Constraining the parameter space of 2HDM models with ScannerS

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Multi-Higgs Workshop 2014, CFTC Lisbon

Based on: arXiv:1409.XXXX with Pedro Ferreira, Renato Guedes, Rui Santos
http://scanners.hepforge.org also with Raul Costa

Prelude – Why study the 2HDMs?

Some reasons to study 2HDM models:

- May help with baryogenesis (SM needs $m_h \lesssim 50$ GeV!)
- Can be related to hierarchy problem (in SUSY theories)
- They are being cornered by LHC data (predictivity)

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Recently, raised interest by the possibility:

- Probing sign changes among Yukawa and Vector boson couplings

  Ferreira, Gunion, Haber, Santos, PRD 89 (2014) 115003

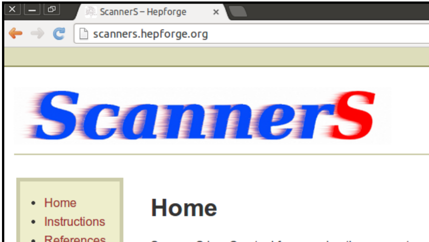
  Dumont, Gunion, Jiang, Kraml, PRD90 (2014) 035021

  Fontes, Romão, Silva, PRD90 (2014) 015021

- Sign change can affect *hgg* and $h\gamma\gamma$ (loop generated)

Prelude – The ScannerS project

Generic C++ **scanning tool** for arbitrary scalar sectors:



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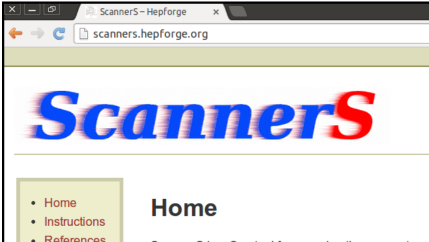

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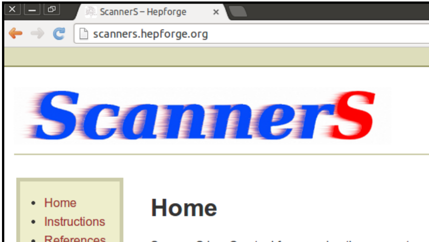
- Fully automated tree level unitarity test



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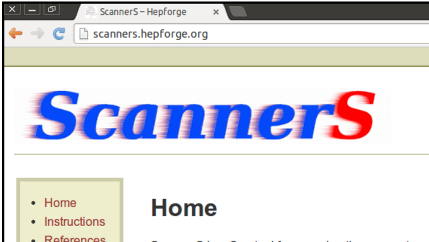

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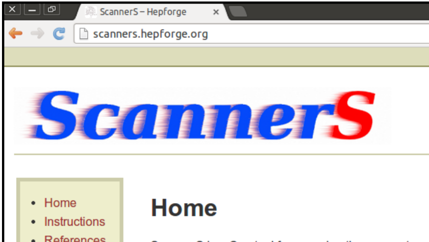
- Flexible user analysis

Look out for version 1.1.0 soon



Outline

1. Implementation of the $\mathbb{Z}_2$-2HDM models
   - Theoretical constraints
   - Experimental constraints
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Vacuum choice and scalar spectrum

Consider (softly broken) $\mathbb{Z}_2$ symmetry; $\Phi_1 \to \Phi_1, \Phi_2 \to -\Phi_2$:

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$$V = m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + \mathrm{h.c.}) + \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4$$
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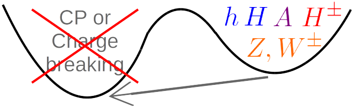
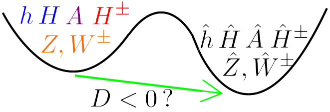
Conditions on the vacuum/parameters

Global stability – It is well known that for this minimum:

- Only CP or charge breaking saddle points above



- Discriminant, *D*, to test if secondary minimum below



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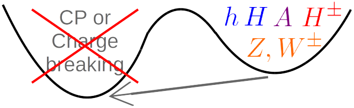

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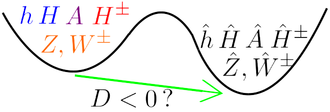
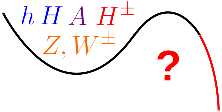


Boundedness from below:

Analytic condition on quartic couplings, λ_i



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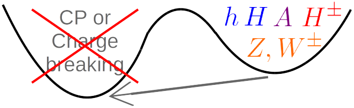

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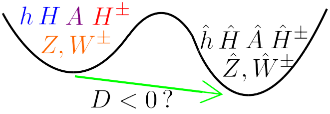

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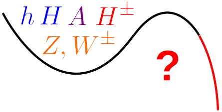

Tree level/perturbative unitarity: Upper bounds on quartic couplings, λ_i, from upper limit on $2 \to 2$ amplitudes.

$\Rightarrow$ General internal module in **ScannerS**

Neutral Higgs Couplings to SM particles

- Couplings to fermions:

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- Couplings to massive gauge bosons

$$h_{SM} \to \{\sin(\beta-\alpha)h, \cos(\beta-\alpha)H\}$$

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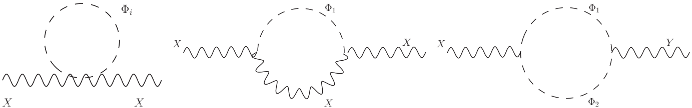
Experimental bounds on unobserved scalars

Require 95% **C.L. consistency with exclusion limits:**

1. ElectroWeak Precision Observables ($\Delta S, \Delta T, \Delta U$)



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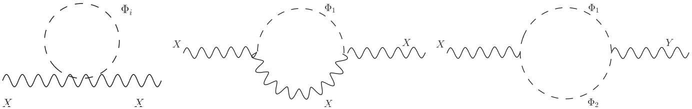

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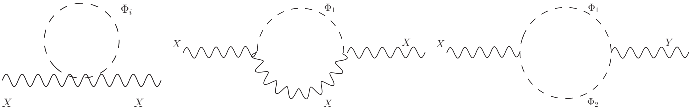

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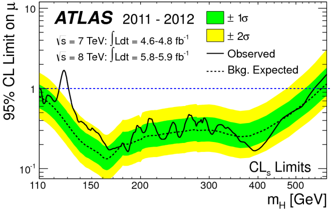
3. Collider bounds (LEP, Tevatron, LHC7+8) on $\phi = h$ or H, A

Signal rates compared with data by HiggsBounds

$$\mu_i = \frac{\sigma_{2HDM}(\phi) \times Br_{2HDM}(\phi \to X_i)}{\sigma_{SM}(\phi) \times Br_{SM}(\phi \to X_i)}$$



Consistency with the observed ∼ 125.9 GeV Higgs.

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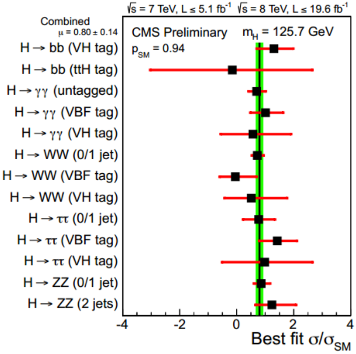

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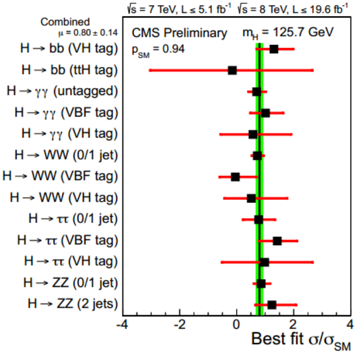

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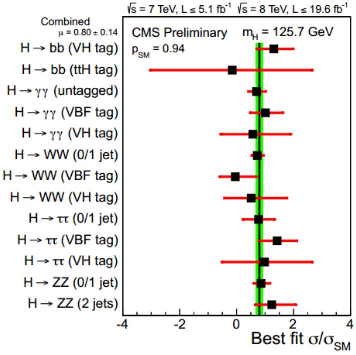

Uses same input as HIGGSBOUNDS (next slide).

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- Neutral scalars: m_i^2, CP, $Br(\phi_i \to X_{SM})$, $Br(\phi_i \to \phi_j\phi_j)$, Γ_i^{Tot},

$$\frac{\sigma_{2HDM}(X \to \phi_i)}{\sigma_{SM}(X \to \phi_i)} \text{ @ LEP, Tevatron, LHC7} + 8$$

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Fitted gg fusion + $b\bar{b}$ annihilation @ NNLO with SusHi:

$$\sigma_{b\bar{b}+gg} = g_{\phi,t}^2 T(m_\phi) + g_{\phi,t} g_{\phi,b} I(m_\phi) + g_{\phi,b}^2 B(m_\phi)$$

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$$\sigma_{b\bar{b}+gg} = g_{\phi,t}^2 T(m_\phi) + g_{\phi,t}g_{\phi,b}I(m_\phi) + g_{\phi,b}^2 B(m_\phi)$$

1. Computed fine 3D grid of points in $(\alpha, \tan\beta, m_\phi)$
2. Fit to extract form functions of m_ϕ for each collider.
   Note: Checked fit quality better than $R^2 = 0.999$.

Implementation in ScannerS

Hadronic input passed to HiggsBounds/Signals

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  $e^+e^- \to H^+H^-$.

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Branching ratios and decay **widths** computed with Hdecay

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Conditions of the scans

Set of free parameters:

$$\alpha \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right] \ , \ \tan\beta \in [0.1, 50] \ , \ m_{12}^2 \in \left[-(900)^2, (900)^2\right]$$

$$m_A \in [50, 1000] \ , \ m_{H^+} \in [50, 1000] \ \mathrm{GeV}$$

- Light scenario $m_h = 125.9$ GeV: $m_H \in [130, 1000]$
- Heavy scenario $m_H = 125.9$ GeV: $m_h \in [70, 120]$

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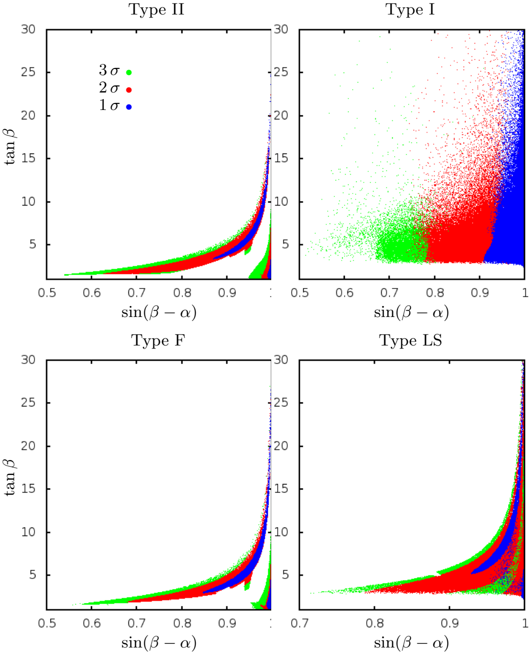
Note: $\tan\beta < 1$ mostly cut by B-Physics.

Parameter space after LHC8 – Light Higgs scenario

Types II, F:

$\sin(\beta - \alpha) = 1 \rightarrow$ SM lim.

$\sin(\beta + \alpha) = 1 \rightarrow$ Wrong sign



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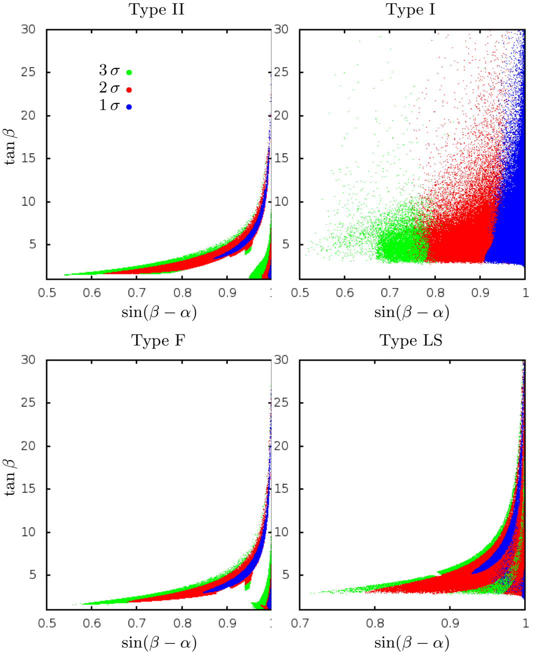
- **Fontes, Romão, Silva, PRD90 (2014) 015021**

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

- Related to b-loop in $gg \rightarrow h$ and $b\bar{b} \rightarrow h$

  $$\propto \frac{\sin^2\alpha}{\cos^2\beta} \rightarrow \infty$$

  except close to SM lim.



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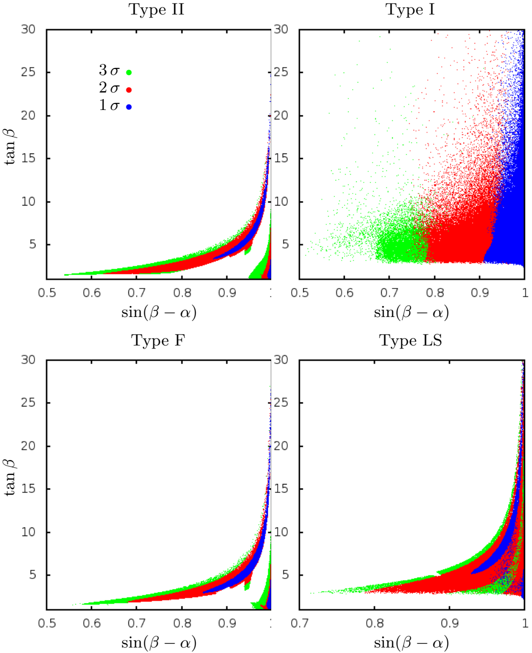


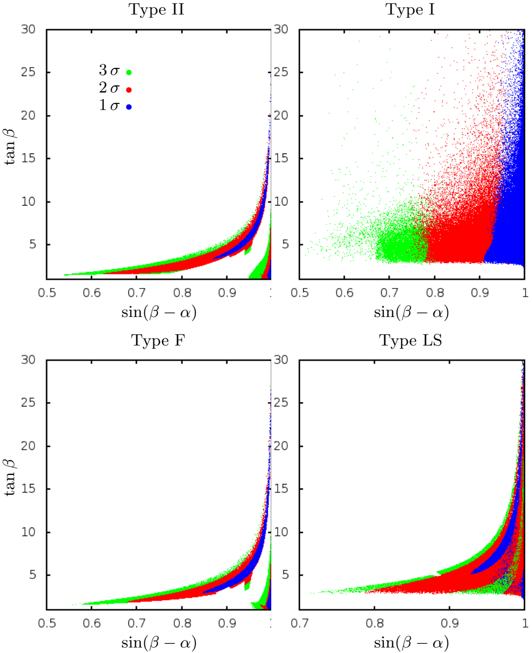
Parameter space after LHC8 – Light Higgs scenario

Types I:

- b-coupling $\propto \dfrac{\cos^2 \alpha}{\sin^2 \beta}$

  $\Rightarrow$ little dependence when $\tan \beta > 1$

- In fact in $h \to b\bar{b}$ approx. $\mu_{VV} \simeq \sin^2(\beta - \alpha)$



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- In fact in $h \to b\bar{b}$ approx. $\mu_{VV} \simeq \sin^2(\beta-\alpha)$

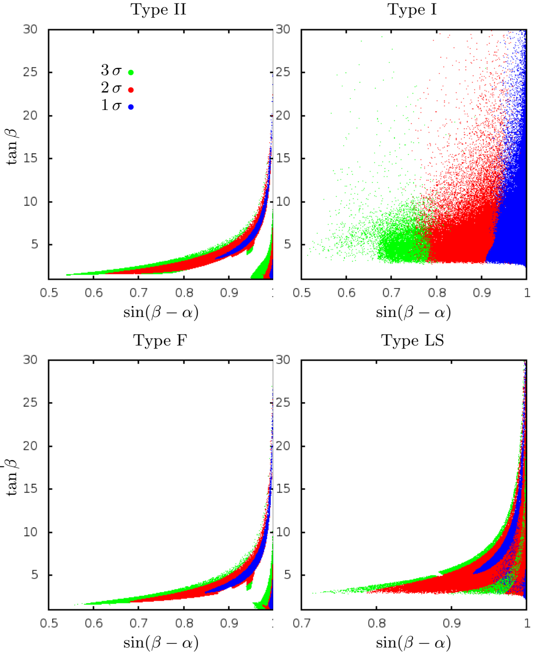
Type LS:

- Lepton coupling $\propto \dfrac{\sin^2\alpha}{\cos^2\beta}$

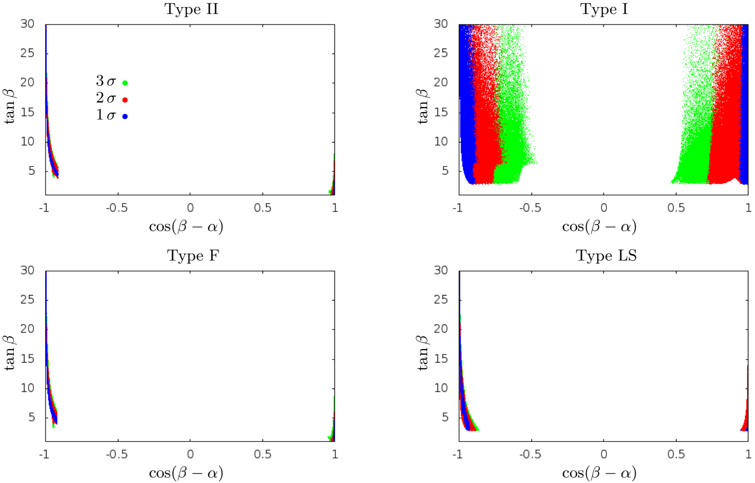
  $\Rightarrow$ constraint from $h \to \tau^+\tau^-$

- $b\bar{b} + \tau^+\tau^-$ approx.

$$\mu_{VV} \simeq \frac{10\sin^2(\beta-\alpha)}{9+\tan^2\beta\tan^2\alpha}$$



Parameter space after LHC8 – Heavy Higgs scenario



In our conventions, same conclusion apply with

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

The wrong sign limit – Gluon κ_g and photon κ_γ

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

κ_g, κ_γ loop gen. but $\kappa_V, \kappa_U, \kappa_D, \kappa_L$ taken to be tree couplings.

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Wrong Sign Limit $\sin(\beta+\alpha) \to 1$

Type	I	II	F	LS
$\kappa_U \to$	$+1$	$+1$	$+1$	$+1$
$\kappa_D \to$	$+1$	-1	-1	$+1$
$\kappa_L \to$	$+1$	-1	$+1$	-1

$$\kappa_W \to \frac{\tan^2\beta - 1}{\tan^2\beta^2 + 1}$$

$$g_{hH^+H^+} \to -\kappa_W \frac{2m_{H^+}^2 - m_h^2}{v^2}$$

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Vertices with interference → potential to probe sign changes:

- Gluon vertex *ggh* contains $\propto \kappa_t$ and $\propto \kappa_b$ contributions $\Rightarrow \kappa_U \kappa_D < 0$ induces deviations from SM value.
- Photon vertex $\gamma\gamma h$: fermions + $\propto \kappa_W$ and $\propto g_{hH^+H^+}$ $\Rightarrow \kappa_D \kappa_W < 0$ may induce deviations from SM value.

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The wrong sign limit – Summary

Light or Heavy scenario !

Type	I	II	F	LS
$\tan\beta > 1$	No	$\kappa_D\,\kappa_W < 0$ $\kappa_D\,\kappa_U < 0$	$\kappa_D\,\kappa_W < 0$ $\kappa_D\,\kappa_U < 0$	No
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Note: Heavy scenario, same since

$$\kappa_F \to -\kappa_F \ , \ \kappa_W \to -\kappa_W$$

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But $g_{hH^+H^+} > 0$!

$\Rightarrow$ Same wrong signs

$\Rightarrow$ But difference due to positive $g_{hH^+H^+}$

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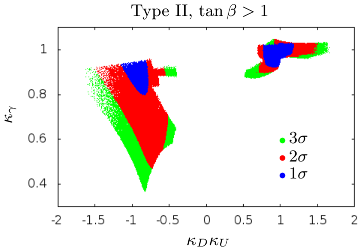
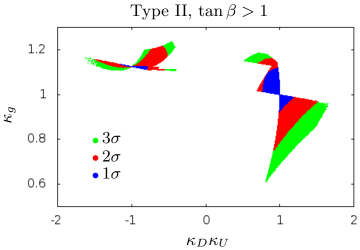
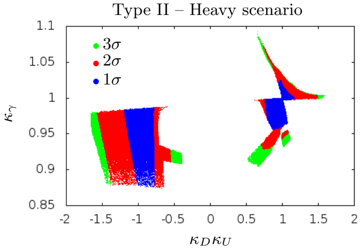
Allowed parameter space after the LHC8

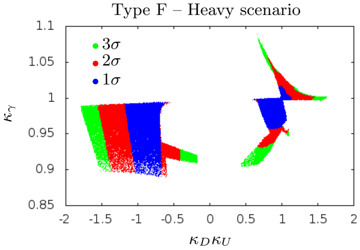
Light scenario (Type F is similar)





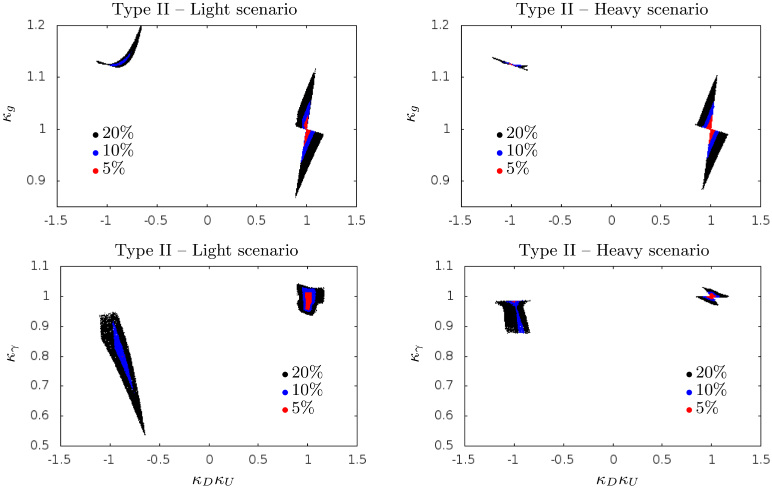
Heavy scenario





Prospects for increase in precision

Assuming all rates measured within 5%, 10%, 20% of SM:



Difficult to distinguish between heavy and light scenario
(though κ_γ goes to larger values in Heavy case!)

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1. We have implemented, $\mathbb{Z}_2$-2HDMs in ScannerS with:
   - **All theoretical** constraints,
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2. Revisited wrong sign scenarios (Light & Heavy):
   - **Same cases** for light and heavy.
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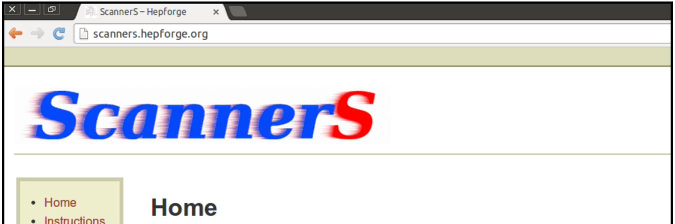
THANK YOU!

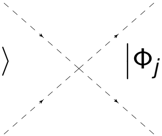


BACKUP

Tree level unitarity module

$$(\ldots,\ |\Phi_i\rangle\ ,\ \ldots) \equiv \left(\frac{1}{\sqrt{2!}} |\phi_1\phi_1\rangle\ , \ldots, \frac{1}{\sqrt{2!}} |\phi_N\phi_N\rangle\ , |\phi_1\phi_2\rangle\ , \ldots, |\phi_{N-1}\phi_N\rangle \right)$$

Tree level unitarity in $2 \to 2$ high energy scattering:

$|\Phi_i\rangle$  $|\Phi_j\rangle$,

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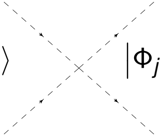

$$\left|\Phi_j\right\rangle\ ,\Re\{a_{ij}^{(0)}\} < \tfrac{1}{2}\ ,\ a_{ij}^{(0)} = \frac{\langle\Phi_i|\ i\mathbf{T}^{(0)}\left|\Phi_j\right\rangle}{16\pi} \sim \sum_{a_4}\ldots\lambda_{a_4}$$

Lee, Quigg, Thacker; PRD16, Vol.5 (1977)

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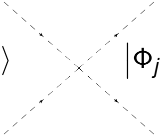

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  $\Rightarrow$ constrains quartic coupling λ, $\Rightarrow$ $\mathbf{m_h^2 < 700}$ **GeV**

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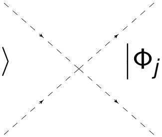
$|\Phi_i\rangle$  $\left|\Phi_j\right\rangle$ $,\ \Re\{a_{ij}^{(0)}\} < \frac{1}{2}\ ,\ \ a_{ij}^{(0)} = \dfrac{\langle\Phi_i|\ i\mathbf{T}^{(0)}\ |\Phi_j\rangle}{16\pi} \sim \sum_{a_4} \ldots \lambda_{a_4}$

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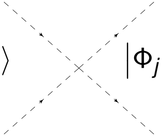
$|\Phi_i\rangle$  $|\Phi_j\rangle$

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- In BSM $\Rightarrow$ bounds on combinations of quartic λ_{a_4}
- Reduces to finding eigenvalues of $a_{ij}^{(0)}$ numerically $\Rightarrow$ **fast!**

Neutral Higgs Couplings to SM particles

- Couplings to fermions:

I	Φ_2		
	u^i	d^i	e^i
h	$\frac{\cos\alpha}{\sin\beta}$		
H	$\alpha \to \alpha - \pi/2$		
A	$\cot\beta$	$-\cot\beta$	

II	Φ_2	Φ_1	
	u^i	d^i	e^i
h	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	
H			
A	$\cot\beta$	$\tan\beta$	

LS	Φ_2		Φ_1
	u^i	d^i	e^i
h	$\frac{\cos\alpha}{\sin\beta}$		$-\frac{\sin\alpha}{\cos\beta}$
H			
A	$\cot\beta$	$-\cot\beta$	$\tan\beta$

F	Φ_2	Φ_1	Φ_2
	u^i	d^i	e^i
h	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$
H			
A	$\cot\beta$	$\tan\beta$	$-\cot\beta$

- Couplings to massive gauge bosons

$$h_{SM} \to \{\sin(\beta-\alpha)h, \cos(\beta-\alpha)H\}$$