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STANDARD MODEL EFT AND EXTENDED SCALAR SECTORS

based on 1704.07851 w/ Sally Dawson

GOALS OF THIS WORK

▸ Are there any simple models where whose first signal might be double Higgs production? Are significant deviations from the SM possible?

▸ How well does the SMEFT describe the kinematic distributions of double Higgs production in these models?

STANDARD MODEL EFFECTIVE FIELD THEORY

▸ expansion in E^2 / Λ^2 , $v^2 < \Lambda^2$

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \ldots$$

▸ a subset of dimension-6 operator affect double Higgs production in models under consideration

$$\mathcal{L}_H^{(6)} = \frac{c_H}{2v^2} \partial_\mu \left(H^\dagger H \right) \partial^\mu \left(H^\dagger H \right) + \frac{c_T}{2v^2} \left| H^\dagger \overleftrightarrow{D}_\mu H \right|^2 - \frac{c_6 \lambda}{v^2} \left(H^\dagger H \right)^3$$
$$+ \frac{\left(H^\dagger H \right)}{v^2} \left[c_b y_b \left(\bar{q}_L b_R H \right) + c_t y_t \left(\bar{q}_L t_R \tilde{H} \right) + c_\tau y_\tau \left(\bar{l}_L \tau_R H \right) + \text{h.c.} \right]$$

in models we consider:

$$c_t = c_b = c_\tau \equiv c_f$$

EXTENDED SCALAR SECTORS

▸ *SU*(2)$_L$ singlets, triplets, quartets

▸ complete set of models (+2HDM) w/ renormalizable Z_2 breaking interaction

$$V\left(H,\phi\right) = V_{SM}\left(H\right) + V_{Z_2}\left(H,\phi\right) + V_{\cancel{Z_2}}\left(H,\phi\right)$$

$$V_{Z_2}\left(H,\phi\right) = \frac{1}{2}M^2\phi^a\phi^a + \lambda_\alpha H^\dagger H\phi^a\phi^a + \lambda_\beta\left(\phi^a\phi^a\right)^2$$

(real ϕ)

$$V_{\cancel{Z_2}} \sim m_1 H^2\phi \quad \text{or} \quad V_{\cancel{Z_2}} \sim \lambda_1 H^3\phi.$$

(additional ϕ terms in singlet model)

TREE LEVEL DIMENSION-6 OPERATORS

single Higgs production   double Higgs production ρ/T parameter

Model	c_H	$c_6\lambda_{SM}$	c_T	c_f
Real Singlet w/ explicit $\cancel{Z_2}$	$\frac{m_1^2 v^2}{M^4}$	$\frac{m_1^2 v^2}{M^4}\left(\lambda_\alpha - \frac{m_1 m_2}{M^2}\right)$	0	0
Real Singlet w/ spontaneous $\cancel{Z_2}$	$\left(\frac{\lambda_\alpha v}{4\lambda_\beta v_\phi}\right)^2$	0	0	0
2HDM	0	$\checkmark$	0	$\checkmark$
Real Triplet	$-\frac{m_1^2 v^2}{2M^4}$	$\frac{m_1^2 v^2 \lambda_\alpha}{4M^4}$	$\frac{m_1^2 v^2}{4M^4}$	$\frac{m_1^2 v^2}{4M^4}$
Complex Triplet	$-\frac{m_1^2 v^2}{2M^4}$	$\frac{m_1^2 v^2}{2M^4}\left(\lambda_{\alpha 1} - \frac{\lambda_{\alpha 2}}{2}\right)$	$-\frac{m_1^2 v^2}{2M^4}$	$\frac{m_1^2 v^2}{2M^4}$
Quartet$_1$	0	$-\frac{\lambda_1^2 v^2}{M^2}$	$\frac{\lambda_1^2 v^4}{2M^4}$	0
Quartet$_3$	0	$-\frac{\lambda_1^2 v^2}{M^2}$	$-\frac{3\lambda_1^2 v^4}{2M^4}$	0

see *e.g.* 1201.4383, 1412.1837, 1412.8480, 1502.07352

THE RHO PARAMETER

▸ ratio of neutral to charged currents at zero momentum

    ▸ experimentally close to 1

$$\rho_{\text{exp.}} = 1 + (3.6 \pm 1.9) \cdot 10^{-4}$$ Erler, Moriond 2017

    ▸ SMEFT: tree level, dimension-6

$$\rho = 1 + c_T$$

    ▸ extra $SU(2)_L$ multiplets: tree level

$$\rho = \frac{\sum_i \left[t(i)\left(t(i)+1\right)) - t_3(i)^2 \right] v_i^2}{2 \sum_i t_3(i)^2 v_i^2}$$

THE RHO PARAMETER

- consider 2 $SU(2)_L$ multiplets w/ vevs

$$v_h = v \cos \beta, \quad v_\phi = v \sin \beta / \sqrt{2 \left[t(\phi) \left(t(\phi) + 1 \right) - t_3(\phi)^2 \right]}$$

$$\tan \beta \propto \frac{v_\phi}{v_h}$$

Model	ρ	3σ upper limit on β
Singlet	1	none
2HDM	1	none
Real Triplet	$\sec^2 \beta$	0.030
Complex Triplet	$2 \left(3 - \cos 2\beta \right)^{-1}$	0.014
Quartet$_1$	$7 \left(4 + 3 \cos 2\beta \right)^{-1}$	0.033
Quartet$_3$	$\left(2 - \cos 2\beta \right)^{-1}$	0.010

CONSTRAINTS FROM SINGLE HIGGS PRODUCTION

PERTURBATIVE UNITARITY

$$S^\dagger S = \mathbf{1} \to |\mathrm{Re}\,(a_0)| \le \tfrac{1}{2} \qquad (a_0)_{i,f} = \frac{1}{16\pi s} \int_{-s}^{0} dt\, \mathcal{M}_{i\to f}(s,t)$$

▸ Unitarity Bound on SMEFT

$$E_{\mathrm{crit.}} \approx \sqrt{\frac{16\pi}{3c_H}}\, v \approx \frac{1\ \mathrm{TeV}}{\sqrt{c_H}} \qquad\qquad c_T \approx 0$$

▸ Perturbativity Bounds on Extended Scalar Sectors

▸ *e.g.*
$$m_H^2 < \frac{16\pi v^2}{\tan^2 \beta_s}$$

singlet model: opposite convention

$$\tan \beta_s = \frac{v_h}{v_\phi}$$

$$\begin{pmatrix} h \\ \mathcal{H} \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h' \\ \varphi \end{pmatrix}$$

PERTURBATIVITY BOUNDS

- require all eigenvalues to satisfy $|\mathrm{Re}\,(a_0)| \leq \frac{1}{2}$

- take $m_H = m_{H^+}$

PERTURBATIVITY BOUNDS

▸ Triplets and Quartets qualitatively similar

  ▸ perturbativity and the ρ parameter force α to be much closer to 0 than Higgs measurements require

  ▸ real triplet w/ $\alpha \approx \beta \approx 0$

$$469 \text{ GeV} > m_H,$$
$$\left(\frac{\beta}{0.03}\right)^2 (11.7 \text{ GeV})^2 > \left| m_{H^+}^2 - m_H^2 \right|$$

  ▸ both single and double Higgs production look SM-like, models are strongly interacting, or have new scalars w/ *m* < 200 GeV

DOUBLE HIGGS PRODUCTION

▸ SM: destructive interference between box and triangle diagrams

graphic by U. Haisch

▸ SMEFT: box and triangle coefficients modified

$$C_\triangle \approx \frac{3m_h^2}{s - m_h^2 + im_h\Gamma_h}\left(1 + c_6 - 2c_H - c_t\right) - \left(c_H + 3c_t\right),$$

$$C_\square \approx 1 - c_H - 2c_t,$$

▸ Extended scalar sectors: resonant enhancement possible when $m_H > 2m_h$

DOUBLE HIGGS PRODUCTION: SMEFT VS. SINGLET MODEL

▸ Unexpectedly good agreement!

CONCLUSIONS

▸ SMEFT vs. Singlet model

  ▸ excellent agreement in p_T and M_{hh} distributions for $m_H \gtrsim 2$ TeV

  ▸ good agreement for p_T, $M_{hh} \lesssim 400$ GeV w/ $m_H \gtrsim 600$ GeV

  ▸ find resonance, best hope for BSM discovery in double Higgs production

▸ Triplet & Quartet models

  ▸ SM-like signal in single & double Higgs production

  ▸ $m_{heavy} \lesssim 500$ GeV: discover through charged Higgs pair production?

▸ to do: 2HDM, (generalized) Georgi-Machacek

THE OTHER SLIDES

SM HIGGS PRODUCTION AT LHC

$m_h \approx 125$ GeV

$$V_{SM} = \boxed{\frac{1}{2} m_h^2 h^2} + \boxed{\lambda_{SM} v h^3} + \boxed{\frac{\lambda_{SM}}{4} h^4}$$

$v \approx 246$ GeV

$$\lambda_{SM} = \frac{m_h^2}{2v^2} \approx 0.13$$

$$\sigma\left(pp \to h\right)_{SM} \sim 45 \text{ pb}$$

discovered

$$\sigma\left(pp \to hh\right)_{SM} \sim 35 \text{ fb}$$

challenging

$$\sigma\left(pp \to hhh\right)_{SM} \sim 0.1 \text{ fb}$$

not going to happen

based on slide by U. Haisch

SMEFT BASES

Operator	Relation to [36]	Operators, O_i			
	References: Coefficients, $\bar{C}_i$:	[36] C_i	[10] a_i	[35] $\frac{\bar{c}_i}{v^2}$	[3] c_i
$\left\lvert D^2 H\right\rvert^2$	$\left\lvert EoM\right\rvert^2$				$\mathcal{O}_D$
$\left(H^\dagger H\right)\left(D_\mu H^\dagger D^\mu H\right)$	$\frac{1}{2}Q_{H\square} - \frac{1}{2}\left(H^\dagger H\right)\left(H^\dagger EoM + \text{ h.c.}\right)$		O_2		$\mathcal{O}_R$
$\left(\partial_\mu\left(H^\dagger H\right)\right)^2$	$-Q_{H\square}$			$2O_H$	$2\mathcal{O}_H$
$\left\lvert H^\dagger \overleftrightarrow{D}_\mu H\right\rvert^2$	$-Q_{H\square} - 4Q_{HD}$			$2O_T$	$2\mathcal{O}_T$
$\left(H^\dagger H\right)\square\left(H^\dagger H\right)$		$Q_{H\square}$	$2O_1$		
$\left\lvert H^\dagger D_\mu H\right\rvert^2$		Q_{HD}	O_T		
$\left(H^\dagger H\right)^3$		Q_H	$\checkmark$	$\frac{1}{\lambda}O_6$	$\mathcal{O}_6$

TREE LEVEL DIMENSION-6 OPERATORS

Model	c_H	$c_6 \lambda_{SM}$	c_T	c_f
Real Singlet w/ explicit $\not{\mathbb{Z}_2}$	$\tan^2 \alpha$	$\tan^2 \alpha \left(\lambda_\alpha - \frac{m_2}{v} \tan \alpha \right)$	0	0
Real Singlet w/ spontaneous $\not{\mathbb{Z}_2}$	$\tan^2 \alpha$	0	0	0
Real Triplet	$-\dfrac{8 \sin^2 \beta \, m_{H+}^4}{m_H^4}$	$\dfrac{4 \sin^2 \beta \, m_{H+}^6}{m_H^4 v^2}$	$\dfrac{4 \sin^2 \beta \, m_{H+}^4}{m_H^4}$	$\dfrac{4 \sin^2 \beta \, m_{H+}^4}{m_H^4}$
Complex Triplet	$-\dfrac{4 \sin^2 \beta \, m_A^4}{m_H^4}$	$\dfrac{8 \sin^2 \beta \, m_A^6}{m_H^4 v^2}$	$-\dfrac{4 \sin^2 \beta \, m_A^4}{m_H^4}$	$\dfrac{4 \sin^2 \beta \, m_A^4}{m_H^4}$
Quartet$_1$	0	$\dfrac{24 \tan^2 \beta \, m_A^4}{7 m_H^2 v^2}$	$\dfrac{24 \tan^2 \beta \, m_A^4}{7 m_H^4}$	0
Quartet$_3$	0	$\dfrac{8 \tan^2 \beta \, m_A^4}{3 m_H^2 v^2}$	$-\dfrac{8 \tan^2 \beta \, m_A^4}{m_H^4}$	0

HIGGS SIGNAL STRENGTH RESULTS

Signal strength	Value	Correlation matrix		μ_{SMEFT}
$\mu_{\text{ggF+tth}}^{\gamma\gamma}$	1.16 ± 0.26	1	-0.30	$1 - c_H + 0.01 c_f$
$\mu_{\text{VBF+Vh}}^{\gamma\gamma}$	1.05 ± 0.43	-0.30	1	$1 - c_H + 2.01 c_f$
$\mu_{\text{ggF+tth}}^{bb}$	1.15 ± 0.97	1	$4.5 \cdot 10^{-3}$	$1 - c_H + 2.55 c_f$
$\mu_{\text{VBF+Vh}}^{bb}$	0.65 ± 0.30	$4.5 \cdot 10^{-3}$	1	$1 - c_H + 0.55 c_f$
$\mu_{\text{ggF+tth}}^{\tau\tau}$	1.06 ± 0.58	1	-0.43	$1 - c_H + 2.55 c_f$
$\mu_{\text{VBF+Vh}}^{\tau\tau}$	1.12 ± 0.36	-0.43	1	$1 - c_H + 0.55 c_f$
$\mu_{\text{ggF+tth}}^{WW}$	0.98 ± 0.21	1	-0.14	$1 - c_H + 0.55 c_f$
$\mu_{\text{VBF+Vh}}^{WW}$	1.38 ± 0.39	-0.14	1	$1 - c_H + 1.45 c_f$
$\mu_{\text{ggF+tth}}^{ZZ}$	1.42 ± 0.35	1	-0.49	$1 - c_H + 0.55 c_f$
$\mu_{\text{VBF+Vh}}^{ZZ}$	0.47 ± 1.37	-0.49	1	$1 - c_H + 1.45 c_f$

PERTURBATIVITY BOUNDS

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DOUBLE HIGGS PRODUCTION: SMEFT VS. SINGLET MODEL

DOUBLE HIGGS PRODUCTION @ 100TEV: EFT VS. SINGLET MODEL

DOUBLE HIGGS PRODUCTION: EFT VS. SINGLET MODEL W/ EXPLICIT Z2 BREAKING

QUARTET MODEL