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

DIS2014

30 April 2014

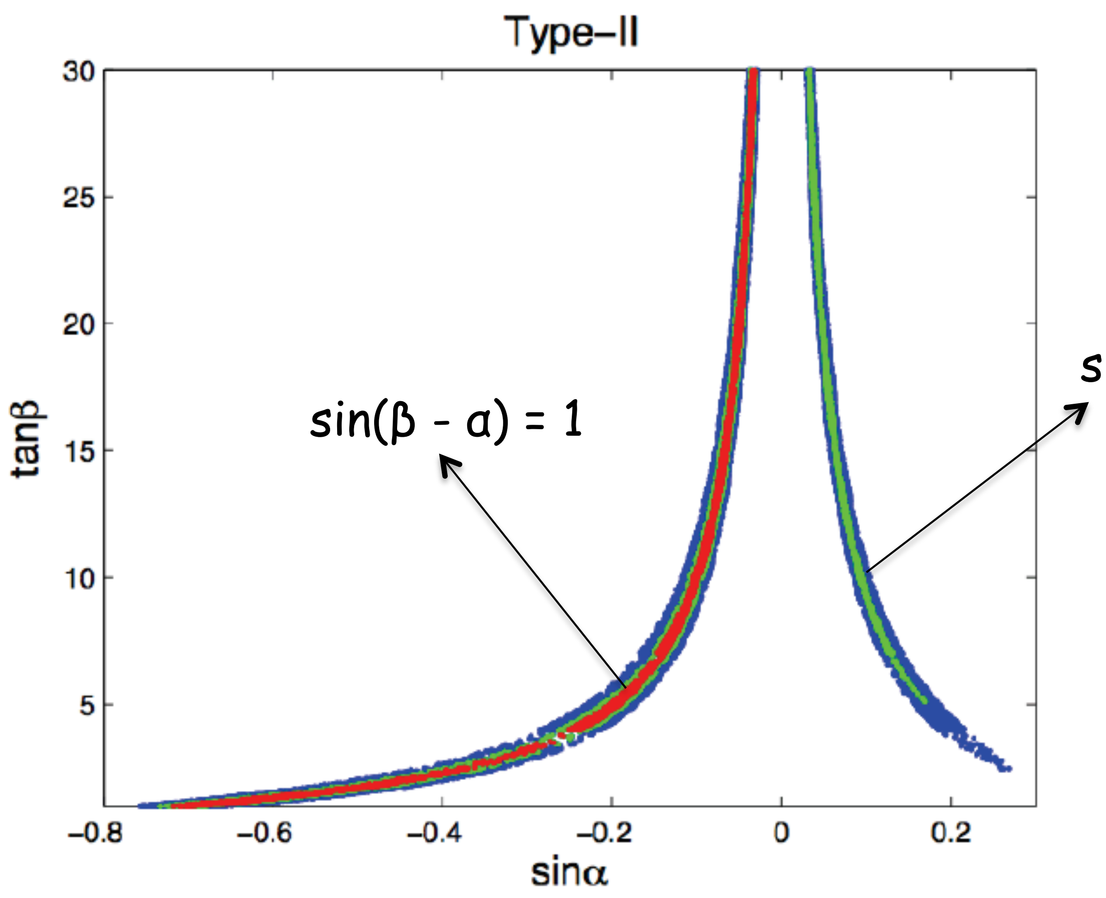
Rui Santos

ISEL & CFTC (Lisboa)

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

and with J. Gunion, H. Haber

What is this talk about?



Red – all rates within 5% of corresponding SM values. Green - 10% and Blue - 20%.

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

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

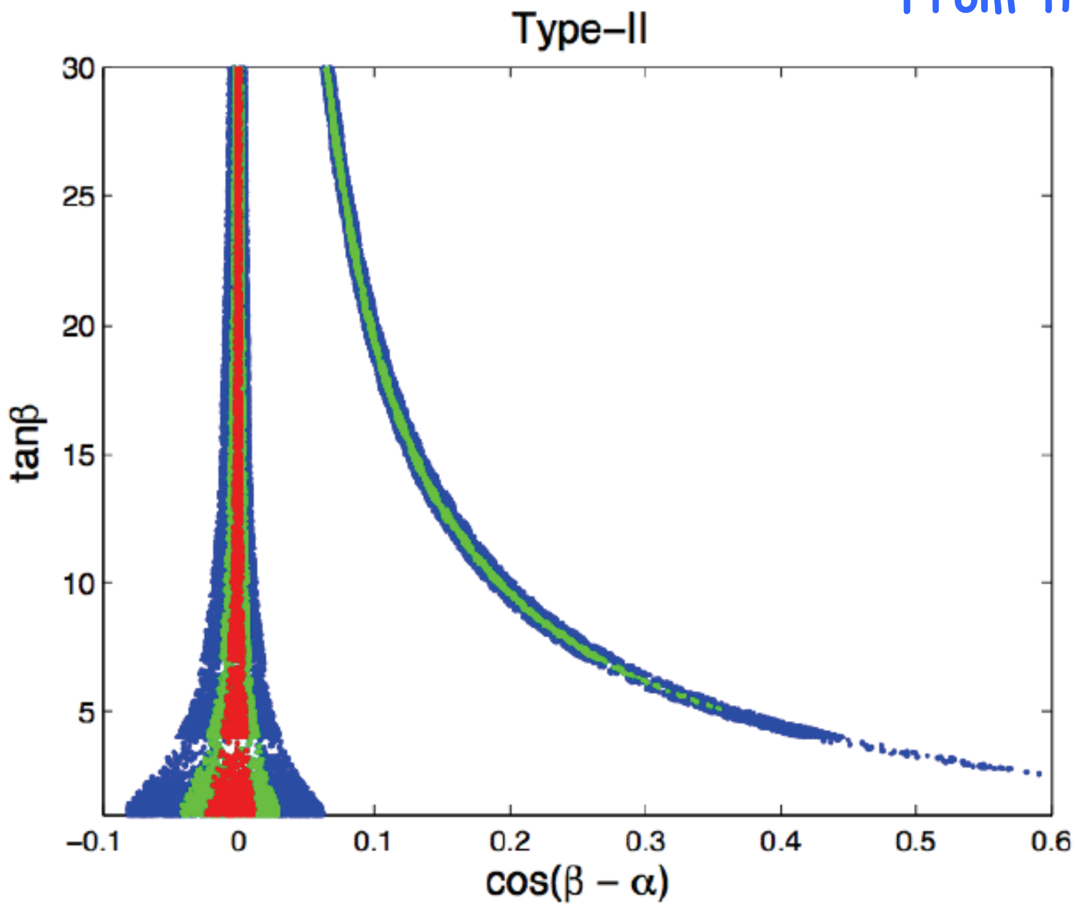
$$\kappa_D^{II} \to 1 \qquad (\sin(\beta-\alpha) \to 1)$$

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

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

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

From the $\cos(\beta - \alpha)$ perspective



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 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).

Z_2 symmetric CP-conserving 2HDM (softly broken)

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

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

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

- 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

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

ScannerS.hepforge.org

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

E-mail: msampaio@ua.pt

ScannerS is linked to

SuShi – Higgs production at NNLO in gg and bb

HDECAY – Higgs decays

Superiso – Flavour physics observables

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

HiggsSignals – Signal rates at the Tevatron and LHC

and ScannerS has the remaining constraints/cross sections

- Perturbative unitarity
- Potential is bounded from below
- Electroweak precision
- Global minimum

Scan

- Set m_h = 125 GeV.

- Generate random values for potential's parameters such that

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

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

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

$$1 \leqslant \tan\beta \leqslant 40$$

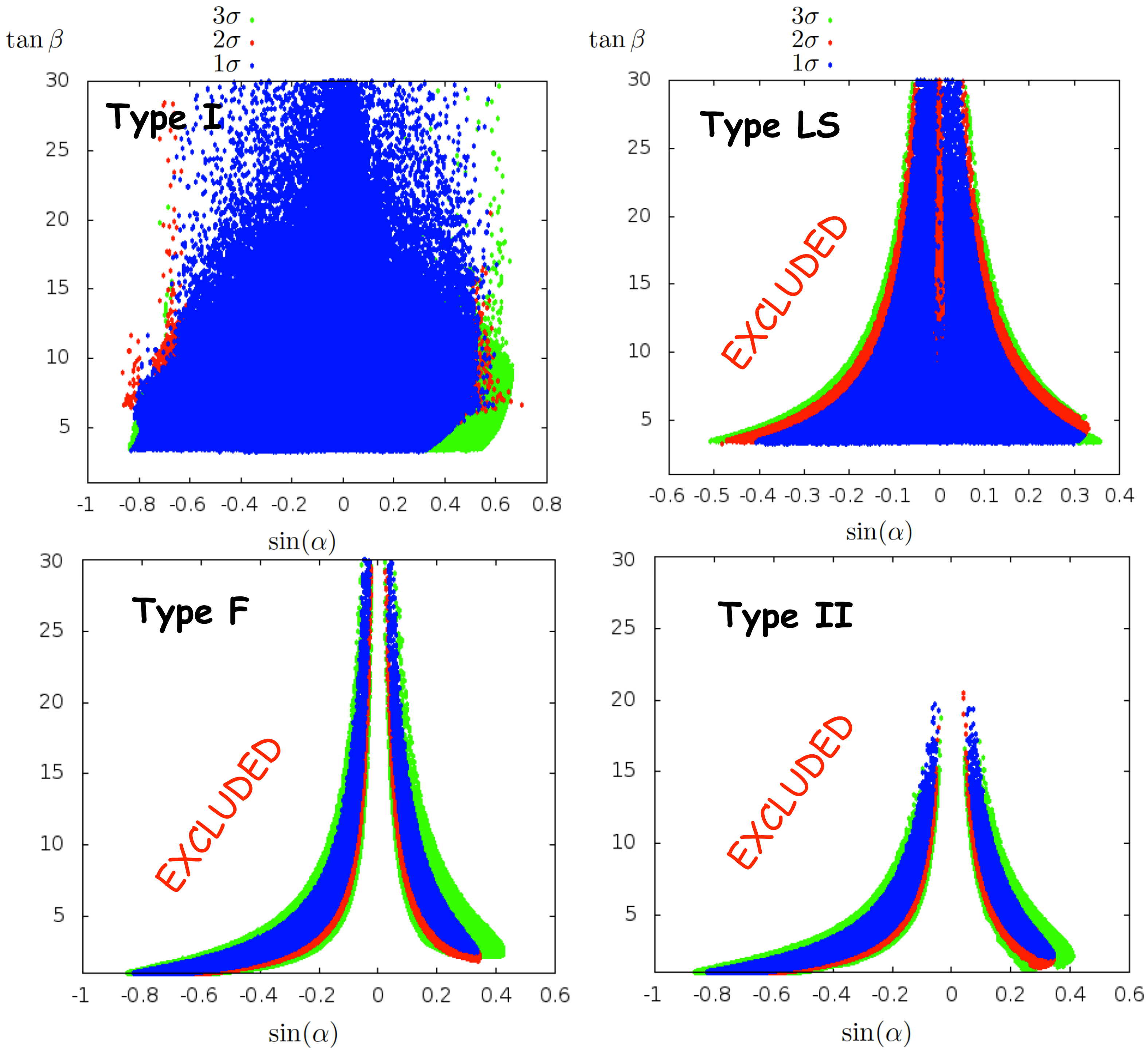
$$-\tfrac{\pi}{2} \leqslant \alpha \leqslant \tfrac{\pi}{2}$$

- Impose all experimental and theoretical constraints previously described.

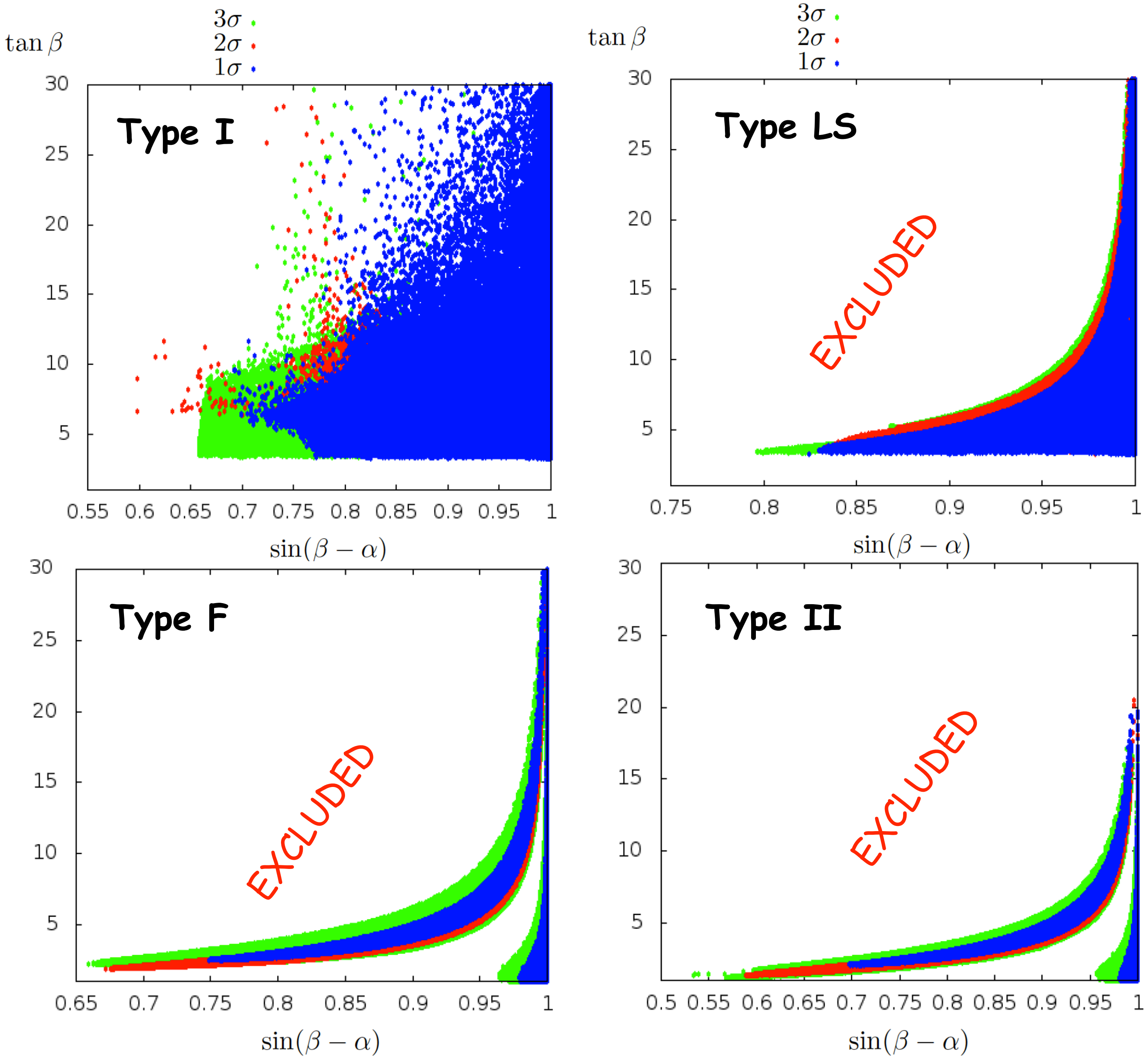
- Calculate all branching ratios and production rates at the LHC.

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

- Use collider constraints via HiggsBounds and HiggsSignals.


tan β
3σ
2σ
1σ
Type I
sin(α)
Type LS
EXCLUDED
Type F
EXCLUDED
Type II
EXCLUDED

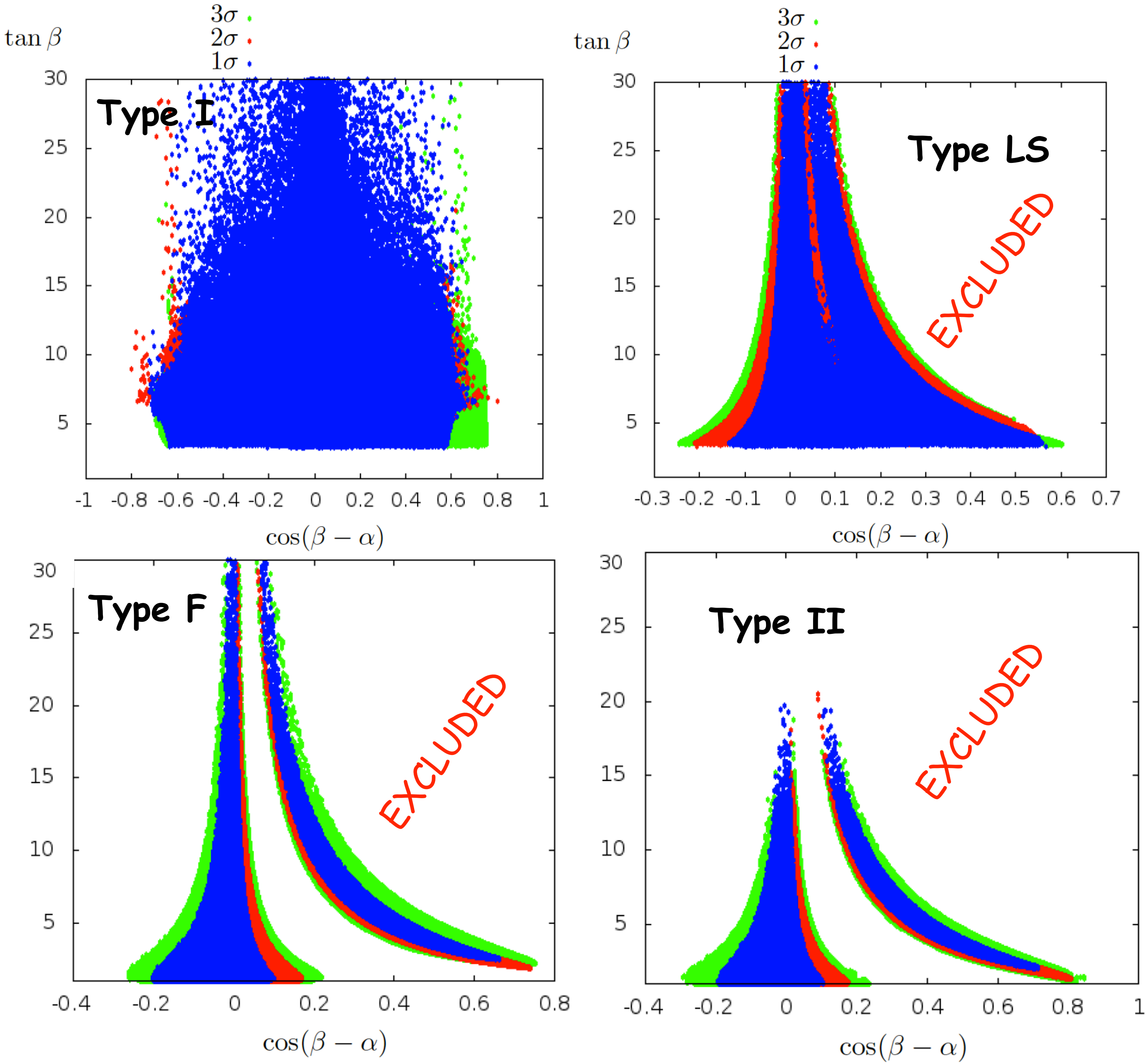
tanβ
vs
sinα



tanβ

vs

sin(β−α)



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]

Type II

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

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

$$\boxed{\begin{array}{l} \sin(\beta+\alpha) = 1 \quad \Rightarrow \quad \kappa_D = -1 \quad (\kappa_U = 1) \\ \qquad\qquad \sin(\beta-\alpha) = \dfrac{\tan^2\beta - 1}{\tan^2\beta + 1} \quad \Rightarrow \quad \kappa_W \geq 0 \ \text{ if } \ \tan\beta \geq 1 \end{array}}$$

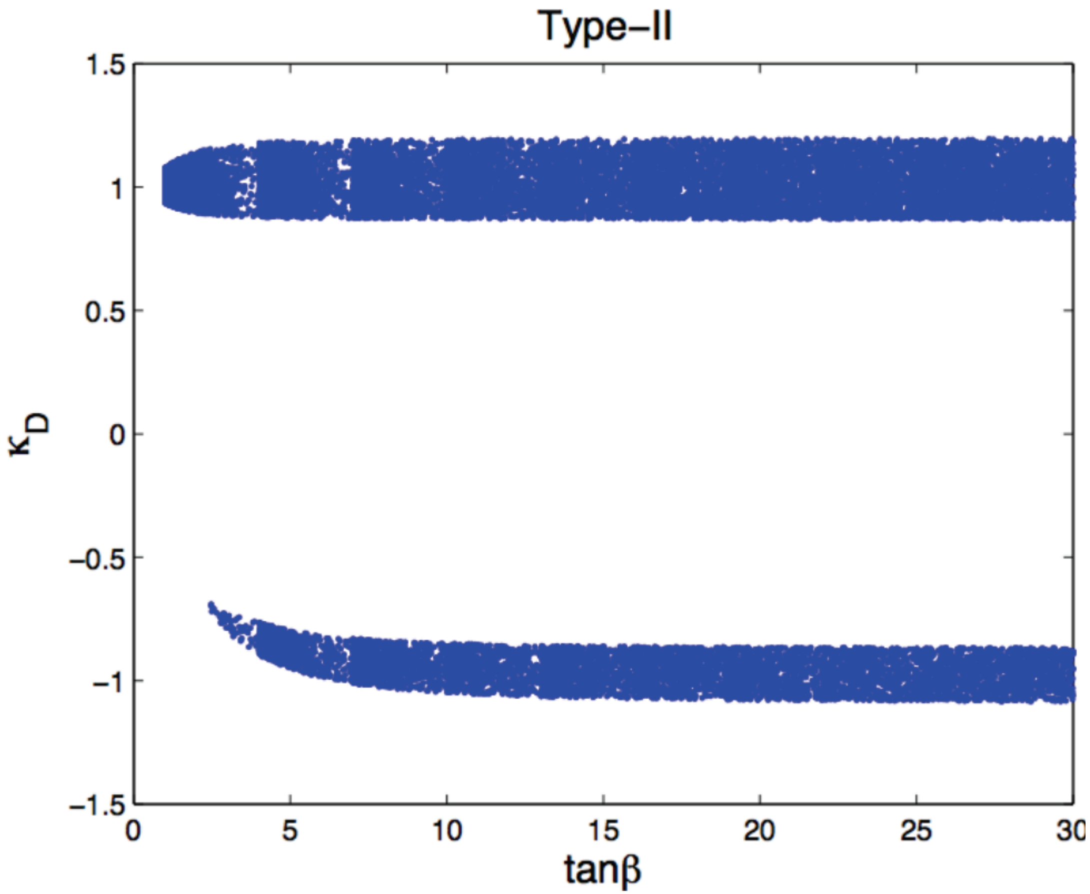
$$\sin(\beta+\alpha) = -1 \quad \Rightarrow \quad \kappa_U = -1 \quad (\kappa_D = 1)$$

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

Type I

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

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



The usual convention

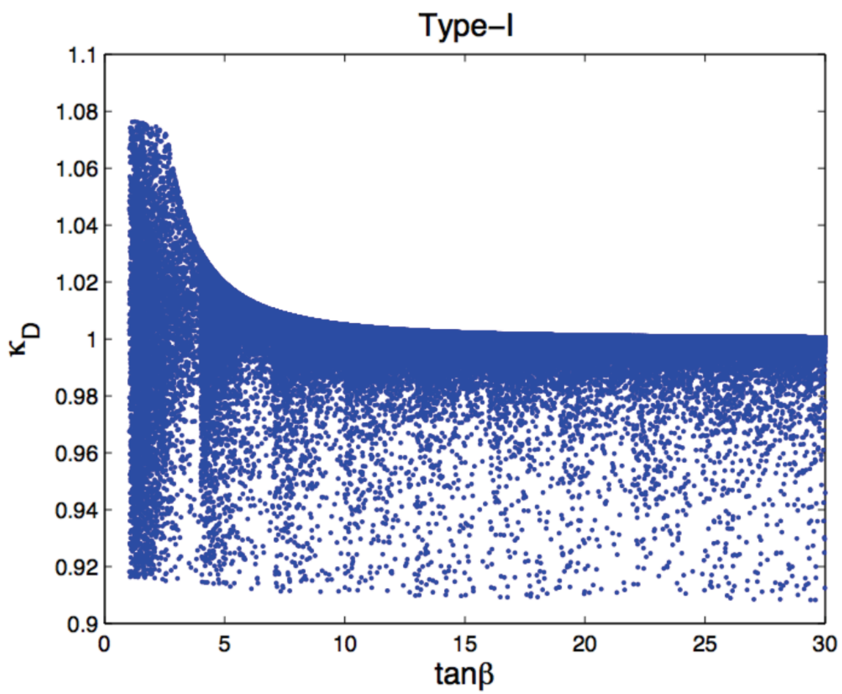
$$|\alpha| \leq \pi/2$$

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

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

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

$$\boxed{\kappa_D^{II} \to 1 \qquad (\sin(\beta-\alpha) \to 1)\,;}$$

Wrong sign

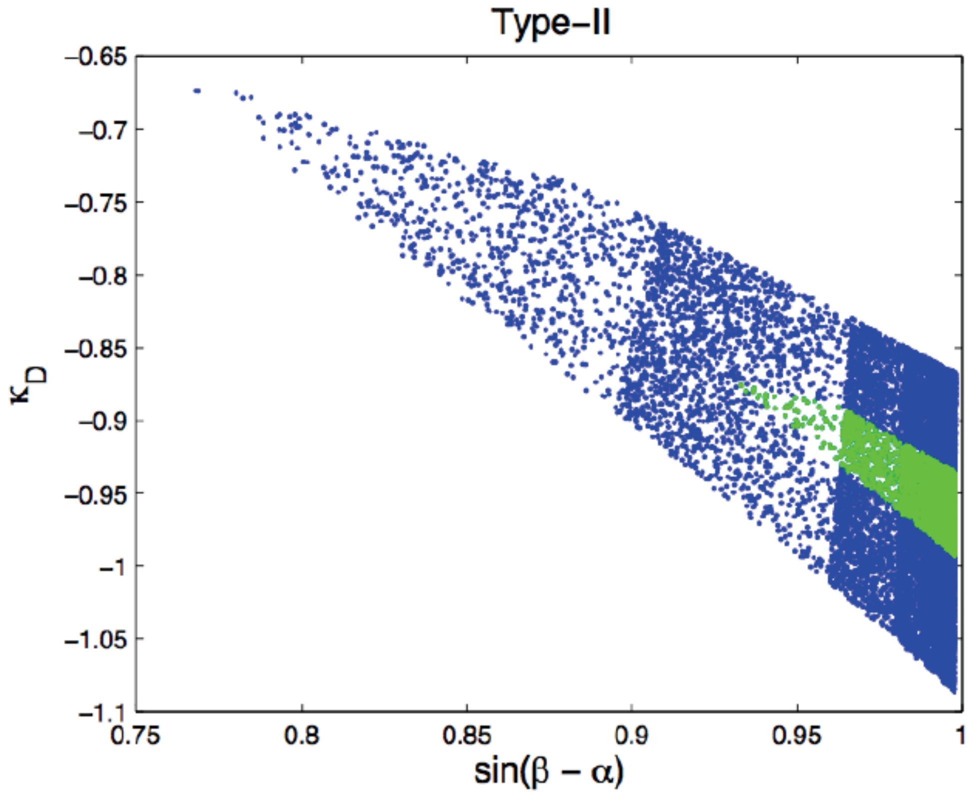
$$\boxed{\kappa_D^{II} \to -1 \qquad (\sin(\beta+\alpha) \to 1)}$$

$$\left\{\begin{array}{l} \kappa_V\,, \dfrac{G_{hhh}^{\rm 2HDM}}{G_{hhh}^{\rm SM}} \to 1 \quad (\sin(\beta-\alpha) \to 1) \\[2ex] \kappa_V\,, \dfrac{G_{hhh}^{\rm 2HDM}}{G_{hhh}^{\rm SM}} \to \dfrac{\tan^2\beta - 1}{\tan^2\beta + 1} \quad (\sin(\beta+\alpha) \to 1) \end{array}\right.$$

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

Difference decreases with tan β

$$\boxed{\sin(\beta+\alpha) - \sin(\beta-\alpha) = \frac{2(1-\epsilon)}{1+\tan^2\beta} \ll 1} \qquad (\text{for } \tan\beta \gg 1)$$



Same colour code

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

Green - 10% and Blue – 20%;

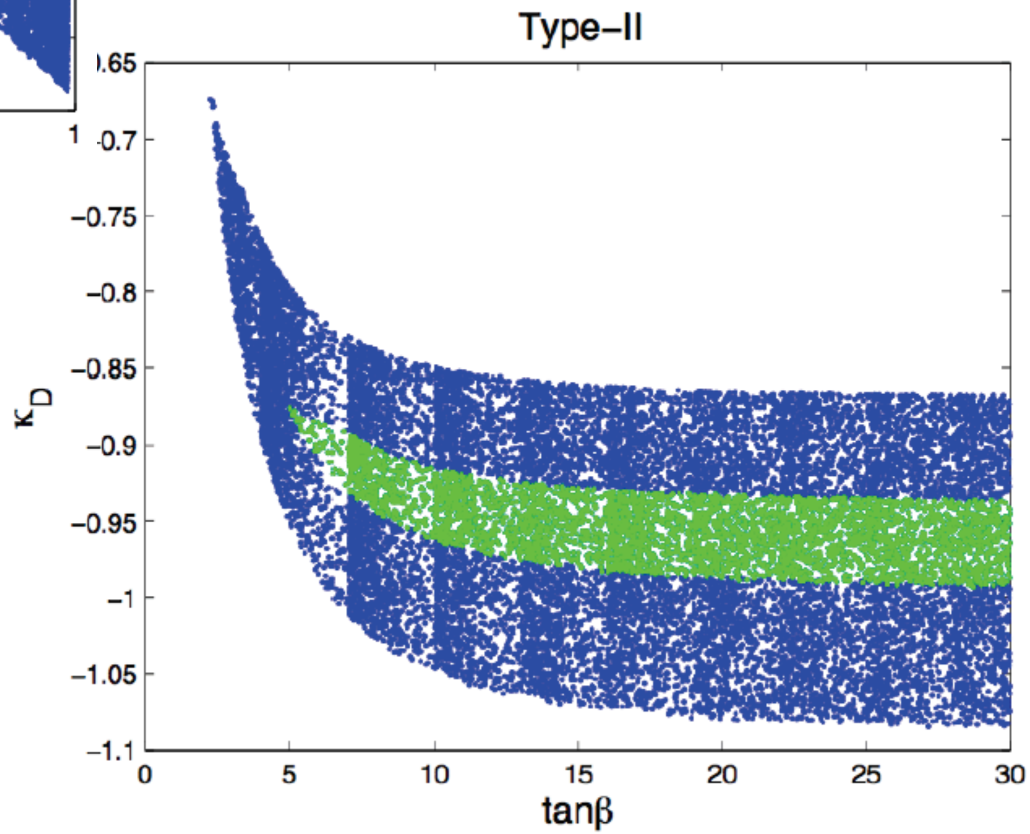
No points at 5 %.

As we approach the wrong sign limit, sin (β – α) approaches 1.

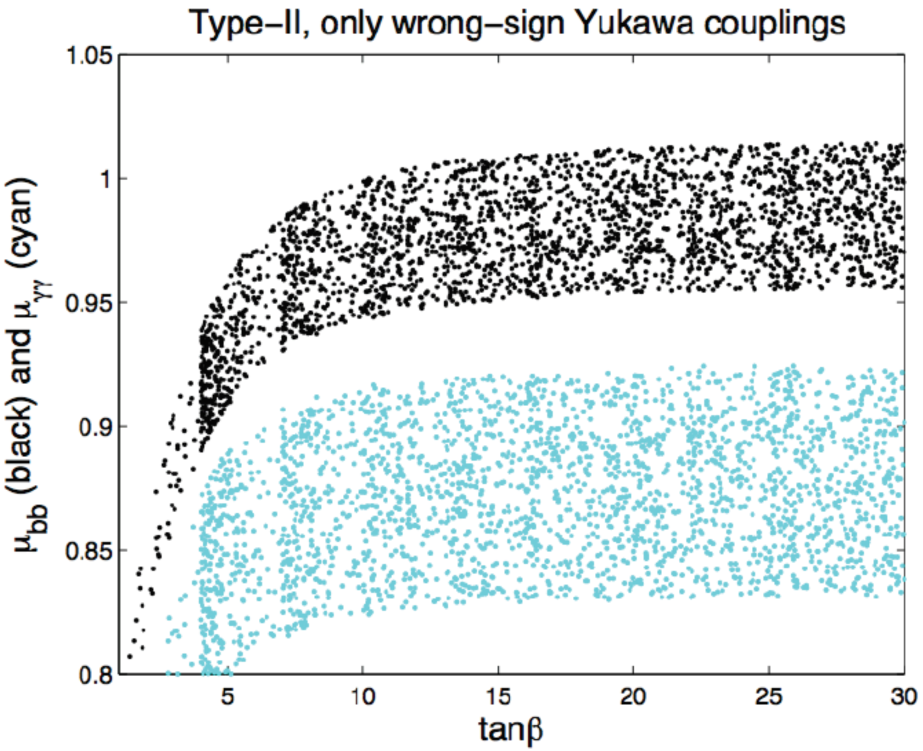
Large tanβ is needed.

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

$$\tan\beta \gg 1$$

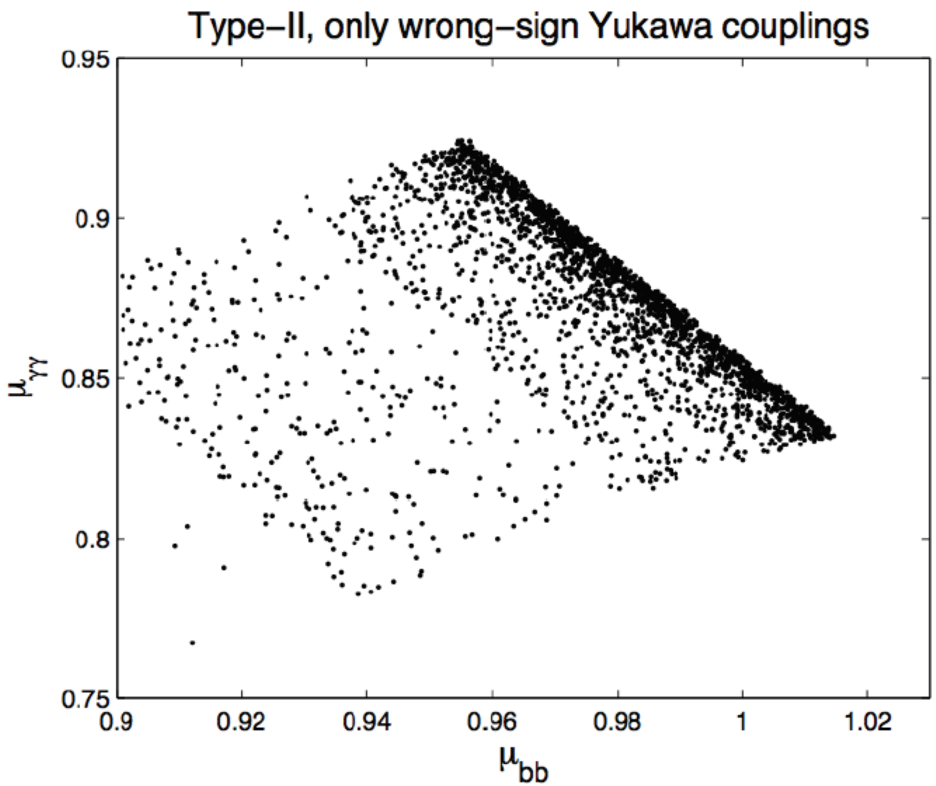


Why isn't it excluded by the $\mu_{\gamma\gamma}$?

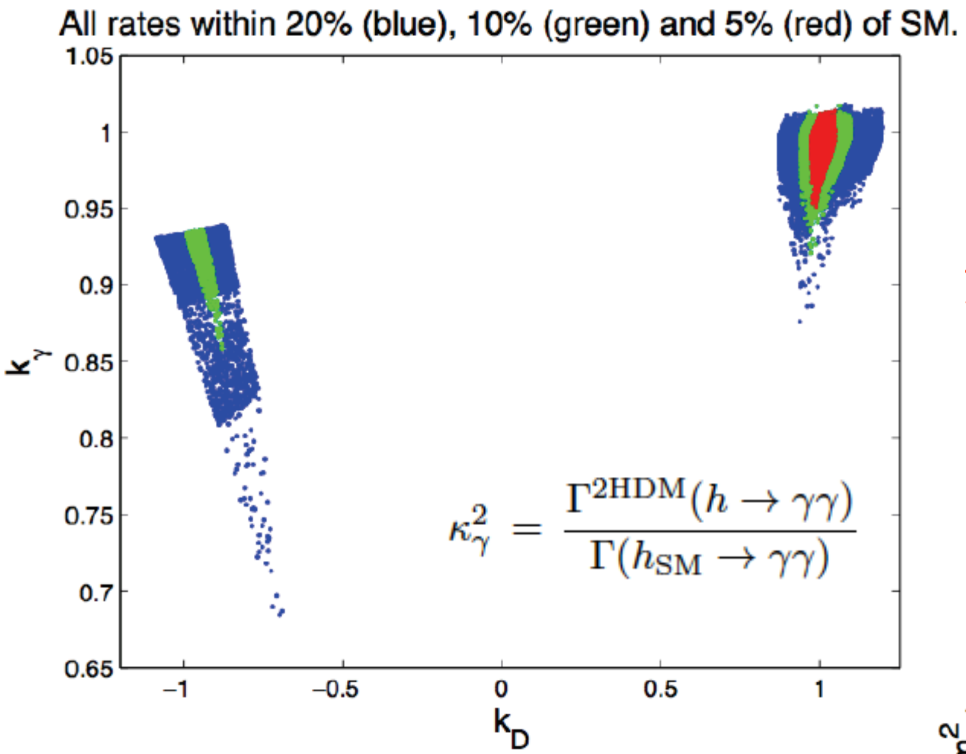


$$\mu_f^h(\mathrm{LHC}) = \frac{\sigma^{\mathrm{2HDM}}(pp \to h)\,\mathrm{BR}^{\mathrm{2HDM}}(h \to f)}{\sigma^{\mathrm{SM}}(pp \to h_{\mathrm{SM}})\,\mathrm{BR}(h_{\mathrm{SM}} \to f)}$$

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



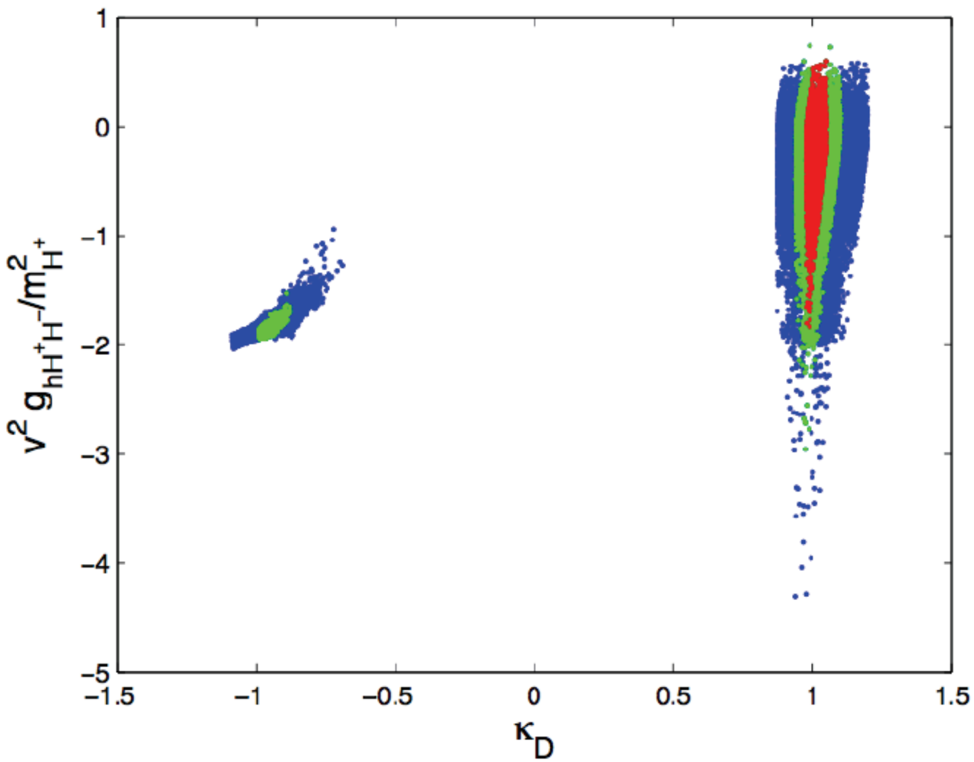
How come we do not have any points at 5 %?



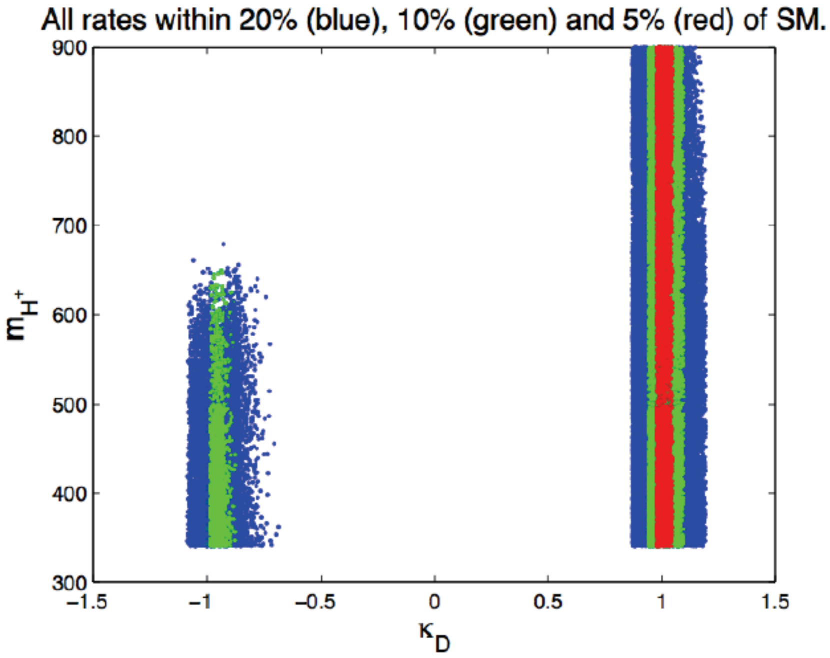
If we were only considering the gauge bosons and fermion loops we should find points at 5 % for the wrong-sign scenario.

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.



… and how do they come about?

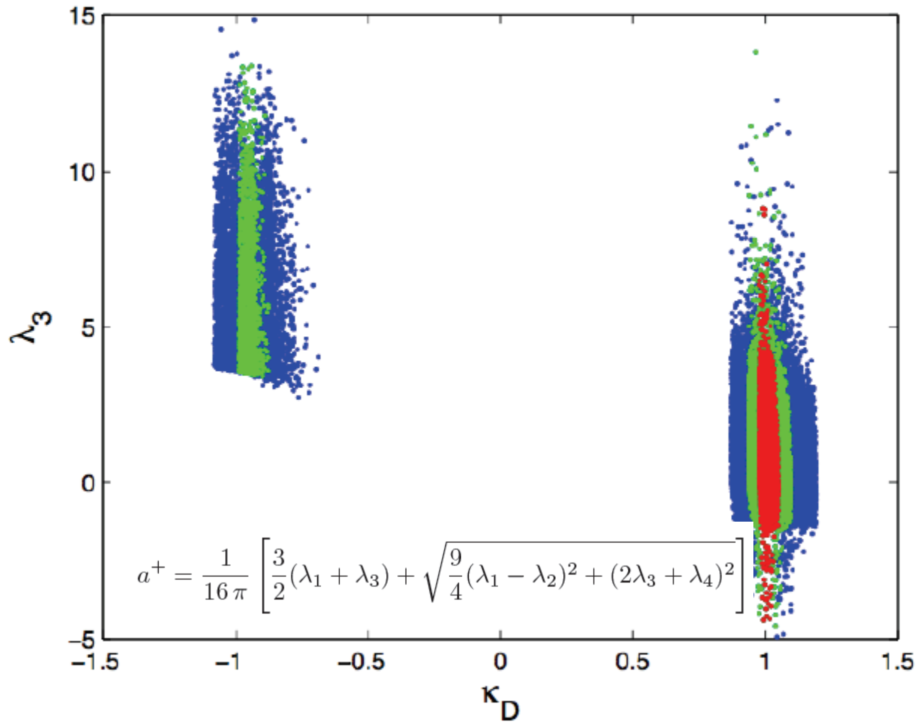


Large non-decoupling charged-Higgs loops contribution until the unitarity limit is reached.

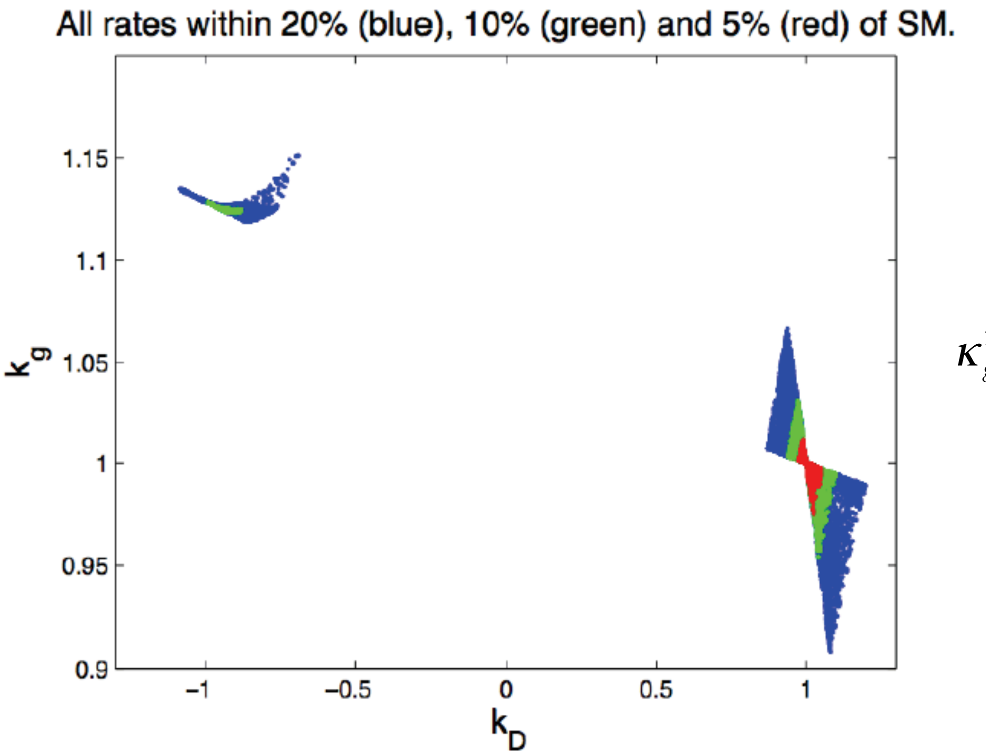
The bound is imposed on λ_3 due to $|a^+| < 0.5$.

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%



How do the effective couplings to gluons behave?



Region will be excluded even in the pessimistic scenario.

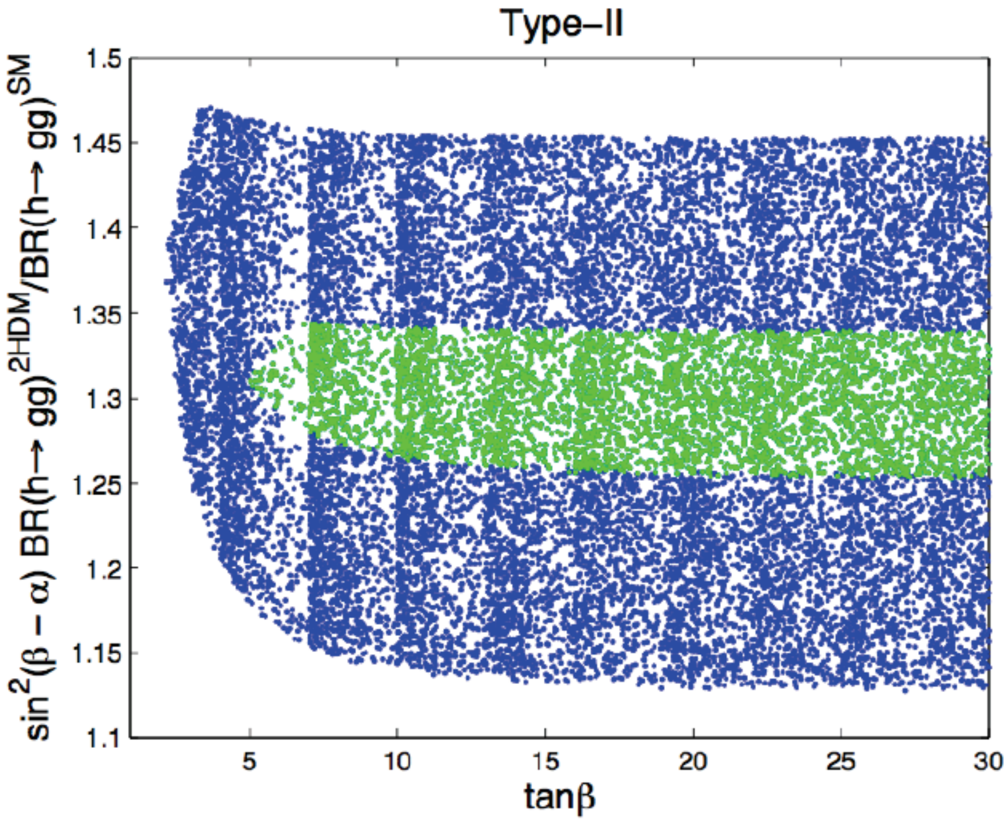
In h -> gg only fermion loops contribute.

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

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



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

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

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

Measurement would exclude all points in the figure.

Conclusions

All CP-conserving 2HDMs have at least $\sin(\beta-\alpha) > 0.6$.

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 be probed at the high luminosity 14 TeV LHC
and/or ILC.

Workshop on
Multi-Higgs Models

2-5 September 2014

Lisbon - Portugal

This Workshop brings together those interested in the theory and phenomenology of Multi-Higgs models. The program is designed to include talks given by some of the leading experts in the field, and also ample time for discussions and collaboration between researchers. A particular emphasis will be placed on identifying those features of the models which are testable at the LHC.

For registration and/or to propose a talk, send an email to:

ferreira@cii.fc.ul.pt

Web Page : http://www.ciul.ul.pt/~2hdmwork/

CFTC Centro de Física Teórica e Computacional

FCT Fundação para a Ciência e a Tecnologia
MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E ENSINO SUPERIOR

Third Edition of the workshop on Multi-Higgs Models

All Welcome!

The end – thank you for your attention!