2HDM after the 8 TeV run
and
probing the wrong-sign Yukawa coupling

LHCP2014

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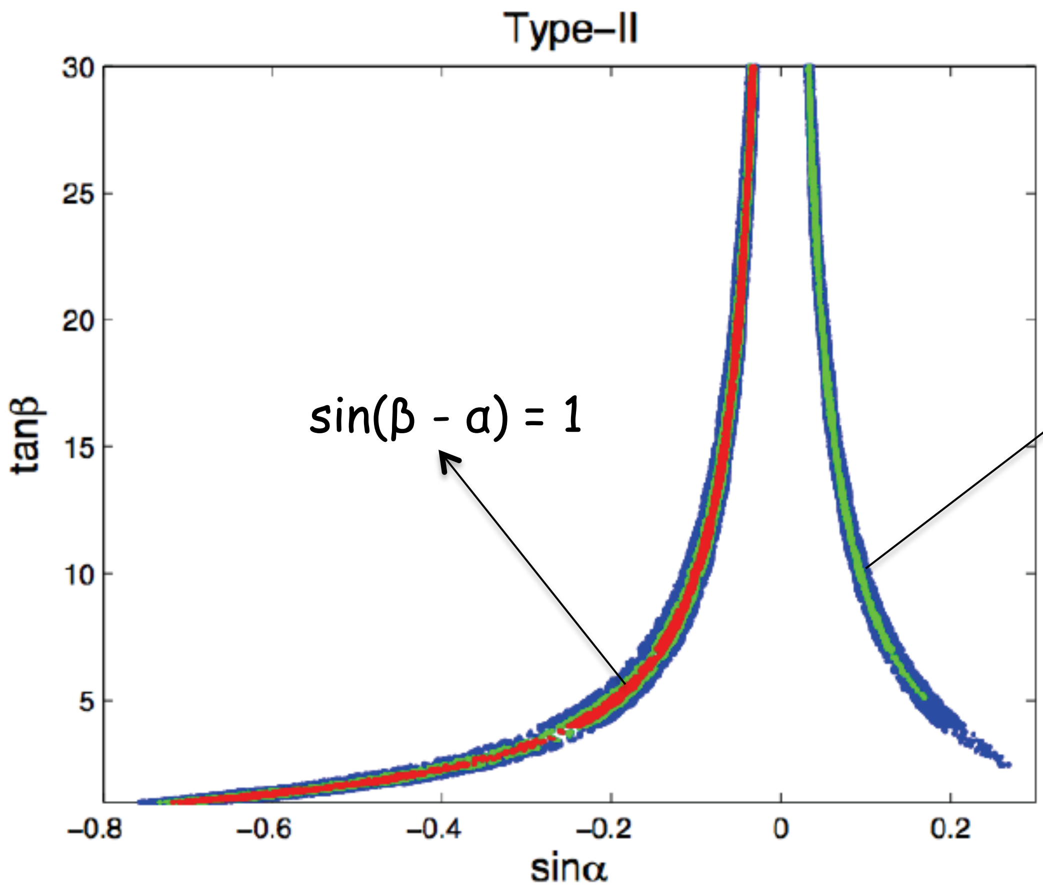
with P. Ferreira, M. Sampaio, R. Guedes

and with J. Gunion, H. Haber

What is this talk about?

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



Red - all rates (μ's) within 5% of corresponding SM values. Green - 10% and Blue - 20%.

$$\kappa_U^{II} = \frac{\cos\alpha}{\sin\beta}$$

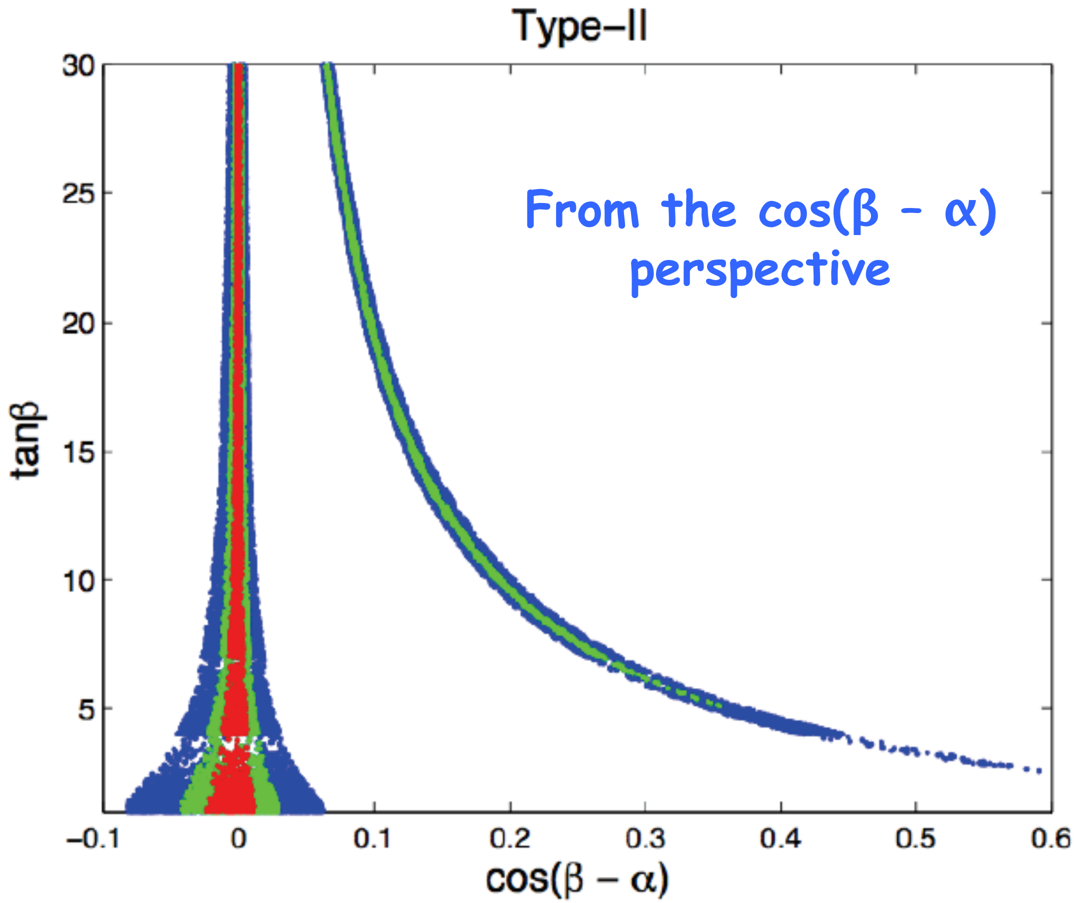
$$\kappa_D^{II} = -\frac{\sin\alpha}{\cos\beta}$$

$$\sin(\beta-\alpha)=1 \quad \Rightarrow \quad \kappa_D^{II}=1 \quad (\kappa_U^{II}=1)$$

$$\sin(\beta+\alpha)=1 \quad \Rightarrow \quad \kappa_D^{II}=-1 \quad (\kappa_U^{II}=1)$$

How to get rid of the right leg of the plot?

P. Ferreira, J. Gunion, H. Haber and RS, 1403.4736 (to appear in PRD)



This scenario is possible only if one of the Yukawa couplings has a different sign from the respective SM one (while the Higgs coupling to gauge boson does not change sign).

Wrong-sign Yukawa coupling – at least one of the couplings of the Higgs to down-type and up-type fermion pairs is opposite in sign to the corresponding coupling of the Higgs to VV (in contrast with the SM).

Z_2 symmetric CP-conserving 2HDM (softly broken)

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

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

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 (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…**

The CP-conserving 2HDM after the 8 TeV run

ScannerS a tool for multi-Higgs calculations

Coimbra, Sampaio, RS, (2013).

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

interfaced with

SuShi – Higgs production at NNLO in *gg* and bb Harlander, Liebler, Mantler, (2013).

HDECAY – Higgs decays Djouadi, Kalinowski, Spira (1997) + Mühlleitner (2013).

Superiso – 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.

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

To find the allowed parameter space we scan

- Set m_h = 125 GeV

- Generate random values for potential's parameters such that

$$50 \text{ GeV} \leq m_{H^+} \leq 700 \text{ GeV}$$

$$m_h + 5 \text{ GeV} \leq m_A ,\, m_H \leq 500 \text{ GeV}$$

$$-50^2 \text{ GeV}^2 \leq m_{12}^2 \leq 300^2 \text{ GeV}^2$$

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

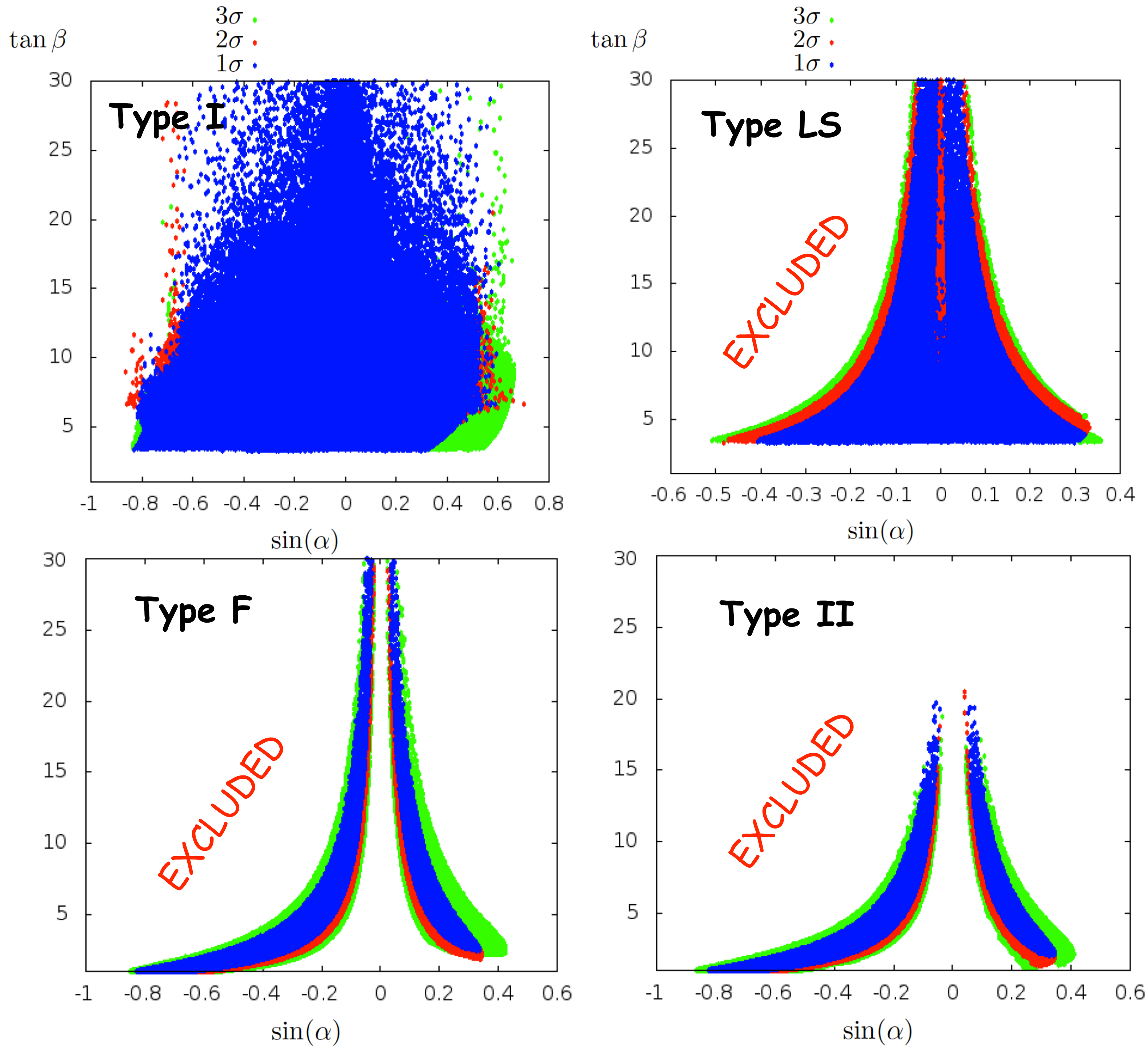
$$-\frac{\pi}{2} \leq \alpha \leq \frac{\pi}{2}$$

- Impose all experimental and theoretical constraints previously described

- Calculate all branching ratios and production rates at the LHC

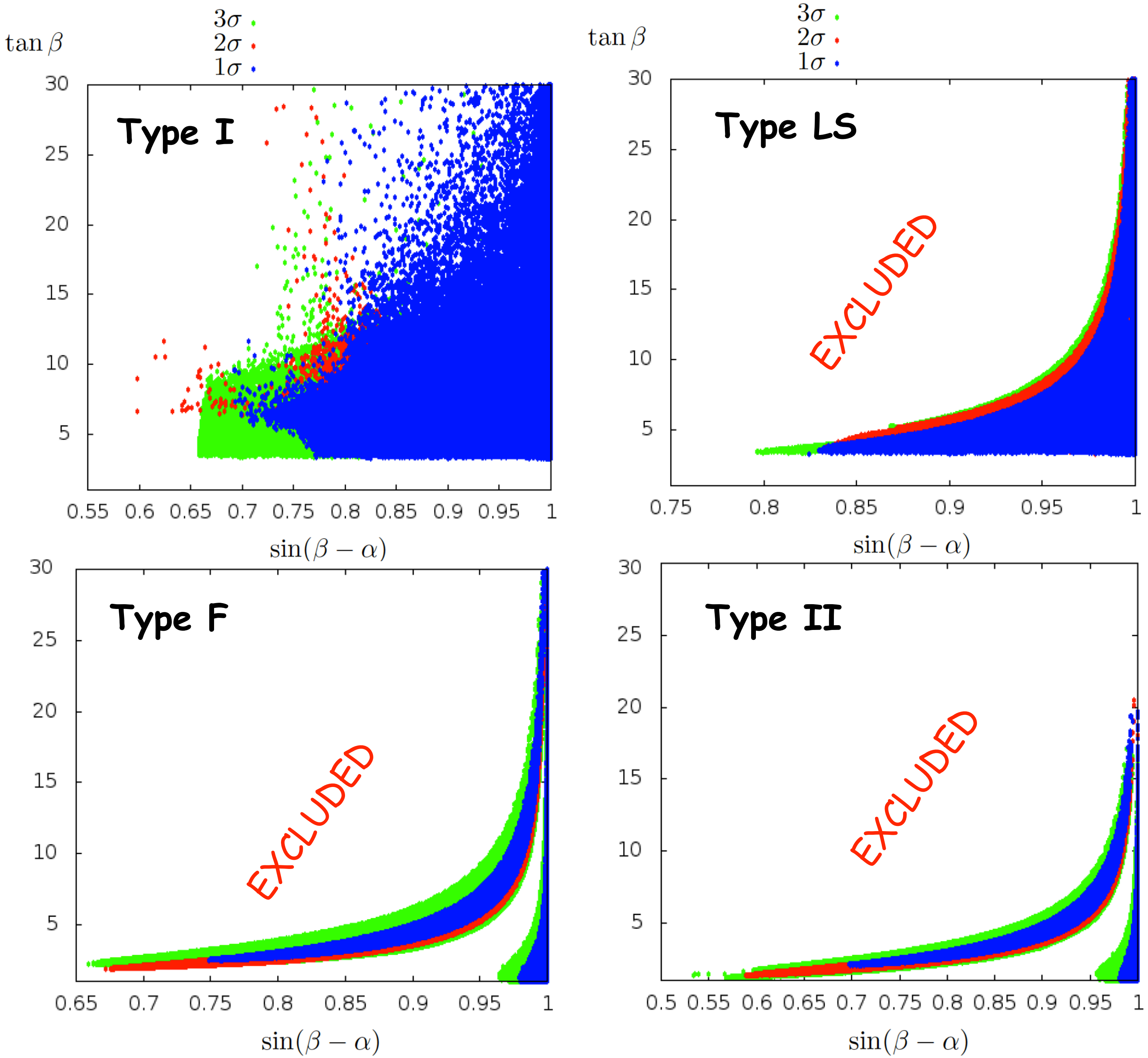
$$\mu_{XX} = \frac{\sigma^{2HDM}(pp \to h) \times BR^{2HDM}(h \to XX)}{\sigma^{SM}(pp \to h) \times BR^{SM}(h \to XX)}$$

- Use collider constraints via HiggsBounds and HiggsSignals



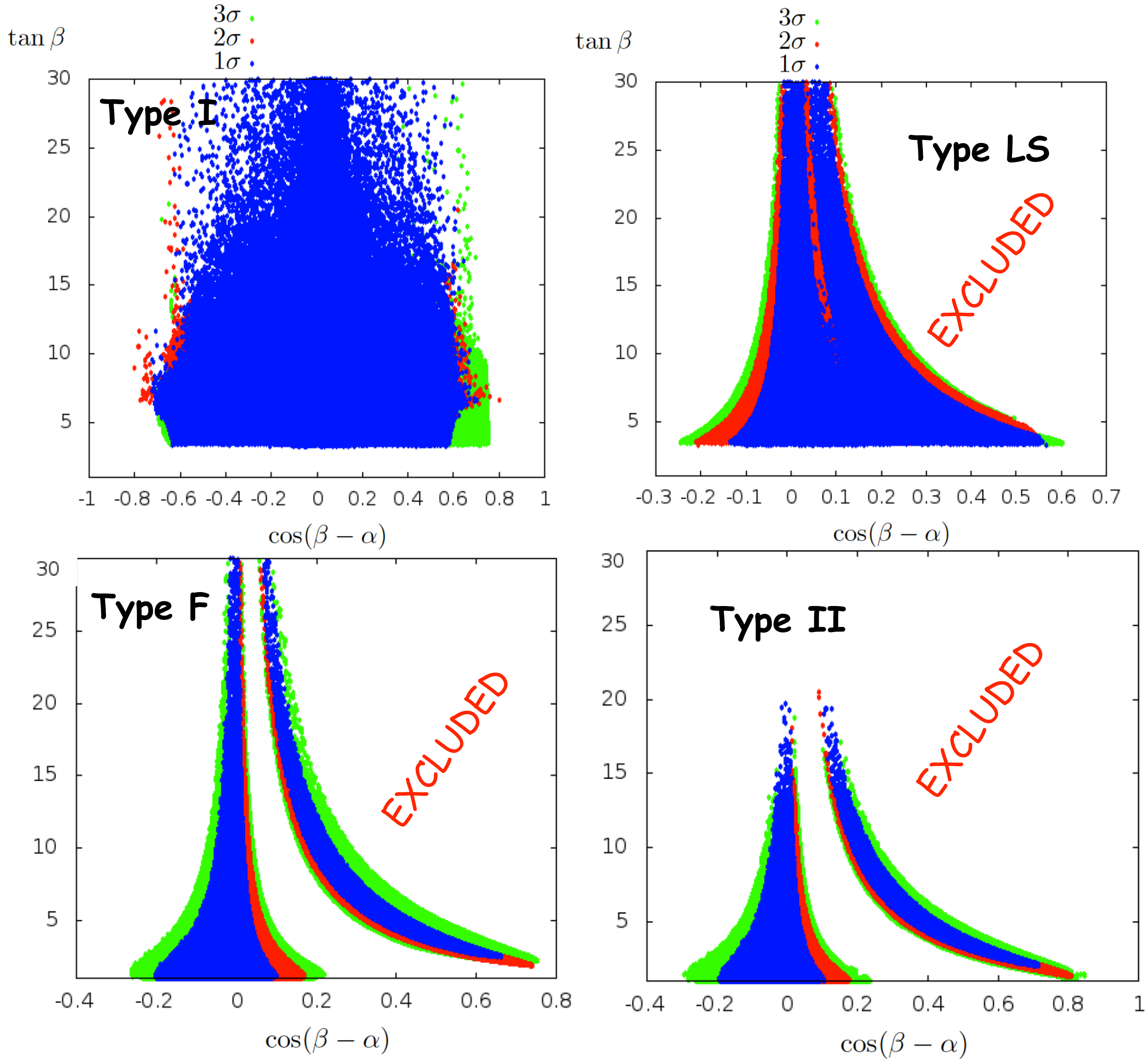
$1 \leq \tan\beta \leq 30$

tanβ vs sinα



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

$\tan\beta$
vs
$\sin(\beta-\alpha)$



$1 \le \tan\beta \le 30$

tanβ vs cos(β−α)

The wrong-sign Yukawa coupling

I.F. Ginzburg, M. Krawczyk and P. Osland, LC Note LC-TH-2001-026, [hep-ph/0101208]

The SM-like limit (alignment) – all tree-level couplings to fermions and gauge bosons are the SM ones.

$$\boxed{\sin(\beta-\alpha)=1 \quad \Rightarrow \quad \kappa_D = 1; \quad \kappa_U = 1; \quad \kappa_W = 1}$$

Wrong-sign Yukawa coupling – at least one of the couplings of h to down-type and up-type fermion pairs is opposite in sign to the corresponding coupling of h to VV (in contrast with SM).

$$\boxed{\kappa_D \kappa_W < 0 \quad \text{or} \quad \kappa_U \kappa_W < 0}$$

The actual sign of each κ_i depends on the chosen range for the angles.

Type II

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

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

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

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

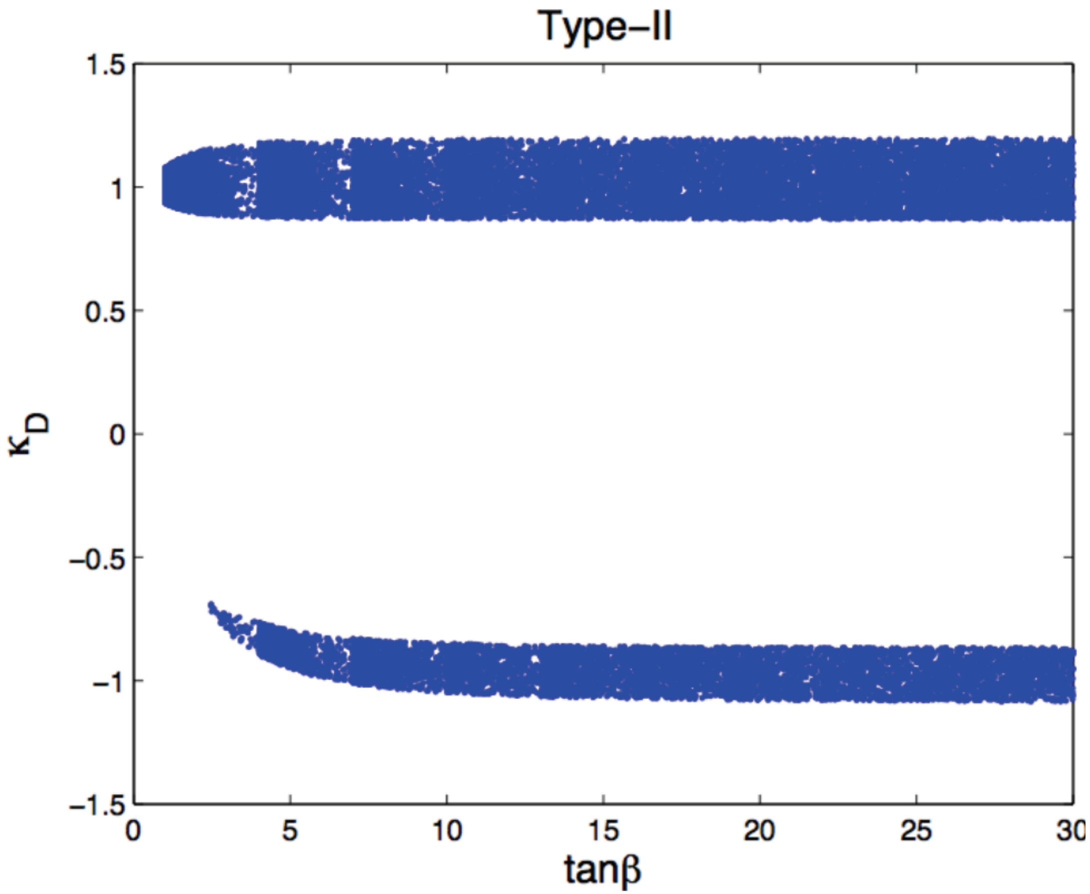
Type I

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

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

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

Because constraints force tanβ to be order 1 or larger, there is no wrong-sign Yukawa coupling in Type I.



With the convention

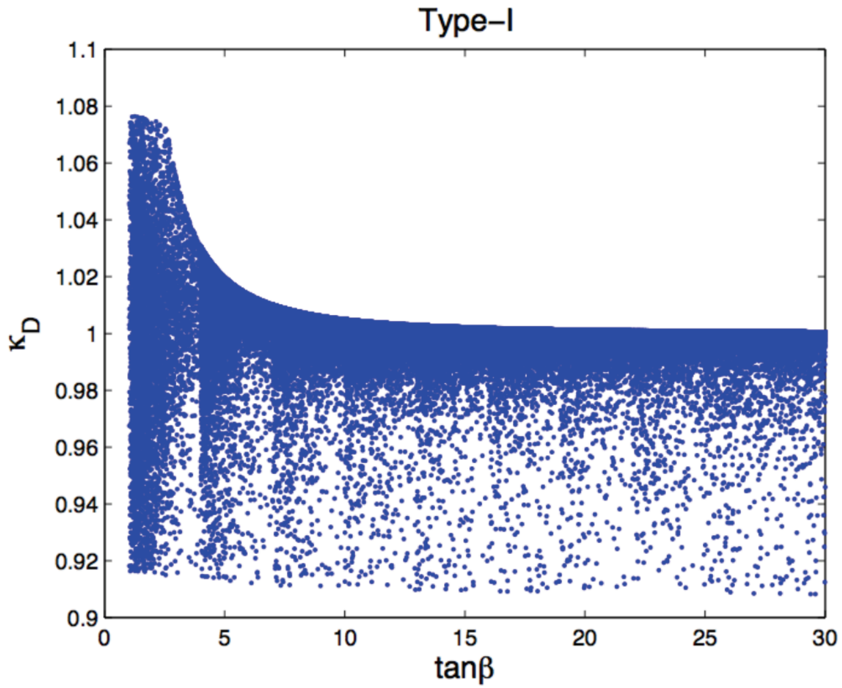
$$|\alpha| \leq \pi/2$$

$$\boxed{\kappa_U = \frac{\cos\alpha}{\sin\beta}}$$

$$\boxed{\kappa_D = -\frac{\sin\alpha}{\cos\beta}}$$

The limit where we have the wrong coupling for down quarks is Type-II (and Flipped).

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



Why is it not excluded yet?

SM-like limit

$$\boxed{\kappa_D \to 1 \qquad (\sin(\beta-\alpha)\to 1)}$$

Wrong sign

$$\boxed{\kappa_D \to -1 \qquad (\sin(\beta+\alpha)\to 1)}$$

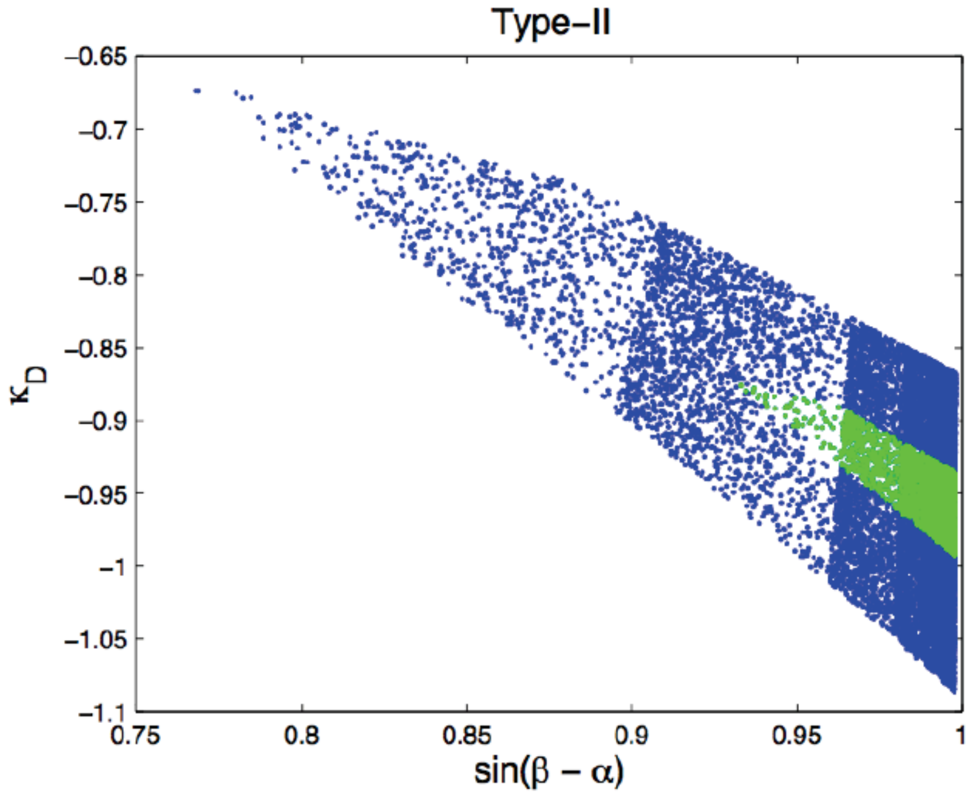
$$\begin{cases} \kappa_V \to 1 & (\sin(\beta-\alpha)\to 1) \\ \kappa_V \to \dfrac{\tan^2\beta - 1}{\tan^2\beta + 1} & (\sin(\beta+\alpha)\to 1) \end{cases}$$

Defining

$$\kappa_D = -\frac{\sin\alpha}{\cos\beta} = -1+\varepsilon$$

$$\boxed{\sin(\beta+\alpha) - \sin(\beta-\alpha) = \frac{2(1-\varepsilon)}{1+\tan^2\beta} << 1} \qquad (\tan\beta >> 1)$$

Difference decreases with tan β



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

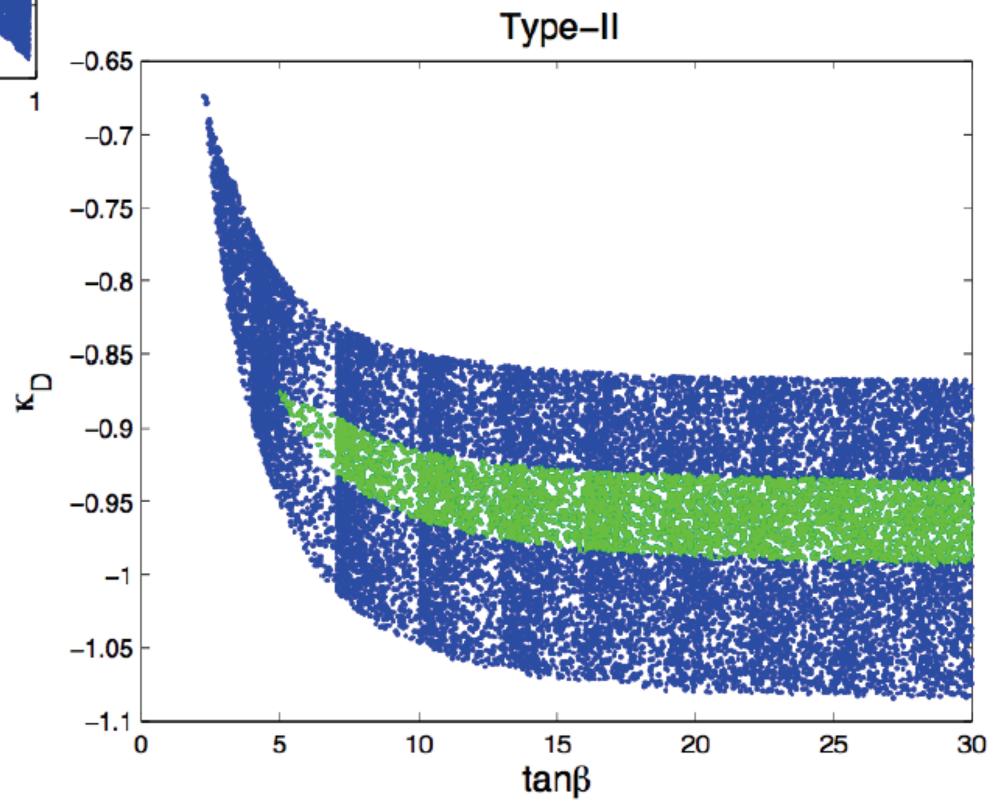
$$\sin(\beta+\alpha)-\sin(\beta-\alpha)=\frac{2(1-\varepsilon)}{1+\tan^2\beta}\ll 1$$

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

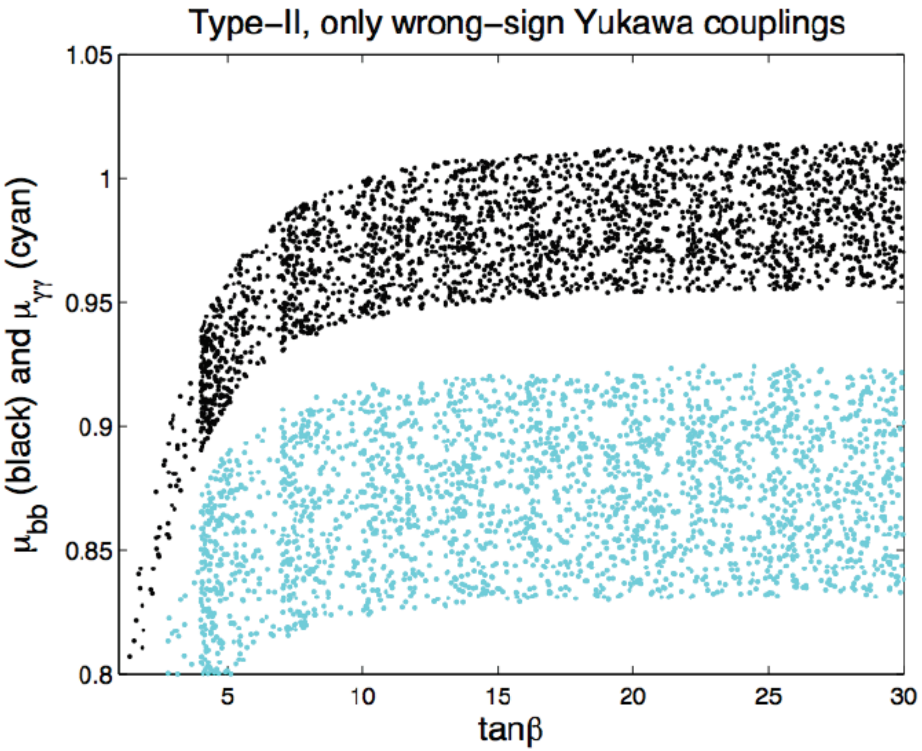
Need interference.

Colour code

Red - all rates within 5% of corresponding SM values.
Green - 10% and Blue - 20%;
No points at 5 %.

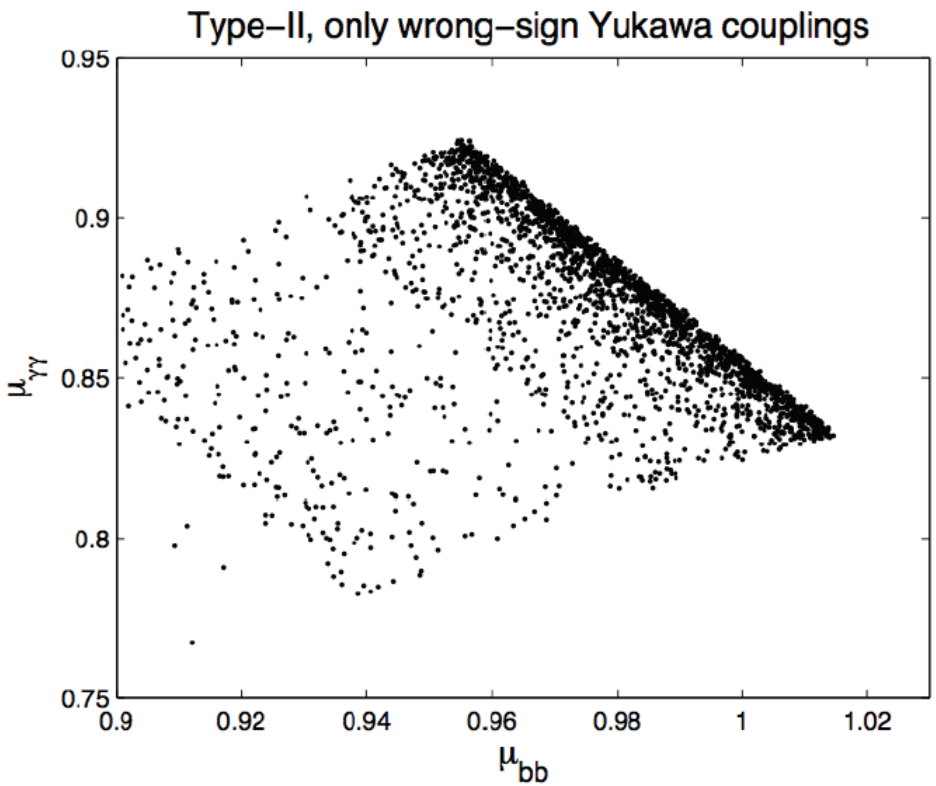


Why isn't it excluded by the $\mu_{\gamma\gamma}$?

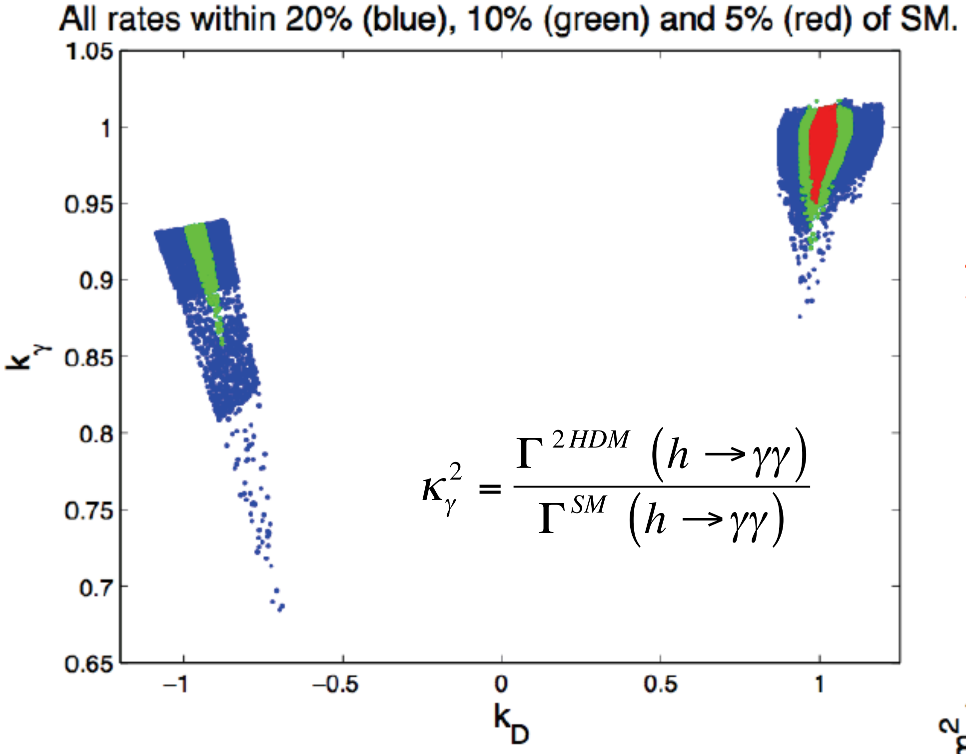


$$\mu_f^h(\mathrm{LHC}) = \frac{\sigma^{2\mathrm{HDM}}(pp \to h)\,\mathrm{BR}^{2\mathrm{HDM}}(h \to f)}{\sigma^{\mathrm{SM}}(pp \to h_{\mathrm{SM}})\,\mathrm{BR}(h_{\mathrm{SM}} \to f)}$$

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

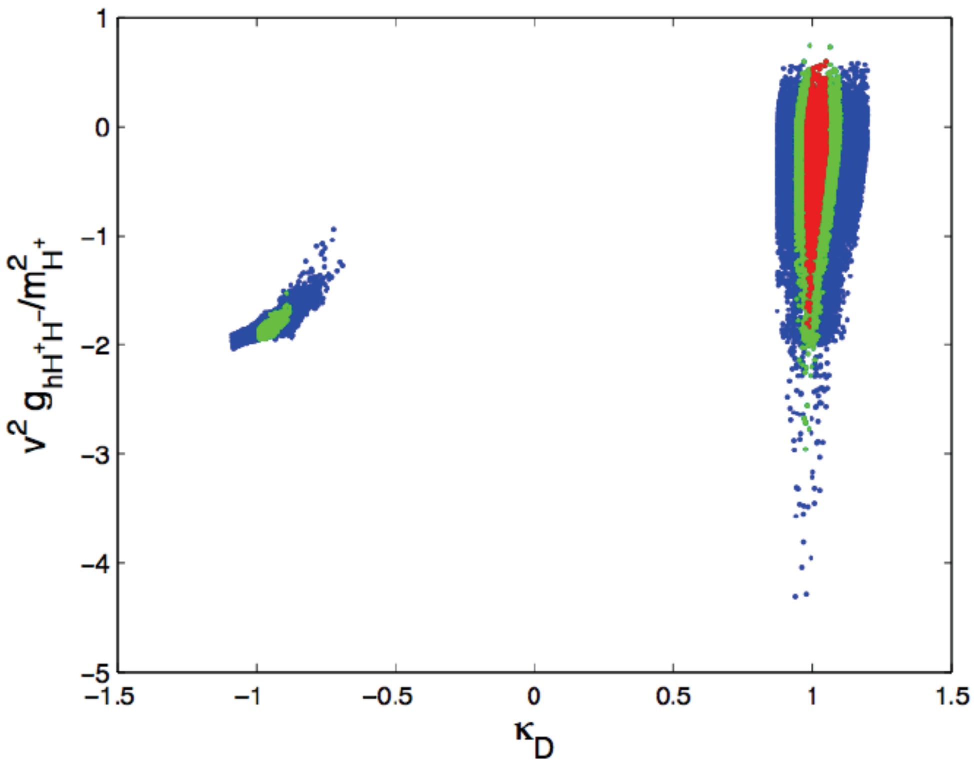


How come we do not have any points at 5 %?



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

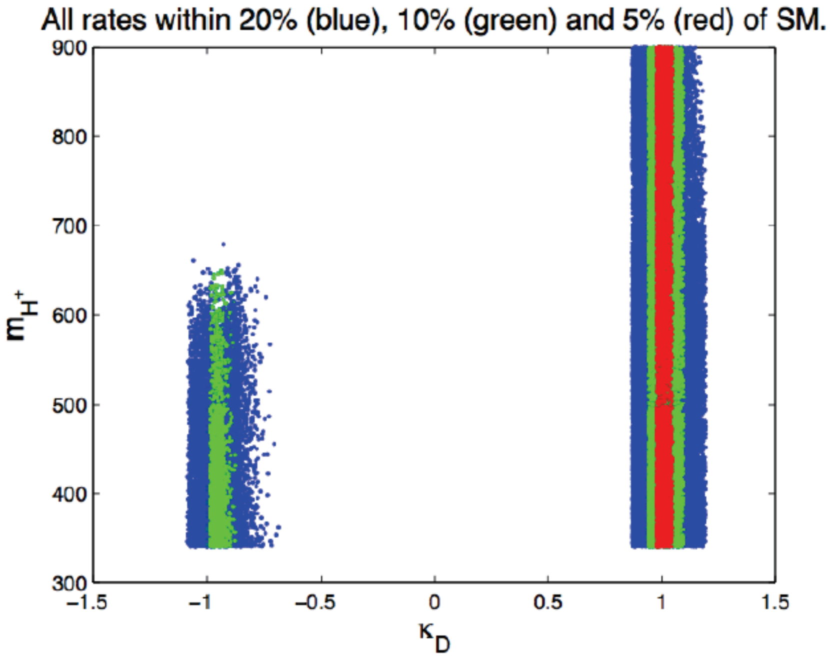
In fact, if the charged Higgs loops were absent, changing the sign of κ_D would imply a change in κ_γ of less than 1 %.



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?



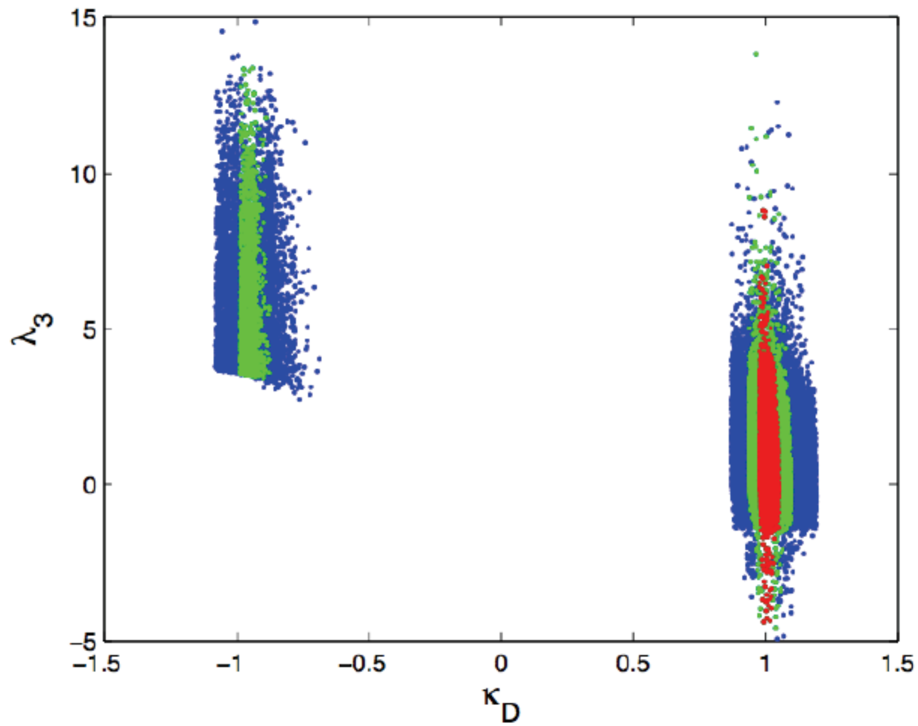
Large non-decoupling charged-Higgs loops contribution until the unitarity limit is reached.

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

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

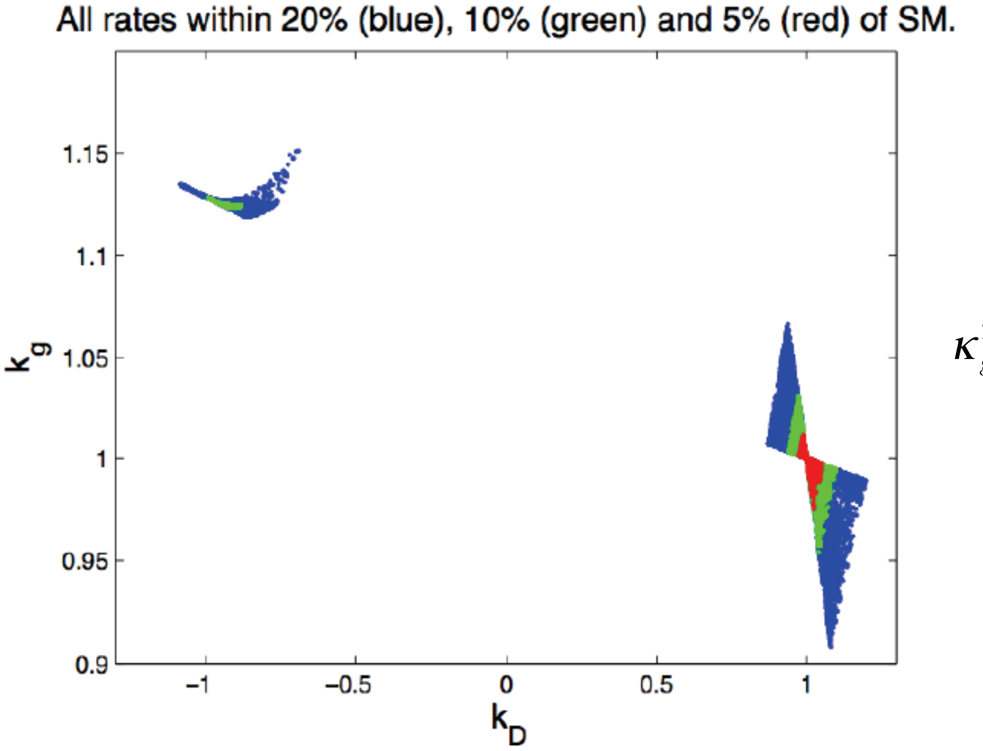
Table 1-20 of 1310.8361

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.

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

Region will be excluded even in the pessimistic scenario.

Table 1-20 of 1310.8361

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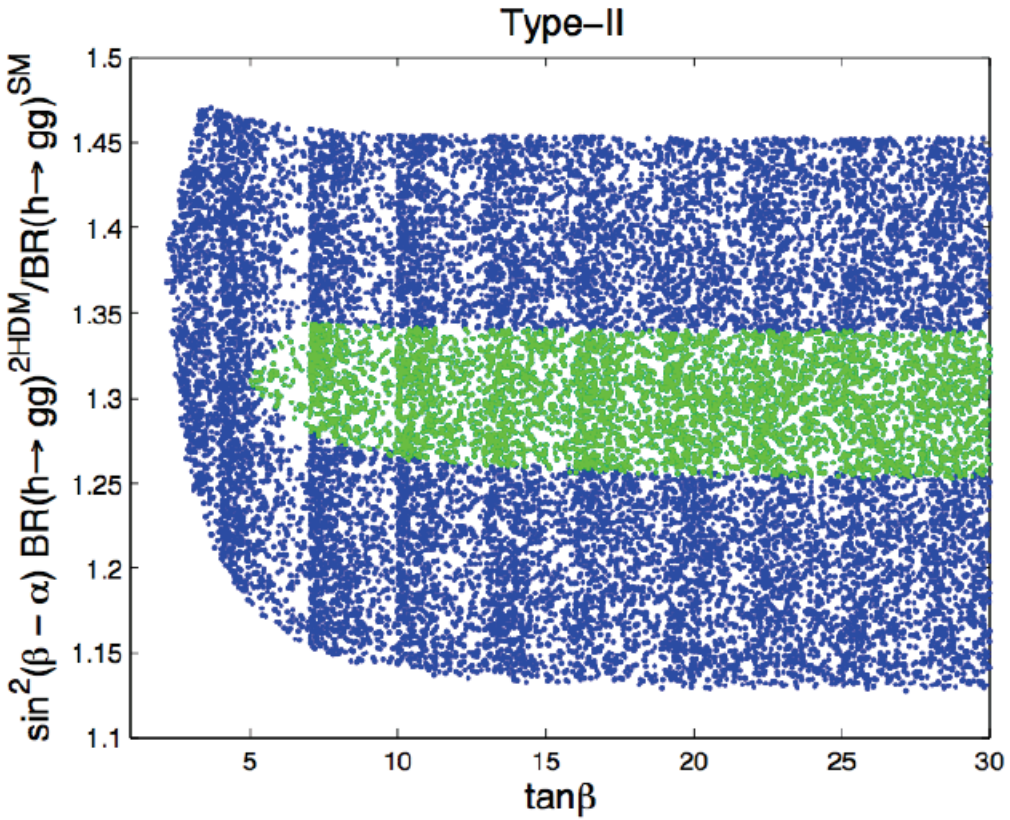
Exclusion at the ILC



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

$$\boxed{\mu^h_{gg}(\mathrm{ILC}) = \frac{\sigma^{2HDM}\ \mathrm{BR}^{2HDM}(h \to gg)}{\sigma^{SM}\ \mathrm{BR}^{SM}(h \to gg)}}$$

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

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 ± 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]].

Conclusions

All CP-conserving 2HDMs have $\sin(\beta-\alpha) \geq 0.5$ at 2σ. However, in some specific scenarios (like the degenerate mass ones) $\sin(\beta-\alpha)$ could be smaller.

Large $\tan\beta$ needs $\sin(\beta-\alpha)$ very close to 1, except for the Type I model.

Models Type-II and Type F have an extra allowed leg for $\sin(\beta+\alpha)\approx 1$.

This scenario will probably be probed at the high luminosity 14 TeV LHC and/or at the ILC.

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All Welcome!

The end – thank you for your attention!