Six dimensional operators in 2HDM and their consequences

Siddhartha Karmakar

IIT Indore

CANDARK 2017, ICTS Bangalore

June 5, 2017

A few words about SMEFT

- A bottom-up approach: to look for deviations from SM in a model-independent way.
- First attempt for the complete basis of 6-dim operators: Leung et al.(1984), Buchmuller&Wyler(1985).
- Redundant operators removed with help of EOMs or equivalently field redefinitions, first complete basis assuming a single flavor. (Warsaw basis, Gradkowski et al., 1008.4884).
- Constraints from EWPTs: bosonic operators constrained by either oblique parameters or anomalous TGVs. Fermionic operators constrained by measurements of W,Z mass, decay widths etc.(Hagiwara et al., 1987; Pomarol et al., 1308.2803)
- LHC is improving the bounds on certain directions. (Falkowski et al.,1303.1812; Ellis et al.,1410.7703)

Why EFT for 2HDM?

- After LHC Run I & II, $\Delta g_{hVV} < 10\%$
  $\Longleftrightarrow$ **Alignment limit** ($c_{\beta-\alpha} \to 0$) for 2HDM.
- Decoupling ($m_A^2 \gg \lambda v^2$) is just a subset of alignment limit.
  $\Longleftrightarrow$ Could be "aligned without decoupling".
  (Carena 1310.2248, Haber 1507.00933)
- If new scalars are not decoupled in the mass spectrum, higher-dim operators involving those are supposed to play a significant role.
- Effects on some processes can be enhanced compared to SMEFT, more room to manoeuvre.

Why a Strongly-interacting light Higgs (SILH) basis?

- A strongly interacting sector to rescue from the hierarchy problem, *i.e.*, Higgs is a Goldstone boson
  $\Longrightarrow$ Little Higgs, Composite Higgs, extra-dimensions ...

  One Lagrangian to rule them all: **SILH basis** of SMEFT (Giudice et al., hep-ph/0703164)

- SILH Basis $\supset$ SILH scenarios.

- A few advntages over Warsaw basis for phenomenological analyses. (Pomarol et al., 1302.5661, 1308.1879)

- BSM scalar sectors arises in many SILH-type scenarios. (Cheng et al.,0308199; Gripaios et al.,0902.1483)

- We introduce **complete** set of 6-dim operators for the SILH basis for 2HDM, including the Z_2 violating ones as well.
  (Earlier works: Diaz–Cruz et al.,0106001, pre-Warsaw, redundant operators; Procura et al., 1608.00975, Warsaw-like basis)

Equation of motions

Lessons from SMEFT (Gradkowski et al.,1008.4884) $\Longrightarrow$
Using EOMs properly is necessary to avoid redundant operators.

$$
\begin{aligned}
\Box\, \varphi_1^i &= -m_{11}^2\varphi_1^i - m_{12}^2\varphi_2^i - 2\lambda_1|\varphi_1|^2\varphi_1^i - \lambda_3|\varphi_2|^2\varphi_1^i \\
&\quad -\lambda_4(\varphi_2^\dagger\varphi_1)\varphi_2^i - \lambda_5(\varphi_1^\dagger\varphi_2)\varphi_2^i - \lambda_7|\varphi_2|^2\varphi_2^i \\
&\quad -((\lambda_6\varphi_1^\dagger\varphi_2 + h.c.)\varphi_1^i + \lambda_6|\varphi_1|^2\varphi_2^i) \\
&\quad -Y_1^{d\dagger}\bar{d}q^i - Y_1^{e\dagger}\bar{e}l^i + Y_1^u\epsilon_{ij}\bar{q}^j u, \\
\Box\, \varphi_2^i &= -m_{22}^2\varphi_2^i - m_{12}^{2*}\varphi_1^i - 2\lambda_2|\varphi_2|^2\varphi_2^i - \lambda_3|\varphi_1|^2\varphi_2^i \\
&\quad -\lambda_4(\varphi_1^\dagger\varphi_2)\varphi_1^i - \lambda_5(\varphi_2^\dagger\varphi_1)\varphi_1^i - \lambda_6|\varphi_1|^2\varphi_1^i \\
&\quad -((\lambda_7\varphi_1^\dagger\varphi_2 + h.c.)\varphi_2^i + \lambda_7|\varphi_2|^2\varphi_1^i) \\
&\quad -Y_2^{d\dagger}\bar{d}q^i - Y_2^{e\dagger}\bar{e}l^i + Y_2^u\epsilon_{ij}\bar{q}^j u, \\
\partial^\rho B_{\rho\mu} &= g'\Big(\sum_{I=1,2} Y_{\varphi I}\,\varphi_I^\dagger\, i\overleftrightarrow{D}_\mu\,\varphi_I + \sum_{\psi=q,l,u,d,e} Y_\psi\bar{\psi}\,\gamma_\mu\psi\Big), \\
\partial^\rho W_{\rho\mu}^i &= \frac{g}{2}\Big(\sum_{I=1,2}\varphi_I^\dagger\, i\overleftrightarrow{D}_\mu\,\varphi_I + \bar{l}\,\gamma_\mu\,\tau^i\, l + \bar{q}\,\gamma_\mu\,\tau^i\, q\Big).
\end{aligned}
$$

The basis

$$\mathcal{L}^{(6)} = \frac{1}{\Lambda^2}\Big(\varphi^4 D^2 + \varphi^2 D^2 X + \varphi^2 X^2 + \varphi^6 + \varphi^3\psi^2 + \varphi^2\psi^2 D + \varphi\psi^2 X + X^3 + D^2 X^2 + \psi^4\Big).$$

In "SILH scenario"s, mechanism of protecting Higgs mass inbuilt $\Longrightarrow$ Allows Z_2 - odd terms in the Lagrangian.

$\varphi^4 D^2$	$\varphi^4 D^2$
$O_{H1} = (\partial_\mu\|\varphi_1\|^2)^2$	$O_{T1} = (\varphi_1^\dagger \overleftrightarrow{D}_\mu \varphi_1)^2$
$O_{H2} = (\partial_\mu\|\varphi_2\|^2)^2$	$O_{T2} = (\varphi_2^\dagger \overleftrightarrow{D}_\mu \varphi_2)^2$
$O_{H1H2} = \partial_\mu\|\varphi_1\|^2\partial^\mu\|\varphi_2\|^2$	$O_{T3} = (\varphi_1^\dagger \overleftrightarrow{D}_\mu \varphi_2)^2 + h.c.$
$O_{H12} = (\partial_\mu(\varphi_1^\dagger\varphi_2 + h.c.))^2$	$O_{(1)21(2)} = (\varphi_1^\dagger D_\mu\varphi_2)(D^\mu\varphi_1^\dagger\varphi_2) + h.c.$
$O_{H1H12} = \partial_\mu\|\varphi_1\|^2\partial^\mu(\varphi_1^\dagger\varphi_2 + h.c.)$	$O_{(1)12(2)} = (\varphi_1^\dagger D_\mu\varphi_1)(D^\mu\varphi_2^\dagger\varphi_2) + h.c.$
$O_{H2H12} = \partial_\mu\|\varphi_2\|^2\partial^\mu(\varphi_1^\dagger\varphi_2 + h.c.)$	$O_{(1)22(1)} = (\varphi_1^\dagger D_\mu\varphi_2)(D^\mu\varphi_2^\dagger\varphi_1)$
$O_{T13} = (\varphi_1^\dagger \overleftrightarrow{D}_\mu \varphi_1)(\varphi_1^\dagger \overleftrightarrow{D}_\mu \varphi_2) + h.c.$	$O_{(2)11(2)} = (\varphi_2^\dagger D_\mu\varphi_1)(D^\mu\varphi_1^\dagger\varphi_2)$
$O_{T23} = (\varphi_2^\dagger \overleftrightarrow{D}_\mu \varphi_2)(\varphi_1^\dagger \overleftrightarrow{D}_\mu \varphi_2) + h.c.$	

$\varphi^2 D^2 X$, $\varphi^2 X^2$, $D^2 X^2, X^3$	φ^6	$\psi^2\varphi^3, \psi^2\varphi X$, $\varphi^2\psi^2 D$
$O_{Wij} = \frac{ig}{2}(\varphi_i^\dagger \vec{\sigma} \overleftrightarrow{D}_\mu \varphi_j) D_\nu \vec{W}^{\mu\nu}$	$\lvert\varphi_1\rvert^6$	$(\bar{l}e\varphi_i)\varphi_j^\dagger\varphi_k$
$O_{Bij} = \frac{ig}{2}'(\varphi_i^\dagger \overleftrightarrow{D}_\mu \varphi_j) D_\nu B^{\mu\nu}$	$\lvert\varphi_2\rvert^6$	$(\bar{q}d\varphi_i)\varphi_j^\dagger\varphi_k$
$O_{\varphi Wij} = ig(D_\mu \varphi_i^\dagger)\vec{\sigma}(D_\nu \varphi_j)\vec{W}^{\mu\nu}$	$\lvert\varphi_1\rvert^4\lvert\varphi_2\rvert^2$	$(\bar{q}u\tilde{\varphi}_i)\varphi_j^\dagger\varphi_k$
$O_{\varphi Bij} = ig'(D_\mu \varphi_i^\dagger)(D_\nu \varphi_j) B^{\mu\nu}$	$\lvert\varphi_1\rvert^2\lvert\varphi_2\rvert^4$	$i(\tilde{\varphi}_i{}^\dagger i\overleftrightarrow{D}_\mu \varphi_j)(\bar{u}\gamma^\mu d)$
$g'^2\, \varphi_i^\dagger \varphi_j\, B_{\mu\nu} B^{\mu\nu}$	$\lvert\varphi_1^\dagger\varphi_2\rvert^2\lvert\varphi_1\rvert^2$	$i(\tilde{\varphi}_i{}^\dagger i\overleftrightarrow{D}_\mu \varphi_j)(\bar{e}\gamma^\mu e)$
$g_s^2\, \varphi_i^\dagger \varphi_j\, G^a_{\mu\nu} G^{a\mu\nu}$	$\lvert\varphi_1^\dagger\varphi_2\rvert^2\lvert\varphi_2\rvert^2$	$i(\tilde{\varphi}_i{}^\dagger i\overleftrightarrow{D}_\mu \varphi_j)(\bar{u}\gamma^\mu u)$
$(D_\mu W^{i\mu\nu})^2$	$((\varphi_1^\dagger\varphi_2)^2 + h.c.)\lvert\varphi_1\rvert^2$	$i(\tilde{\varphi}_i{}^\dagger i\overleftrightarrow{D}_\mu \varphi_j)(\bar{d}\gamma^\mu d)$
$(D_\mu B^{\mu\nu})^2$	$((\varphi_1^\dagger\varphi_2)^2 + h.c.)\lvert\varphi_2\rvert^2$	$i(\tilde{\varphi}_i{}^\dagger i\overleftrightarrow{D}_\mu \varphi_j)(\bar{q}\gamma^\mu q)$
$(D_\mu G^{a\mu\nu})^2$	$\lvert\varphi_1^\dagger\varphi_2\rvert^2(\varphi_1^\dagger\varphi_2 + h.c.)$	$(\tilde{\varphi}_i{}^\dagger i\overleftrightarrow{D}^I_\mu \varphi_j)(\bar{q}\tau^I\gamma^\mu q)$
$\epsilon_{abc} W^a_{\mu\nu} W^{b\mu}_\rho W^{c\rho\nu}$	$\lvert\varphi_1\rvert^4(\varphi_1^\dagger\varphi_2 + h.c.)$	$\bar{q}\sigma^{\mu\nu}X_{\mu\nu}u\tilde{\varphi}_i$
$f_{abc} G^a_{\mu\nu} G^{b\mu}_\rho G^{c\rho\nu}$	$\lvert\varphi_2\rvert^4(\varphi_1^\dagger\varphi_2 + h.c.)$	$\bar{q}\sigma^{\mu\nu}X_{\mu\nu}d\varphi_i$
	$\lvert\varphi_1\rvert^2\lvert\varphi_2\rvert^2(\varphi_1^\dagger\varphi_2 + h.c.)$	$\bar{l}\sigma^{\mu\nu}X_{\mu\nu}e\varphi_i$
	$(\varphi_1^\dagger\varphi_2 + h.c.)^3$	

Kinetic diagonalisation

$$\varphi_i = \begin{pmatrix} \phi_i^+ \\ \frac{1}{\sqrt{2}}(v_i + \rho_i) + i\,\eta_i \end{pmatrix} \qquad \tan\beta = v_2/v_1$$

Kinetic terms get modified when two scalars in operator of type $\varphi^4 D^2$ get vevs.

$$\begin{aligned} \mathcal{L}_{kin} \;=\; & \frac{1}{2}\begin{bmatrix} \partial_\mu \rho_1 \\ \partial_\mu \rho_2 \end{bmatrix}^T \begin{bmatrix} 1 + \frac{\Delta_{11\rho}}{2f^2} & \frac{\Delta_{12\rho}}{4f^2} \\ \frac{\Delta_{12\rho}}{4f^2} & 1 + \frac{\Delta_{22\rho}}{2f^2} \end{bmatrix} \begin{bmatrix} \partial^\mu \rho_1 \\ \partial^\mu \rho_2 \end{bmatrix} \\ & + \frac{1}{2}\begin{bmatrix} \partial_\mu \eta_1 \\ \partial_\mu \eta_2 \end{bmatrix}^T \begin{bmatrix} 1 + \frac{\Delta_{11\eta}}{2f^2} & \frac{\Delta_{12\eta}}{4f^2} \\ \frac{\Delta_{12\eta}}{4f^2} & 1 + \frac{\Delta_{22\eta}}{2f^2} \end{bmatrix} \begin{bmatrix} \partial^\mu \eta_1 \\ \partial^\mu \eta_2 \end{bmatrix} \\ & + \begin{bmatrix} \partial_\mu \phi_1^\pm \\ \partial_\mu \phi_2^\pm \end{bmatrix}^T \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \partial^\mu \phi_1^\pm \\ \partial^\mu \phi_2^\pm \end{bmatrix} \end{aligned}$$

Notice: No kinetic diagonalisation for charged scalars.

Redefine by : $\qquad \rho_1 \;\to\; \rho_1\left(1 - \dfrac{\Delta_{11\rho}}{4f^2}\right) - \rho_2\dfrac{\Delta_{12\rho}}{8f^2} \qquad$ etc.

Mass diagonalisation

$\Delta m^2_{\rho,\eta,\phi} = \Big(\text{Contributions from } \varphi^4 D^2\Big) + \Big(\text{Contributions from } \varphi^6\Big)$
After minimization of effective potential: $V_{eff} = V(\varphi_1, \varphi_2) + \{\varphi^6\}$,

- $\Delta m^2_\eta\big|_{\varphi^6}, \;\; \Delta m^2_\phi\big|_{\varphi^6} \propto (\,\mathrm{WC\,s}\,)\dfrac{v^2}{f^2}\begin{bmatrix}\tan\beta & -1 \\ -1 & \cot\beta\end{bmatrix}.$

- $\Delta m^2_\phi\big|_{\varphi^4 D^2} = 0$. $\Delta m^2_\eta\big|_{\varphi^4 D^2} \neq 0$, has null determinant.

$\implies$ Goldstones massless at $\mathcal{O}(1/f^2)$ (✓)

	$\mathcal{L}^{(4)}$	$\mathcal{L}^{(4)}+\varphi^6$	$\mathcal{L}^{(4)} + \varphi^4 D^2$	$\mathcal{L}^{(4)} + \varphi^4 D^2 + \varphi^6$
pseudoscalar	β	β	$\neq \beta$	β_η
charged scalar	β	β	β	β
neutral scalar	α	$\neq \alpha$	$\neq \alpha$	α'

$g_{hVV} = g^{SM}_{hVV} \sin(\beta_V - \alpha') \quad (\beta_V = \beta \text{ for } W,\ \beta_\eta \text{ for } Z).$

Constraints from precision observables and implication on $\Gamma(h \to WW, ZZ)$

Precision observables

Let's take into account the SILH suppressions.

$$\mathcal{L} \supset \frac{1}{(g_\rho f)^2}(c_{Wij} O_{Wij} + c_{Bij} O_{Bij}) + \frac{1}{(4\pi f)^2}(c_{\varphi Wij} O_{\varphi wij} + c_{\varphi Bij} O_{\varphi Bij}) + \frac{1}{f^2}\{\varphi^4 D^2\}$$

- TGVs

$$\delta g_Z^1 = \frac{1}{\cos^2\theta_w}\Big(\tilde{c}_{\varphi W} + \tilde{c}_W\Big)$$
$$\delta\kappa_\gamma = (\tilde{c}_{\varphi W} + \tilde{c}_{\varphi B})$$

$$\text{LEP II}: \quad -3.5\times 10^{-2} \lesssim \delta g_Z^1 \lesssim 6\times 10^{-3},$$
$$-7.2\times 10^{-2} \lesssim \delta\kappa_\gamma \lesssim 1.7\times 10^{-2}.$$

- $S = \frac{16\sin^2\theta_w}{\alpha_{em}}(\tilde{c}_W + \tilde{c}_B), \qquad S \in [-0.03, 0.15].$

$$(\tilde{c}_W + \tilde{c}_B) \sim 10^{-3}.$$

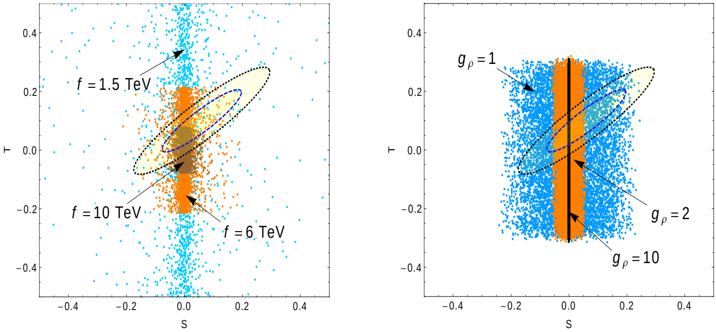
Notation: For $X = W, B, \varphi W, \varphi B$

$$\tilde{c}_X = (c_{X11}\, c_\beta^2 + c_{X22}\, s_\beta^2 + 2\, c_{X12}\, c_\beta\, s_\beta) m_W^2 (\times \text{SILH suppression}).$$

T-parameter

$\varphi^4 D^2$ $(\Pi_{VV}(0) = 0)$	$\varphi^4 D^2(\Pi_{ZZ}(0) \neq 0)$
$O_{H1} = (\partial_\mu \lvert\varphi_1\rvert^2)^2$	$O_{T1} = (\varphi_1^\dagger \overleftrightarrow{D}_\mu \varphi_1)^2$
$O_{H2} = (\partial_\mu \lvert\varphi_2\rvert^2)^2$	$O_{T2} = (\varphi_2^\dagger \overleftrightarrow{D}_\mu \varphi_2)^2$
$O_{H1H2} = \partial_\mu \lvert\varphi_1\rvert^2 \partial^\mu \lvert\varphi_2\rvert^2$	$O_{T3} = (\varphi_1^\dagger \overleftrightarrow{D}_\mu \varphi_2)^2 + h.c.$
$O_{H12} = (\partial_\mu(\varphi_1^\dagger \varphi_2 + h.c.))^2$	$O_{(1)21(2)} = (\varphi_1^\dagger D_\mu \varphi_2)(D^\mu \varphi_1^\dagger \varphi_2) + h.c.$
$O_{H1H12} = \partial_\mu \lvert\varphi_1\rvert^2 \partial^\mu (\varphi_1^\dagger \varphi_2 + h.c.)$	$O_{(1)12(2)} = (\varphi_1^\dagger D_\mu \varphi_1)(D^\mu \varphi_2^\dagger \varphi_2) + h.c.$
$O_{H2H12} = \partial_\mu \lvert\varphi_2\rvert^2 \partial^\mu (\varphi_1^\dagger \varphi_2 + h.c.)$	$O_{(1)22(1)} = (\varphi_1^\dagger D_\mu \varphi_2)(D^\mu \varphi_2^\dagger \varphi_1)$
	$O_{(2)11(2)} = (\varphi_2^\dagger D_\mu \varphi_1)(D^\mu \varphi_1^\dagger \varphi_2)$
	$O_{T13} = (\varphi_1^\dagger \overleftrightarrow{D}_\mu \varphi_1)(\varphi_1^\dagger \overleftrightarrow{D}_\mu \varphi_2) + h.c.$
	$O_{T23} = (\varphi_2^\dagger \overleftrightarrow{D}_\mu \varphi_2)(\varphi_1^\dagger \overleftrightarrow{D}_\mu \varphi_2) + h.c.$

$$T = \frac{1}{\alpha_{em}} \frac{v^2}{f^2} (c_{T1} c_\beta^4 + c_{T2} s_\beta^4 + (\ldots) s_\beta^2 c_\beta^2 + (\ldots) s_\beta c_\beta^3 + (\ldots) s_\beta^3 c_\beta), \qquad T \in [0.03, 0.17].$$



(a) (b)

All WCs $\in [-1, 1]$, $\tan\beta = 5$.

In (a) $g_\rho \in [1, 2\pi]$.

In (b) $f = 5$ TeV.

$T \propto 1/f^2$ and $S \propto 1/m_\rho^2$.

Decays of Higgs into WW, ZZ

O_{Wij}, O_{Bij}, $O_{\varphi Wij}$ and $O_{\varphi Bij}$ contribute to $\Gamma(h \to WW, ZZ)$ and they were constrained from TGV and S.

$$\mathcal{L} \supset \left[C_{V\partial V} V_\mu \partial_\nu V^{\mu\nu} + C_{VV} V_{\mu\nu} V^{\mu\nu} \right] \frac{h}{v}$$

$$\text{where, } C_{W\partial W} = \frac{m_W^2}{m_\rho^2} (-c_\beta s_\alpha c_{W11} + s_\beta c_\alpha c_{W22} + c_{\beta-\alpha} c_{W12}) + \ldots \text{ etc}$$

Notice: The same operators contributed to the S parameter in a different manner!

$$S = \frac{16\pi v^2}{m_\rho^2} (c_\beta^2 c_{W11} + s_\beta^2 c_{W22} + 2 s_\beta c_\beta c_{W12} + \ldots)$$

$$\text{In } WWhh \text{ coupling, } c_{WWhh} = (s_\alpha^2 c_{W11} + c_\alpha^2 c_{W22} + c_{W12} + \ldots)$$

Happens in 2HDM because mass eigenstates are not the ones which get vevs.

Could arrange $\tan\beta$ and $c_{\beta-\alpha}$ in a way that gives enhancement than SMEFT.

$\tilde{c}_W \approx \tilde{c}_{\varphi B} \approx -10^{-3}$, $\tilde{c}_B \approx -2 \times 10^{-3}$, $\tilde{c}_{\varphi W} \approx -10^{-2}$.

	$\tan\beta$	$c_{\beta-\alpha}$	$X_{WW} = X_{ZZ}$	Y_{WW}	Y_{ZZ}
BP1	2	0.1	-1%	-2.4%	-2.1%
BP2	1	0.1	-1%	-4.1%	-3.6%
BP3	1	0	0	-3.9%	-3.4%

$X_{VV} = (\Gamma_{VV}^{2HDM} - \Gamma_{VV}^{SM}) / \Gamma_{VV}^{SM}$ and $Y_{VV} = \Gamma_{VV}^{6-dim} / \Gamma_{VV}^{SM}$

Close to alignment limit, the effects of 6-dim operators can be substantial.

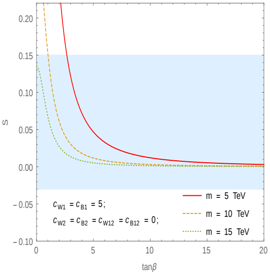
BP3 mimics SM-like situation ($s_\beta = c_\beta = c_\alpha$).
$\rightarrow$ Contribution in 2HDMEFT can be even larger than in SMEFT!

Summary and Conclusion

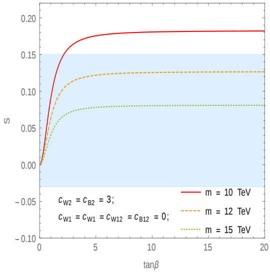
- 2HDMEFT can be important in scenarios of non-decoupling of heavier scalars.
- We write down the complete SILH basis for 2HDM. The basis is applicable for 2HDMs in non SILH scenarios as well.
- Precision observables constrain most of the (bosonic) 6-dim operators, as in SMEFT.
- Higher dimensional operators play important role close to the alignment limit.
- While imposing precision constraints on $h \to WW, ZZ$ decay width an important effect was noticed which is absent in SMEFT. Same operator can contribute differently in processes involving different number of Higgs fields. Can lead to enhanced effect compared to SMEFT.
- Can confuse the tree-level realisation of the alignment limit.

Thank You

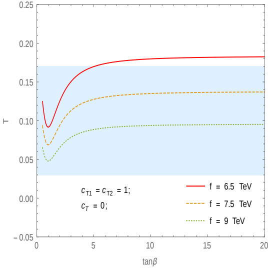
Back up


S
tanβ
$c_{W1} = c_{B1} = 5$;
$c_{W2} = c_{B2} = c_{W12} = c_{B12} = 0$;
m = 5 TeV
m = 10 TeV
m = 15 TeV

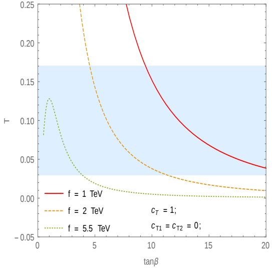
(c)


S
tanβ
$c_{W2} = c_{B2} = 3$;
$c_{W1} = c_{W1} = c_{W12} = c_{B12} = 0$;
m = 10 TeV
m = 12 TeV
m = 15 TeV

(d)


T
tanβ
$c_{T1} = c_{T2} = 1$;
$c_T = 0$;
f = 6.5 TeV
f = 7.5 TeV
f = 9 TeV

(e)


T
tanβ
f = 1 TeV
f = 2 TeV
f = 5.5 TeV
$c_T = 1$;
$c_{T1} = c_{T2} = 0$;

(f)

The suppression of WCs in SILH scenarios

$$\mathcal{L}_{EFT} = \frac{m_\rho^4}{g_\rho^2}\,\mathcal{L}\left(\frac{D_\mu}{m_\rho}, \frac{g_\rho \phi}{m_\rho}, \frac{g_\rho f_{L,R}}{m_\rho^{3/2}}, \frac{g_{SM} X}{m_\rho^2}\right)$$

- Two mass scales in SILH scenarios: $m_\rho \sim g_\rho f$,

$$g_{SM} \ll g_\rho \lesssim 4\pi.$$

Suppressions in a SILH scenario

- $(1/f^2)$ for $\varphi^4 D^2$, φ^6, $\varphi^2\psi^2 D$, $\varphi^3\psi^2$ and ψ^4. Least suppressed in a SILH scenario.
- $(1/m_\rho^2)$ $[1/(4\pi f)^2]$ for $\varphi^2 D^2 X$, depending upon whether can be generated at tree [one-loop] level.
- (g_{SM}^2/g_ρ^2) on top of $1/(4\pi f)^2$ for $\varphi^2 X^2$.
- $1/m_\rho^2$ for X^3, D^2X^2.

The CCWZ

(Giudice et al., hep-ph/0703164)

$$\begin{aligned}
U &= \exp(iT^a\pi^a) && \text{(pNGB matrix)}\\
U^\dagger(\partial_\mu + iA_\mu)U &= i\mathcal{D}^A_\mu T^A + i\epsilon^a_\mu T^a && (T^{A,a} \to \text{Unbroken, broken generators})\\
\epsilon_\mu = \epsilon^a_\mu T^a &= A_\mu - \frac{i}{2}\Pi\overleftrightarrow{D}_\mu\Pi + \ldots\\
\mathcal{D}_\mu = \mathcal{D}^A_\mu T^A &= D_\mu\Pi - \frac{1}{6}\left[\Pi, \Pi\overleftrightarrow{D}_\mu\Pi\right] + \ldots\\
F_{\mu\nu}(\epsilon) &= \partial_\mu\epsilon_\nu - \partial_\nu\epsilon_\mu - i[\epsilon_\mu, \epsilon_\nu].
\end{aligned}$$

Objects invariant under unbroken global group :

$$\begin{aligned}
Tr[F_{\mu\nu}(\epsilon)F^{\mu\nu}(\epsilon)] &\to O_{Wij}, O_{Bij}\\
Tr[\mathcal{D}_\mu\mathcal{D}_\nu F^{\mu\nu}(\epsilon)] &\to O_{\varphi Wij}, O_{\varphi Bij}\\
Tr[\mathcal{D}_\mu\mathcal{D}^\mu], Tr[\epsilon_\mu\epsilon^\mu] &\to \partial_\mu(H^\dagger H)\partial^\mu(H^\dagger H) + H^\dagger H\partial_\mu H^\dagger\partial^\mu H\\
&\quad +(H^\dagger\overleftrightarrow{D}_\mu H)^2\\
H^i &\to H^i + (H^\dagger H)H^i \text{ type of transformation}\\
&\quad \text{puts the second term in last eqn. to zero}
\end{aligned}$$

Transformations used

$$
\begin{aligned}
O_{Bij} &= \mathbf{T} + O_{\varphi Bij} + \frac{1}{4}(O_{WBij} + O_{BBij}) \\
O_{Wij} &= \mathbf{T} + O_{\varphi Wij} + \frac{1}{4}(O_{WBij} + O_{WWij}) \\
(\varphi_m^\dagger \tau^I \overleftrightarrow{D}_\mu \varphi_n) D_\nu W^{I\mu\nu} &= \sum_{i=1,2} \frac{g}{2}(\varphi_m^\dagger \tau^I \overleftrightarrow{D}_\mu \varphi_n)(\varphi_i^\dagger \tau^I \overleftrightarrow{D}^\mu \varphi_i) \\
&\quad + \frac{g}{2}(\varphi_m^\dagger \tau^I \overleftrightarrow{D}_\mu \varphi_n)(\bar{l} \tau^I \gamma^\mu l) \\
&\quad + \frac{g}{2}(\varphi_m^\dagger \tau^I \overleftrightarrow{D}_\mu \varphi_n)(\bar{q} \tau^I \gamma^\mu q) \\
(\varphi_m^\dagger \overleftrightarrow{D}_\mu \varphi_n) D_\nu B^{\mu\nu} &= \sum_{i=1,2} g' Y_{\varphi_i} (\varphi_m^\dagger \overleftrightarrow{D}_\mu \varphi_n)(\varphi_i^\dagger \overleftrightarrow{D}^\mu \varphi_i) \\
&\quad + \sum_{\psi=q,l,u,d,e} g' Y_\psi (\varphi_m^\dagger \overleftrightarrow{D}_\mu \varphi_n)(\bar{\psi} \gamma^\mu \psi).
\end{aligned}
$$

$\tilde{c}_W \approx \tilde{c}_B \approx \tilde{c}_{\varphi W} \approx \tilde{c}_{\varphi B} \approx -10^{-3}$.

	$\tan\beta$	$c_{\beta-\alpha}$	$X_{WW} = X_{ZZ}$	Y_{WW}	Y_{ZZ}
BP4	2	0.05	-0.0025%	-0.36%	-0.39%
BP5	1	0.05	-0.0025%	-0.61%	-0.66%
BP6	1	0	0	-0.59%	-0.64%

- $U = 0$, $W \propto c_{2W}$, $Y \propto c_{2B}$ and $Z \propto c_{2G}$.

$$\begin{aligned}\mathcal{L}_{TGV} \quad = \quad & ig\cos\theta_w \Big[\delta g_Z^1 (W_\mu^- W^{+\mu\nu} - W_\mu^+ W^{\mu\nu}) Z^\mu \\ & + \delta\kappa_Z Z_{\mu\nu} W^{+\mu} W^{-\nu} + \frac{\lambda_Z}{m_W^2} Z_{\mu\nu} W_\rho^{+\mu} W^{-\nu\rho}\Big] \\ & + ig\cos\theta_w \Big[\delta\kappa_\gamma F_{\mu\nu} W^{+\mu} W^{-\nu} + \frac{\lambda_\gamma}{m_W^2} Z_{\mu\nu} W_\rho^{+\mu} W^{-\nu\rho}\Big]\end{aligned}$$

- $\lambda_Z = \lambda_\gamma = c_{3W}$ where, $O_{3W} = \epsilon^{abc} W_{\mu\nu}^a W_\rho^{b\mu} W^{c\nu\rho}$
  $\delta\kappa_Z = \delta g_Z^1 - \tan^2\theta_w \delta\kappa_\gamma$

Why SILH

- Represents the Universal theories better, *i.e.,* theories where most of the effects can be parametrized in terms of bosonic operators only. SILH does it with 14 operators. More required for Warsaw. Leads to strong correlation between WCs in Warsaw basis.
- In Warsaw basis O_{WW} and O_{WB} are mixing of tree and loop level operators. Creates complication in RG analysis of the WCs.
  (Pomarol et al., 1302.5661, 1308.1879)