Portraying Multi-Higgs sectors

David López-Val

based on work together with
♭ A. Freitas & D. Gon calves (Pittsburgh U.), T. Plehn (ITP Heidelberg), M. Rauch (KIT Karlsruhe) , & more!

arXiv:1308.1979, JHEP 1310 & **arXiv:1401.0080 [hep-ph], PRD 91** & **arXiv:1510.03443 [hep-ph], PRD 93**
arXiv:1607.08614 [hep-ph] & **arXiv:1607.08251 [hep-ph], PRD 93** & **LHCHXSWG YR4**

Institut für Theoretische Physik
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BCTP & Univ. Bonn Beyond the Standard Higgs-System
Nov 29th 2016

Outline

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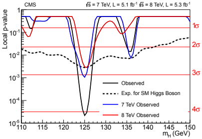
Motivation

We are building on an evidence . . . of THE GENUINE ONE? Or rather an almost perfect copy?



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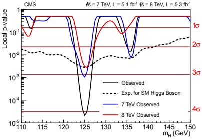
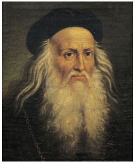


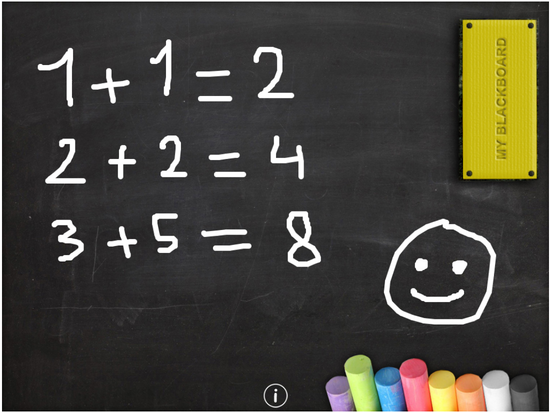


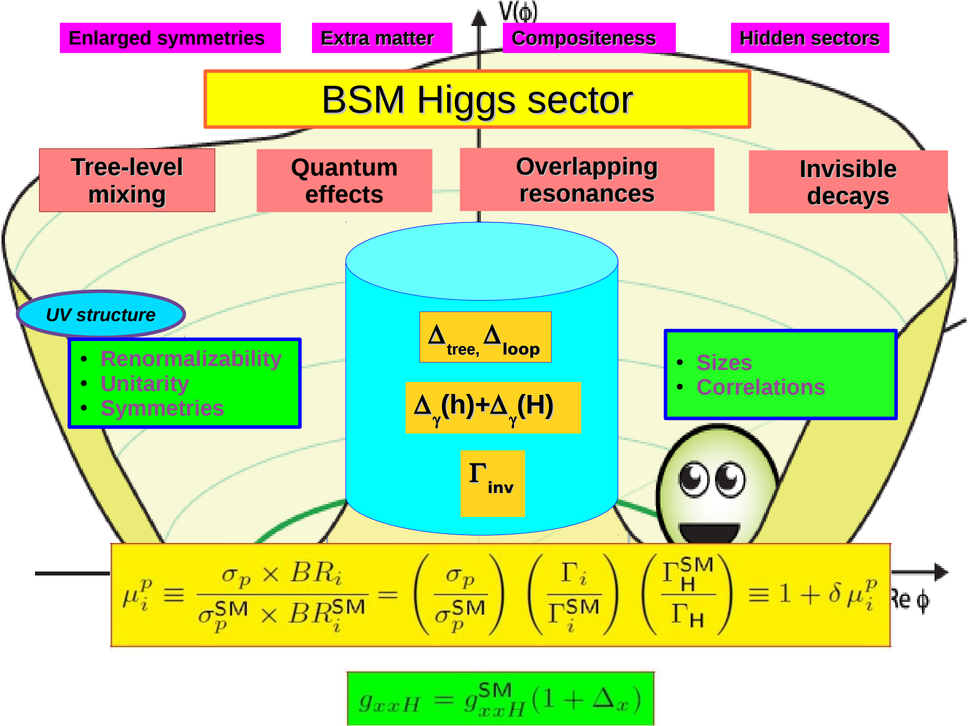
Hints for the art of Da Vinci's secret apprentice

- **Fundamental** or **composite**?
- **Single** or **multiple**? Or even **overlapped**?
- **Natural**? **Weakly** or **strongly** coupled?
- **Stable**? Up to an arbitrary UV scale? During inflation?

The MultiHiggs setup

A blackboard will help here !





V(ϕ)
Enlarged symmetries
Extra matter
Compositeness
Hidden sectors
BSM Higgs sector
Tree-level mixing
Quantum effects
Overlapping resonances
Invisible decays
UV structure
• Renormalizability
• Unitarity
• Symmetries
$\Delta_{tree,}\ \Delta_{loop}$
$\Delta_\gamma(h)+\Delta_\gamma(H)$
Γ_{inv}
• Sizes
• Correlations
Re ϕ
$\mu_i^p \equiv \frac{\sigma_p \times BR_i}{\sigma_p^{SM} \times BR_i^{SM}} = \left(\frac{\sigma_p}{\sigma_p^{SM}}\right)\left(\frac{\Gamma_i}{\Gamma_i^{SM}}\right)\left(\frac{\Gamma_H^{SM}}{\Gamma_H}\right) \equiv 1 + \delta\,\mu_i^p$
$g_{xxH} = g_{xxH}^{SM}(1+\Delta_x)$

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Coupling shifts

- **Multiscalar sectors** induce **characteristic** **coupling shifts**

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

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$g_{xxH} = g^{\text{SM}}_{xxH}(1+\Delta_x)$		$hf\bar{f}$			
extension	model	universal rescaling		non-universal rescaling	
singlet	inert ($v_S = 0$)	θ	$\Delta_f < 0$		
	EWSB ($v_S \neq 0$)				
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	$\Delta_f \gtrless 0$	$\mathcal{O}(y_f, \lambda_H)$	$\Delta_f \gtrless 0$

Higgs Coupling in the 2HDM – LO patterns

- ♠ Expanding the 2HDM around the

decoupling limit

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$1+\Delta_v \simeq 1 - \xi^2/2$ $1+\Delta_t \simeq 1 + \cot\beta\,\xi - \xi^2/2$ $1+\Delta_b \simeq 1 + \cot\beta\,\xi - \xi^2/2$

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

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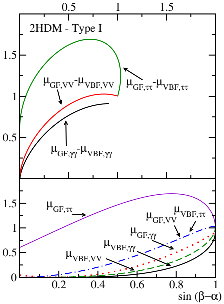

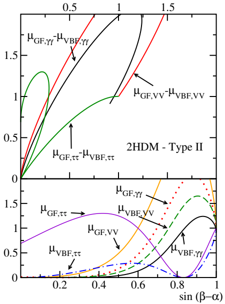

Coupling shifts from theory uncertainties

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

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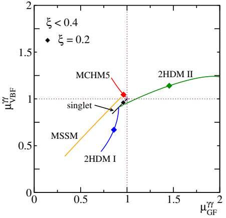

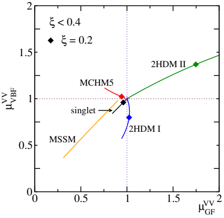

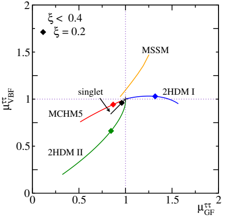

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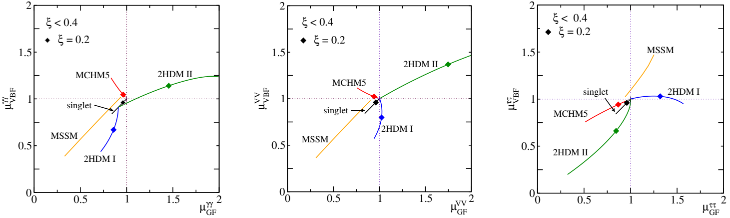
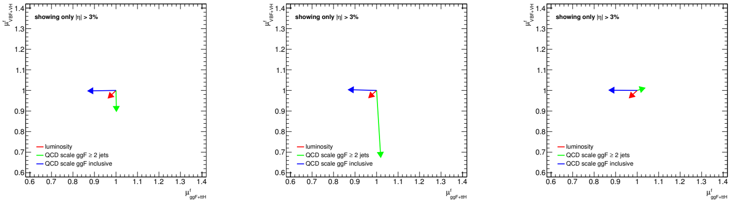


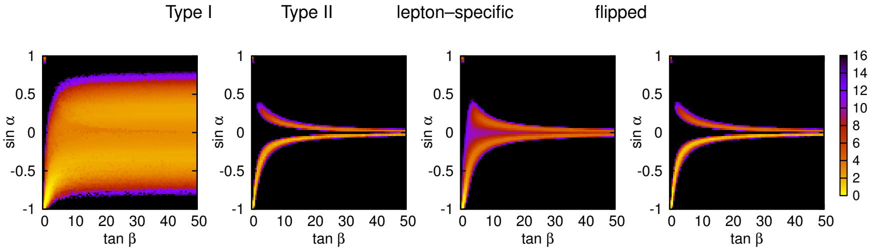


Geometry in the $\mu^i_p - \mu^{i'}_{p'}$ plane ⇔ tell apart BSM from uncertainties

Cranmer, Kreiss, DLV, Plehn 1401.0080

Coupling fits to LHC data

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



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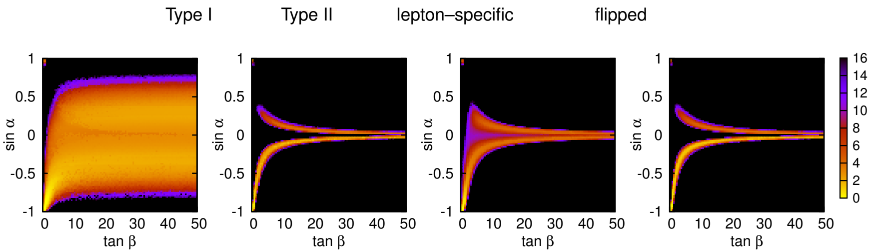

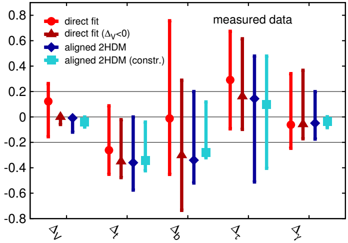

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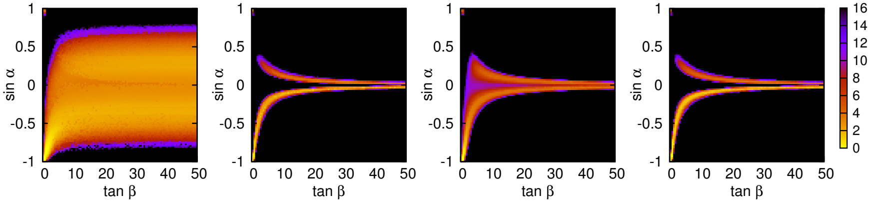
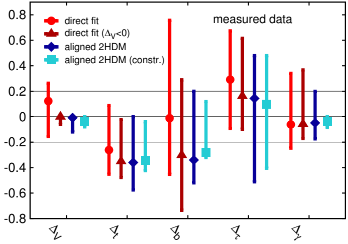
Type I | Type II | lepton–specific | flipped





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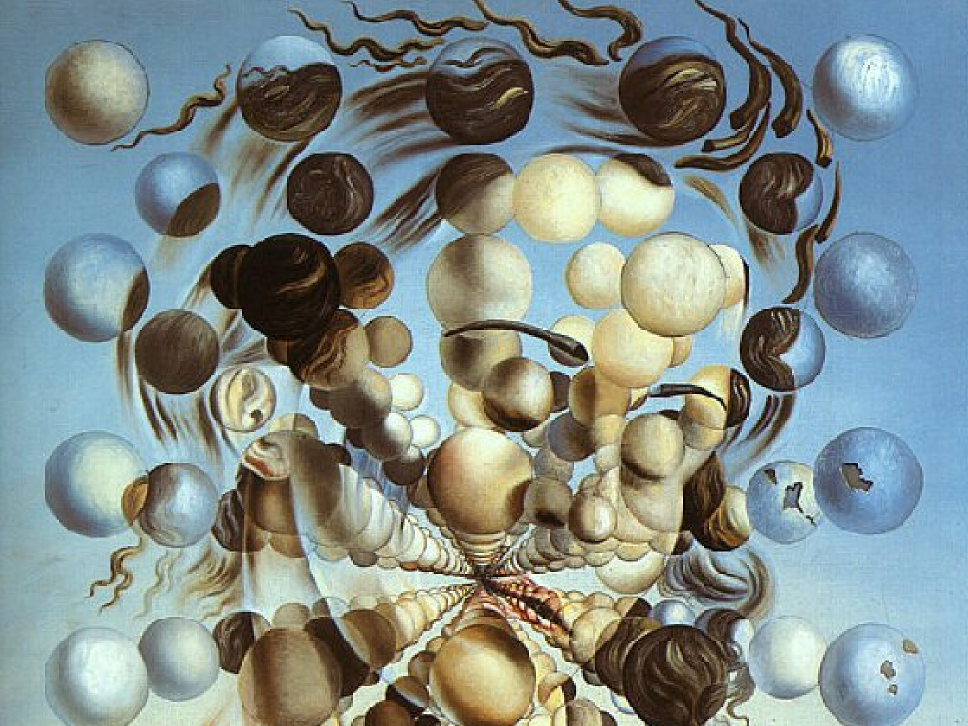
A not-to-miss: updated fits & off-shell couplings: Corbett, Plehn et al. [arXiv:1505.05516]

Outline



EFT basics

Building blocks

$$\mathcal{L}_{\text{eff}}(\phi, m) = \mathcal{L}_{\text{SM}} + \sum_{d=5}^{\infty} \sum_{a_d} \frac{C_{a_d}^{(d)}}{\Lambda^{d-4}}(\{g_{\text{UV}}\}, \Lambda)\, \mathcal{O}_{a_d}^{(d)}(\phi)$$

- Short-distance physics: is averaged ⇒
  - ♣ Effective coupling strength c_i encoding $\{g_{\text{UV}}\}$ through **matching**
- Long-distance physics: ⇒
  - ♣ light-field local interactions parametrized by $\hat{\mathcal{O}}$
  - ♣ $d > 4$ operators dependent on ϕ & underlying symmetries

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INTEGRATING OUT **TRUNCATING** **MATCHING**

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HEFT parametrization SILH basis Giudice, Grojean, Pomarol, Ratazzi ['07]

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \frac{\bar{c}_H}{2v^2}\, \partial^\mu(\phi^\dagger \phi)\, \partial_\mu(\phi^\dagger \phi) + \frac{\bar{c}_T}{2v^2}\, (\phi^\dagger \overleftrightarrow{D}^\mu \phi)\, (\phi^\dagger \overleftrightarrow{D}_\mu \phi) - \frac{\bar{c}_6 \lambda}{v^2} (\phi^\dagger \phi)^3$$
$$+ \frac{i g \bar{c}_W}{2m_W^2}\, (\phi^\dagger \sigma^k \overleftrightarrow{D}^\mu \phi)\, D^\nu\, W^k{}_{\mu\nu} + \frac{i g' \bar{c}_B}{2m_W^2}\, (\phi^\dagger \overleftrightarrow{D}^\mu \phi)\, \partial^\nu\, B_{\mu\nu} + \ldots$$

Our target

"Given the future experimental resolution, ***full calculations*** *in a* ***UV complete model*** *do not offer considerable advantage in accuracy over the* ***effective theory****"*

Our target

UV-complete model **QFT framework** **Effective Field Theory**

*"Given the future experimental resolution, **full calculations** in a **UV complete model** do not offer considerable advantage in accuracy over the **effective theory**"* ?

Key questions

- Is there a scale hierarchy $\Lambda \gg v$ for typical models testable at the LHC ?
- How accurately does the linear, d6 HEFT reproduce full model predictions for trademark extended Higgs sectors?
- **Where** and **why** may **discrepancies** arise?
  - **WHERE:** **Models**, **processes**, **observables**?
  - **WHY:** **UV model structures**; **EFT construction** (matching, truncation, multiscales)
- May full model versus EFT departures be quantitatively relevant for BSM Higgs analyses?
- How do these conclusions extend to LOOP EFFECTS ? arXiv:1607.08251 [hep-ph]

EFT challenges

BSM Higgs program at the LHC **challenges** the EFT approach

♠ **RELEVANCE** VS **VALIDITY**

♣ EFT accurate if $E_{\text{phys}} < \Lambda$ ♣ relevant if $\Delta_{xxH}(\Lambda) \sim \mathcal{O}(10)\%$ LHC accuracy

$$\left| \frac{\sigma \times \text{BR}}{(\sigma \times \text{BR})_{\text{SM}}} - 1 \right| = \frac{g^2 m_H^2}{\Lambda^2} \gtrsim 0.1$$

$\Rightarrow$ $\Lambda < \sqrt{10}\, g\, m_H \simeq 280 \text{ GeV}$, if $g^2 < 1/2$

$\Rightarrow$ $\Lambda \lesssim \sqrt{10}\, g\, m_H \simeq 5 \text{ TeV}$, if $g^2 \lesssim 4\pi$

LHC poorly sensitive to large UV scales in weakly–coupled theories

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NEW PHYSICS FEATURES

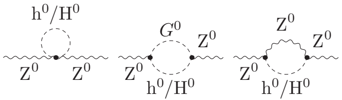
- Strong couplings
- Multiple & v-induced scales
- Light scales

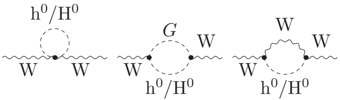
- **Innacurate truncation** — competing orders
- **Matching ambiguities** — scale & gauge phase
- **Kinematics** — OS resonances, OffS shapes

Outline

Oblique parameters

Oblique parameters new physics contribution to WB polarization **♠ Full model**

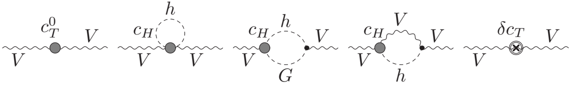




$$\frac{\alpha_{\rm em}}{4 s_w^2 c_w^2} S = \left[-\Pi'_{\gamma\gamma} + \Pi'_{ZZ} - \Pi'_{\gamma Z} \frac{c_w^2 - s_w^2}{c_w s_w} \right] - \left[\cdots \right]_{\rm SM}$$

$$\alpha_{\rm em} T = \left[\Pi_{WW} - \Pi_{ZZ} \right] - \left[\cdots \right]_{\rm SM}$$

♠ EFT



$$\alpha_{\rm em} T \Big|_{\text{tree insertion}} = c_T \frac{v^2}{\Lambda^2}\,, \qquad S \Big|_{\text{tree insertion}} = 4\pi \frac{v^2}{\Lambda^2} \left(c_W + c_B \right) \text{ (+ finite loop parts)}$$

The singlet-extended SM

Lagrangian & field content

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \partial^\mu S \partial_\mu S - \mu_s^2\, S^2 - \lambda_2\, S^4 - \lambda_3\, \Phi^\dagger\, \Phi S^2$$

$$\Phi = \begin{pmatrix} G^+ \\ \dfrac{v + \phi_h + iG^0}{\sqrt{2}} \end{pmatrix}$$

$$S = \frac{v_s + \phi_s}{\sqrt{2}}$$

m_h	m_H	$\sin\alpha$
$\sin\alpha$	v	$\tan\beta \equiv \dfrac{v_s}{v}$

Salient parameter relations:

$$\sin^2\alpha = \frac{m_h^2 - 2\lambda_1\, v^2}{m_h^2 - m_H^2}\;; \qquad \tan^2\beta = \frac{v_s^2}{v^2} = \frac{m_h^2 + m_H^2 - 2\lambda_1 v^2}{2\lambda_2\, v^2} \qquad m_H^2 \approx 2\lambda_2\, v_s^2$$

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Interactions

$$g_{xxy} = g_{xxy}^{\text{SM}}(1 + \Delta_{xy}) \quad \text{with} \quad 1 + \Delta_{xy} = \begin{cases} \cos\alpha & y = h \\ \sin\alpha & y = H \end{cases}$$

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$$\begin{array}{lll} m_h & m_H & \sin\alpha \\ \sin\alpha & v & \tan\beta \equiv \dfrac{v_s}{v} \end{array}$$

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♠ Motivations: Simplified model $\to \mathcal{L}_{\text{UV}}$ | EW baryogenesis | LHC searches

Singlet model oblique corrections

$$\Pi_{WW}(0) = -\frac{\alpha_{\rm em}\,\sin^2\alpha}{16\pi s_w^2}\Bigg\{3m_W^2\Delta_\epsilon - 4m_W^2\,\log\frac{m_H^2}{\mu^2} + \frac{5m_W^2 - m_H^2}{2} + m_W^2\log\frac{m_W^2}{\mu^2} - \frac{m_W^2}{m_H^2 - m_W^2}\left(4m_W^2 - m_H^2\right)\log\frac{m_H^2}{m_W^2}\Bigg\}$$

$$S \approx \frac{\sin^2\alpha}{12\pi}\left(-\log\frac{m_h^2}{m_Z^2} + \log\frac{m_H^2}{m_Z^2}\right) \approx \frac{\lambda_3^2}{24\pi\lambda_2}\,\frac{v^2}{m_H^2}\,\log\frac{m_H^2}{m_h^2}$$

$$T = \frac{-3\sin^2\alpha}{16\pi\, s_w^2\, m_W^2}\left(m_Z^2\log\frac{m_H^2}{m_h^2} - m_W^2\log\frac{m_H^2}{m_h^2}\right) \approx \frac{-3\lambda_3^2 v^2}{32\pi\, s_w^2\,\lambda_2\, m_W^2}\left(\frac{m_Z^2}{m_H^2} - \frac{m_W^2}{m_H^2}\right)\log\frac{m_H^2}{m_h^2}$$

Effective Lagrangian at tree-level

$$e^{iS_{\text{eff}}[\phi]} = \int [D\Phi] e^{iS[\phi,\Phi]} = \int [D\eta] e^{i\left(S[\phi,\Phi_{\text{class}}]+\mathcal{O}(\eta^2)\right)}$$

$$\Phi(x) = \Phi_{\text{class}}(x) + \eta(x)$$

$$\left.\frac{\delta S}{\delta \Phi}\right|_{\Phi=\Phi_{\text{class}}} = 0$$

Effective Lagrangian at tree-level

$$e^{iS_{\text{eff}}[\phi]} = \int [D\Phi] e^{iS[\phi,\Phi]} = \int [D\eta] e^{i\left(S[\phi,\Phi_{\text{class}}]+\mathcal{O}(\eta^2)\right)}$$

$$\Phi(x) = \Phi_{\text{class}}(x) + \eta(x)$$

$$\left.\frac{\delta S}{\delta \Phi}\right|_{\Phi=\Phi_{\text{class}}} = 0$$

Singlet model EFT

$$s^0_{\text{class}} = -\frac{\lambda_3 v_s\,(\phi^\dagger\phi)}{-\partial^2 - \mu_s^2 + \mathcal{F}(\phi)} = -\frac{\lambda_3\,v_s(\phi^\dagger\phi)}{\mu_s^2} + \mathcal{O}(\phi^3)$$

$$\mathcal{L}^{\text{tree}}_{\text{eff}} \supset \frac{\lambda_3^2}{4\lambda_2^2\,v_s^2}\,\partial_\mu\,(\phi^\dagger\phi)\,\partial^\mu\,(\phi^\dagger\phi) \quad \Leftrightarrow \quad \mathcal{L}_{\text{eff}} \supset \frac{\bar{c}_H}{2\Lambda^2}\,\partial_\mu\,(\phi^\dagger\phi)\,\partial^\mu\,(\phi^\dagger\phi)$$

$$\Lambda^2 = 2\lambda_2\,v_s^2 \qquad \bar{c}_H = \frac{\lambda_3^2}{2\lambda_2}$$

Effective Lagrangian at one-loop

$$e^{iS_{\text{eff}}[\phi]} = \int [D\Phi] e^{iS[\phi,\Phi]} = \int [D\eta] e^{i\left(S[\phi,\Phi_{\text{class}}] + \frac{1}{2} \left.\frac{\delta^2 S}{\delta \Phi^2}\right|_{\Phi=\Phi_{\text{class}}} \eta^2 + \mathcal{O}(\eta^3)\right)}$$

$$\approx e^{iS[\phi,\Phi_{\text{class}}]} \left[\text{det} \left(- \left.\frac{\delta^2 S}{\delta \Phi^2}\right|_{\Phi=\Phi_{\text{class}}} \right) \right]^{-\frac{1}{2}} \approx e^{iS[\phi,\Phi_{\text{class}}] - \frac{1}{2} \text{Tr} \log \left(- \left.\frac{\delta^2 S}{\delta \Phi}\right|_{\Phi=\Phi_{\text{class}}} \right)}$$

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$$\mathcal{L}_{\text{eff}}^{\text{1-loop}} \supset -\frac{1}{2(4\pi)^2\, M^2}\left\{\frac{1}{6}U^3 + \frac{1}{12}(P_\mu\, U)^2\right\} = -\frac{\lambda_3^2}{24(4\pi)^2\,\Lambda^2}\hat{\mathcal{O}}_H + \frac{1}{48(4\pi)^2\,\Lambda^2}\left(\frac{\lambda_3^2}{\lambda_{\text{SM}}}\right)\hat{\mathcal{O}}_6$$

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c_W, c_B, c_T ??

Renormalization

Renormalizing the Effective Lagrangian

$$\mathcal{L}_{\text{eff}}^{\text{bare}}(\{c_i^{\text{bare}}) \to \mathcal{L}_{\text{eff}}(\{c_i\}) + \delta\mathcal{L}_{\text{eff}}(\delta c_i)$$

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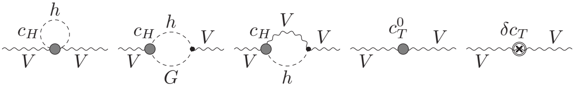

$$\Pi_{WW}(0) = \frac{\alpha_{\text{em}}\,\overline{c}_H}{16\pi s_w^2}\left\{3m_W^2\Delta_\epsilon - 4m_W^2\,\log\frac{m_h^2}{\mu^2} + \frac{5m_W^2 - m_h^2}{2} + \right.$$
$$\left. + m_W^2\log\frac{m_W^2}{\mu^2} - \frac{m_W^2}{m_h^2 - m_W^2}\left(4m_W^2 - m_h^2\right)\log\frac{m_h^2}{m_W^2}\right\} + \Xi[\delta Z_{c_{W,B,T}}]$$

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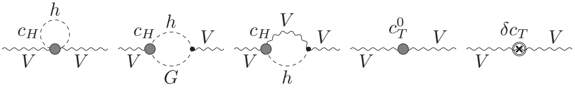

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$$\gamma_{\text{TH}} \equiv \gamma_{\text{H}\to\text{T}} = \frac{3}{2}\frac{e^2}{c_w^2}$$

$$\frac{v^2}{\Lambda^2}c_T(m_Z) = -\frac{3\alpha_{\text{ew}}\,\tan^2\theta_W}{(4\pi)^2}\left(\frac{\lambda_3^2\,v^2}{2\lambda_2\,(2\lambda_2 v_s^2)}\right)\log\left(\frac{2\lambda_2\,v_s^2}{m_Z^2}\right)$$

Matching prescriptions

♠ Multiple M_{heavy}'s | ♠ Symmetry breaking | ♠ v-induced scales & splittings

♣ Λ choice | ♣ gauge phase | ♣ truncation

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♠ Default matching

- Matching scale $\Lambda = M_{\text{heavy}} \quad (M_{\text{heavy}} \gg \mu_{\text{EWSB}})$
- $\mathcal{O}(\Lambda^{-2})$ truncation
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$\Rightarrow$ **Hazards!** Sizable BSM-Higgs couplings

- $m_{\text{phys}} \sim M_{\text{heavy}} \pm \mathcal{O}(gv)$ $\Rightarrow$ spoilt scale separation & sizable mass splittings
- Large $d > 6$ contributions $\mathcal{O}^d \propto \mathcal{O}^{d=6}\,(\Phi^\dagger\Phi)^{d-6}$

♠ v-improved matching: absorb $\mathcal{O}\left(\frac{v}{\Lambda}\right)^{d-6}$ terms into $\mathcal{L}_{\text{eff}}^{d=6}$.

- Matching scale $\Lambda = M_{\text{phys}}$
- Wilson coefficients written in terms of mass-eigenstate & mixing

$$\mathcal{O}_H : \frac{\lambda_3^2}{2\lambda_2}\frac{v^2}{\Lambda^2}\left[\partial_\mu(\Phi^\dagger\,\Phi)\,\partial^2\mu(\Phi^\dagger\,\Phi)\right] \quad \text{VS} \quad \frac{2(1-\cos\alpha)\,v^2}{m_H^2}\left[\partial_\mu(\Phi^\dagger\,\Phi)\,\partial^\mu(\Phi^\dagger\,\Phi)\right]$$

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♠ Broken phase matching

Include v-dependent finite parts to loop-induced $\hat{\mathcal{O}}$'s

- $c(\mu)$ evaluated **directly** at $\mu < \mu_{\text{EWSB}}$ through explicit matching

$$\Gamma^{\text{1PI}}_{\text{full}}\,[\phi]\,(\{g_{\text{full}}\}, \mu = \Lambda) = \Gamma^{\text{1PI}}_{\text{EFT}}\,[\phi]\,(\{c_i\}, \mu = \Lambda)$$

$\mathcal{O}_T|_{\text{LL-L}}$: $\dfrac{c_T(\mu)}{\Lambda^2} = -\dfrac{3\alpha_{\text{ew}}\, s_w^2\, \lambda_3^2}{32\pi c_w^2 \lambda_2 \Lambda^2}\,\log\dfrac{\Lambda^2}{\mu^2}$ VS $\dfrac{c_T(\mu)}{\Lambda^2} = -\dfrac{\alpha_{\text{ew}}\, s_w^2\, \lambda_3^2}{32\pi c_w^2 \lambda_2 \Lambda^2}\left(-\dfrac{5}{2} + 3\log\dfrac{\Lambda^2}{\mu^2}\right)$

EFT setups

Matching schemes

- **LL-L: Leading-log loop-induced**:

$$\frac{c_T(\mu)}{\Lambda^2} = -\frac{3\alpha_{\text{ew}}\, s_w^2\, \lambda_3^2}{32\pi c_w^2\, \lambda_2 \Lambda^2}\, \log\frac{\Lambda^2}{\mu^2}$$

- **LL-TL: Leading-log loop-induced plus c_{tree}-mediated loops**

LL-L + c_H − insertions with $\frac{c_H}{\Lambda^2} = \frac{\lambda_3^2}{2\lambda_2\Lambda^2}$

- **LL-TLv: v-improved LL-TL**

$$\frac{c_T(\mu)}{\Lambda^2} = -\frac{3\alpha_{\text{ew}}\, s_w^2\, (1-c_\alpha)}{8\pi c_w^2\, v^2}\, \log\frac{m_H^2}{\mu^2}$$

- **BP-TL: Broken phase matching & weak-scale loops:**

$$\frac{c_T(\mu)}{\Lambda^2} = -\frac{\alpha_{\text{ew}}\, s_w^2\, \lambda_3^2}{32\pi c_w^2\, \lambda_2 \Lambda^2}\left(-\frac{5}{2} + 3\log\frac{\Lambda^2}{\mu^2}\right) + c_H - \text{insertions}$$

- **BP-TLv: v-improved BP-TL:**

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Singlet HEFT versus full model comparison

Benchmarks

Parameters

	m_H	s_α	$\tan\beta$	$\Lambda = \sqrt{2\lambda v_s^2}$	λ_1	λ_2	λ_3	$c_H v^2/\Lambda^2$ LL-TL	$c_H v^2/\Lambda^2$ BP-TLv
S1	300	0.1	10	298.8	0.13	7.1×10^{-3}	1.2×10^{-2}	6.9×10^{-3}	1.0×10^{-2}
S2	700	0.1	10	696.6	0.16	3.9×10^{-2}	7.5×10^{-2}	9.5×10^{-3}	1.0×10^{-2}
S3	300	0.3	10	288.6	0.18	6.6×10^{-3}	3.4×10^{-2}	6.5×10^{-2}	9.2×10^{-2}
S4	500	0.3	10	668.8	0.46	3.6×10^{-2}	2.2×10^{-1}	9.2×10^{-2}	9.2×10^{-2}

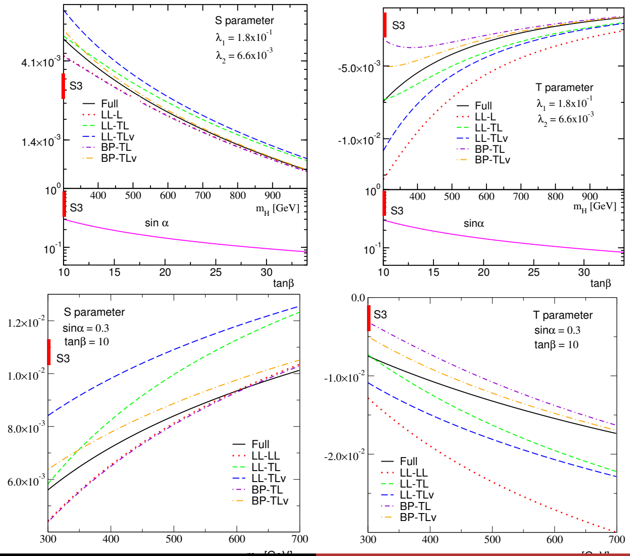
Predictions

		full model	LL-L	LL-TL	BP-TL	BP-TLv
S	S1	6.22×10^{-4}	4.79×10^{-4}	6.26×10^{-4}	4.74×10^{-4}	6.94×10^{-4}
	S2	1.13×10^{-3}	1.08×10^{-3}	1.29×10^{-3}	1.08×10^{-3}	1.14×10^{-3}
	S3	5.60×10^{-3}	4.43×10^{-3}	5.83×10^{-3}	4.38×10^{-3}	6.38×10^{-3}
	S4	1.01×10^{-2}	1.04×10^{-2}	1.23×10^{-2}	1.03×10^{-2}	1.05×10^{-2}
T	S1	-8.30×10^{-4}	-1.39×10^{-3}	-8.07×10^{-4}	-3.67×10^{-4}	-5.41×10^{-4}
	S2	-1.93×10^{-3}	-3.14×10^{-3}	-2.34×10^{-3}	-1.74×10^{-3}	-1.85×10^{-3}
	S3	-7.47×10^{-3}	-1.28×10^{-2}	-7.32×10^{-3}	-3.14×10^{-3}	-4.97×10^{-3}
	S4	-1.74×10^{-2}	-3.00×10^{-2}	-2.22×10^{-2}	-1.63×10^{-2}	-1.70×10^{-2}

Freitas, DLV, Plehn arXiv:1607.08251 [hep-ph]

Singlet HEFT versus full model comparison

♠ Decoupling behavior: *fixed couplings* (above) VS *fixed mixing* (below)   Freitas, DLV, Plehn   arXiv:1607.0825



Outline

Seeking additional scalars

WHY?

- ♠ A direct probe for scalars in the light & mid-mass ranges
- ♠ A tool for setting constraints on **mass VS coupling strength** space

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  - :) Handle on **Yukawas** :(Challenging **background**

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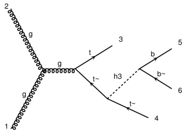
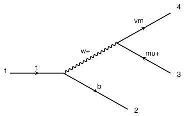
$pp \to t\bar{t}A \to t\bar{t}b\bar{b}$ with dileptonic tops





Simulation details

Setup

- Signal process: $pp \to t\bar{t}A/H \to t\bar{t}b\bar{b}$ MG5-MC@NLO + PYTHIA8
- Backgrounds: $pp \to\to t\bar{t}b\bar{b}, t\bar{t}Z$ SHERPA + OPENLOOPS
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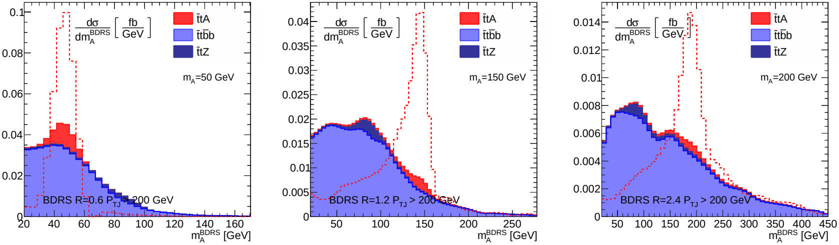
Signal VS background for different m_A hypotheses



$m_A = 50$ GeV | $m_A = 100$ GeV | $m_A = 150$ GeV

2HDM interpretation

- Simplified Model simulation: $$\mathcal{L} \supset \kappa_t \frac{i y_t A \bar{t} \gamma_5 t}{\sqrt{2}} + \kappa_b \frac{i y_b A \bar{b} \gamma_5 b}{\sqrt{2}}$$

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A 2HDM interpretation

- CP-odd scalar
- Alignment-without-decoupling
- UV-complete embedding for freely variable couplings

Type I: $\kappa_t = \cot\beta; \quad \kappa_b = -\cot\beta$

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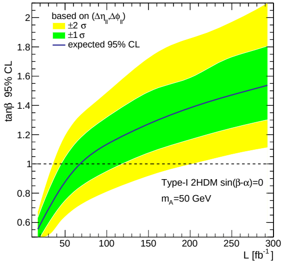
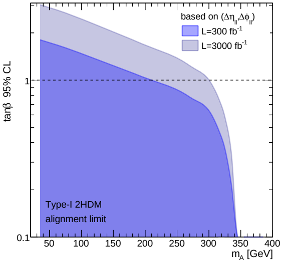
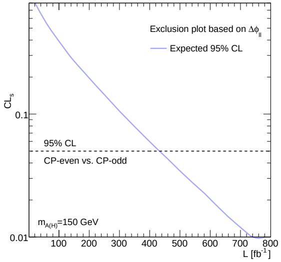
Exemplary benchmarks

BI: $m_A > 125 \quad \cos(\beta-\alpha) = 0$	
• $m_h = 125$	• $m_H = (220 - 300)$
• $m_{H\pm} = \text{max}(175, m_A)$	• $m_{12}^2 = \dfrac{m_A^2 \tan\beta}{1+\tan^2\beta}$
BII: $63 < m_A < 125 \quad \sin(\beta-\alpha) = 0$	
• $m_h = 120$	• $m_H = 125$
• $m_{H\pm} = 175$	• $m_{12}^2 = 0$
BIII: $m_A < 63 \quad \sin(\beta-\alpha) = 0$	
• $m_h = 120$	• $m_H = 125$
• $m_{H\pm} = 175$	• $m_{12}^2 = \dfrac{(m_H^2 + 2m_A^2)\tan\beta}{2(1+\tan^2\beta)}$

2HDM interpretation







$\tan\beta$ bound VS $\mathcal{L}$

$\tan\beta - m_A$ constraints

CP characterization

- $\mu_{\text{sig}} \sim \cot^2\beta$ $\Rightarrow$ 95% C.L $\tan\beta$ reach growing with $\mathcal{L}$
- 95% C.L m_A reach up to 320 GeV with $\mathcal{L} = 3000$ fb^{-1}
- CP sensitivity through $\Delta\phi_{ll}$ $\Rightarrow$ enhanced for large $p_T(A)$ thanks to $t_L\bar{t}_R + t_R\bar{t}_L$

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Fingerprinting **MultiHiggs** very much like **Setting out on a journey**

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- ♠ Collider signatures $\longleftrightarrow$ *The landmarks*
- ♠ Precision $\longleftrightarrow$ *The local's tips*
- ♠ Benchmarking $\longleftrightarrow$ *Sleeping & eating*
- ♠ Effective Field Theories $\longleftrightarrow$ *Transportation*

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Vielen Dank ;)