

A Non-linear Representation of General Scalar Extensions of the SM for HEFT Matching

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Outline

- Introduction and motivation: EFTs, SMEFT, HEFT, Matching
- The non-linear representation of general scalar extensions for HEFT matching
- Matching HEFT to the Real Higgs Triplet Extension
- Summary and discussion

Why EFT

• Higgs and nothing in direct search of new particles.

_	Model	S	Signature	fL di	[fb ⁻¹]	Mass limit				Reference
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$	0 e, µ mono-jet	2-6 jets 1-3 jets	$E_T^{\text{miss}} = 1$ $E_T^{\text{miss}} = 36$	39 q 5.1 q	1.] 0.1	1.0 9	1.85	$m(\tilde{\chi}^0_1) < 400 \text{ GeV} \ m(\tilde{\chi}^0) - m(\tilde{\chi}^0_1) = 5 \text{ GeV}$	2010.14293 2102.10874
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$	0 <i>e</i> , <i>µ</i>	2-6 jets	E_T^{miss} 1	39 <mark>8</mark> ğ	Forbio	iden	2.3 1.15-1.95	$m(\tilde{\chi}_{1}^{0})=0 \text{ GeV}$ $m(\tilde{\chi}_{1}^{0})=1000 \text{ GeV}$	2010.14293 2010.14293
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}W\tilde{\chi}_1^0$	1 e, µ	2-6 jets	1	39 <u>š</u>			2.2	$m(\tilde{\chi}_{1}^{0}) < 600 GeV$	2101.01629
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell)\tilde{\chi}_1^0$	ee, µµ	2 jets	E_T^{miss} 36	5.1 <u>ğ</u>		1.2		$m(\tilde{g})-m(\tilde{\chi}_1^0)=50 \text{ GeV}$	1805.11381
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$	0 e,μ SS e,μ	7-11 jets 6 jets	E_T^{miss} 1	39 <i>k</i> 39 <i>k</i>		1.15	1.97	$m(\tilde{\chi}_{1}^{0}) < 600 \text{ GeV}$ $m(\tilde{\chi}_{1}^{0})=200 \text{ GeV}$	2008.06032 1909.08457
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t \tilde{\chi}_1^0$	0-1 <i>e</i> , μ SS <i>e</i> , μ	3 b 6 jets	E_T^{miss} 79	9.8 <u>g</u> 39 <u>g</u>		1.25	2.25	m(\tilde{x}_{1}^{0})<200 GeV m(\tilde{g})-m(\tilde{x}_{1}^{0})=300 GeV	ATLAS-CONF-2018-041 1909.08457
	$\tilde{b}_1 \tilde{b}_1$	0 <i>e</i> , <i>µ</i>	2 b	E_T^{miss} 1	39 <u>b</u>	0.68	1.255		m($\tilde{\chi}_{1}^{0}$)<400 GeV 10 GeV<∆m($\tilde{\delta}_{1}$, $\tilde{\chi}_{1}^{0}$)<20 GeV	2101.12527 2101.12527
4	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_2^0 \rightarrow b h \tilde{\lambda}_2$	$\tilde{k}_1^0 \qquad 0 e, \mu \\ 2\tau$	6 b 2 b	$E_T^{\text{miss}} = 1$ $E_T^{\text{miss}} = 1$	39 <i>b</i> 39 <i>b</i>	rbidden 0.13-0.85	0.23-1.35	4	$\Delta m(\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{0}) = 130 \text{ GeV}, m(\tilde{\chi}_{1}^{0}) = 100 \text{ GeV}$ $\Delta m(\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{0}) = 130 \text{ GeV}, m(\tilde{\chi}_{1}^{0}) = 0 \text{ GeV}$	1908.03122 ATLAS-CONF-2020-031
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$	0-1 e, µ	≥ 1 jet	E_T^{miss} 1	39 ī,		1.25		$m(\hat{x}_1^0)=1 \text{ GeV}$	2004.14060,2012.03799
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0$	1 e, µ	3 jets/1 b	E_T^{miss} 1	39 ī	Forbidden 0.65			$m(\tilde{\chi}_1^0)$ =500 GeV	2012.03799
	$\tilde{I}_1 \tilde{I}_1, \tilde{I}_1 \rightarrow \tilde{\tau}_1 bv, \tilde{\tau}_1 \rightarrow \tau 0$	G 1-2 τ	2 jets/1 b	E_T^{miss} 1	39 <i>ī</i> ₁	Forbidden	1.4		m(ī;)=800 GeV	ATLAS-CONF-2021-008
-	$\tilde{I}_1 \tilde{I}_1, \tilde{I}_1 \rightarrow c \tilde{\chi}_1^0 / \tilde{c} \tilde{c}, \tilde{c} \rightarrow$	$c\tilde{\chi}_1^0 = 0 e, \mu$ $0 e, \mu$	2 c mono-jet	Emiss 36	5.1 č 39 č	0.85			$m(\tilde{\chi}_1)=0 \text{ GeV}$ $m(\tilde{\chi}_1,\tilde{c})-m(\tilde{\chi}_1)=5 \text{ GeV}$	1805.01649 2102.10874
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow Z/I$	$h\tilde{\chi}_{1}^{0}$ 1-2 e, µ	1-4 b	ET 1	39 ī	0.	.067-1.18		$m(\tilde{\chi}_2^0)=500 \text{ GeV}$	2006.05880
_	$\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 e. µ	1 <i>b</i>	ET 1	39 ī ₂	Forbidden 0.86		m	$n(\tilde{\chi}_{1}^{0})=360 \text{ GeV}, m(\tilde{t}_{1})-m(\tilde{\chi}_{1}^{0})=40 \text{ GeV}$	2006.05880
	$\tilde{\chi}_1^{\star}\tilde{\chi}_2^0$ via WZ	Multiple ℓ/jet ee, μμ	ts ≥ 1 jet	E_T^{miss} 1 E_T^{miss} 1	39 x 39 x	205	.96		$m(\tilde{\chi}_{\perp}^{0})=0$, wino-bino $m(\tilde{\chi}_{\perp}^{\pm})$ - $m(\tilde{\chi}_{\perp}^{0})=5$ GeV, wino-bino	2106.01676, ATLAS-CONF-2021-022 1911.12606
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp}$ via WW	2 e, µ		ET 1	39 <i>X</i>	0.42			$m(\tilde{\chi}_1^0)=0$, wino-bino	1908.08215
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_2^0$ via Wh	Multiple ℓ/jet	ts	E_T^{miss} 1	39 <i>X</i>	len	1.06		$m(\tilde{\chi}_1^0)$ =70 GeV, wino-bino	2004.10894, ATLAS-CONF-2021-022
	$\lambda_{1}^{\pm} \tilde{\chi}_{1}^{\pm} via \tilde{\ell}_{L} / \tilde{v}$	2 e, µ		E_T^{miss} 1	39 8		1.0		$m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	1908.08215
Ū.	$ = \frac{1}{2} \frac$	27	Q into	ET 1	39 T	0.16-0.3 0.12-0.39			$m(\tilde{\chi}_{1}^{0})=0$	1911.06660
	$\ell_{L,R}\ell_{L,R}, \ell \rightarrow \ell \ell_1$	ee, μμ	≥ 1 jet	E_T^{miss} 1	39 1	0.256			$m(\tilde{\ell})-m(\tilde{\chi}_{1}^{0})=10 \text{ GeV}$	1908.08215
	$\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$	0 e, µ	$\geq 3b$	Emiss 36	5.1 <i>H</i>	13-0.23 0.29-0.88	1		$BR(\tilde{\chi}^0_J \rightarrow h\tilde{G})=1$	1806.04030
		4 <i>e</i> ,μ 0 <i>e</i> ,μ	0 jets ≥ 2 large jets	$E_T^{\text{miss}} = 1$ $E_T^{\text{miss}} = 1$	39 H 39 H	0.55 0.45-0.9	93		$BR(\tilde{\chi}_1^0 \rightarrow Z\tilde{G})=1$ $BR(\tilde{\chi}_1^0 \rightarrow Z\tilde{G})=1$	2103.11684 ATLAS-CONF-2021-022
-	Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., lo	ng-lived $\tilde{\chi}_1^{\pm}$ Disapp. trk	1 jet	E_T^{miss} 1	39 x	0.66			Pure Wino Pure higgsino	ATLAS-CONF-2021-015 ATLAS-CONF-2021-015
	Stable g R-hadron		Multiple	36	5.1 ž			2.0		1902.01636,1808.04095
Long- Dartic	Metastable g R-hadr	on, $\tilde{g} \rightarrow qq \tilde{\chi}_1^0$	Multiple	36	5.1 🛛 🖁	0.2 ns]		2.05 2.4	4 m(<i>ι</i> ⁰ ₁)=100 GeV	1710.04901,1808.04095
	$\vec{l}, \vec{l} \rightarrow l \vec{G}$	Displ. lep		E_T^{miss} 1	39 ē, Ť	0.34			$\begin{aligned} r(\tilde{\ell}) &= 0.1 \text{ ns} \\ r(\tilde{\ell}) &= 0.1 \text{ ns} \end{aligned}$	2011.07812 2011.07812
PV	$\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} / \tilde{\chi}_1^0, \tilde{\chi}_1^{\pm} \rightarrow Z \ell \rightarrow \ell$	<i>ℓℓℓ</i> 3 <i>e</i> , μ		1	39 🗴	1, BR(Ze)=1] 0.625	1.05		Pure Wino	2011.10543
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} / \tilde{\chi}_2^0 \rightarrow WW/Z\ell\ell$	<i>llvv</i> 4 <i>e</i> ,μ	0 jets	E_T^{miss} 1	39 🕺	$\lambda_{12k} \neq 0] \qquad $.95 1	.55	$m(\bar{x}_{1}^{0})=200 \text{ GeV}$	2103.11684
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow q$	99	4-5 large jets	36	5.1 <u>ĝ</u>	eV, 1100 GeV]	1.3	1.9	Large X''_112	1804.03568
	$\sum_{i=1}^{n} \frac{ii}{i} \rightarrow t \chi_1^i, \chi_1^i \rightarrow t b s$		Multiple	36	20 7	Forbidden 0	1.05		$m(\chi_1^*)=200 \text{ GeV}, \text{ bino-like}$	ATLAS-CONF-2018-003
	$\begin{array}{c} \mathbf{u} \\ i \\ $		2 jets + 2 b	36	5.7 6	0.42 0.61			11(41)=500 Gev	1710.07171
	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$	2 e, µ	26	36	5.1 ī		0.4-1.4	5	$BR(\tilde{t}_1 \rightarrow be/b\mu) > 20\%$	1710.05544
		1μ	DV	1	36	<1e-8, 3e-10< X <3e-9]	1.0	1.6	$BR(\tilde{i}_1 \rightarrow q\mu) = 100\%, \cos\theta_i = 1$	2003.11956
	-+		>C into		20 2	0.0.0.20			Pure biggeing	ATLAC CONE 2021 007

New particles "seems" heavy.

Supersymmet

- 1. Colliders of higher luminosity, higher energy, e.g. CEPC, muon collider.
- 2. Indirect effects, e.g. κ formalism, EFT.

Two EFTs: SMEFT and HEFT

Both are invariant under $SU(3)_c \times SU(2)_L \times U(1)_Y$ symmetry and contains SM fields.

• SMEFT, linear realization of the Higgs and Goldstones, canonical dimension

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} G^+ \\ v + h + iG^0 \end{pmatrix}, \quad \mathcal{L}_{\text{SMEFT}} \supset \frac{1}{2} D_{\mu} H^{\dagger} D^{\mu} H + \frac{m^2}{2} H^{\dagger} H - \lambda (H^{\dagger} H)^2 + \frac{C_H}{\Lambda^2} (H^{\dagger} H)^3 + \cdots$$

• HEFT, nonlinear realization, chiral dimension

$$h, U \equiv \exp\left(\frac{i\pi_i\sigma_i}{v_{\rm EW}}\right), \quad \mathcal{L}_{\rm HEFT}^{\rm LO} \supset \frac{1}{2}D_{\mu}hD^{\mu}h - V(h) + \frac{v_{\rm EW}^2}{4}F(h)\mathrm{Tr}(D_{\mu}U^{\dagger}D^{\mu}U) + \cdots$$
$$V(h) = \frac{1}{2}m_h^2h^2\left[1 + (1 + \Delta\kappa_3)\frac{h}{v_{\rm EW}} + \cdots\right], \quad F(h) = 1 + 2(1 + \Delta a)\frac{h}{v_{\rm EW}} + \cdots$$

[H. Sun, M.-L. Xiao, and J.-H. Yu, 2206.07722]

HEFT is similar to chiral perturbation theory (χ^{PT}) in scalar sector.

- $^{\circ}$ Goldstones are embedded in the U matrix.
- Power counting use chiral dimension. e.g. p^2, p^4 .
- However, Higgs is a general scalar, not necessarily composite.







From Jaco ter Hoeve, ICHEP 2024

Matching is a procedure that relate the Wilson coefficients to the masses and couplings of UV models.

- Any EFT deviations from the SM should be explained by a UV model.
- Could we match a same UV model to two EFTs?
- The matching of SMEFT is mature at one-loop level (diagrammatic method and functional method). How to make the matching of HEFT simply and programmable?

Matching UV Model to EFT (Functional Method)

For tree level matching, solve EoM to get $\Phi_c[\phi]$ and put it back to the Lagrangian.

SMEFT matching procedure (Covariant Derivative Expansion)



Real Higgs Triplet Extension of the SM (RHTE)

 A singlet extension, a second doublet extension (2HDM), next is triplet.

[G. Buchala et al, 1608.03564, 2312.13885], [S. Dawson et al, 2205.01561, 2311.16897], [F. Arco et al, 2307.15693]

 The custodial violation appears at tree level with a nonzero VEV.

The Model: the SM plus a real $SU(2)_L$ triplet with Y = 0Linear form

$$\mathbf{H} = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}} \left(v_{\mathbf{H}} + h + iG^0 \right) \end{pmatrix}, \qquad \Sigma = \frac{1}{2} \Sigma_i \sigma_i = \frac{1}{2} \begin{pmatrix} v_{\Sigma} + \Sigma^0 & \sqrt{2}\Sigma^+ \\ \sqrt{2}\Sigma^- & -v_{\Sigma} - \Sigma^0 \end{pmatrix}, i = 1, 2, 3,$$

$$\begin{split} \mathscr{L}_{\mathrm{RHTE}}(\mathrm{H},\Sigma) &\supset D_{\mu}\mathrm{H}^{\dagger}D^{\mu}\mathrm{H} + \langle D_{\mu}\Sigma^{\dagger}D^{\mu}\Sigma \rangle - V(H,\Sigma), \\ V(\mathrm{H},\Sigma) &= Y_{1}^{2}\mathrm{H}^{\dagger}\mathrm{H} + Z_{1}(\mathrm{H}^{\dagger}\mathrm{H})^{2} + Y_{2}^{2}\langle\Sigma^{\dagger}\Sigma\rangle + Z_{2}\langle\Sigma^{\dagger}\Sigma\rangle^{2} + Z_{3}\mathrm{H}^{\dagger}\mathrm{H}\langle\Sigma^{\dagger}\Sigma\rangle + 2Y_{3}\mathrm{H}^{\dagger}\Sigma\mathrm{H} \end{split}$$

 $Z_i s$ are dimensionless, $Y_i s$ are dimensional $< \ldots >$ denotes trace

Matching RHTE to SMEFT

 $\mathscr{L}_{\rm RHTE}({\rm H},\Sigma)\supset D_{\mu}{\rm H}^{\dagger}D^{\mu}{\rm H}+\langle D_{\mu}\Sigma^{\dagger}D^{\mu}\Sigma\rangle-V(H,\Sigma),$ $V(\mathbf{H}, \Sigma) = Y_1^2 \mathbf{H}^{\dagger} \mathbf{H} + Z_1 (\mathbf{H}^{\dagger} \mathbf{H})^2 + Y_2^2 \langle \Sigma^{\dagger} \Sigma \rangle + Z_2 \langle \Sigma^{\dagger} \Sigma \rangle^2 + Z_3 \mathbf{H}^{\dagger} \mathbf{H} \langle \Sigma^{\dagger} \Sigma \rangle + 2Y_3 \mathbf{H}^{\dagger} \Sigma \mathbf{H}$ $\mathscr{L}^{\Sigma} = \frac{1}{2} \overrightarrow{\Sigma}^{T} (-D_{\mu} D^{\mu} - Y_{2}^{2} - Z_{3} H^{\dagger} H) \overrightarrow{\Sigma} + Y_{3} \overrightarrow{\Sigma} \cdot H^{\dagger} \overrightarrow{\sigma} H - \frac{1}{4} Z_{2} (\overrightarrow{\Sigma} \cdot \overrightarrow{\Sigma})^{2}$ EoM of Σ : $(-D_{\mu}D^{\mu} - Y_{2}^{2} - Z_{3}H^{\dagger}H)\overrightarrow{\Sigma}_{c} = -Y_{3}H^{\dagger}\overrightarrow{\sigma}H + Z_{2}(\overrightarrow{\Sigma}_{c}\cdot\overrightarrow{\Sigma}_{c})\overrightarrow{\Sigma}_{c}$ $\vec{\Sigma}_{c} = -\frac{1}{-D_{\mu}D^{\mu} - Y_{2}^{2} - Z_{3}H^{+}H}Y_{3}H^{+}\vec{\sigma}H + \frac{1}{-D_{\mu}D^{\mu} - Y_{2}^{2} - Z_{3}H^{+}H}Z_{2}(\vec{\Sigma}_{c}\cdot\vec{\Sigma}_{c})\vec{\Sigma}_{c}$ Expansion with $1/Y_2^2$ $\mathscr{L}_{\text{SMEFT}} = \frac{1}{2Y_2^2} Y_3^2 \mathrm{H}^{\dagger} \vec{\sigma} H \cdot \mathrm{H}^{\dagger} \vec{\sigma} \mathrm{H} + \frac{1}{2} (\mathrm{H}^{\dagger} \vec{\sigma} H)^T \frac{1}{Y_2^2} (-D_{\mu} D^{\mu} - Z_3 H^{\dagger} H) \frac{1}{Y_2^2} \mathrm{H}^{\dagger} \vec{\sigma} H + \cdots$

> T. Corbett, A. Helset, A. Martin, M. Trott, [2102.02819] J. Ellis, K. Mimasu, F. Zamperdri, [2304.06663]

Matching RHTE to HEFT

$$h, U \equiv \exp\left(\frac{i\pi_i\sigma_i}{v_{\rm EW}}\right), \quad \mathscr{L}_{\rm HEFT}^{\rm LO} \supset \frac{1}{2}D_{\mu}hD^{\mu}h - V(h) + \frac{v_{\rm EW}^2}{4}F(h)\mathrm{Tr}(D_{\mu}U^{\dagger}D^{\mu}U) + \cdots$$
$$V(h) = \frac{1}{2}m_h^2h^2\left[1 + (1 + \Delta\kappa_3)\frac{h}{v_{\rm EW}} + \cdots\right], \quad F(h) = 1 + 2(1 + \Delta a)\frac{h}{v_{\rm EW}} + \cdots$$

RHTE in linear form

$$\mathbf{H} = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}} \left(v_{\mathbf{H}} + h + iG^0 \right) \end{pmatrix}, \qquad \Sigma = \frac{1}{2} \Sigma_i \sigma_i = \frac{1}{2} \begin{pmatrix} v_{\Sigma} + \Sigma^0 & \sqrt{2}\Sigma^+ \\ \sqrt{2}\Sigma^- & -v_{\Sigma} - \Sigma^0 \end{pmatrix}, i = 1, 2, 3,$$

$$\begin{pmatrix} G_{\rm EW}^+ \\ H^+ \end{pmatrix} = \begin{pmatrix} \cos \delta - \sin \delta \\ \sin \delta & \cos \delta \end{pmatrix} \begin{pmatrix} G^+ \\ \Sigma^+ \end{pmatrix} \qquad \begin{pmatrix} h \\ K \end{pmatrix} = \begin{pmatrix} \cos \gamma & -\sin \gamma \\ \sin \gamma & \cos \gamma \end{pmatrix} \begin{pmatrix} h^0 \\ \Sigma^0 \end{pmatrix}$$
$$\tan \delta = 2v_{\Sigma}/v_{\rm H}.$$

- 1. Solve EoMs of H^{\pm}, K .
- 2. Embed $G_{\rm EW}^{\pm}$, G^0 into an exponential matrix form. **?!** It must be complicated.

Find a non-linear representation of the UV model for HEFT matching

Non-linear Form

1.
$$\mathbf{H} = U \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_{\mathrm{H}} + h^0 \end{pmatrix}, \quad U \equiv \exp\left(\frac{i\pi_i\sigma_i}{v_{\mathrm{H}}}\right) \qquad \Sigma = \frac{1}{2}\Sigma_i\sigma_i = \frac{1}{2} \begin{pmatrix} v_{\Sigma} + \Sigma^0 & \sqrt{2}\Sigma^+ \\ \sqrt{2}\Sigma^- & -v_{\Sigma} - \Sigma^0 \end{pmatrix}, i = 1, 2, 3,$$

The mass mixing between Goldstones π^{\pm} and Σ^{\pm} still exists.

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The mass mixing between Goldstones π^{\pm} and Σ^{\pm} still exists.

2.
$$H = U \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_{\rm H} + h^0 \end{pmatrix} , \quad U \equiv \exp\left(\frac{i\pi_i \sigma_i}{v_{\rm H}}\right)$$

$$\Sigma = U\Phi U^{\dagger}, \ \Phi = \frac{1}{2}\phi_i\sigma_i = \frac{1}{2} \begin{pmatrix} v_{\Sigma} + \phi^0 & \sqrt{2}\phi^+ \\ \sqrt{2}\phi^- & -v_{\Sigma} - \phi^0 \end{pmatrix}$$

 $2Y_3 H^{\dagger}\Sigma H$

Good news: U disappears in potential, the mass mixing disappears.

Bad news: a term of kinetic mixing appears.

 $\langle D_{\mu} \Sigma^{\dagger} D^{\mu} \Sigma \rangle \supset - v_{\Sigma} \epsilon_{3jk} D_{\mu} \phi_{j} D^{\mu} \pi_{k}$

Non-linear Form

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Good news: U disappears in potential, the mass mixing disappears. Bad news: a term of kinetic mixing appears.

 $\langle D_{\mu} \Sigma^{\dagger} D^{\mu} \Sigma \rangle \supset - v_{\Sigma} \epsilon_{3jk} D_{\mu} \phi_{j} D^{\mu} \pi_{k} / v_{\rm EW}$

3.
$$H = U \frac{1}{\sqrt{2}} \begin{pmatrix} \chi^{\pm} \\ v_{H} + h^{0} + i\chi^{0} \end{pmatrix}, U \equiv \exp\left(\frac{i\pi_{i}\sigma_{i}}{v_{EW}}\right)$$
$$\Sigma = U\Phi U^{\dagger}, \ \Phi = \frac{1}{2}\phi_{i}\sigma_{i} = \frac{1}{2} \begin{pmatrix} v_{\Sigma} + \phi^{0} & \sqrt{2}\phi^{+} \\ \sqrt{2}\phi^{-} & -v_{\Sigma} - \phi^{0} \end{pmatrix}$$

$$\chi^{\pm} = 2 \frac{v_{\Sigma}}{v_{\mathrm{H}}} \phi^{\pm}, \chi^{0} = 0 \qquad D_{\mu} H^{\dagger} D^{\mu} H \supset v_{\mathrm{H}} \epsilon_{3jk} D_{\mu} \chi_{j} D^{\mu} \pi_{k} / (2v_{\mathrm{EW}})$$

Both mass mixing and kinetic mixing disappear!

The U matrix is separated from heavy states, to "integrate out" heavy states and leave U in HEFT become straightforward.

A Diagrammatic View: Find the Correct ${\cal U}$

$$\begin{split} \mathbf{H} &= U \begin{pmatrix} \chi^{\pm} \\ \frac{1}{\sqrt{2}} (v_{\mathrm{H}} + h^{0} + i\chi^{0}) \end{pmatrix}, U \equiv \exp\left(\frac{i\pi_{i}\sigma_{i}}{v_{EW}}\right) \quad \chi^{\pm} = 2\frac{v_{\Sigma}}{v_{\mathrm{H}}}\phi^{\pm}, \chi^{0} = 0 \\ \Sigma &= U\Phi U^{\dagger}, \ \Phi = \frac{1}{2}\phi_{i}\sigma_{i} = \frac{1}{2} \begin{pmatrix} v_{\Sigma} + \phi^{0} & \sqrt{2}\phi^{+} \\ \sqrt{2}\phi^{-} & -v_{\Sigma} - \phi^{0} \end{pmatrix} \qquad (\pi_{i}s, h^{0}, \phi^{\pm}, \phi^{0}) \end{split}$$



- Use "rotated" scalars.
- Cancel out kinetic mixing.

Does these two rules suitable for a general SU(2) representations? E.g. a quadruplet, a quintet.

Quadruplet with Y = 3/2



General Scalar Extensions

$$\begin{split} \Phi_{ijklm\cdots} &= U_{i_{1}}^{i} U_{j_{1}}^{j} U_{k_{1}}^{k} U_{l_{1}}^{l} U_{k_{1}}^{k} U_{m_{1}}^{m} \cdots \phi_{i_{1}j_{1}k_{1}l_{1}m_{1}\cdots} \underbrace{ \underbrace{ \underbrace{ \underbrace{ \vdots \cdots \vdots \underbrace{ 2\cdots : 2 } } }_{j=y=1,j+y=1}^{\text{for positive charge}} \\ (D\Phi^{*i_{1}i_{2}i_{3}i_{4}i_{5}\cdots}) (D\Phi_{i_{1}i_{2}i_{3}i_{4}i_{5}\cdots}) & \underbrace{ \underbrace{ \vdots \cdots : \underbrace{ 2\cdots : 2 } } \\ (D\phi^{*i_{1}i_{2}i_{3}i_{4}i_{5}\cdots}) (D\phi_{i_{1}i_{2}i_{3}i_{4}i_{5}\cdots}) + (DU^{*i_{n}}_{k_{n}} DU^{j_{n}}_{i_{n}}) \phi^{*\cdots i_{n-1}k_{n}i_{n+1}\cdots} & \underbrace{ \underbrace{ \cdots : 2 \cdots : 2 } \\ (U^{*i_{n}} DU^{j_{n}}_{i_{n}} D\phi^{*\cdots i_{n-1}k_{n}i_{n+1}\cdots} \phi_{\cdots i_{n-1}j_{n}i_{n+1}} \cdots + DU^{*i_{n}}_{k_{n}} U^{j_{n}}_{i_{n}} \phi^{*\cdots i_{n-1}k_{n}i_{n+1}\cdots} D\phi_{\cdots i_{n-1}j_{n}i_{n+1}\cdots} \\ & + (U^{*i_{m}}_{k_{m}} DU^{j_{m}}_{i_{m}} DU^{*i_{n}}_{k_{n}} U^{j_{n}}_{i_{n}} + DU^{*i_{m}}_{k_{m}} U^{j_{m}}_{i_{m}} U^{*i_{n}}_{k_{n}} DU^{j_{n}}_{i_{n}}) \\ \phi^{*\cdots i_{n-1}k_{m}i_{m+1}\cdots i_{n-1}k_{n}i_{n+1}\cdots} \phi_{\cdots i_{m-1}j_{m}i_{m+1}\cdots i_{n-1}j_{n}i_{n+1}\cdots} \\ & + (U^{*i_{m}}_{k_{m}} DU^{j_{m}}_{i_{m}} DU^{*i_{n}}_{k_{n}} U^{j_{m}}_{i_{m}} + DU^{*i_{m}}_{k_{m}} U^{j_{m}}_{i_{m}} U^{*i_{n}}_{k_{n}} DU^{j_{n}}_{i_{n}}) \\ & \phi^{*\cdots i_{n-1}k_{m}i_{m+1}\cdots i_{n-1}k_{n}i_{n+1}\cdots} \phi_{\cdots i_{m-1}j_{m}i_{m+1}\cdots i_{n-1}j_{n}i_{n+1}\cdots} \\ & (4.12) \\ & \supset \frac{v_{\phi}}{\sqrt{2}} \left[(j+y)(U^{\dagger} DU)^{2}_{2} + (j-y)(U^{\dagger} DU)^{1}_{1} \right] D(\phi^{0*} - \phi^{0}) \\ & + v_{\phi}/\sqrt{2}(U^{\dagger} DU)^{2}_{1} \left[\sqrt{(j-y)(j+y+1)}D\phi^{-*} - \sqrt{(j+y)(j-y+1)}D\phi^{-} \right] \\ & + v_{\phi}/\sqrt{2}(U^{\dagger} DU)^{2}_{1} \left[\sqrt{(j-y)(j+y+1)}D\phi^{-*} - \sqrt{(j+y)(j-y+1)}D\phi^{+} \right] \\ & \chi^{+} & = \frac{v_{\phi}}{v_{H}} (\sqrt{(j-y)(j+y+1)}\phi^{-*} - \sqrt{(j+y)(j-y+1)}\phi^{+}) \quad \chi^{0} & = -\frac{2yv_{\phi}}{v_{H}} \eta^{0} \\ \end{array}$$

In this non-linear representation, U and heavy states are separate. As HEFT matching is to "integrate out" heavy states and leave Goldstones in U form, under this representation the matching become straight and simple, further programmable. HEFT matching of the real Higgs triplet extension (RHTE)

HEFT Matching of the real Higgs triplet extension

Non-linear representation

$$H = U \begin{pmatrix} \chi^{\pm} \\ \frac{1}{\sqrt{2}} (v_{H} + h^{0} + i\chi^{0}) \end{pmatrix}, U \equiv \exp \begin{pmatrix} \frac{i\pi_{i}\sigma_{i}}{v_{EW}} \end{pmatrix} \qquad \chi^{\pm} = 2\frac{v_{\Sigma}}{v_{H}} \phi^{\pm}$$

$$\Sigma = U \Phi U^{\dagger}, \Phi = \frac{1}{2} \phi_{i}\sigma_{i} = \frac{1}{2} \begin{pmatrix} v_{\Sigma} + \phi^{0} & \sqrt{2}\phi^{+} \\ \sqrt{2}\phi^{-} & -v_{\Sigma} - \phi^{0} \end{pmatrix}$$

$$\mathcal{L}_{RHTE}(H, \Sigma) \supset (D_{\mu}H)^{\dagger} (D^{\mu}H) + \langle D_{\mu}\Sigma^{\dagger}D^{\mu}\Sigma \rangle - V (H, \Sigma) ,$$

$$V (H, \Sigma) = Y_{1}^{2}H^{\dagger}H + Z_{1}(H^{\dagger}H)^{2} + Y_{2}^{2} \langle \Sigma^{\dagger}\Sigma \rangle + Z_{2} \langle \Sigma^{\dagger}\Sigma \rangle^{2} + Z_{3}H^{\dagger}H \langle \Sigma^{\dagger}\Sigma \rangle + 2Y_{3}H^{\dagger}\Sigma H$$

$$Minimum \ condition \qquad Y_{1}^{2} = -Z_{1}v_{H}^{2} - Z_{3}v_{\Sigma}^{2}/2 + Y_{3}v_{\Sigma}, \quad Y_{2}^{2} = -Z_{3}v^{2}/2 - Z_{2}v_{\Sigma}^{2} + \frac{Y_{3}v^{2}}{2v_{\Sigma}} .$$

$$\psi_{i}^{2} = \begin{pmatrix} \cos\gamma & -\sin\gamma \\ \sin\gamma & \cos\gamma \end{pmatrix} \begin{pmatrix} h^{0} \\ \phi^{0} \end{pmatrix} \qquad m_{h,K}^{2} = Z_{1}v_{H}^{2} + Z_{2}v_{\Sigma}^{2} + \frac{Y_{3}v_{H}^{2}}{4v_{\Sigma}} \mp \sqrt{\left(Z_{1}v_{H}^{2} - Z_{2}v_{\Sigma}^{2} - \frac{Y_{3}v_{H}^{2}}{4v_{\Sigma}}\right)^{2} + v_{H}^{2}(Z_{3}v_{\Sigma} - Y_{3})^{2}}$$

$$m_{\phi^{\pm}^{\pm}}^{2} = (v_{H}^{2} + 4v_{\Sigma}^{2})\frac{Y_{3}}{2v_{\Sigma}}$$

Theoretical constraints

 $\begin{pmatrix} h \\ K \end{pmatrix}$

$$Z_{1}, Z_{2} \ge 0, \quad |Z_{3}| \ge -2\sqrt{Z_{1}Z_{2}}$$
$$\max(0, Y_{3}^{-}) < Y_{3} < Y_{3}^{+} \qquad Y_{3}^{\pm} = \frac{1}{2v_{\Sigma}} \left(Z_{1}v_{H}^{2} + 2Z_{3}v_{\Sigma}^{2} \pm \sqrt{Z_{1}^{2}v_{H}^{4} + 4Z_{1}Z_{3}v_{H}^{2}v_{\Sigma}^{2} + 16Z_{1}Z_{2}v_{\Sigma}^{4}} \right)$$

Power Counting

Experiment constraints

- Custodial symmetry breaking is constrained by the $\rho = m_W^2 / (m_Z^2 \cos^2 \theta_W)$ parameter. $\xi \equiv \frac{v_{\Sigma}}{v_H} \lesssim 0.02$
- $v_{\rm EW} = 246 \; {\rm GeV}$
- $m_h = 125 \text{ GeV}$

Parameter set Power counting

$$(Z_1, Z_2, Z_3, Y_3, v_{\rm EW}, \xi)$$

$$\begin{split} m_h^2 &= 2Z_1 v_H^2 - 2\xi Y_3 v_H - 4\xi^2 v_H^2 (2Z_1 - Z_3) + O(\xi^3) \\ m_K^2 &= \frac{Y_3 v_H}{2\xi} + 2\xi Y_3 v_H + 4\xi^2 v_H^2 (2Z_1 - Z_3) + 2\xi^2 v_H^2 Z_2 + O(\xi^3) , \\ m_{\phi^{\pm}}^2 &= \frac{\overline{Y_3 v_H}}{2\xi} + 2\xi Y_3 v_H \\ K &= K_0 + \xi K_1 + \xi^2 K_2 + \dots \\ \phi_1 &= \phi_{10} + \xi \phi_{11} + \xi^2 \phi_{12} + \dots \\ \phi_2 &= \phi_{20} + \xi \phi_{21} + \xi^2 \phi_{22} + \dots, \end{split} \qquad \begin{aligned} \xi &\to 0 \\ \text{corresponds to a decoupling limit.} \end{aligned}$$

The HEFT (ξ^2)

The HEFT (ξ^3)

Operators	$P(h)/\left[\xi^3/(Y_3v^3)\right]/(4Z_1-Z_3)$
$\langle V_{\mu}V^{\mu} angle$	$-2hv^5 - 10h^2v^4 - 22h^3v^3 - 23h^4v^2 - 11h^5v - 2h^6$
$\langle V_\mu \sigma_3 angle \langle V^\mu \sigma_3 angle$	$2hv^5 + 9h^2v^4 + 16h^3v^3 + 14h^4v^2 + 6h^5v + h^6$
$D_{\mu}hD^{\mu}h$	$20h^2v^2 + 24h^3v + 8h^4$
	$h^2v^6(4Z_1-Z_3)+h^3v^5(16Z_1-5Z_3)+rac{1}{4}h^4v^4(60Z_1-41Z_3)$
V(h)	$-h^5v^3(4Z_1+11Z_3-rac{1}{2}h^6v^2(24Z_1+13Z_3)-2h^7v(3Z_1+Z_3)$
	$-rac{1}{4}h^8(4Z_1+Z_3)+(-4h^2v^4-10h^3v^3-8h^4v^2-2h^5v)Y_3^2/(4Z_1-Z_3)$

Operator	$P(h)/\left[\xi^3/(Y_3v^3) ight]$
$\langle V_{\mu}V^{\mu}\rangle\langle V_{\nu}V^{\nu}\rangle$	$(h+v)^4$
$\langle V_{\mu}\sigma_{3} angle\langle V^{\mu}\sigma_{3} angle\langle V_{ u}V^{ u} angle$	$-2(h+v)^{4}$
$\langle V_{\mu}\sigma_{3} angle\langle V_{ u}\sigma_{3} angle\langle V^{\mu}V^{ u} angle$	$2(h+v)^4$
$\langle V_{\mu}V_{ u}\sigma_3 angle\langle V^{\mu}\sigma_3 angle D^{ u}h$	$-4(h+v)^3$
$\langle V_{\mu}V_{ u}\sigma_3 angle\langle V^{ u}\sigma_3 angle D^{\mu}h$	$4(h+v)^{3}$
$\langle V_{\mu}V^{\mu} angle D_{ u}hD^{ u}h$	$4(h+v)^2$
$\langle V_\mu \sigma_3 \rangle \langle V^\mu \sigma_3 \rangle D_ u h D^ u h$	$-4(h+v)^2$
$\langle V_{\mu}V_{ u} angle D^{\mu}hD^{ u}h$	$-8(h+v)^{2}$
$\langle V_\mu \sigma_3 angle \langle V_ u \sigma_3 angle D^\mu h D^ u h$	$4(h+v)^{2}$
$D_{\mu}hD^{\mu}hD_{ u}hD^{ u}h$	4

 p^2

 p^4

The Standard HEFT

$\mathcal{L}_{ ext{HEFT}}^{ ext{LO}} \supset \frac{1}{2} \mathcal{K}(h) D_{\mu} h D^{\mu} h - \mathcal{V}(h) - rac{v_{ ext{EW}}^2}{4} \mathcal{F}(h) \langle V_{\mu} V^{\mu} angle + rac{v_{ ext{EW}}^2}{4} \mathcal{G}(h) \langle V_{\mu} \sigma_3 angle \langle V^{\mu} \sigma_3 angle \ - rac{v_{ ext{EW}}}{\sqrt{2}} (ar{Q}_L U \mathcal{Y}_Q(h) Q_R + ar{L}_L U \mathcal{Y}_L(h) L_R + h.c.) \ ,$

$\mathcal{K}(h) = 1 + c_1^\kappa rac{1}{v_{\mathrm{EW}}} + c_2^\kappa rac{1}{v_{\mathrm{EW}}^2} + \cdots,$	
$\mathcal{V}(h) = rac{1}{2}m_h^2 h^2 \left[1 + (1 + \Delta \kappa_3) rac{h}{v_{ m EW}} + rac{1}{4}(1 + \Delta \kappa_4) rac{h^2}{v_{ m EW}^2} ight]$	$\left[\frac{1}{N}+\cdots\right],$
$\mathcal{F}(h) = 1 + 2(1+\Delta a)rac{h}{v_{ m EW}} + (1+\Delta b)rac{h^2}{v_{ m EW}^2} + \cdots,$	
${\cal G}(h)=\Delta lpha+\Delta a^{{\cal C}}rac{h}{v_{ m EW}}+\Delta b^{{\cal C}}rac{h^2}{v_{ m EW}^2}+\cdots,$	
$\mathcal{Y}_Q(h) = ext{diag}\left(\sum_n Y_U^{(n)} rac{h}{v_{ ext{EW}}^n}, \sum_n Y_D^{(n)} rac{h^n}{v_{ ext{EW}}^n} ight),$	
${\mathcal Y}_L(h) = { m diag}\left(0, \sum_n Y_\ell^{(n)} rac{h^n}{v_{ m EW}^n} ight).$	

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$\mathcal{O}(\xi)$	ξ^2	ξ^3
$\Delta \kappa_3$	$-2\left(2-\frac{Z_3}{Z_1}\right)$	$\frac{2Z_3}{Z_1^2} \frac{Y_3}{v_{\rm EW}} - \frac{4(12Z_1^2 - 7Z_1Z_3 + Z_3^2)}{Z_1} \frac{v_{\rm EW}}{Y_3}$
$\Delta\kappa_4$	$-4\left(\frac{22}{3}-\frac{3Z_3}{Z_1}\right)$	$\frac{12Z_3}{Z_1^2} \frac{Y_3}{v_{\rm EW}} - \frac{8(4Z_1 - Z_3)(41Z_1 - 15Z_3)}{3Z_1} \frac{v_{\rm EW}}{Y_3}$
Δa	4	$4(4Z_1-Z_3)rac{v_{ m EW}}{Y_3}$
Δb	16	$40(4Z_1-Z_3)rac{v_{\rm EW}}{Y_3}$
$\Delta lpha$	2	0
Δa^{C}	8	$8(4Z_1-Z_3)rac{v_{ m EW}}{Y_3}$
Δb^{C}	12	$36(4Z_1 - Z_3) rac{v_{ m EW}}{Y_3}$
$\left< V_{\mu} V^{\mu} \right> \left< V_{\nu} V^{\nu} \right>$	0	$\frac{v_{\rm EW}}{Y_3}$
$\left< V_{\mu}\sigma_3 \right> \left< V^{\mu}\sigma_3 \right> \left< V_{\nu}V^{\nu} \right>$	0	$-2rac{v_{\mathrm{EW}}}{Y_3}$
$\left< V_{\mu}\sigma_3 \right> \left< V_{\nu}\sigma_3 \right> \left< V^{\mu}V^{\nu} \right>$	0	$2\frac{v_{\rm EW}}{Y_3}$
$\left< V_{\mu}V_{\nu}\sigma_3 \right> \left< V^{\mu}\sigma_3 \right> D^{\nu}h$	0	$-4\frac{1}{Y_3}$
$\langle V_{\mu}V_{\nu}\sigma_3\rangle \langle V_{\nu}\sigma_3\rangle D^{\mu}h$	0	$4\frac{1}{Y_3}$
$\left< V_{\mu}V^{\mu} \right> D_{\nu}hD^{\nu}h$	0	$4\frac{1}{Y_3 v_{\rm EW}}$
$V_{\mu}\sigma\rangle\left\langle V^{\mu}\sigma_{3} ight angle D_{ u}hD^{ u}h$	0	$-4\frac{1}{Y_3 v_{\rm EW}}$
$\langle V_{\mu}V_{\nu}\rangle D^{\mu}hD^{\nu}h$	0	$-8\frac{1}{Y_3 v_{\rm EW}}$
$V_{\mu}\sigma_{3}\rangle\left\langle V_{ u}\sigma_{3} ight angle D^{\mu}hD^{ u}h$	0	$4\frac{1}{Y_3v_{\rm EW}}$
$D_{\mu}hD^{\mu}hD_{\nu}hD^{\nu}h$	0	$4rac{1}{Y_3 v_{ m EW}^3}$
m_h^2	$2v_{\rm EW}^2 Z_1 - 2v_{\rm EW}$	$Y_3\xi - 4v^2(4Z_1 - Z_3)\xi^2 - 2\left[(4Z_1 - Z_3)^2v_{\rm EW}^2 - 6Y_3^2\right]\frac{v_{\rm EW}}{Y_3}\xi^3$

$$SMEFT Matching (Warsaw basis)$$
$$\mathscr{L}_{SMEFT} = \frac{1}{2Y_2^2} Y_3^2 H^{\dagger} \vec{\sigma} H \cdot H^{\dagger} \vec{\sigma} H + \frac{1}{2} (H^{\dagger} \vec{\sigma} H)^T \frac{1}{Y_2^2} (-D_{\mu} D^{\mu} - Z_3 H^{\dagger} H) \frac{1}{Y_2^2} H^{\dagger} \vec{\sigma} H + \cdots$$



Numerical Results (When Y_2^2 **is Large)** $V(H, \Sigma) = Y_1^2 H^{\dagger}H + Z_1(H^{\dagger}H)^2 + Y_2^2 \langle \Sigma^{\dagger}\Sigma \rangle + Z_2 \langle \Sigma^{\dagger}\Sigma \rangle^2 + Z_3 H^{\dagger}H \langle \Sigma^{\dagger}\Sigma \rangle + 2Y_3 H^{\dagger}\Sigma H$

The bare mass term of Σ



 $WW \rightarrow hh, ZZ \rightarrow hh$ process

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Numerical Results (When Y_2^2 is Small)



down near the resonance





Power counting, SMEFT: $1/Y_2^2$ HEFT: ξ or $1/m_{\phi^{\pm}}^2$ The SMEFT's regular part is consistent with the HEFT's

$$Y_2^2 = -Z_3 v_H^2 / 2 + m_{\phi^{\pm}}^2 + \mathcal{O}(\xi)$$



 $Y_2^2 < 0$ represents that there exists **another source of spontaneously symmetry breaking**, which cause the breakdown of SMEFT. Only HEFT works.

Summary

- HEFT encompasses SMEFT. Through matching a UV model to both HEFT and SMEFT, we study their distinction.
- We build a non-linear representation of general scalar extensions of the SM, which is great for HEFT matching in functional method. The key point is that by using "rotated" scalars, we separate the Goldstones' *U* matrix and heavy states in the UV model.
- We match the real Higgs triplet extension (RHTE) to both HEFT and SMEFT in the decoupling scenario. HEFT converges faster than SMEFT in the region of $Y_2^2 > 0$. In the parameter region of $Y_2^2 < 0$ (there exists another source of spontaneously symmetry breaking), only HEFT is suitable.

Thanks for your attention!

backups

 $Y_2^2 = -Z_3 v_H^2 / 2 - Z_2 v_H^2 \xi^2 + \frac{Y_3 v_H}{2\xi}$

Next Plan

Parameter set 1 $(Z_1, Z_2, Z_3, Y_3, v_{EW}, \xi)$

$$m_{\phi^{\pm}}^{2} = \frac{Y_{3}v_{H}}{2\xi} + 2\xi Y_{3}v_{H}$$

Decoupling case

Parameter set 2 $(Z_1, Z_2, Z_3, m_{\phi^{\pm}}^2, v_{EW}, \xi)$

While $m_{\phi^{\pm}}^2$ approaches infinity, ξ could be kept as a constant, the real model triplet model will not decouple to the SM.

Non-decoupling case

Next Plan

$$\mathscr{L}_{\text{RHTE}} \supset \frac{1}{2} \begin{pmatrix} K & \phi_1 & \phi_2 \end{pmatrix} \mathscr{X} \begin{pmatrix} K \\ \phi_1 \\ \phi_2 \end{pmatrix}$$

1-loop

$$\mathcal{X} = \begin{pmatrix} -\partial^{2} - m_{K}^{2} - 2d_{3}h - 2z_{3}h^{2} \\ -(1+3c_{\gamma}^{2})\langle V_{\mu}V^{\mu}\rangle/2 + c_{\gamma}^{2}V_{\mu}^{3}V_{3}^{\mu} \\ c_{\gamma}V_{\mu}^{3}V_{1}^{\mu} - 2i(c_{\gamma} - v_{\Sigma}s_{\gamma}/v_{H})V_{\mu}^{2}D^{\mu} \\ c_{\gamma}V_{\mu}^{3}V_{1}^{\mu} - 2i(c_{\gamma} - v_{\Sigma}s_{\gamma}/v_{H})V_{\mu}^{2}D^{\mu} \\ c_{\gamma}V_{\mu}^{3}V_{2}^{\mu} + 2i(c_{\gamma} - v_{\Sigma}s_{\gamma}/v_{H})V_{\mu}^{2}D^{\mu} \\ c_{\gamma}V_{\mu}^{3}V_{2}^{\mu} + 2i(c_{\gamma} - v_{\Sigma}s_{\gamma}/v_{H})V_{\mu}^{1}D^{\mu} \\ (c_{\gamma}V_{\mu}^{3}V_{2}^{\mu} + 2i(c_{\gamma} - v_{\Sigma}s_{\gamma}/v_{H})V_{\mu}^{1}D^{\mu} \\ (c_{\gamma}V_{\mu}^{3}V_{\mu}^{\mu} + 2i(c_{\gamma} - v_{\Sigma}s_{\gamma}/v_{H})V_{\mu}^{\mu} \\ (c_{\gamma}V_{\mu}^{3}V_{\mu}^{\mu} + 2i(c_{\gamma}V_{\mu}^{\mu} + 2i(c_{\gamma}V_{\mu}^{\mu} + 2i(c_{\gamma} - v_{\Sigma}v_{\mu})V_{\mu}^{\mu} \\ (c_{\gamma}V_{\mu}^{3}V_{\mu}^{\mu} + 2i(c_{\gamma}V_{\mu}^{\mu} + 2i(c_{\gamma}V_{\mu}^{\mu} + 2i(c_{\gamma}V_{\mu}^{\mu} + 2i(c_{\gamma}V_{\mu}^{\mu} +$$

$$D_{ij}^{\mu} \equiv \partial^{\mu} \delta_{ij} - g' B^{\mu} \epsilon_{ij}, \text{ with } i, j \in 1, 2$$
(B.6)

$$V^i_{\mu} = \langle U^{\dagger} D_{\mu} U \sigma_i \rangle \tag{B.7}$$

While $Y_2^2 = 0$

$$Y_2^2 = -Z_3 v_H^2 / 2 - Z_2 v_{\Sigma}^2 + \frac{Y_3 v_H^2}{2v_{\Sigma}}$$



 $Y_3 = 24.65 \text{ GeV}, Z_2 = 1, Z_3 = 10$