\; \tan\beta\ge 1$$



Type I and LS

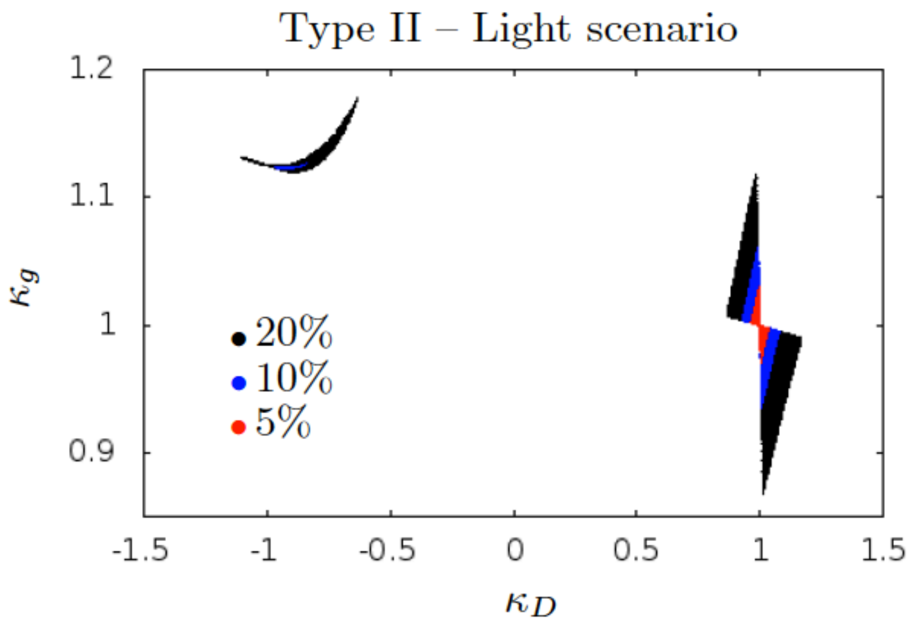
$$\cos(\beta+\alpha)=1 \quad \Rightarrow \quad \kappa_D = \kappa_U = -1$$

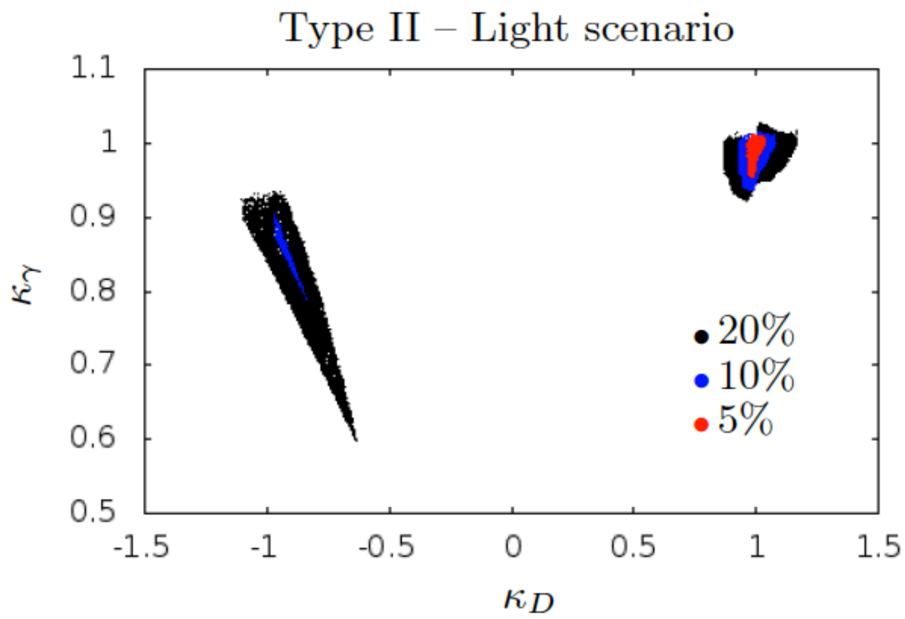
$$\cos(\beta-\alpha) = -\frac{\tan^2\beta-1}{\tan^2\beta+1} \quad \Rightarrow \quad \kappa_V \leq 0 \quad \text{if} \quad \tan\beta \geq 1$$

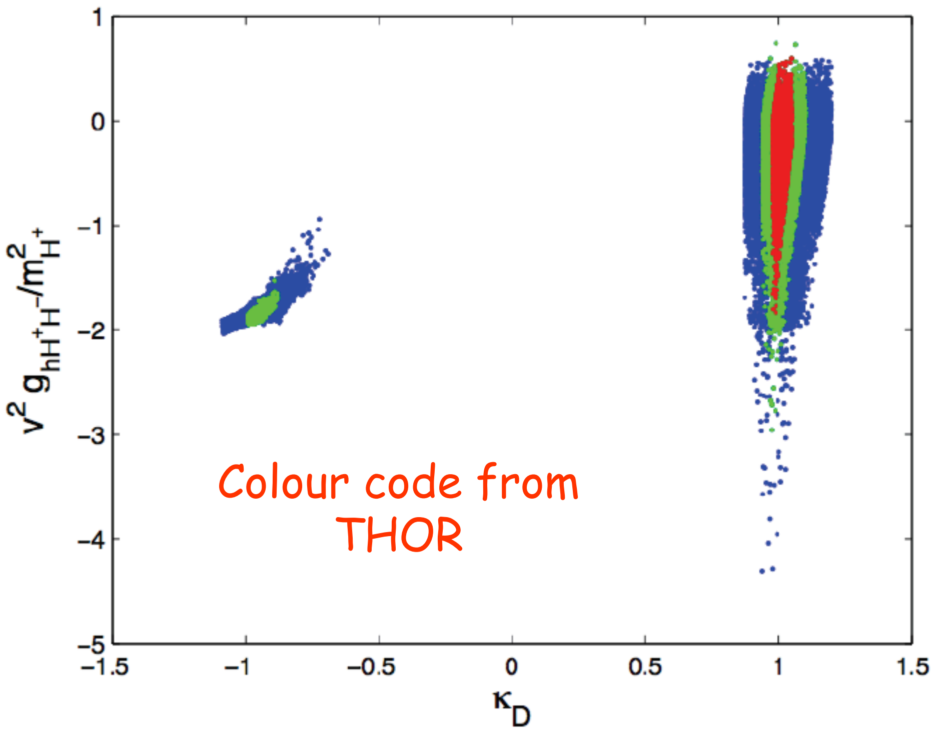
All couplings change sign – same conclusions as for the light scenario.

The Future

Surprises in h-> $\gamma\gamma$



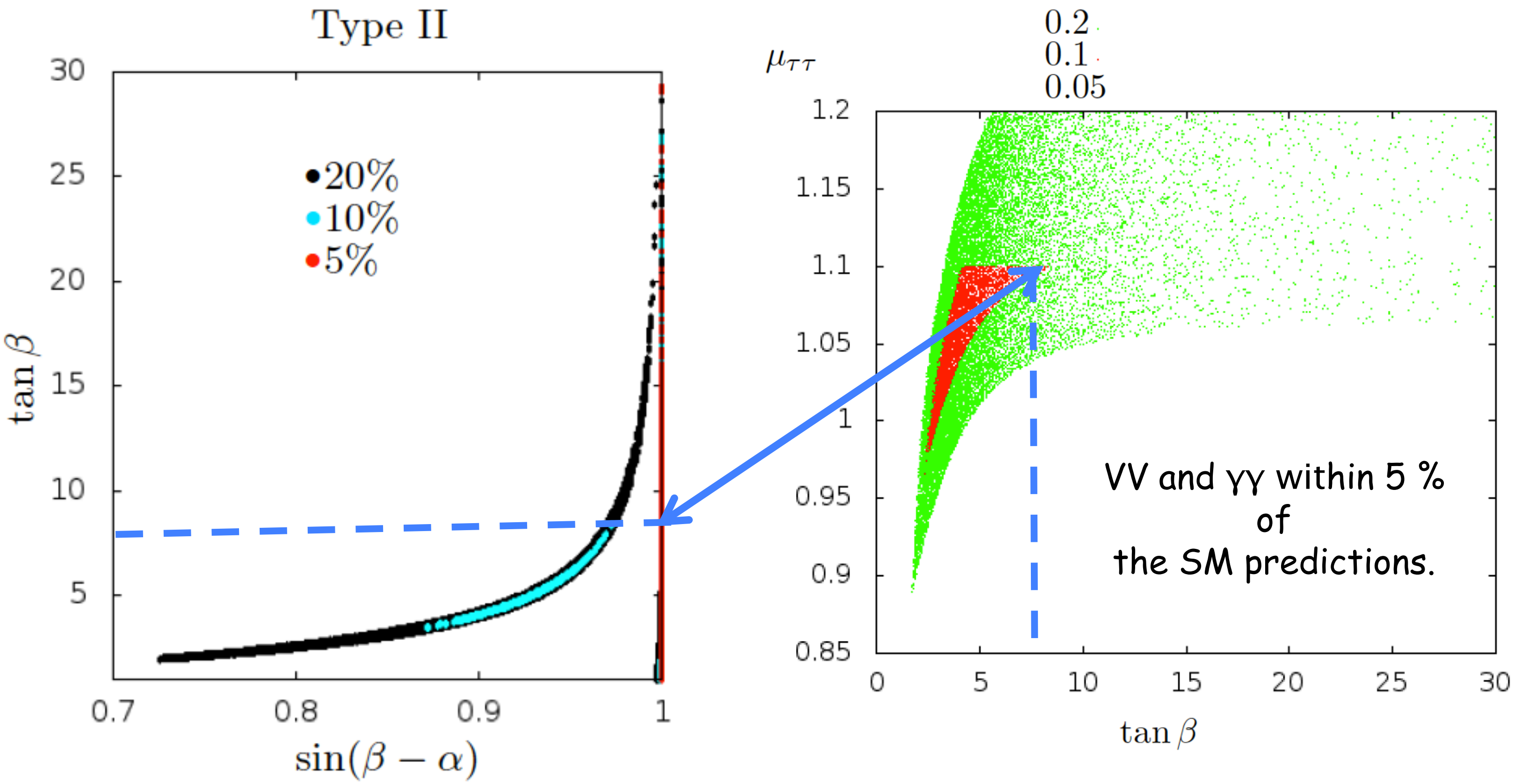




If we were only considering the gauge bosons and fermion loops we should find points at 5 % for the wrong-sign scenario.

In fact, if the charged Higgs loops were absent, changing the sign of κ_D would imply a change in κ_γ of less than 1 %.

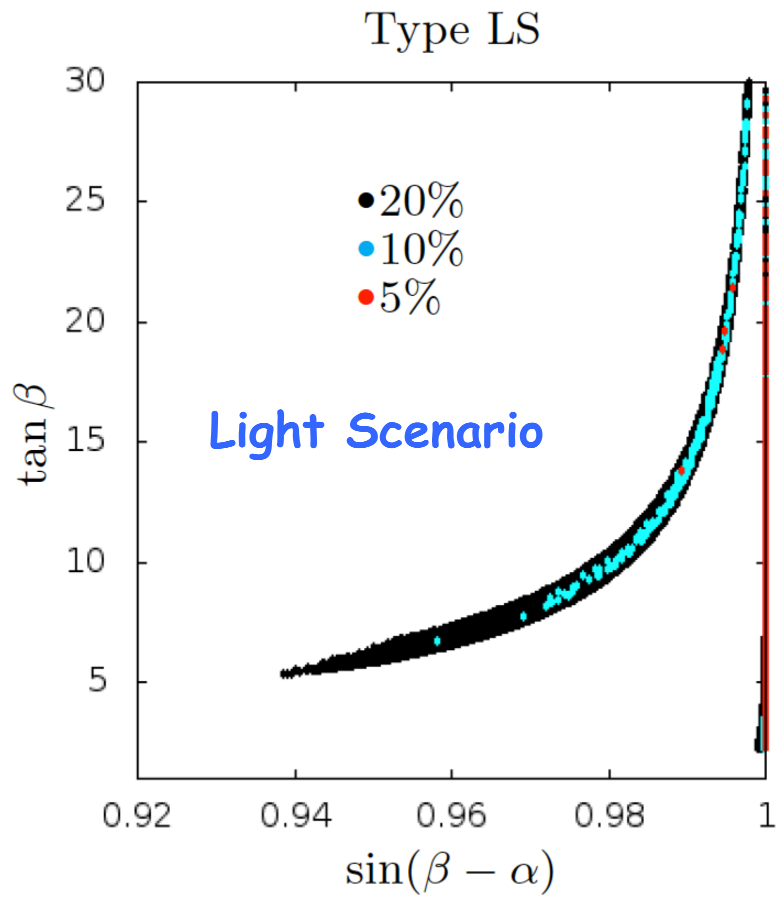
The relative negative values (and almost constant) contribution from the charged Higgs loops forces the wrong sign $\mu_{\gamma\gamma}$ to be below 1.



A measurement of the rates at 5% will exclude the wrong sign leg.

And in this case sin(β−α) = 1 and the 2HDM can go home.

If $\mu_{\tau\tau}$ is within 10% of the SM prediction, large values of tanβ are excluded.



The two legs of type LS

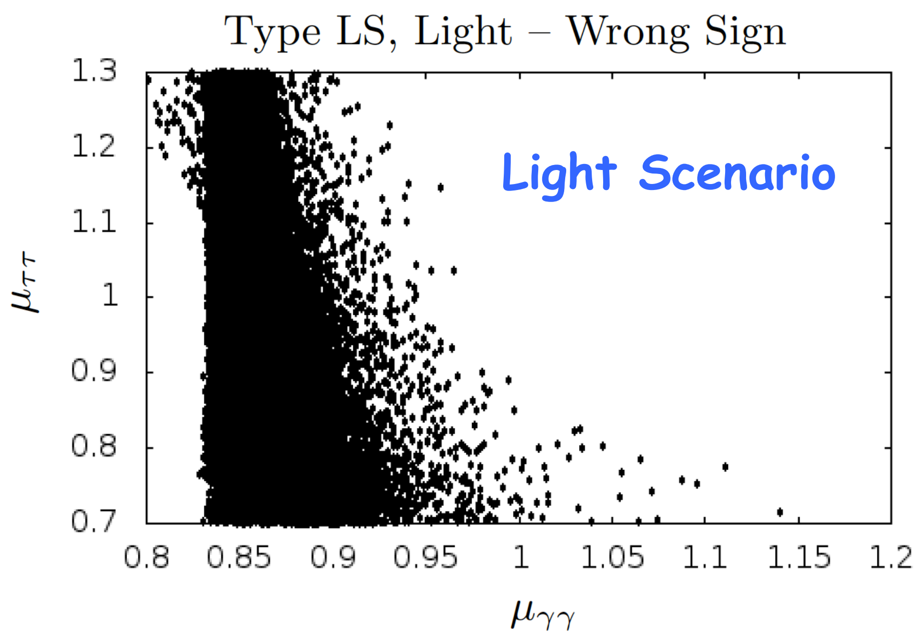
No *wrong sign limit* but ***symmetric limit***.

$$\sin(\beta+\alpha)=1$$

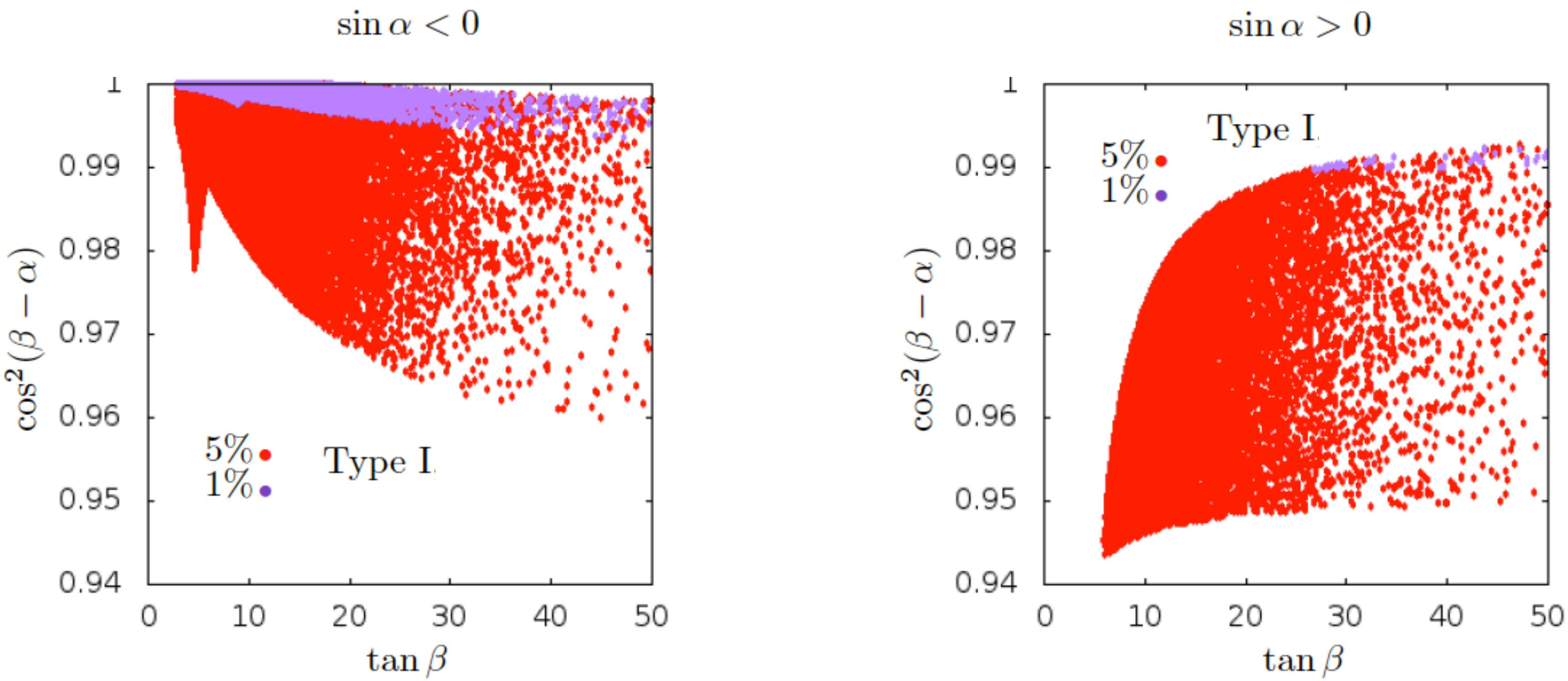
$$\sin(\beta-\alpha)=\frac{\tan^2\beta-1}{\tan^2\beta+1} \Rightarrow \kappa_V \leq 0 \ \text{ if } \ \tan\beta \leq 1$$

In the symmetric limit the κ_g and κ_γ are not affected.

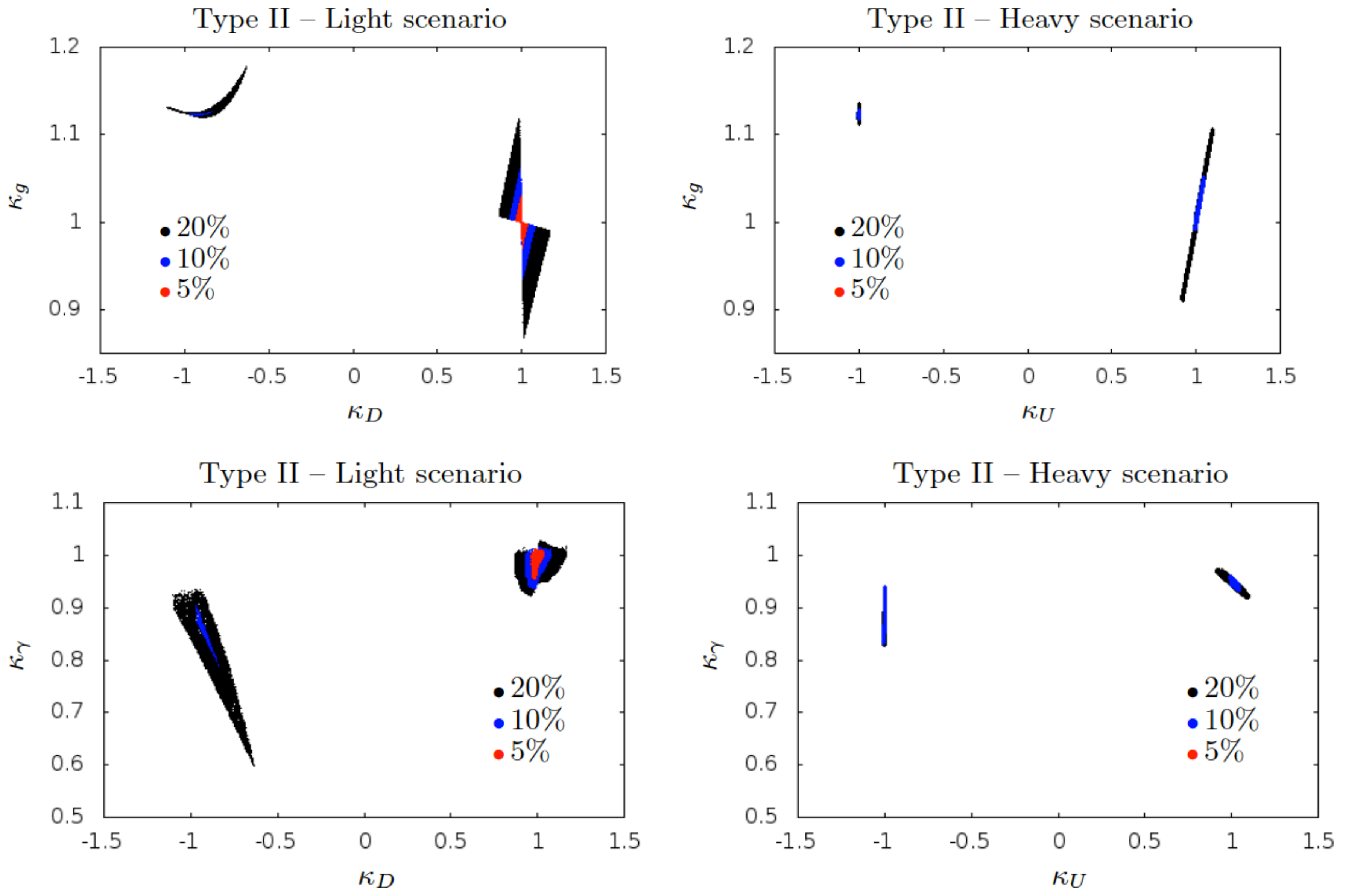
The combination of the two rates leaves just a few points at 5 % - scan in progress.



Heavy scenario for type I



It is clear the points are not close to 1 in the *symmetric limit*.



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.

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:

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

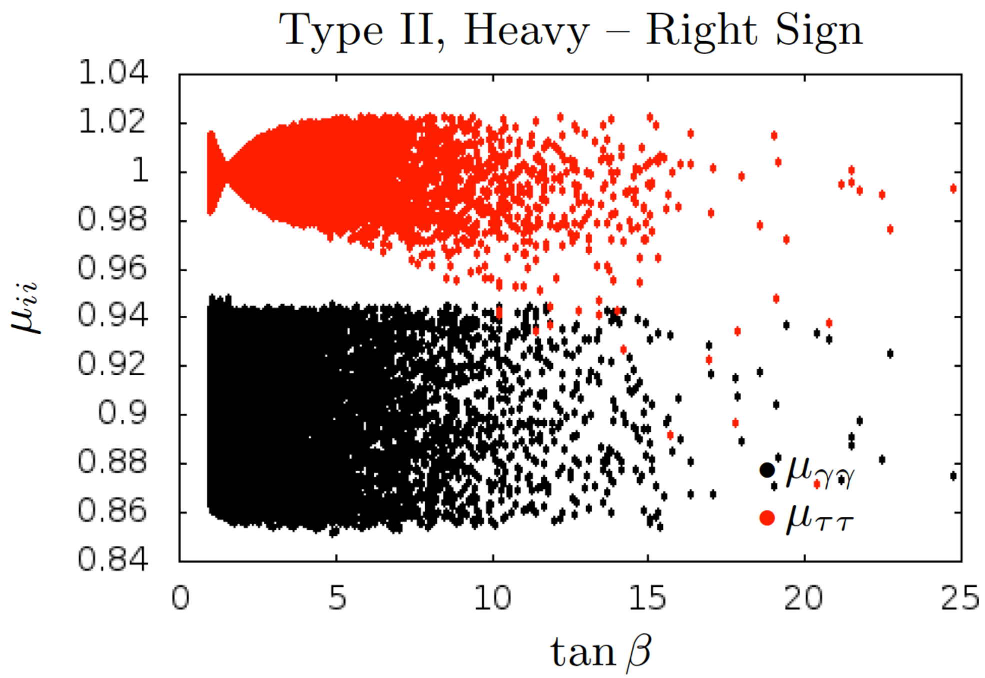
$$h^0 b\bar{b}/h_{SM} b\bar{b} = -\frac{\sin\alpha}{\cos\beta} \to 1 \ , \ (h^0 \bar{t}t)/h_{SM} t\bar{t} = \frac{\cos\alpha}{\sin\beta} \to 1$$

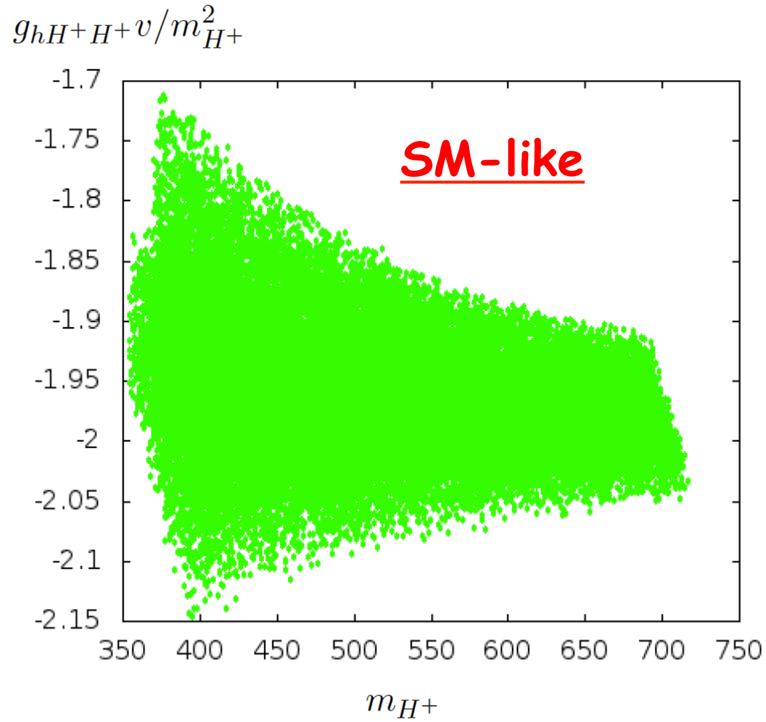
$$H^0VV \propto \cos(\beta - \alpha) \to 0 \ , \ (hhh)/(hhh)_{SM} \to 1$$

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

Gunion, Haber (2003)

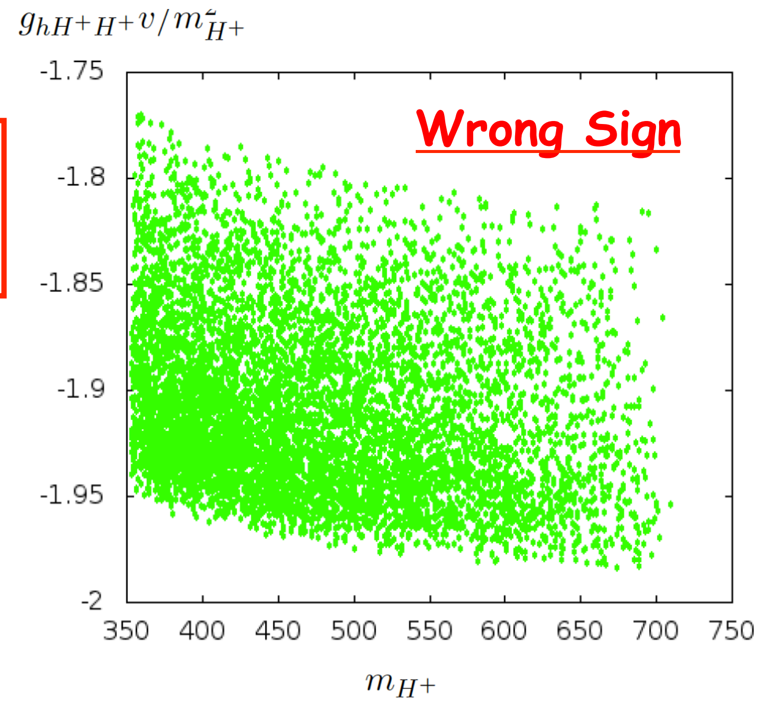
Heavy scenario and boundness from below





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

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



Boundness from below

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

b -> s γ

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

Short comment on the charged Higgs bounds

Experimental constraints on the charged Higgs mass

- **LEP** $e^+e^- \to H^+H^-$

ALEPH, DELPHI, L3 and OPAL Collaborations
The LEP working group for Higgs boson searches[1]

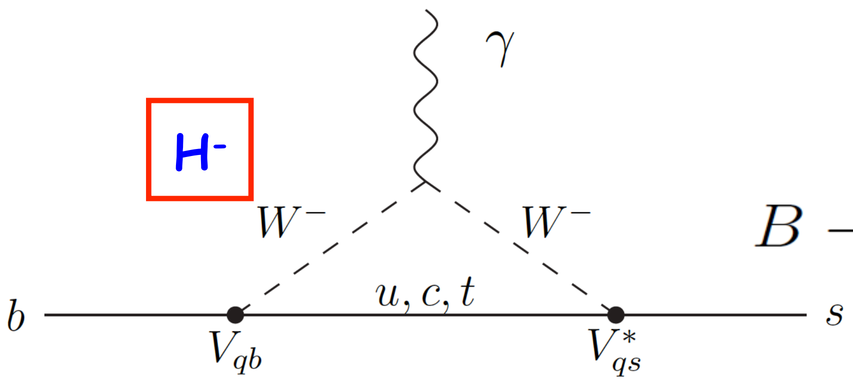
arXiv:1301.6065v1

Any $BR(H^+ \to \tau^+\nu)$ $m_{H^\pm} \gtrsim 80\ GeV$

$BR(H^+ \to \tau^+\nu) \approx 1$ $m_{H^\pm} \gtrsim 94\ GeV$ **(Type LS)**

- **B factories**

Hermann, Misiak, Steinhauser (2012)



$B \to X_s\gamma$

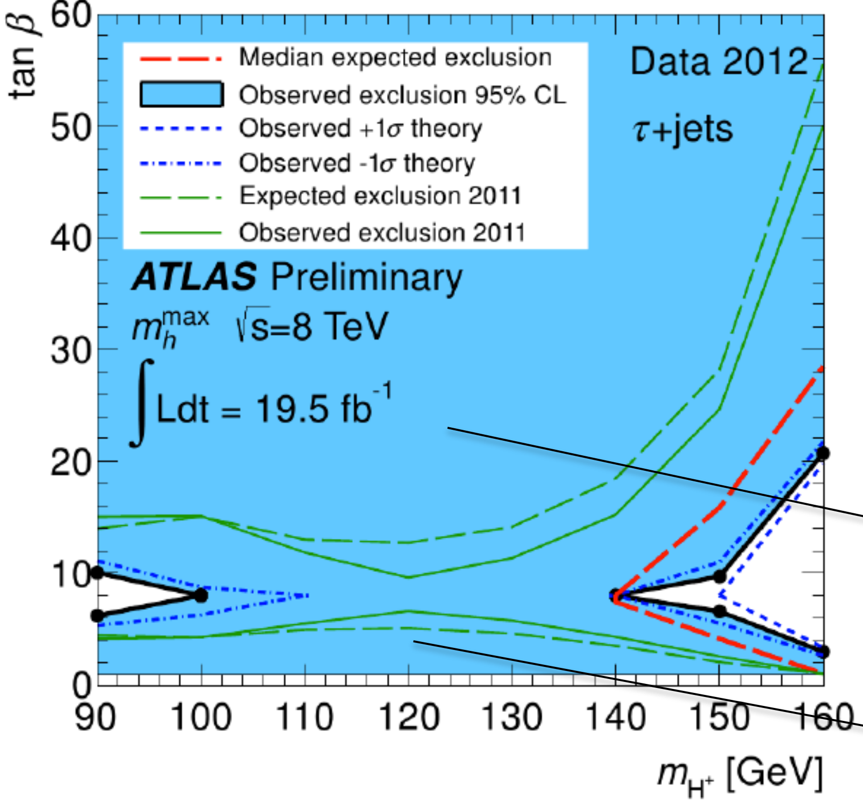
Models II and Y $m_{H^\pm} \gtrsim 360\ GeV$

Best available bound on the charged Higgs mass

Experimental (LHC)

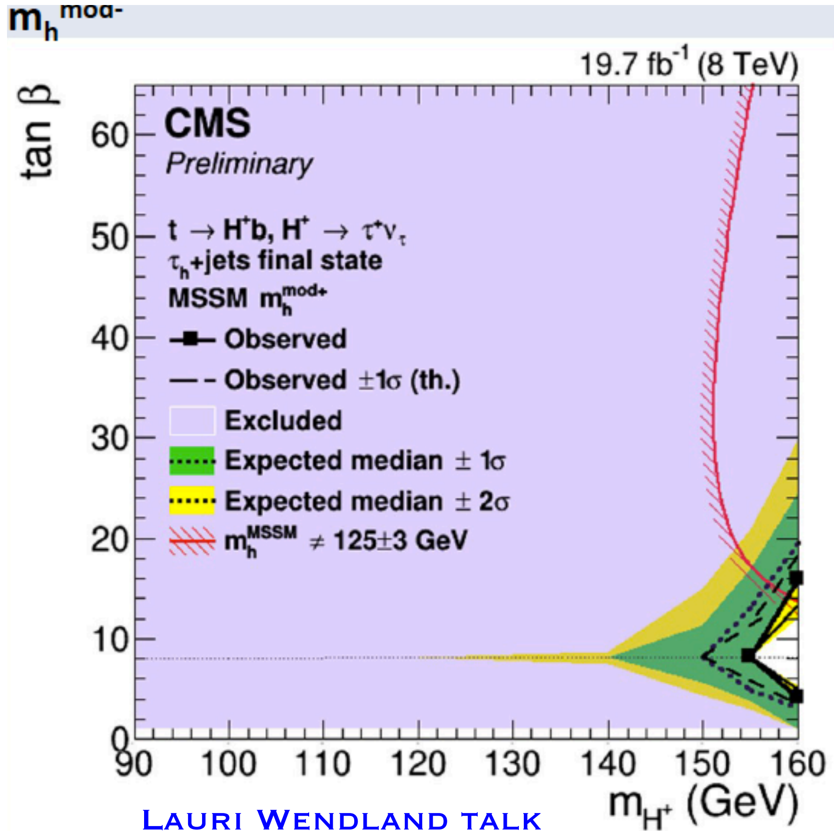
$$pp \to \bar{t}t \to \bar{b}bW^+H^-$$

ATLAS-CONF-2013-090



$$m_b \tan\beta$$

$$\frac{m_t}{\tan\beta}$$



LAURI WENDLAND TALK

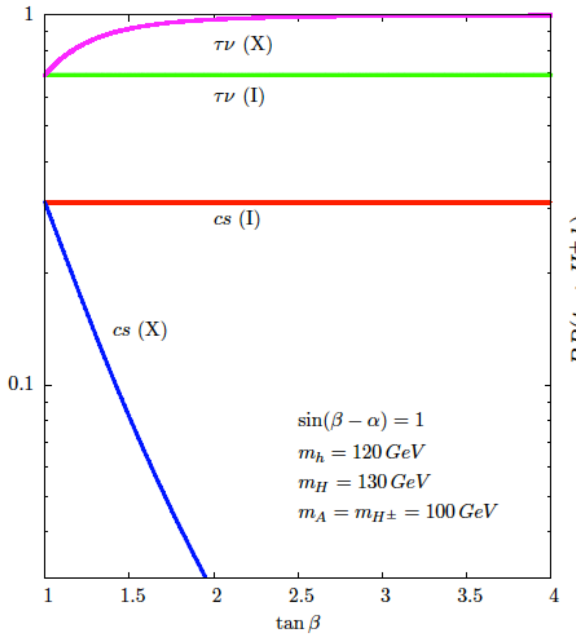
G. Aad *et al.* [ATLAS Collaboration], JHEP **1206** (2012) 039

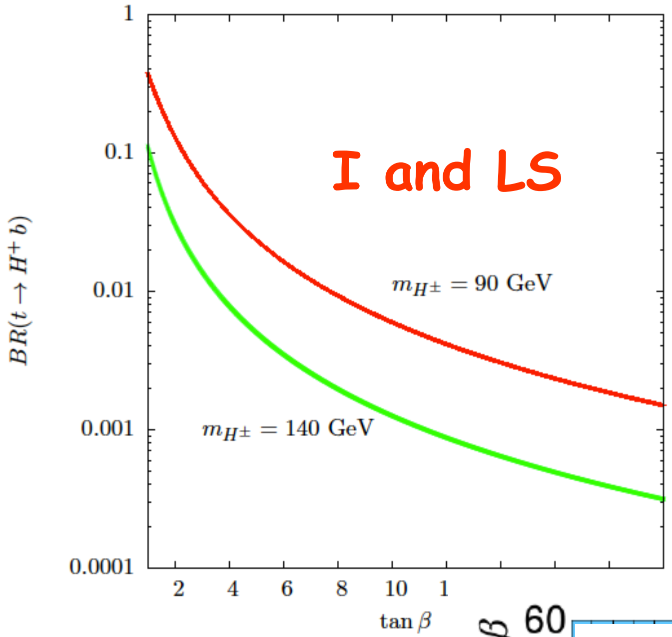
S. Chatrchyan *et al.* [CMS Collaboration], JHEP **1207** (2012) 143

Corrected for

$$BR(H^- \to \tau\bar{\nu})$$

$m_{H^+} = 90$ GeV	I	II	F	LS
$\tan\beta$	4.3	6.4	3.2	5.2





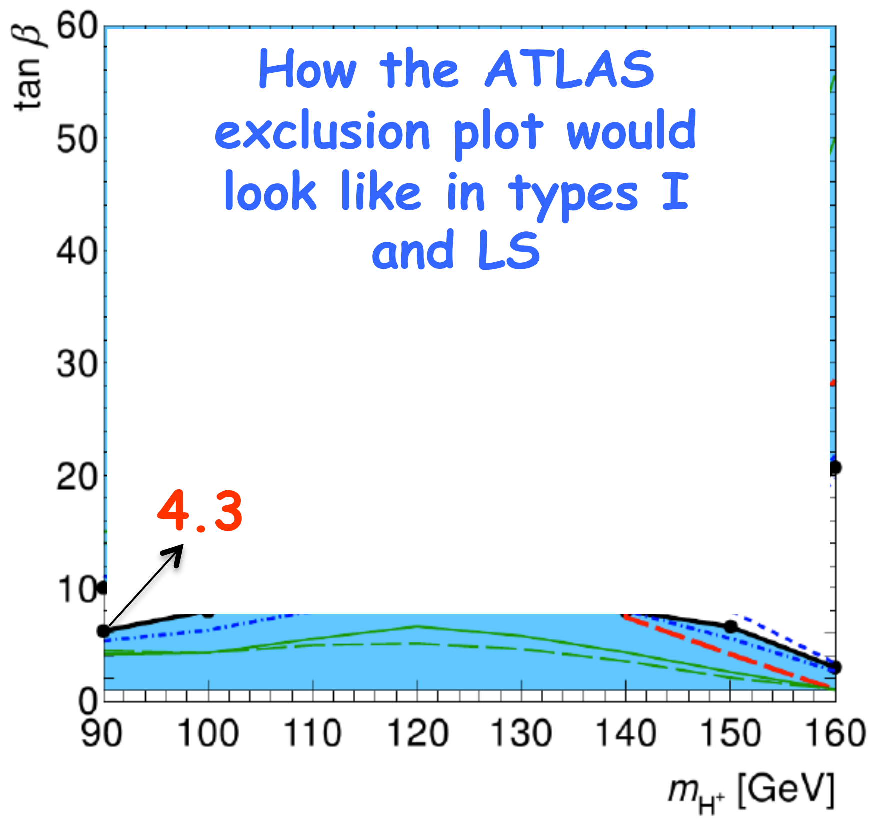
top and charged Higgs Branching Ratios in models I and LS

top decays to charged Higgs (+b); charged Higgs decays to tau (+ nu). Could be more complicated,

$H^+ \to W^+ A$.

$$q\bar{q} \rightarrow \gamma, Z \rightarrow H^+ H^-$$

no tanβ dependence (except for the decays)



The Aligned "Model" after the 8 TeV run

A. Pich and P. Tuzón, Phys. Rev. D **80** (2009) 091702 [arXiv:0908.1554 [hep-ph]].

E. Cervero and J. -M. Gerard, Phys. Lett. B **712** (2012) 255 [arXiv:1202.1973 [hep-ph]].

W. Altmannshofer, S. Gori and G. D. Kribs, Phys. Rev. D **86** (2012) 115009 [arXiv:1210.2465 [hep-ph]].

Y. Bai, V. Barger, L. L. Everett and G. Shaughnessy, Phys. Rev. D **87** (2013) 115013 [arXiv:1210.4922 [hep-ph]].

A. Celis, V. Ilisie and A. Pich, JHEP **1307** (2013) 053 [arXiv:1302.4022 [hep-ph]].

V. Barger, L. L. Everett, H. E. Logan and G. Shaughnessy, arXiv:1308.0052 [hep-ph].

D. Lopez-Val, T. Plehn and M. Rauch, JHEP **1310** (2013) 134 [arXiv:1308.1979 [hep-ph]].

V. Ilisie, arXiv:1310.0931 [hep-ph].

Analytical dependence

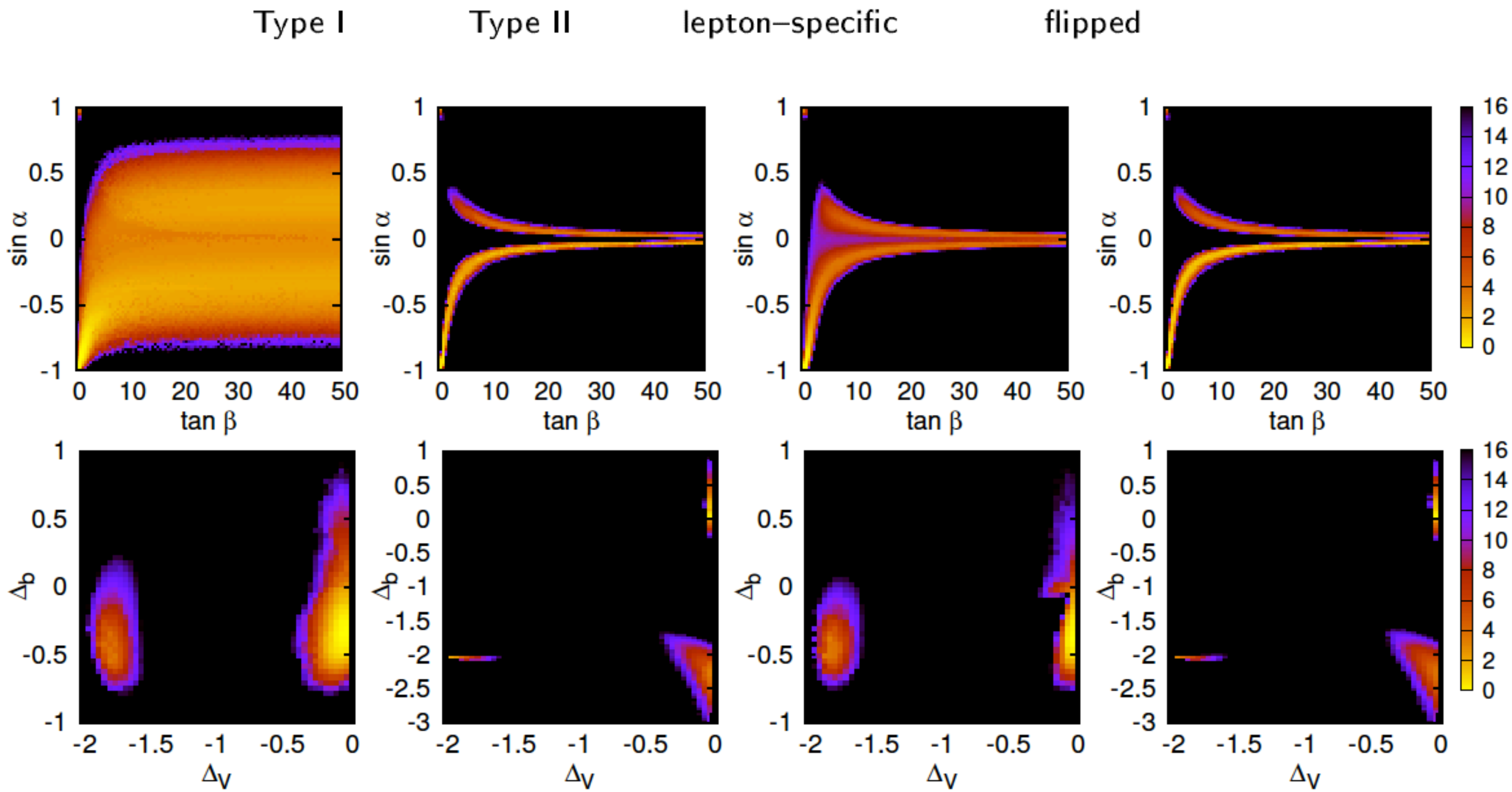
	h^0	H^0	A^0
$1+\Delta_W$	$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$	0
$1+\Delta_Z$	$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$	0
$1+\Delta_t$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{1}{\tan\beta}$
$1+\Delta_b$	$-\frac{\sin(\alpha-\gamma_b)}{\cos(\beta-\gamma_b)}$	$\frac{\cos(\alpha-\gamma_b)}{\cos(\beta-\gamma_b)}$	$\tan(\beta-\gamma_b)$
$1+\Delta_\tau$	$-\frac{\sin(\alpha-\gamma_\tau)}{\cos(\beta-\gamma_\tau)}$	$\frac{\cos(\alpha-\gamma_\tau)}{\cos(\beta-\gamma_\tau)}$	$\tan(\beta-\gamma_\tau)$
$1+\Delta_\gamma$	$\Delta_\gamma(\alpha,\tan\beta,m_{12}^2,m_{H\pm}^2)$	$\Delta_\gamma(\alpha,\tan\beta,m_{12}^2,m_{H\pm}^2)$	$\Delta_\gamma(\alpha,\tan\beta)$
$1+\Delta_g$	$\Delta_g(\Delta_t,\Delta_b)$	$\Delta_g(\Delta_t,\Delta_b)$	$\Delta_g(\Delta_t,\Delta_b)$

Type I: $\gamma_{b,\tau}=\pi/2$ **Type II:** $\gamma_{b,\tau}=0$

Table from: Lopez-Val, Plehn, Rauch, 1308.1979

The typical Z2 symmetric (softly broken) models can be obtained from the aligned by setting some phases to zero.

Plot from: Lopez-Val, Plehn, Rauch, 1308.1979



The upper row shows the allowed parameter space in the Z_2 symmetric models (softly broken). The lower row shows deviations from the hVV and hbb couplings relative to the SM.

A complex 2HDM after the 8 TeV run

I. F. Ginzburg, M. Krawczyk and P. Osland, hep-ph/0211371; W. Khater and P. Osland, Nucl. Phys. B **661**, 209 (2003) [hep-ph/0302004]; A. Wahab El Kaffas, P. Osland and O. M. Ogreid, Phys. Rev. D **76**, 095001 (2007) [arXiv:0706.2997 [hep-ph]]; B. Grzadkowski and P. Osland, Phys. Rev. D **82**, 125026 (2010) [arXiv:0910.4068 [hep-ph]]; A. Arhrib, E. Christova, H. Eberl and E. Ginina, JHEP **1104**, 089 (2011) [arXiv:1011.6560 [hep-ph]]; A. Barroso, P. M. Ferreira, R. Santos and J. P. Silva, Phys. Rev. D **86**, 015022 (2012) [arXiv:1205.4247 [hep-ph]]; B. Coleppa, K. Kumar and H. E. Logan, Phys. Rev. D **86**, 075022 (2012) [arXiv:1208.2692 [hep-ph]]; D. Fontes, J. C. Romão and J. P. Silva, arXiv:1408.2534 [hep-ph].

- The parameter space;
- The amount of mixture between CP-even and CP-odd states that is still allowed.

The CP-violating 2HDM potential

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

$$\phi_1 \to \phi_1 \qquad \phi_2 \to -\phi_2$$

We choose m^2_{12} and λ_5 complex and the vacuum configuration

$$2\ \arg\left[m_{12}^2\right] \neq \arg\left[\lambda_5\right]$$

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

$$2\ \mathrm{Im}\left[m_{12}^2\right] = v_1 v_2\,\mathrm{Im}\left[\lambda_5\right]$$

Minimum condition

10 + 2 parameters - 3 are fixed by the minimum conditions and one by the W mass $v^2 = v_1^2 + v_2^2$. The remaining 8 have to be chosen.

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

Parametrisation (8)

- 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**

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

2HDM Lagrangian (for the CP-violating potential)

- couplings that involve gauge bosons

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

- couplings that involve fermions

Extending the Z_2 symmetry to the fermions – 4 models with no FCNC at tree-level

	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	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}$	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}$

$$\tan\beta$$

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

To find the allowed parameter space

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

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

$$m_{h1} \leq m_{h2} \leq 900\ GeV$$

$$-(1000)^2\ Gev^2 \leq Re(m_{12}^2) \leq 1000^2\ GeV^2$$

$$-\pi/2 < \alpha_1 \leq \pi/2$$

$$-\pi/2 < \alpha_2 \leq \pi/2$$

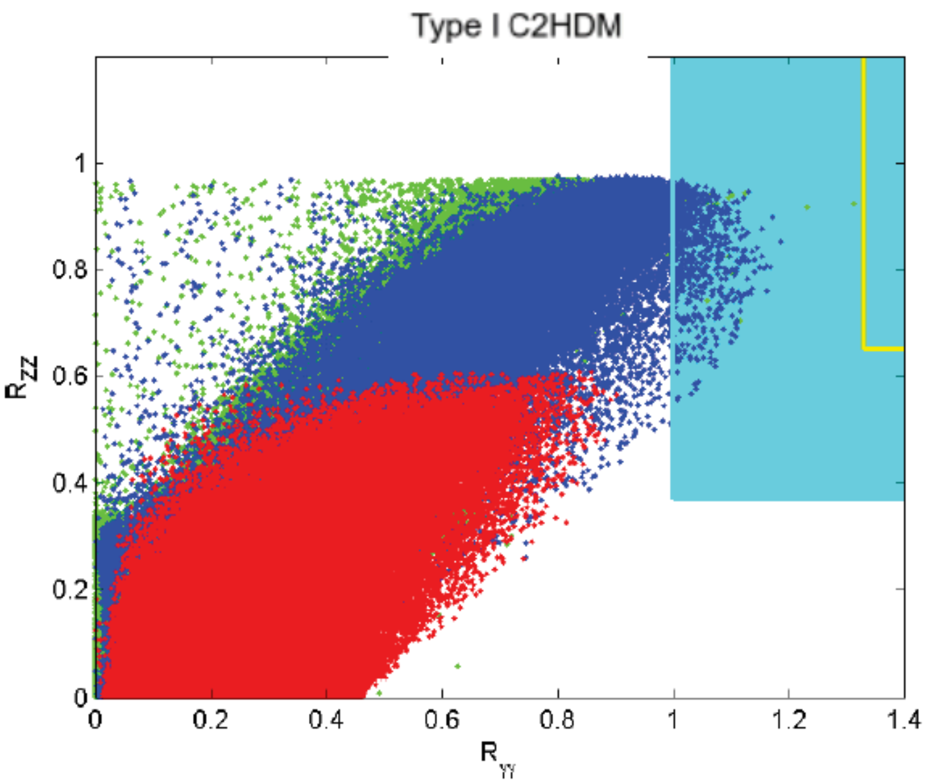
$$0 \leq \alpha_3 \leq \pi/2$$

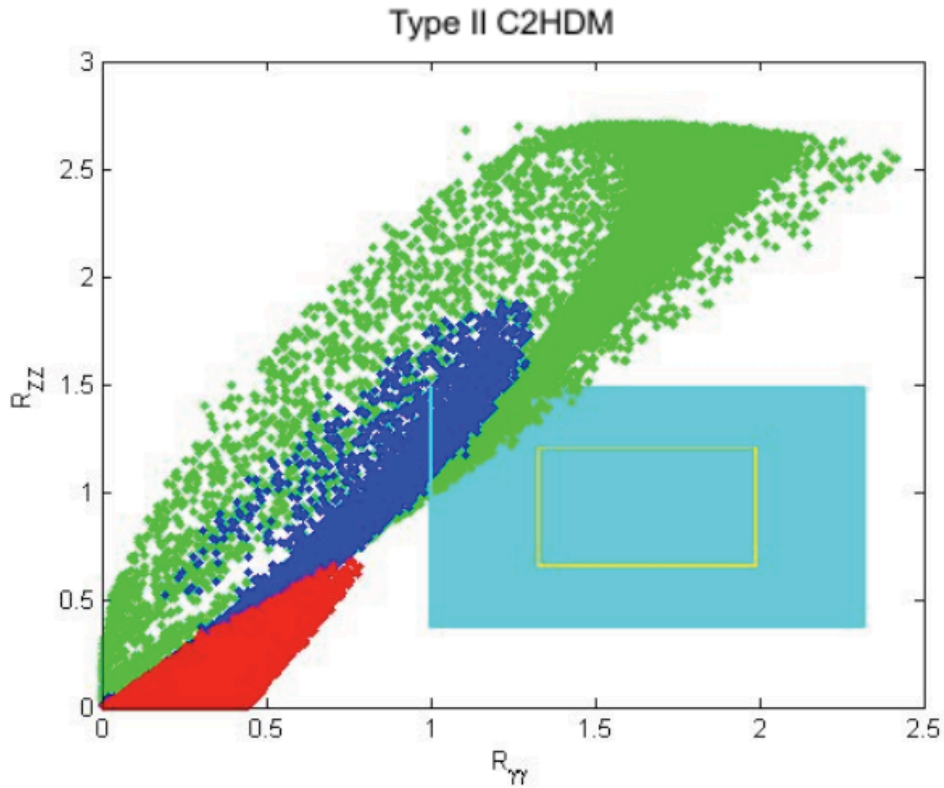
$$|s_2| = 0 \ \Rightarrow \ h_1 \text{ is a pure scalar,}$$

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

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \eta_1 \\ \eta_2 \\ \eta_3 \end{pmatrix} \qquad R = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{pmatrix}$$

Barroso, Ferreira, RS, Silva (2012).





$|s_2| < 0.1$ green

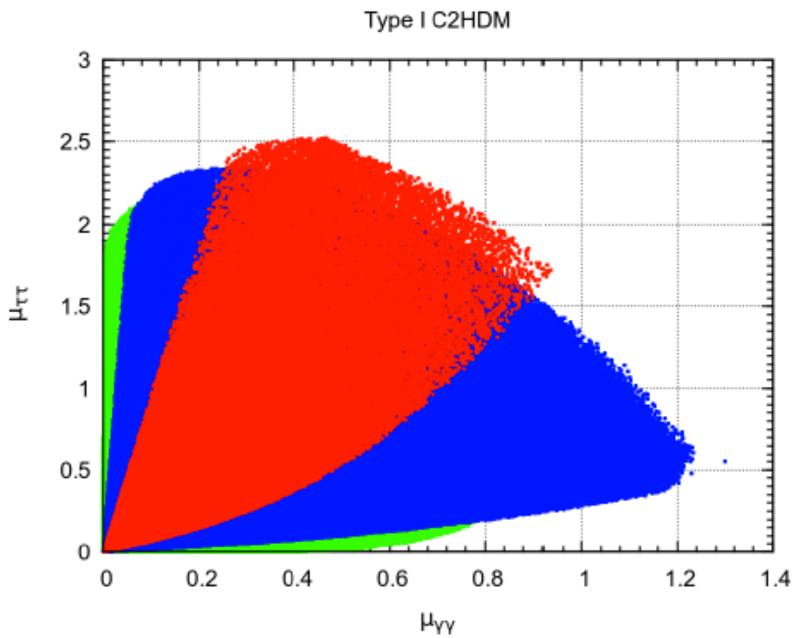
$0.45 < |s_2| < 0.55$ blue

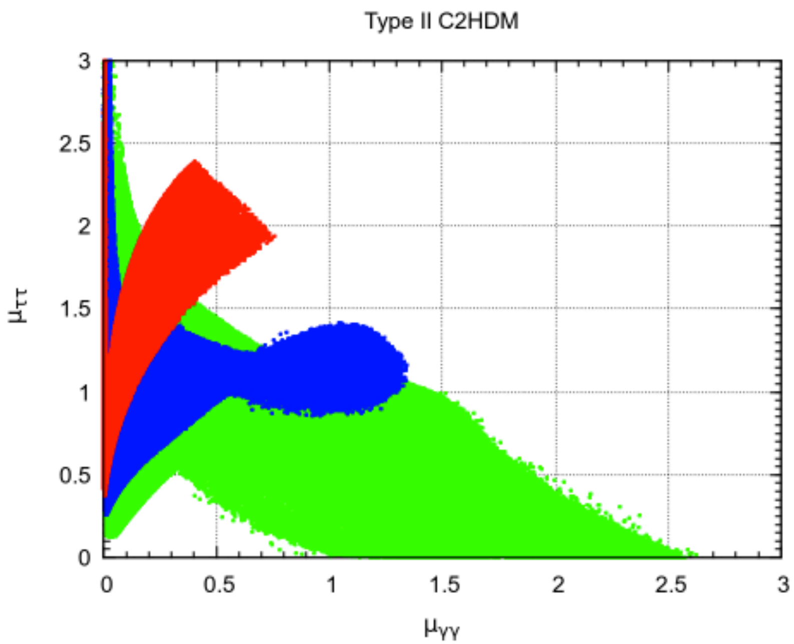
$|s_2| > 0.83$ red

How close are we (will we be) to $s_2 = 0$?

Plots show that very close to (1,1) there are many blue points. Will not be excluded by the rates.

Plot from: D. Fontes, J.C. Romão, J.P. Silva, 1408.2534.





$|s_2| < 0.1$ green

$0.45 < |s_2| < 0.55$ blue

$|s_2| > 0.83$ red

How close are we (will we be) to $s_2 = 0$?

Recently reviewed by FRS with the same conclusions new interesting plots.

Plot from: D. Fontes, J.C. Romão, J.P. Silva, 1408.2534.

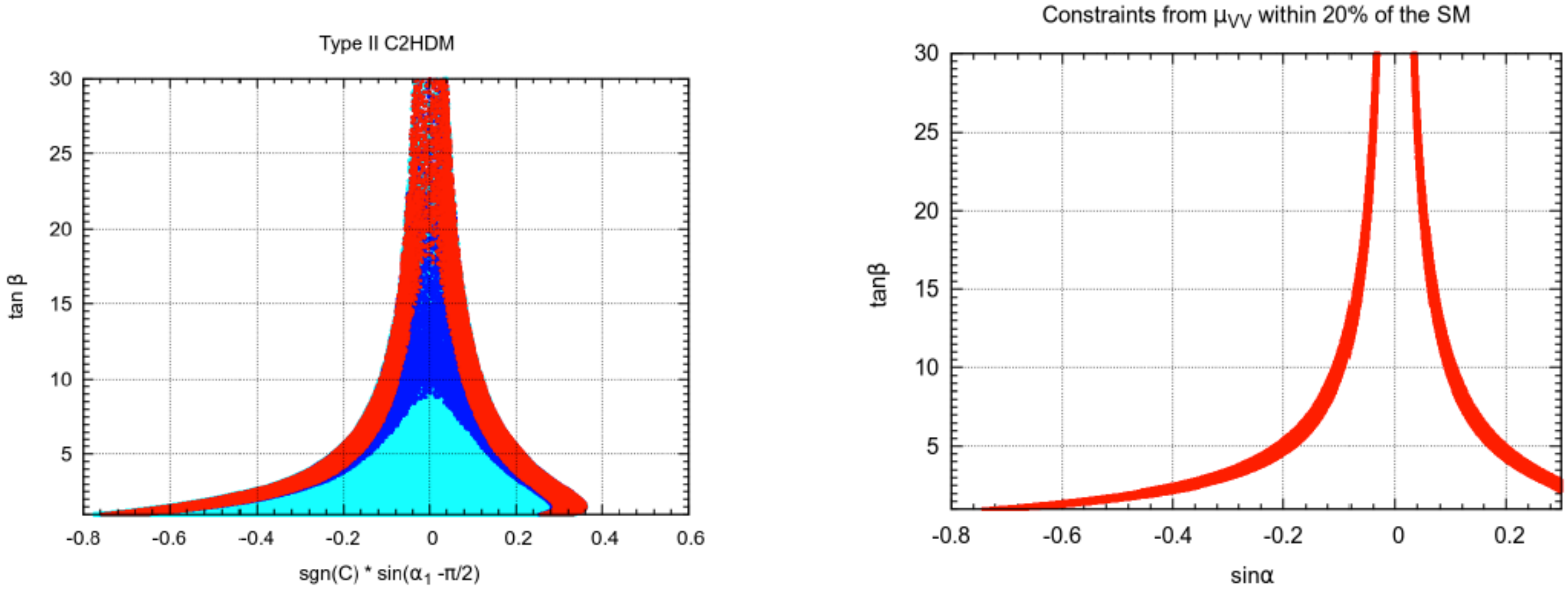


Figure 8. On the left (right) panel, we show the results of the simulation of Type II C2HDM (real 2HDM) on the $\mathrm{sgn}(C)\,\sin(\alpha_1 - \pi/2)$-$\tan\beta$ ($\sin\alpha$-$\tan\beta$) plane. On the left panel, in cyan/light-grey we show all points obeying $\mu_{VV} = 1.0 \pm 0.2$; in blue/black the points that satisfy in addition $|s_2|$, $|s_3| < 0.1$; and in red/dark-grey the points that satisfy $|s_2|$, $|s_3| < 0.05$.

Conclusions

The allowed space of softly broken Z_2 symmetric 2HDMs is now cornered into two regions – the SM like limit where $\sin(\beta-\alpha)$ is very close to 1 independently of $\tan\beta$ and the wrong sign limit (or symmetric limit) where large values of $\tan\beta$ are excluded but smaller values of
$\sin(\beta-\alpha)$ are allowed (strongly correlated).

In types I and LS there is no wrong sign limit but rather a symmetric limit that will be very hard to resolve especially for large $\tan\beta$.

An interesting non-decoupling effect allows for a possible exclusion of a type II model in the SM-like limit of a heavy Higgs scenario.

Large mixing between the neutral states is still allowed in CP-violating models.

The 8-parameter CP-conserving 2HDM after the 8 TeV run

CP-even scalar as the SM-like Higgs

G. Burdman, C. E. F. Haluch and R. D. Matheus, Phys. Rev. D **85**, 095016 (2012) [arXiv:1112.3961 [hep-ph]]; A. Freitas and P. Schwaller, Phys. Rev. D **87**, no. 5, 055014 (2013) [arXiv:1211.1980 [hep-ph]]; S. Chatrchyan *et al.* [CMS Collaboration], Phys. Rev. Lett. **110**, 081803 (2013) [arXiv:1212.6639 [hep-ex]]; G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **726**, 120 (2013) [arXiv:1307.1432 [hep-ex]].

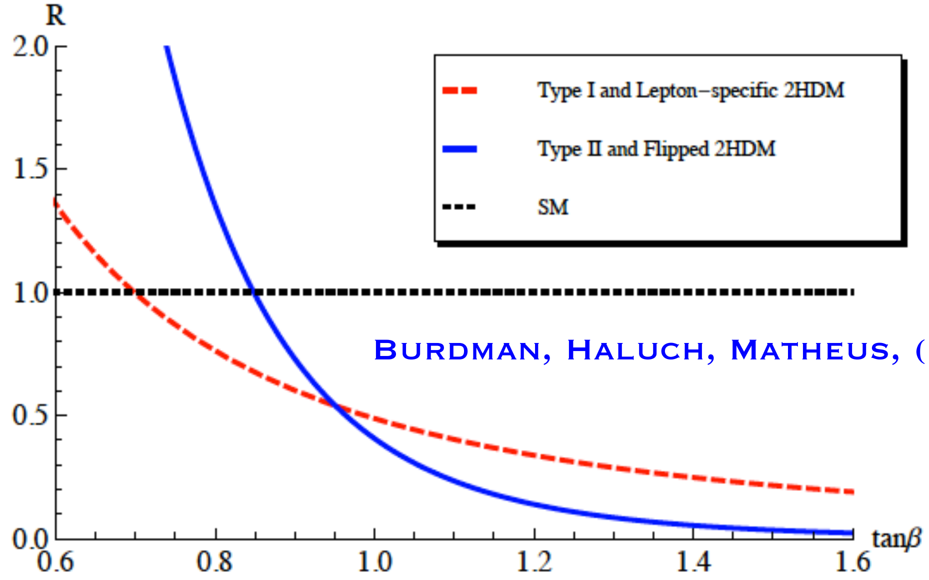
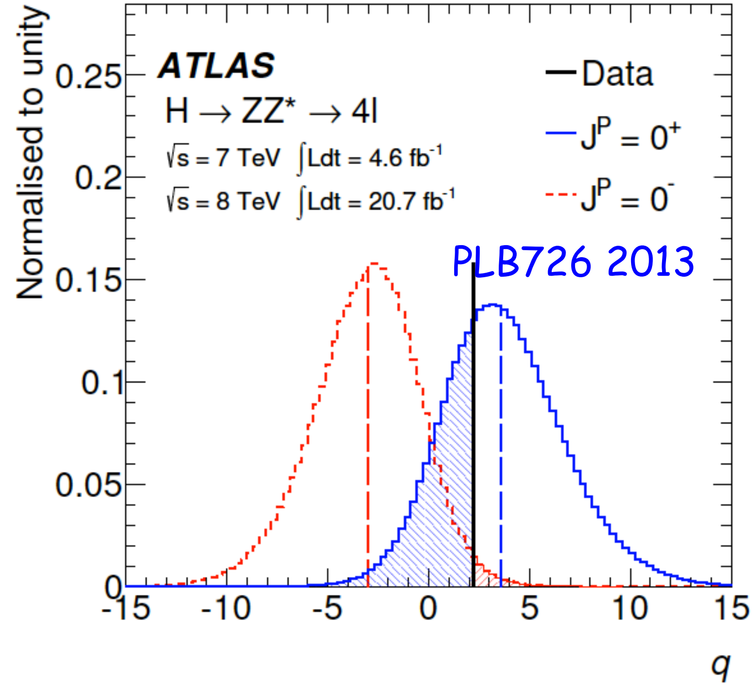
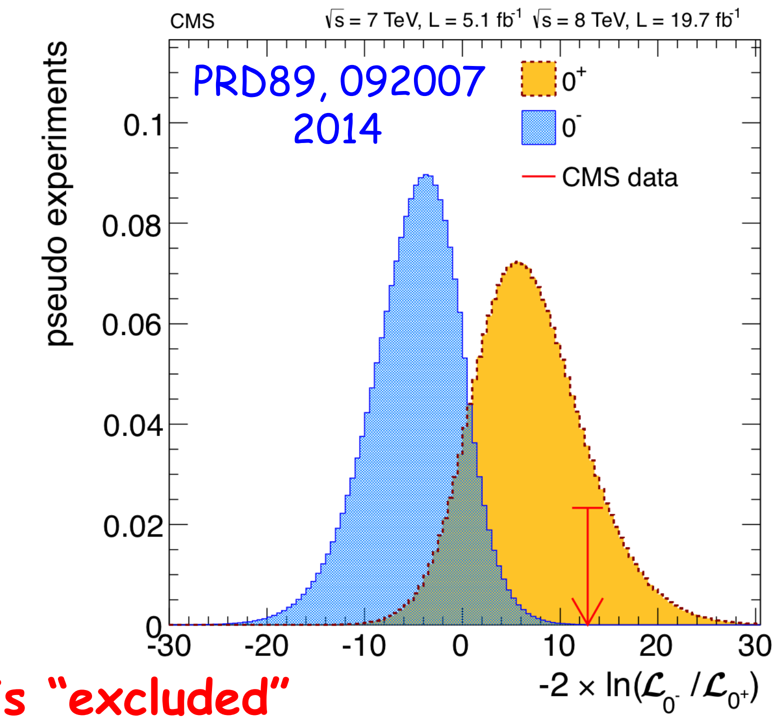


FIG. 1: The ratio $R = \sigma \times BR(gg \to A \to \gamma\gamma)/\sigma \times BR(gg \to h \to \gamma\gamma)$ vs. $\tan\beta$. The dashed line corresponds to the type I and lepton-specific schemes, with the solid curve being for the type II and flipped cases. The horizontal dotted line corresponds to $\sigma \times BR(gg \to A \to \gamma\gamma)$ equal to the prediction for this process mediated by the SM Higgs.

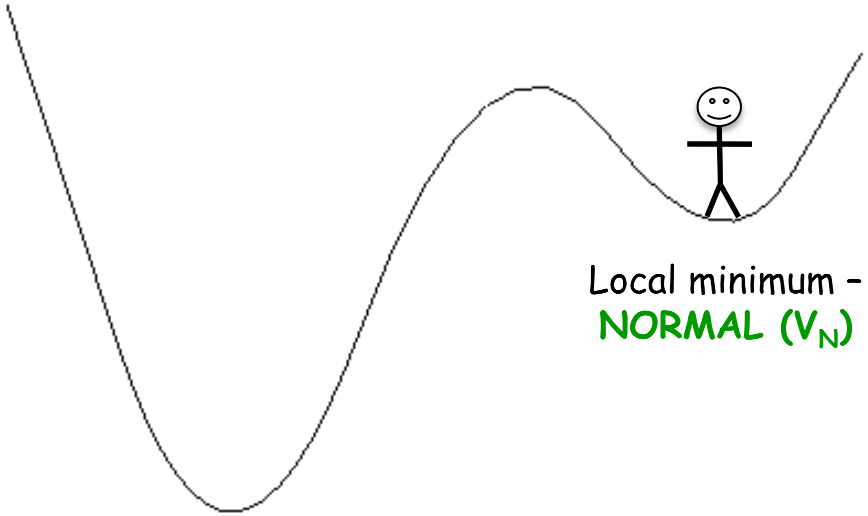


First analysis on the CP-odd Scalar as the SM-like Higgs in the context of the 2HDM.
Even with no couplings to massive gauge bosons involved it was already a problematic scenario with tanβ below 1.



0- hypothesis "excluded"

Vacuum structure of 2HDMs



Local minimum – NORMAL (V_N)

$$m_\gamma = 0$$

A. Barroso, P. Ferreira, RS

PLB603(2004), PLB632(2006), PLB652(2007)

M. Maniatis, A. von Manteuffel, O. Nachtmann and F. Nagel

EPJC48(2006)805

I. Ivanov

PRD75(2007)035001, PRD77(2008)15017

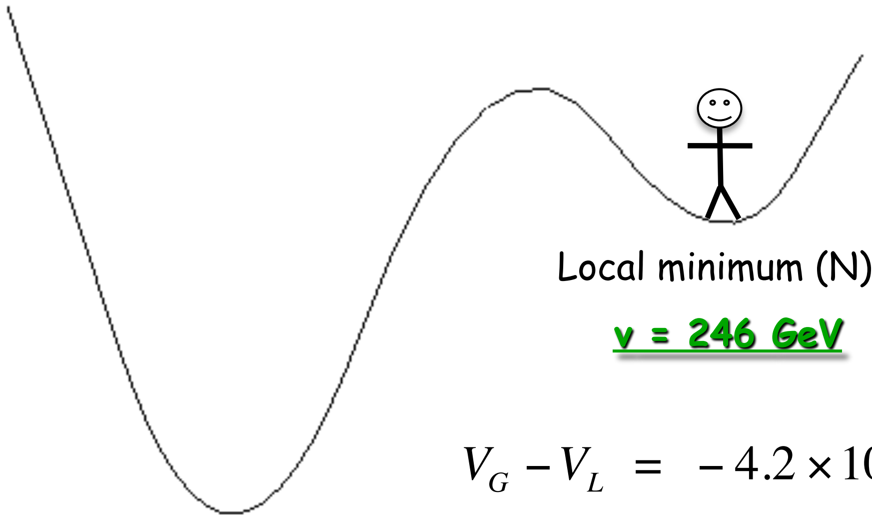
Global minimum – CHARGE BREAKING (V_{CB})

$$m_\gamma \neq 0 \ !$$

The tree-level global picture

1. 2HDM have at most two minima
2. Minima of different nature never coexist
3. Unlike Normal, CB and CP minima are uniquely determined
4. If a 2HDM has only one normal minimum then this is the absolute minimum – all other SP if they exist are saddle points
5. If a 2HDM has a CP breaking minimum then this is the absolute minimum – all other SP if they exist are saddle points

Two normal minima - potential with the soft breaking term



Local minimum (N) -

v = 246 GeV $\quad m_W = 80.4\ \text{GeV}$

$$V_G - V_L = -4.2 \times 10^8\ \text{GeV}$$

Global minimum (N) -

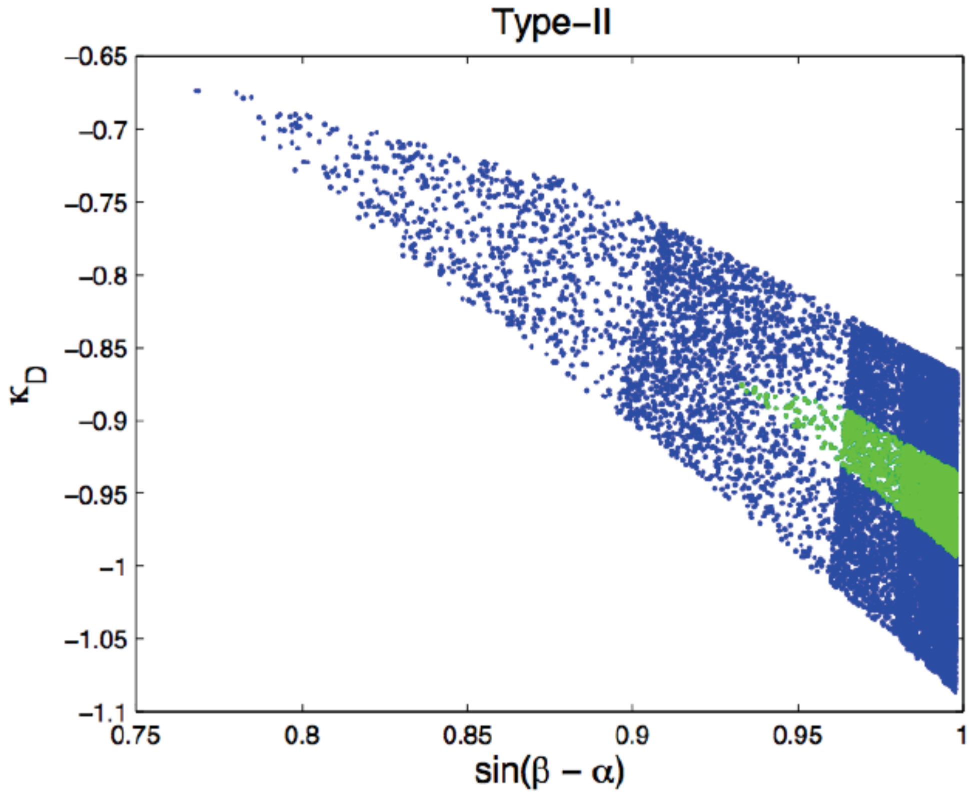
v = 329 GeV $\quad m_W = 107.5\ \text{GeV}$

THE PANIC VACUUM!

and this is one that can actually occur...

A. Barroso, P.M. Ferreira, I.P. Ivanov, RS, JHEP06 (2013) 045.

A. Barroso, P.M. Ferreira, I.P. Ivanov, RS, J.P. Silva, Eur. Phys. J. C73 (2013) 2537.



In the large tanβ limit, as κ_V = sin(β−α) approaches 1, sin(β+α) approaches sin(β−α).

$$\sin(\beta+\alpha) - \sin(\beta-\alpha) = \frac{2(1-\varepsilon)}{1+\tan^2\beta} \ll 1$$

$$(\tan\beta \gg 1)$$

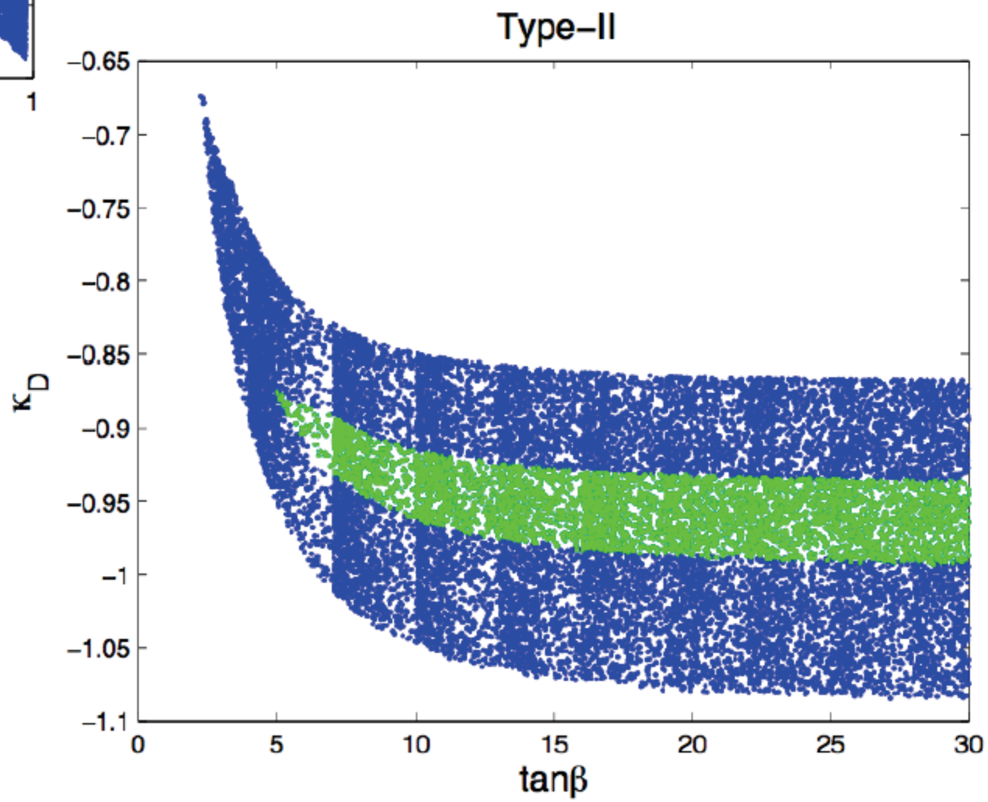
Need interference.

Colour code

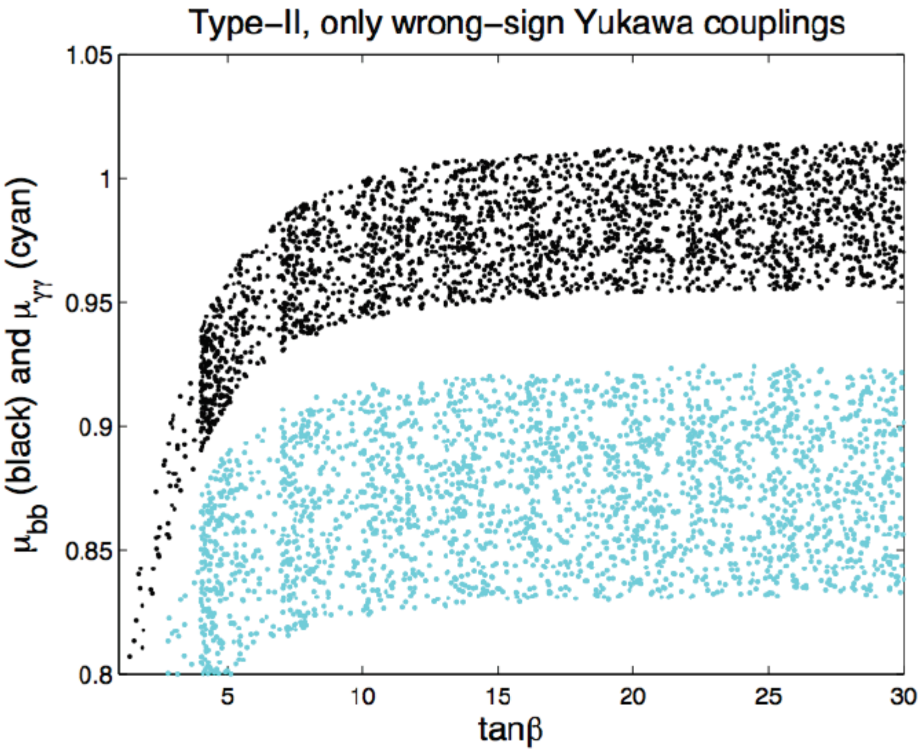
Red - all rates within 5% of corresponding SM values.

Green - 10% and Blue - 20%;

No points at 5 %.

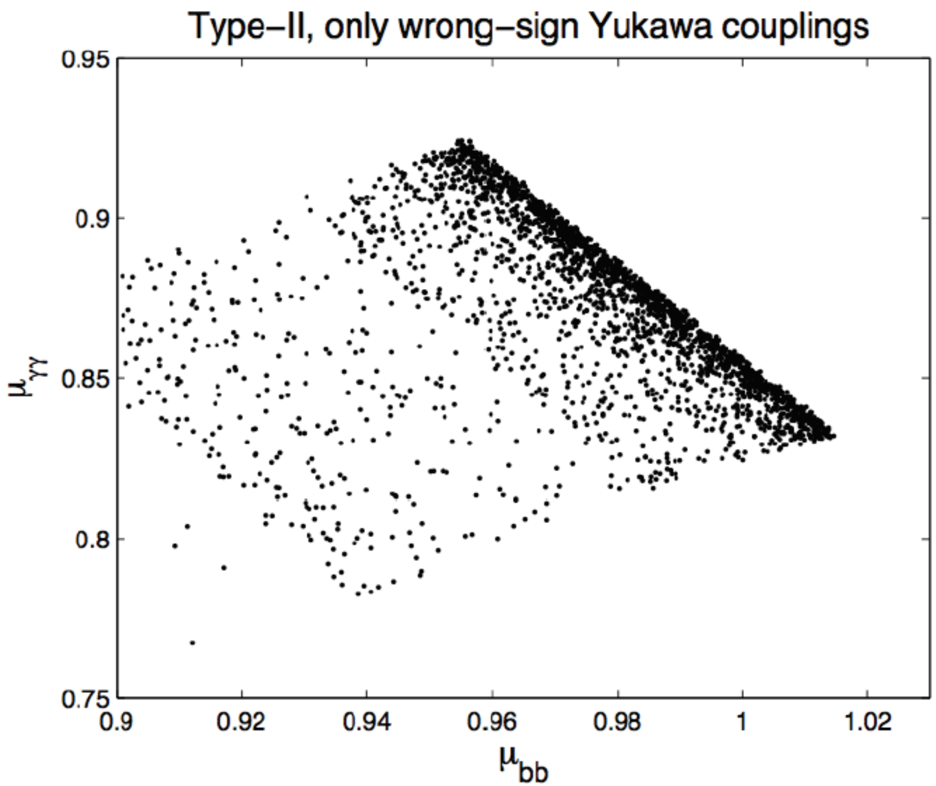


Why isn't it excluded by the $\mu_{\gamma\gamma}$?

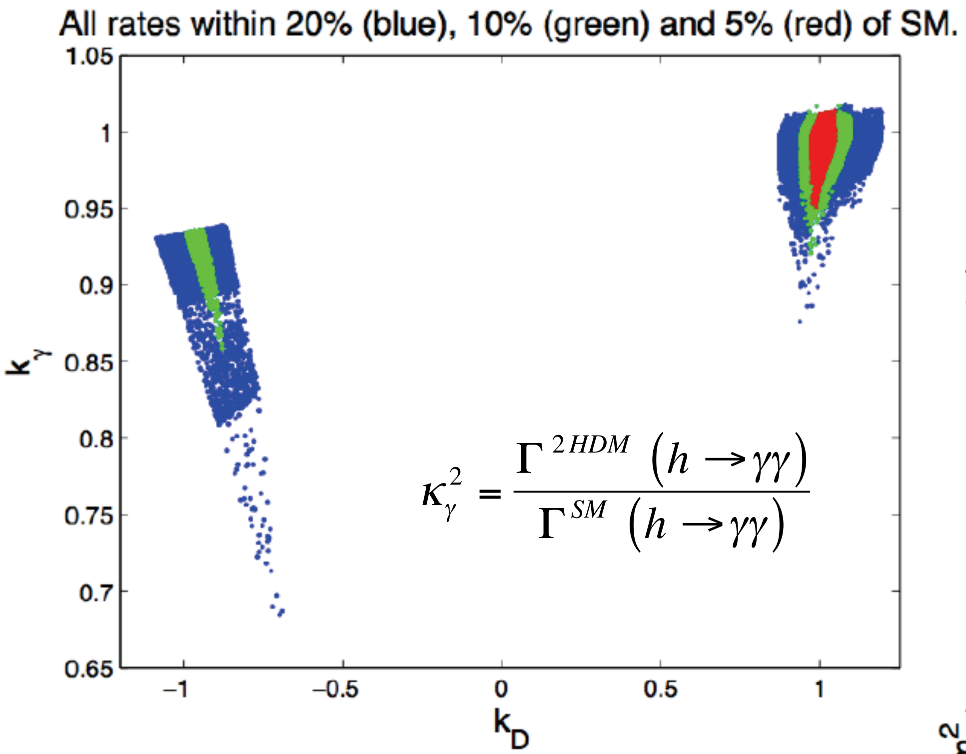


$$\mu_f^h(\text{LHC}) = \frac{\sigma^{2\text{HDM}}(pp \to h)\,\text{BR}^{2\text{HDM}}(h \to f)}{\sigma^{\text{SM}}(pp \to h_{\text{SM}})\,\text{BR}(h_{\text{SM}} \to f)}$$

Assuming WW and ZZ rates to be within 5 % of the SM predictions.

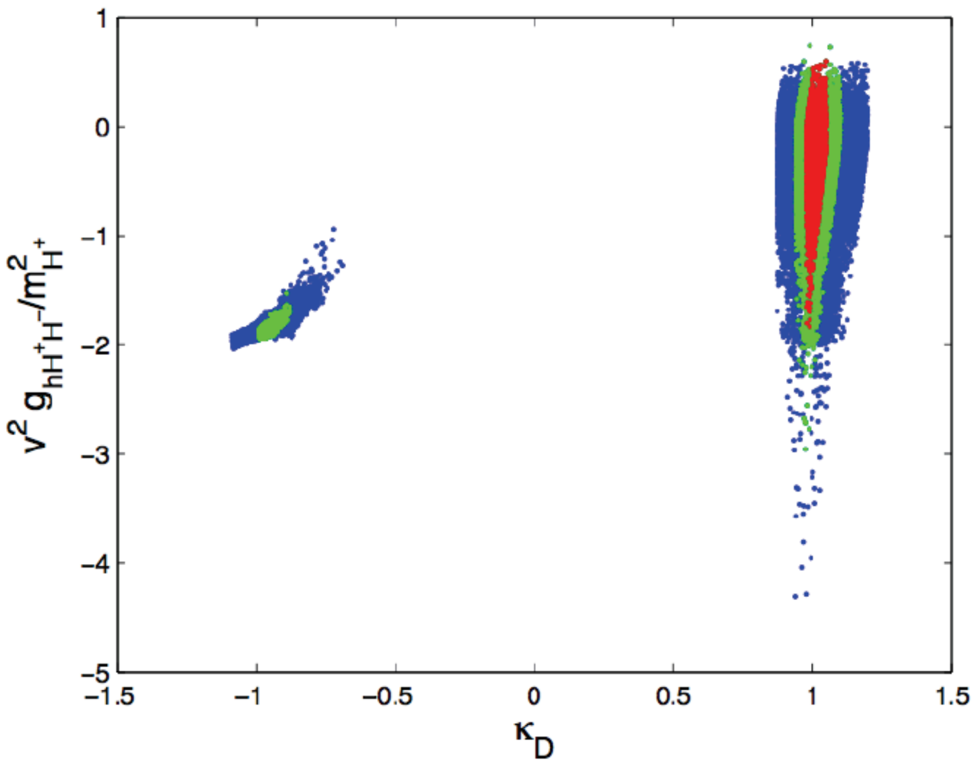


How come we do not have any points at 5 %?



If we were only considering the gauge bosons and fermion loops we should find points at 5 % for the wrong-sign scenario.

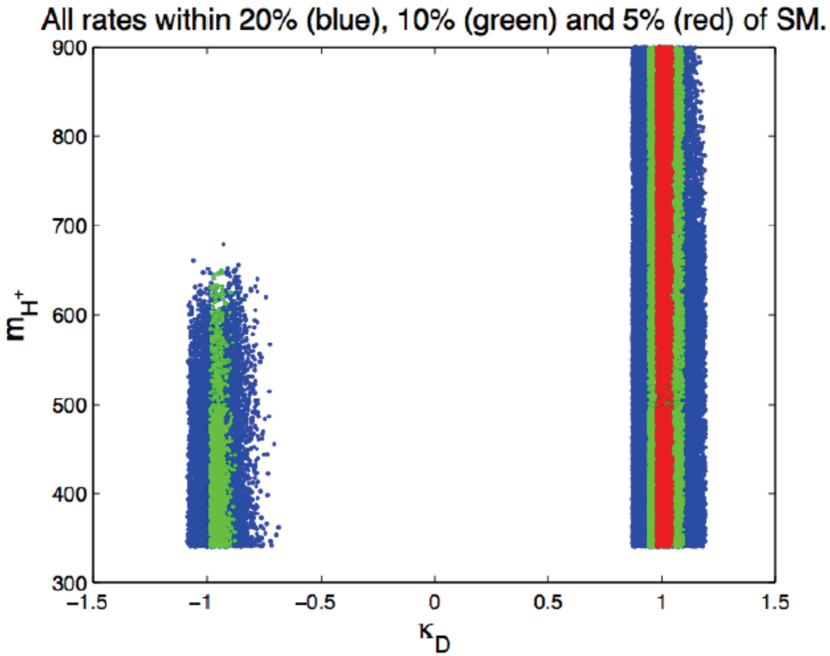
In fact, if the charged Higgs loops were absent, changing the sign of κ_D would imply a change in κ_γ of less than 1 %.



The relative negative values (and almost constant) contribution from the charged Higgs loops forces the wrong sign $\mu_{\gamma\gamma}$ to be below 1.

It is an indirect effect.

What is the origin of this indirect effect?



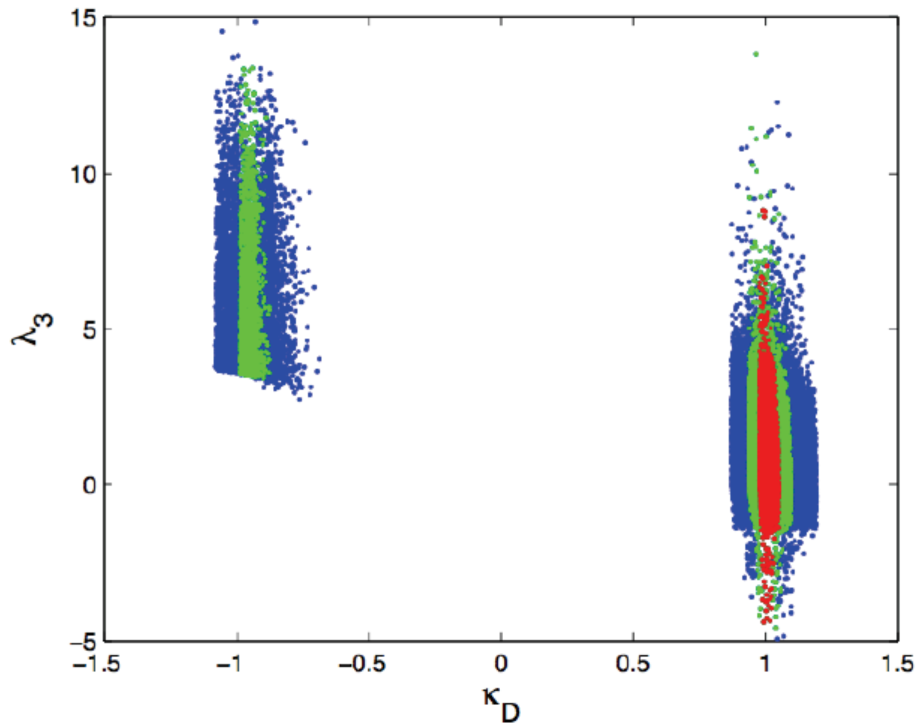
Large non-decoupling charged-Higgs loops contribution until the unitarity limit is reached.

The bound is imposed on λ_3 due to $|a^+| < 0.5$.

$$a^+ = \frac{1}{16\pi}\left[\frac{3}{2}(\lambda_1+\lambda_3)+\sqrt{\frac{9}{4}(\lambda_1-\lambda_2)^2+(2\lambda_3+\lambda_4)^2}\right]$$

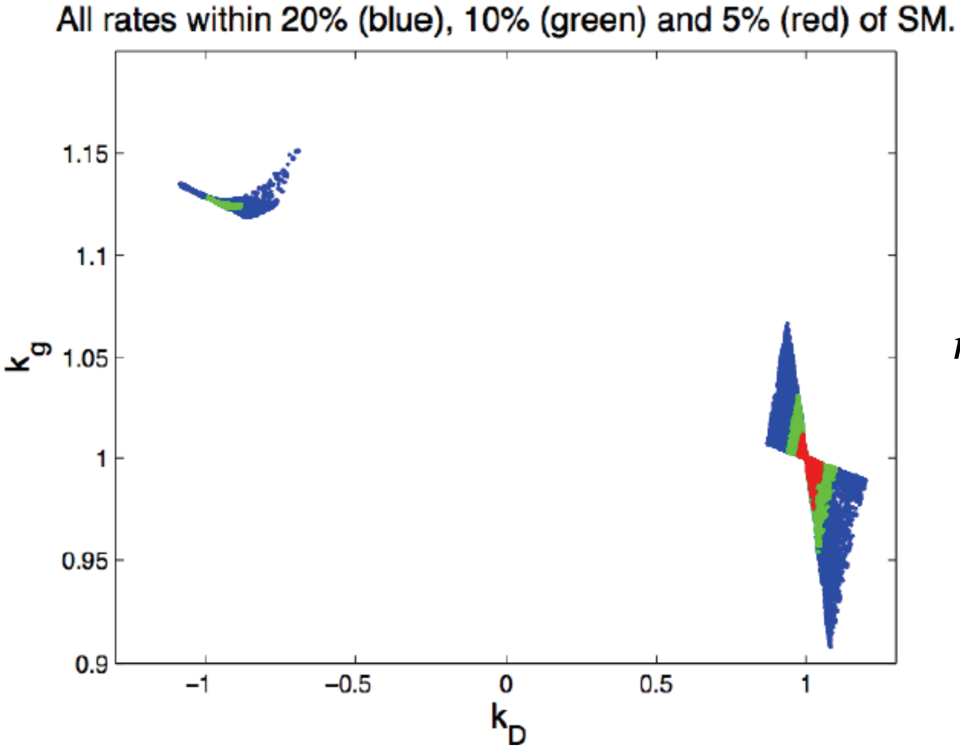
Table 1-20 of 1310.8361

Facility	LHC	HL-LHC	ILC500
$\sqrt{s}$ (GeV)	14,000	14,000	250/500
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500
κ_γ	5 − 7%	2 − 5%	8.3%
κ_g	6 − 8%	3 − 5%	2.0%
κ_W	4 − 6%	2 − 5%	0.39%
κ_Z	4 − 6%	2 − 4%	0.49%
κ_ℓ	6 − 8%	2 − 5%	1.9%
$\kappa_d = \kappa_b$	10 − 13%	4 − 7%	0.93%
$\kappa_u = \kappa_t$	14 − 15%	7 − 10%	2.5%



S. Dawson, A. Gritsan, H. Logan, J. Qian, C. Tully, R. Van Kooten et al., arXiv:1310.8361 [hep-ex].

Should one expect a direct effect in the coupling to gluons?



In h -> gg only fermion loops contribute.

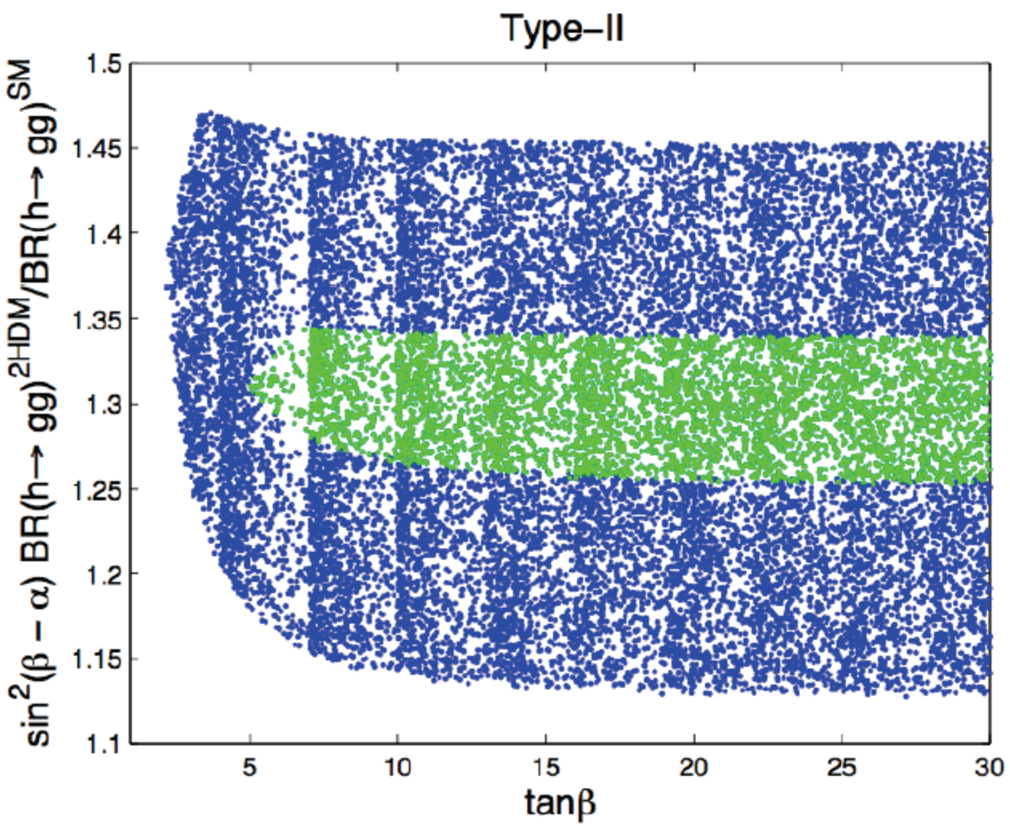
$$\kappa_g^2 = \frac{\Gamma^{2HDM}(h \to gg)}{\Gamma^{SM}(h \to gg)} = 1.27 \Leftarrow \sin(\beta + \alpha) = 1$$

Region will be excluded even in the pessimistic scenario.

Table 1-20 of 1310.8361

Facility	LHC	HL-LHC	ILC500
$\sqrt{s}$ (GeV)	14,000	14,000	250/500
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500
κ_γ	$5-7\%$	$2-5\%$	8.3%
κ_g	$6-8\%$	$3-5\%$	2.0%
κ_W	$4-6\%$	$2-5\%$	0.39%
κ_Z	$4-6\%$	$2-4\%$	0.49%
κ_ℓ	$6-8\%$	$2-5\%$	1.9%
$\kappa_d = \kappa_b$	$10-13\%$	$4-7\%$	0.93%
$\kappa_u = \kappa_t$	$14-15\%$	$7-10\%$	2.5%

Exclusion at the ILC



$$e^+e^- \rightarrow Zh \rightarrow Zgg$$

$$\mu_{gg}^{h}(\mathrm{ILC}) = \frac{\sigma^{2HDM}\ \mathrm{BR}^{2HDM}(h \rightarrow gg)}{\sigma^{SM}\ \mathrm{BR}^{SM}(h \rightarrow gg)}$$

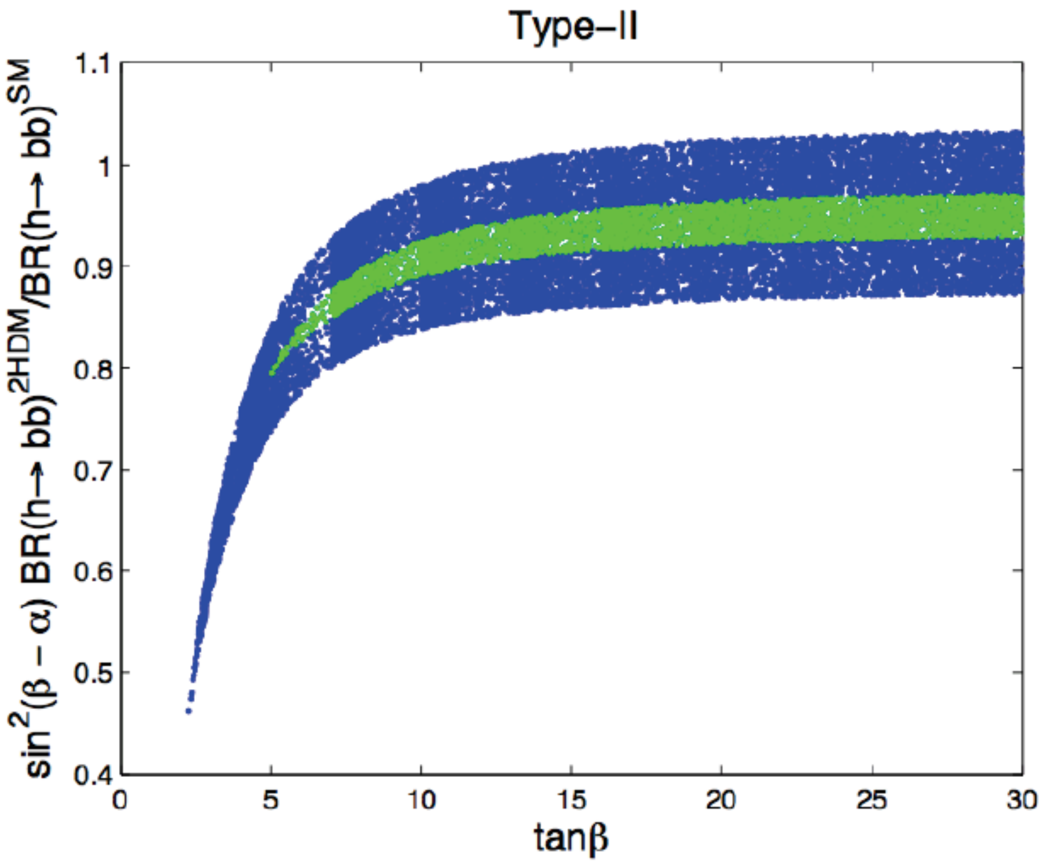
$$\mu_{gg}^{h}(\mathrm{ILC}) = \sin^2(\beta - \alpha)\frac{\mathrm{BR}^{2HDM}(h \rightarrow gg)}{\mathrm{BR}^{SM}(h \rightarrow gg)}$$

At the ILC, the 95% CL predicted measurement for a center-of-mass energy of 350 GeV and 250 fb^{-1} luminosity is $\mu_{\gamma\gamma} = 1.02 \pm 0.07$.

Measurement would exclude all points in the figure.

S. Dawson, A. Gritsan, H. Logan, J. Qian, C. Tully, R. Van Kooten et al., arXiv:1310.8361 [hep-ex].
H. Ono and A. Miyamoto, Eur. Phys. J. C 73 (2013) 2343 [arXiv:1207.0300 [hep-ex]].

Exclusion at the ILC



Could also work due to expected precision-
at 95% CL predicted measurement for a center-of-mass energy of 350 GeV and 250 fb^{-1} luminosity is

μ_{bb} = 1.00 ± 0.01.

$$e^+e^- \to Zh \to Zb\bar{b}$$

$$\mu^h_{bb}(\text{ILC}) = \sin^2(\beta-\alpha)\frac{\text{BR}^{2HDM}\left(h \to b\bar{b}\right)}{\text{BR}^{SM}\left(h \to b\bar{b}\right)}$$

Other processes will be measured with less precision but can also be used.

$$e^+e^- \to Zh \to Zc\bar{c} \qquad e^+e^- \to Zh \to Z\tau^+\tau^-$$

Experimental - not considered

SM – 3.4σ deviation

Type I $\frac{1}{\tan\beta \, m_{H\pm}}$

Type X,Y $\frac{1}{m_{H\pm}}$

For most of the parameter space 2HDM=SM

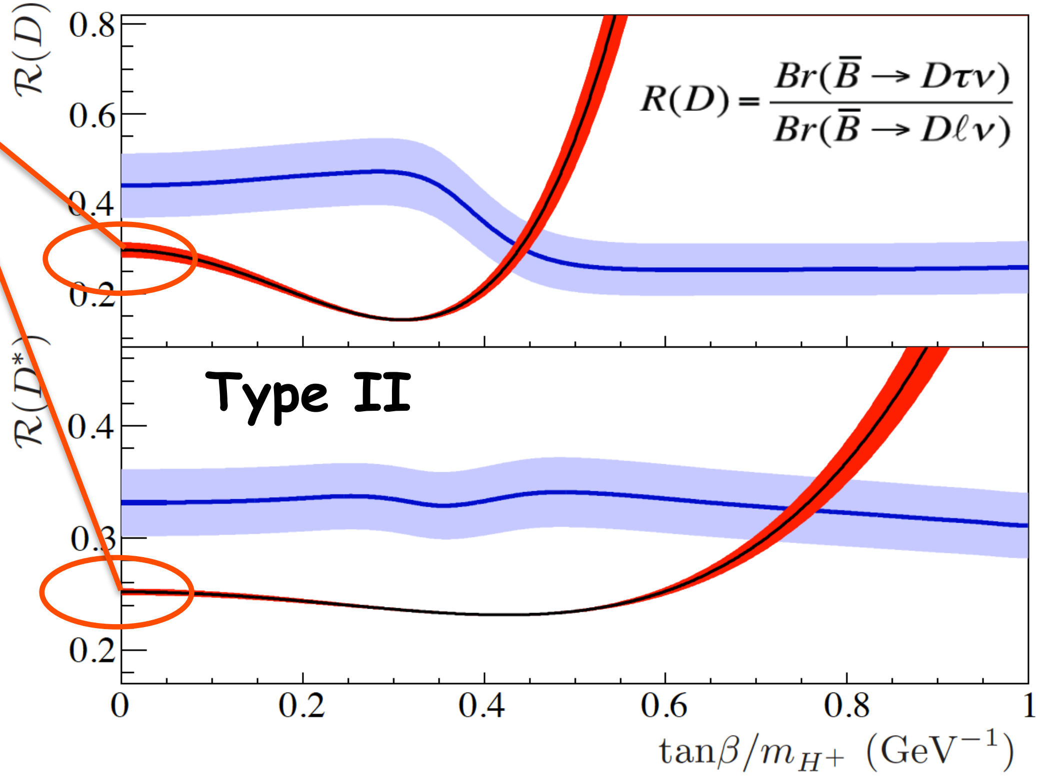
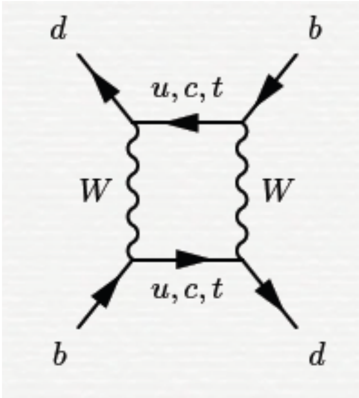


FIG. 2. (Color online) Comparison of the results of this analysis (light gray, blue) with predictions that include a charged Higgs boson of type II 2HDM (dark gray, red). The SM corresponds to $\tan\beta/m_{H+} = 0$.

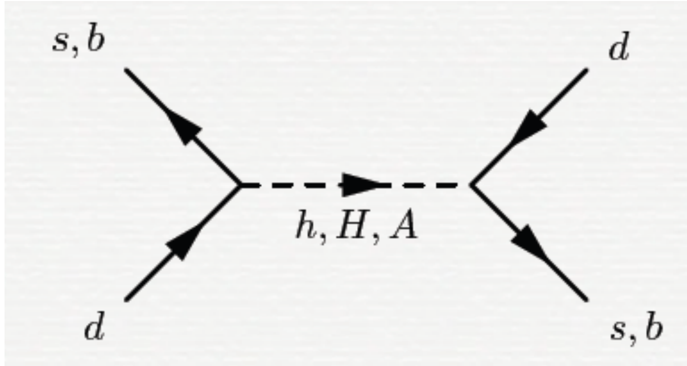
J.P. Lees et al. [BaBar Collaboration]
Evidence for an excess of B → $D^{(*)}\tau\nu$ *decays*
Phys. Rev. Lett. **109**, 101802 (2012)

FCNC constraints in 2HDM

➡ B_d^0–$\overline{B}_d^0$ and B_s^0–$\overline{B}_s^0$ mixing



New tree-level FCNC diagrams



➡ Rare B decays