Higgs couplings beyond the Standard Model

David López-Val

based on work together with K. Cranmer & S. Kreiss (NYU New York), M. Rauch (KIT Karlsruhe), T. Plehn (ITP Heidelberg)

1308.1979 & **1401.0080**

CP3 - Université catholique de Louvain

GDR Terascale meeting 2014, Heidelberg - **December 12th 2014**

Outline

Context

We are building on an evidence . . .

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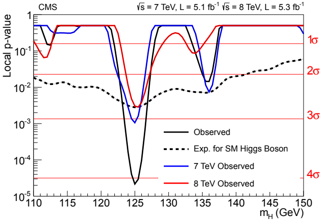
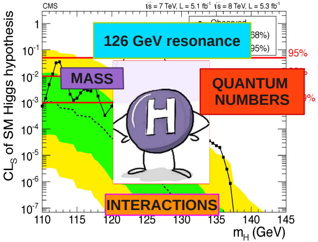


Whys and wherefores



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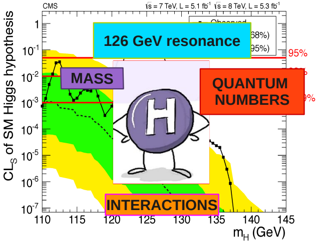

Is it the *Standard* one . . .

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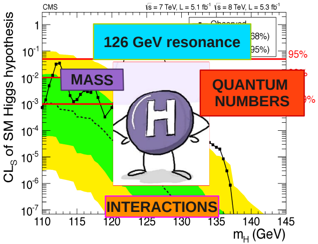

Is it the *Standard* one . . .

. . . or one piece from *beyond* ?

fundamental

single

weakly coupled

natural

admixture

light partners

strongly coupled

stable

composite

heavy partners

Seeking for BSM imprints

$$\mathcal{L}_{\mathsf{SM}} \longrightarrow \mathcal{L}[g'_{\mathsf{SM}}, g_{\mathsf{BSM}}, \phi_{SM}, \phi_{\mathsf{BSM}}]$$

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$$g_{xxH} = g_{xxH}^{\mathsf{SM}}(1 + \Delta_x)$$

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BSM patterns $\Longleftrightarrow$ signal strength deviations

BSM patterns	signal strength deviations
mixing	$\Delta_x^{\text{tree}}, \Delta_x^{\text{loop}}$
new charged/colored states	Δ_x^{loop}
degenerate states	$\Delta_\phi \to \Delta_{h^0} + \Delta_{H^0}$
hidden sectors	Γ_{inv}

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- Scale $\Lambda \sim 0.55 - 2.5$ TeV
- Structure

MODEL

Englert et al. 1403.7191

- Size $\Delta \sim 0.01 - 0.2$
- Correlations

Outline

Coupling shifts

- Multiscalar sectors induce **characteristic** shifted coupling patterns

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"The way you are shifted tells you about your shifter . . ."

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"The way you are shifted tells you about your shifter ..."

$g_{xxH} = g^{SM}_{xxH}(1+\Delta_x)$		$hf\bar{f}$			
extension	model	universal rescaling		non-universal rescaling	
singlet	inert ($v_S = 0$)				
	EWSB ($v_S \neq 0$)	θ	$\Delta_f < 0$		
doublet	inert ($v_d = 0$)				
	type-I	$\alpha - \beta$	$\Delta_f \gtrless 0$	$\mathcal{O}(y_f, \lambda_H)$	$\Delta_f \gtrless 0$
	type-II			$\alpha - \beta$, $\mathcal{O}(y_f, \lambda_H)$	$\Delta_f \gtrless 0$
	aligned/MFV	y_f,	$\Delta_f \gtrless 0$	$y_f, \mathcal{O}(y_f, \lambda_H)$	$\Delta_f \gtrless 0$
singlet+doublet		y_f, θ	$\Delta_f \gtrless 0$	$y_f, \mathcal{O}(y_f, \lambda_H)$	$\Delta_f \gtrless 0$
triplet		β_n	$\Delta_f \gtrless 0$	$\mathcal{O}(y_f, \lambda_H)$	$\Delta_f \gtrless 0$

Outline

Dark singlet

♠ The simplest extension . . .

DARK SINGLET

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DARK SINGLET

$$V(\Phi, S) = \mu_1^2 \, (\Phi^\dagger \, \Phi) + \lambda_1 \, |\Phi^\dagger \Phi|^2 + \lambda_3 \, |\Phi^\dagger \, \Phi| S^2$$

– e.g. McDonald ['94]

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$$\Gamma_{\mathsf{inv}} = \frac{\lambda_3^2 v^2}{32\pi\, m_h}\,\sqrt{1-\frac{4m_s^2}{m_h^2}} \equiv \xi^2\,\Gamma_{\mathsf{SM}} \qquad \text{with} \qquad \mu_{p,d} = \frac{\Gamma_{\mathsf{SM}}}{\Gamma_{\mathsf{SM}}+\Gamma_{\mathsf{inv}}} = 1-\xi^2+\mathcal{O}(\xi^3)\;.$$

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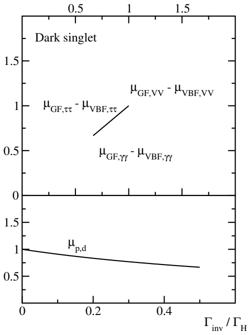
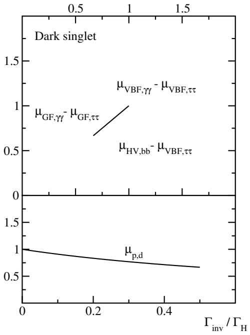
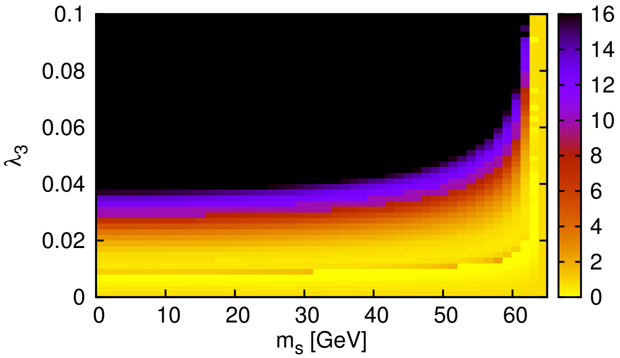




Dark singlet

Correlated relative log-likelihood $-2\Delta \log \mathcal{L}$



2HDM at decoupling

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$$\xi \equiv \cos(\beta - \alpha) \simeq \frac{v^2}{M^2_{\text{heavy}}} \qquad \boxed{\xi \ll 1 \Rightarrow \sin\alpha \sim \cos\beta} \qquad \xi \simeq \frac{2\tan\beta}{1+\tan^2\beta}$$

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$\Delta_g = \Delta_g(\Delta_f(\tan\beta,\xi))$ $\Delta_\gamma(\Delta_f(\tan\beta,\xi), m^2_{H^\pm}(\xi), \tilde{\lambda}(\xi))$

2HDM at decoupling

♠ Increasing complexity . . . **Types I and II 2HDM at decoupling**

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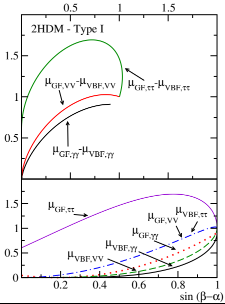
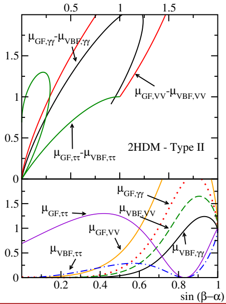
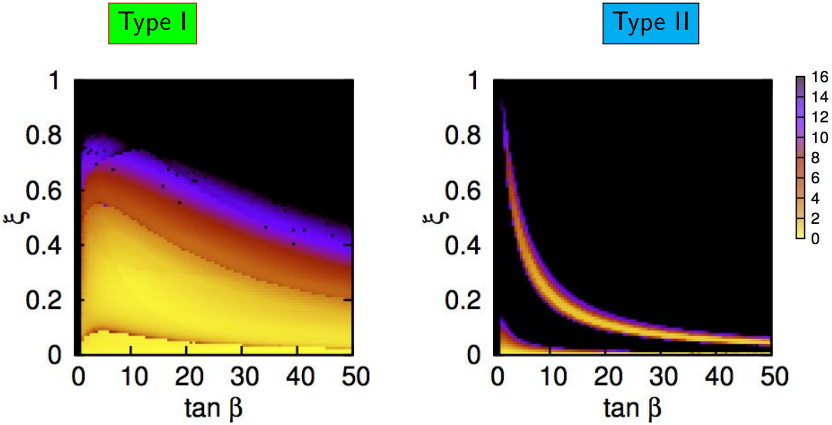




Hierarchical 2HDM

Correlated relative log-likelihood $-2\Delta \log \mathcal{L}$



DLV, Plehn, Rauch 1308.1979

Aligned 2HDM

- Aligned 2HDM   Pich, Tuzón ['09]

Aligned 2HDM

♠ Aligned 2HDM Pich, Tuzón ['09]

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: $\gamma_{b,\tau} = 0$

Aligned 2HDM

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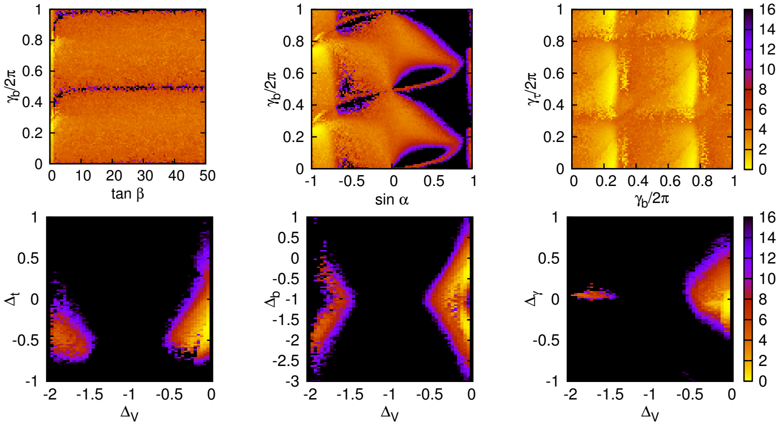


DLV, Plehn, Rauch 1308.1979

Aligned 2HDM

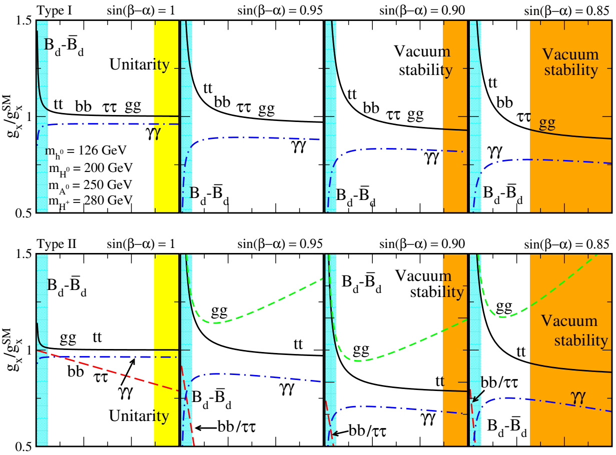
	unconstrained		constrained	
	$\tan < 1$	$\tan\beta > 1$	$\tan\beta < 1$	$\tan\beta > 1$
$\tan\beta$	0.338	1.231	0.890	1.324
$\sin\alpha$	-0.977	-0.871	-0.900	-0.810
$\gamma_b/(2\pi)$	0.744	0.261	0.732	0.267
$\gamma_\tau/(2\pi)$	0.389	0.070	0.542	0.678
M_H	750.5	257.3	587.2	487.4
$\tilde{\lambda}$	-3.00	0.44	3.80	2.88
Δ_V	-0.006	-0.069	-0.038	-0.044
Δ_t	-0.332	-0.367	-0.345	-0.265
Δ_b	-0.298	-0.412	-0.281	-0.318
Δ_τ	0.176	0.107	0.099	-0.102
Δ_γ	-0.058	-0.045	-0.034	-0.031
$\Delta_\gamma^{\text{tot}}$	0.023	-0.036	0.009	-0.017
$-2\log\mathcal{L}$	26.6	26.9	27.1	28.5

DLV, Plehn, Rauch 1308.1979

Outline

Higgs Coupling in the 2HDM – LO patterns

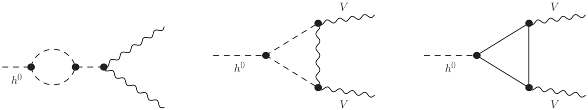
♠ **Higgs coupling deviations** – a parameter space portray



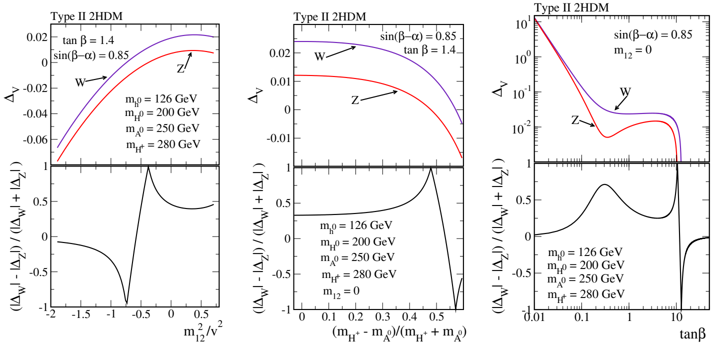
Over $\tan\beta$

Higgs Coupling in the 2HDM: quantum effects

♠ **Higgs coupling deviations – adding quantum effects**

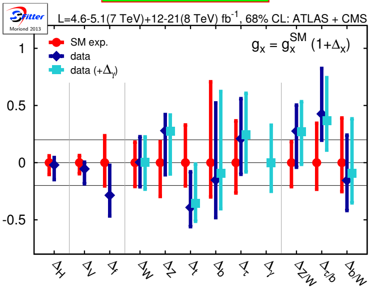


♠ fermionic loops essential for $\Delta_V > 0$ and $\Delta_Z \neq \Delta_W$

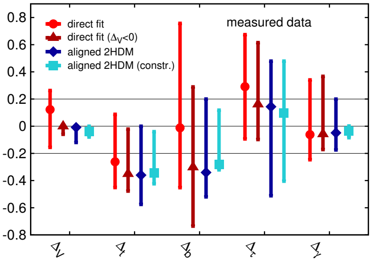


LHC data: free couplings VS 2HDM

Free couplings



2HDM



♠ a **2HDM** with aligned Yukawas & quantum effects

⇒ Yukawa alignment – Pich, Tuzón ['09]

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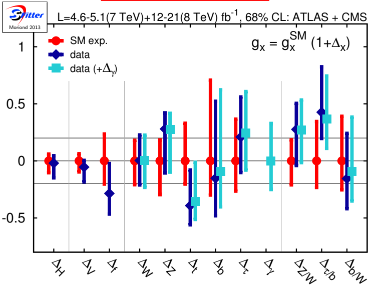
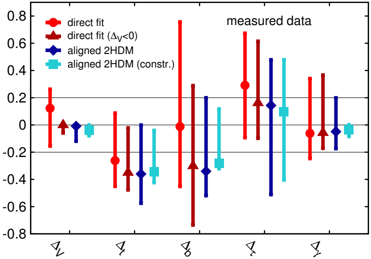


2HDM



♠ a **2HDM** with aligned Yukawas & quantum effects

⇒ Yukawa alignment – Pich, Tuzón ['09]

♠ Renormalizable, perturbative, UV–complete embedding for **fully independent Higgs couplings**

A word on theory uncertainties

♠ BSM & TH uncertainties ⇔ **Coupling shifts** ⇔ Signal strength correlations

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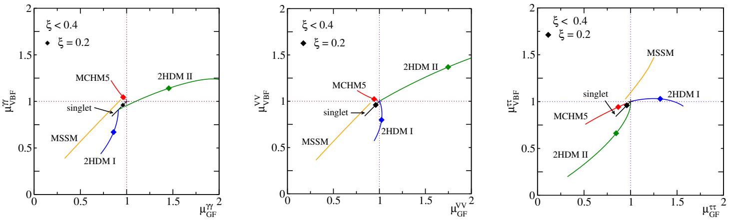

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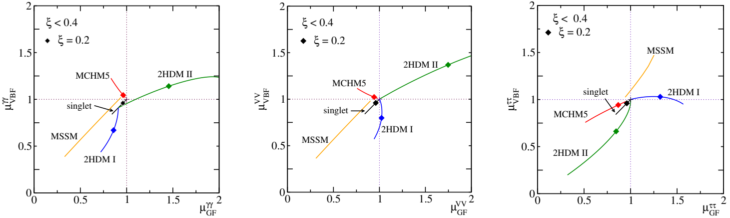

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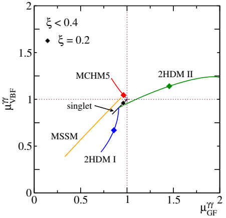

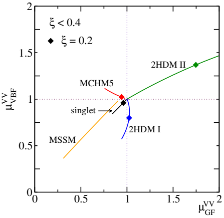

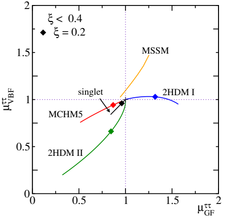

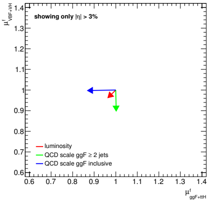

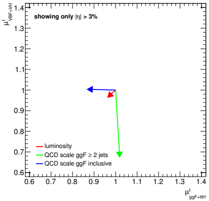

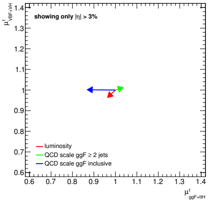

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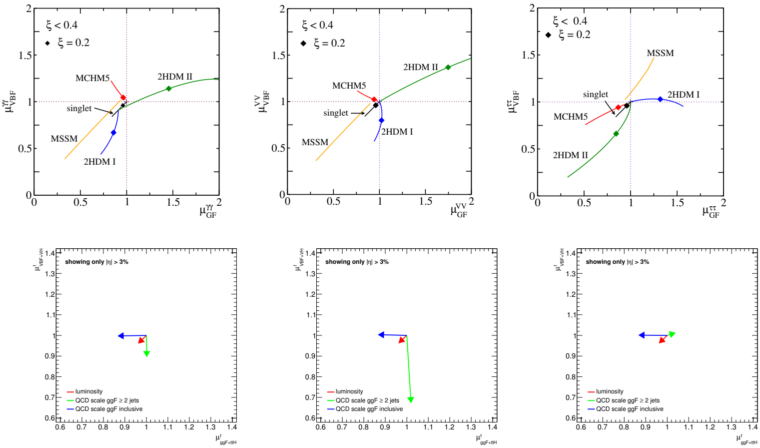

Geometry in the $\mu^i_p - \mu^{i'}_{p'}$ plane ⇔ ket to tell apart BSM from uncertainties

Cranmer, Kreiss, DLV, Plehn 1401.0080

Outline

Take–home ideas

- Extended Higgs sectors give rise to characteristic coupling shifts $g_{xxh} = g_{xxh}(1+\Delta_x)$
- with distinctive **sizes** $\Delta_x \sim \mathcal{O}(v^2/\Lambda^2)$ and **correlations** $\Delta_x - \Delta_y$
- different from theory uncertainties
- Generic multiscalar sectors $\Rightarrow$ compatible with data – if decoupling limit can be realized
- The Aligned 2HDM @ NLO EW $\Rightarrow$ **minimal** ultraviolet completion of a SM-like Higgs sector with **free couplings**
  - Best–fit points: $\tan\beta \simeq 1$, interpolates between types I-II
  - $\alpha - \beta$ correlation, sign degeneracies, excluded fermiophobia

Joyeux Noël, Frohe Weinachten !!