# Mapping New Physics to Observables in the SMEFT Paradigm


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EFTs and Beyond 2024

# Outline

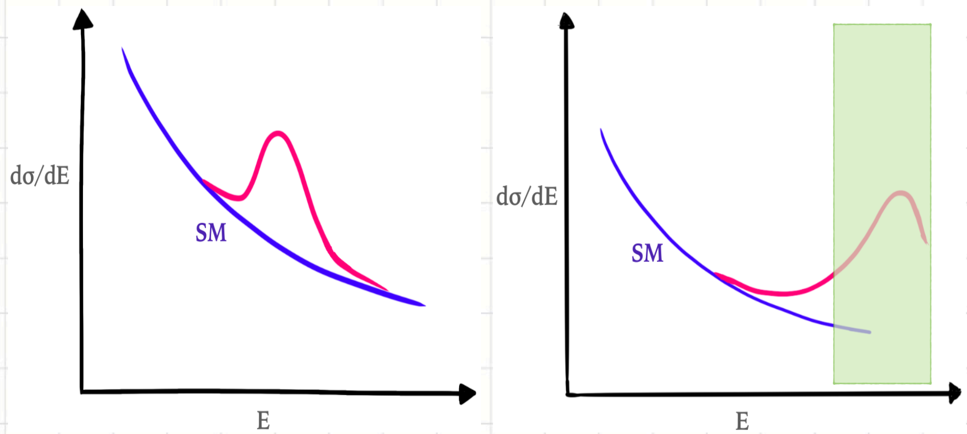
- The SMEFT paradigm: what it is and why is it important now?
- Going beyond dimension-six SMEFT
- A brief review on Heat Kernel Method
- Universal One-loop Effective Lagrangian up to dimension-eight
- Integrating out a heavy electroweak complex triplet scalar
- Integrating out a heavy electroweak complex doublet scalar
- Summary and Outlook

# What is SMEFT and Why is it important now?

- Generically, we can search for new physics either **directly** through new resonance production or **indirectly** by measuring precisely the SM interactions.

So far, no new Physics beyond the SM has been observed at the LHC, so what now?

New Physics might just be beyond the LHC reach and when integrated out, this would lead to indirect effects in deviations of couplings involving the Higgs and the gauge bosons, for new non-resonant Physics effects at the LHC.




- An Effective Field Theory is a field theory that describes the low energy phenomena of an underlying UV sector in terms of only the light particles.

SMEFT = Effective Field Theory of SM fields + SM symmetries but allows for $d > 4$ operators.

Fundamental assumption: new physics nearly decoupled: $\Lambda \gg (v, E)$.

dimension-6

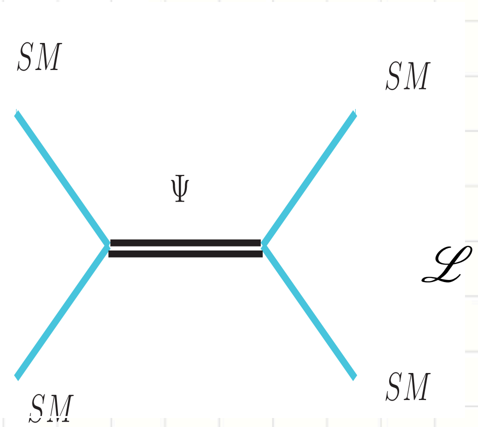
$$\mathscr{L} = \mathscr{L}_{\rm SM}^{(4)} + \frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \frac{1}{\Lambda^3}\sum_k C_k^{(7)} Q_k^{(7)} + \mathscr{O}\left(\frac{1}{\Lambda^4}\right)$$

$C_k$ :BSM effects, $Q_k$ :SM particles

# EFT Expansion and Going Beyond the Dim-6 SMEFT

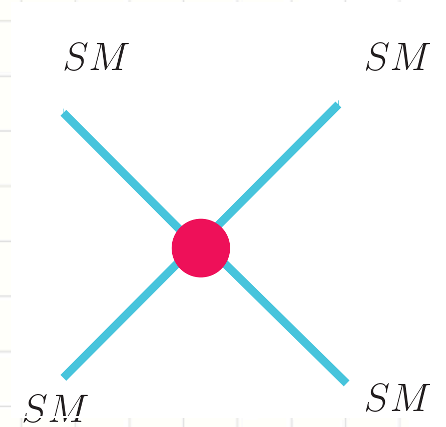
**EFT Expansion:**

$$\mathscr{A}^{(n)}_{\rm BSM}(E,M) \sim E^{4-n}\left(a_0 + a_1\frac{E}{M} + a_2\frac{E^2}{M^2} + \dots\right), \quad E \ll M$$




$$\frac{g^2}{p^2 - M^2} \approx -\frac{g^2}{M^2}\left(1 + \frac{p^2}{M^2} + \frac{p^4}{M^4} + \dots\right)$$

$$\mathscr{L} \sim g(\phi^\dagger\phi)\Psi \approx \frac{g^2}{M^2}(\phi^\dagger\phi)^2 + \frac{g^2}{M^4}(\phi^\dagger\phi)(\partial^\mu\phi^\dagger)(\partial_\mu\phi) + \frac{g^2}{M^6}(\partial^\mu\phi^\dagger)(\partial_\mu\phi)(\partial^\nu\phi^\dagger)(\partial_\nu\phi) + \dots$$




$\mathbf{s = p^2 \ll M^2}$ : EFT validity criterion

**g not too large: perturbative UV completion.**

*Is the EFT interpretation valid?*

Theoretical framework : $\mathscr{A}_{\rm SMEFT} = \mathscr{A}_{\rm SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathscr{A}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4}\mathscr{A}_j^{(8)} + \mathscr{O}\left(\frac{1}{\Lambda^5}\right)$

*We measure cross-sections:* $\sigma_{\rm SMEFT} \propto |\mathscr{A}_{\rm SMEFT}|^2 = |\mathscr{A}_{\rm SM}|^2 + 2{\rm Re}[\mathscr{A}^*_{\rm SM}\mathscr{A}_{\text{dim-6}}] + |\mathscr{A}_{\text{dim-6}}|^2 + 2{\rm Re}[\mathscr{A}^*_{\rm SM}\mathscr{A}_{\text{dim-8}}] + \dots$

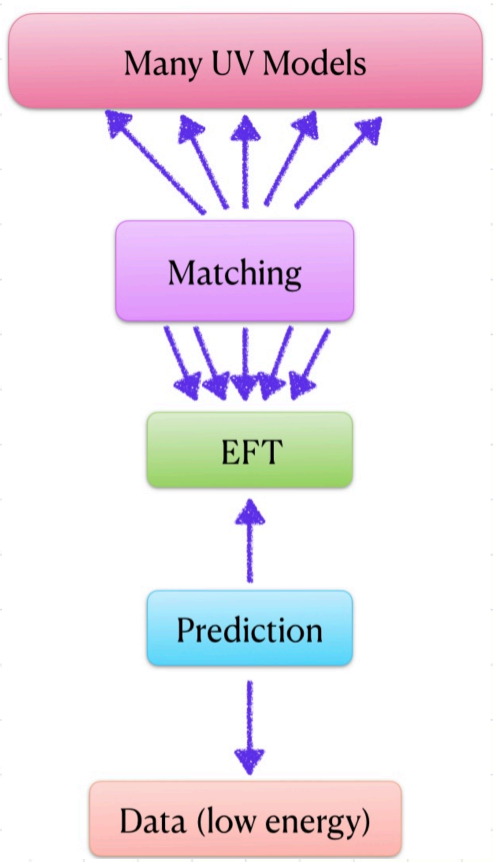
*Ideally, we would be sensitive enough to neglect $\Lambda^{-4}$, but in practice, not always the case.*

**$\mathscr{O}(\Lambda^{-4})$: When might it matter?**

- Data are not very sensitive: $c_i/\Lambda^2$ poorly constrained (e.g., 4-top production).
- Dim-6 interference term is suppressed at high energy: helicity selection *[Azatov et al., PRD 95 (2017) no.6, 065014].*
- Sensitivity from energy-growing effects. Some effects only arise at dim-8 (e.g., neutral triple gauge interactions: $ZZZ, \dots$).
- Global fits, UV model interpretations, validity, unique dim-8 effects, ...

# Bottom-up vs Top-down Approach

EFT serves as an interface between UV physics and ‘low energy’ phenomena.

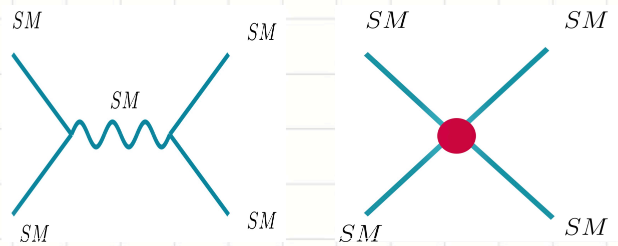



## Bottom-Up Approach

Exact nature of new physics need not be known.

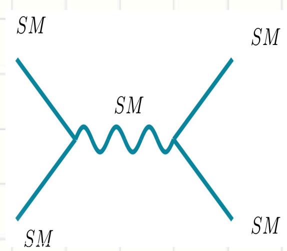
WCs are free parameters without origin

$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + \sum_{i,n} \frac{C_i^{(n)}}{\Lambda^{n-4}} \mathscr{O}_i^{(n)} + \dots$$




$$\uparrow$$

$$\mathscr{L}_{\rm SM}$$

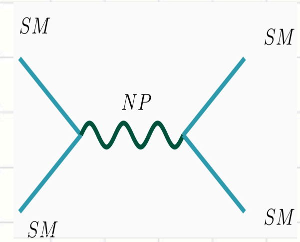



## Top-Down Approach

WCs determined in terms of BSM parameters

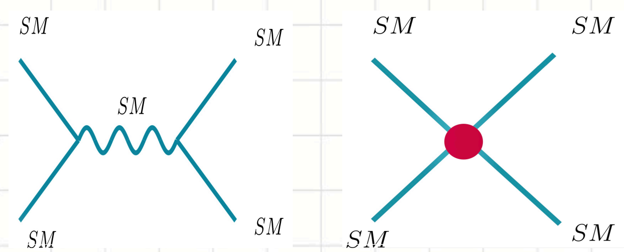
UV-complete Lagrangian must be known

$$\mathscr{L}_{\rm BSM}$$




$$\downarrow$$

$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + \sum_{i,n} \frac{C_i^{(n)}}{\Lambda^{n-4}} \mathscr{O}_i^{(n)} + \dots$$



# New effects at dimension-8 & EFT validity

**Higher dimensional operators ⇒ new Lorentz structures**

More derivatives = higher energy growth

**'Disentangling' effects**

Anomalous QGC independent from TGC: beyond $\mathscr{O}_W = \varepsilon_{IJK} W_\mu^{I,\nu} W_\nu^{J,\rho} W_\rho^{K,\mu}$

$h^4$ independent from $h^3$: $(\phi^\dagger\phi)^3$ and $(\phi^\dagger\phi)^4$

**New gauge self-interactions emerge**

$$F_{\mu\nu}F^{\mu\rho}F_{\rho\sigma}F^{\sigma\nu} \quad \text{(Light-by-light)}$$

$$G_A^{\mu\nu}G_{\mu\nu}^A V^{\rho\sigma}V_{\rho\sigma}, \quad V = Z,\gamma,W^\pm \quad (\text{gg} \to \text{VV})$$

$$i\phi^\dagger B_{\mu\nu}W^{\mu\rho}\{D_\rho, D^\nu\}\phi \quad \text{(Neutral TGC)}$$

**Much is left to study**

- Non-redundant basis is known *[Murphy; JHEP 10 (2020) 174],Li et al.; PRD 104 (2020) 015026]*

**a) Model independent: study effects of dim-8 operators**

- Understand where these could be relevant *[Boughezal et. al; PRD 104 (2021) 9, 095022]*
- Global analyses up to dimension-8 (not yet...) *[Boughezal et. al; PRD 104 (2021) 1, 016005]*
- Identify processes/observables that are uniquely sensitive, . . .

**b) Model dependent: predict effects of dim-8 operators**

- Apply results of (a) by making some assumptions about $c_i^{(8)}$ *[Hays et al.; JHEP 02 (2019) 123]* *[Hays et al.; JHEP 11 (2020) 087]*
- Study classes of explicit UV models up to dimension-8:

  2HDM *[Dawson et al.; PRD 106 (2022) 5, 055012]*
  Triplet scalar & dark photon *[Corbett et al.; JHEP 06 (2021) 076]*
  Vector-like quarks *[Dawson, Homiller & Sullivan; PRD 104 (2021) 11, 115013]*

# Heat Kernel Method

Let us the part of the UV Lagrangian that is bilinear in $\Phi$:

$$\mathscr{L}^c = \Phi^\dagger (D^2 + U + M^2)\Phi = \Phi^\dagger (\Delta)\Phi$$

The Heat-Kernel for an operator $\Delta$ can be written as,

$$K(t,x,y,\Delta) = \langle x|e^{-t\Delta}|y\rangle$$

The Heat-Kernel satisfies the heat equation,

$$(\partial_t + \Delta)K(t,x,y,\Delta) = 0 \quad \text{with initial condition} \quad K(0,x,y,\Delta) = \delta(x-y)$$

The HK for the operator $\Delta$,

$$K(t,x,y,\Delta) = K_0(t,x,y)H(t,x,y,\Delta)$$

$$\frac{1}{(4\pi t)^{d/2}} e^{\frac{-(x-y)^2}{4t} - tM^2} \qquad \sum_k \frac{(-t)^k}{k!} b_k(x,y)$$

Here, $b_k(x,y)$ : Heat-Kernel coefficients *[A.A. Bel'kov et al., hep-ph/9606307, L.G. Avramidi, Nucl.Phys.B, 355(1991)]*

Obtaining one-loop effective action in terms of Heat-Kernel coefficients:

$$\mathscr{L}_{\text{eff,1-loop}} = c_s tr\log(-P^2 + U + M^2) = c_s \text{tr} \int_0^\infty \frac{dt}{t} e^{-t\Delta} = c_s \text{tr} \int_0^\infty \frac{dt}{t} K(t,x,x,\Delta)$$

$$= c_s \text{tr} \int_0^\infty \frac{dt}{t} (4\pi t)^{-d/2} e^{-tM^2} \sum_k \frac{(-t)^k}{k!} \text{tr}[b_k] = \frac{c_s}{(4\pi)^{d/2}} \sum_{k=0}^\infty M^{d-2k} \frac{(-1)^k}{k!} \Gamma[k-d/2] \text{tr}[b_k]$$

# One-loop effective action and relevant coefficients

Obtaining one-loop effective action in terms of Heat-Kernel coefficients:

$$\mathscr{L}_{\text{eff,1-loop}} = \frac{c_s}{(4\pi)^{d/2}} \sum_{k=0}^{\infty} M^{d-2k} \frac{(-1)^k}{k!} \Gamma[k-d/2] \text{tr}[b_k]$$

For $k \leq d/2$, the Gamma function has simple poles. Assuming $d = 4-\varepsilon$, the divergent part of the one-loop effective action:

$$\mathscr{L}_{\text{eff}}^{\text{div}} = \frac{c_s}{(4\pi)^{2-\varepsilon/2}} M^{d-2k} \frac{(-1)^k}{k!} \frac{(\varepsilon/2-3+k)!}{(\varepsilon/2-1)!} (2/\varepsilon - \gamma_E + \mathscr{O}(\varepsilon)) \text{tr}[b_k]$$

and we renormalise the one-loop effective action.

Relevant coefficients for higher dimensional operators:

$$\begin{aligned}
\text{tr}[b_0] &= \text{tr} I, \\
\text{tr}[b_1] &= \text{tr}[U], \\
\text{tr}[b_2] &= \text{tr}[U^2 + \frac{1}{6}(G_{\mu\nu})^2], \\
\text{tr}[b_3] &= \text{tr}[-U^3 - \frac{1}{2}(P_\mu U)^2 - \frac{1}{2} U\,(G_{\mu\nu})^2 - \frac{1}{10}(J_\nu)^2 + \frac{1}{15} G_{\mu\nu}\, G_{\nu\rho}\, G_{\rho\mu}] \\
\text{tr}[b_4] &= \ldots, \\
\text{tr}[b_6] &= \ldots \\
\text{tr}[b_8] &= \ldots
\end{aligned}$$

*[U. Banerjee, J. Chakrabortty, S. U. Rahaman and K. Ramkumar, Eur. Phys. J. Plus **139** (2024) no.2, 159].*

# Universal One-loop Effective Lagrangian up to $D8$

$$\mathscr{L}_{\text{eff}}^{d\leq 8} = \frac{c_s}{(4\pi)^2} M^4 \left[-\frac{1}{2}\left(\ln\left[\frac{M^2}{\mu^2}\right]-\frac{3}{2}\right)\right] + \frac{c_s}{(4\pi)^2}\text{tr}\Bigg\{ M^2\left[-\left(\ln\left[\frac{M^2}{\mu^2}\right]-1\right) U\right]$$

$$+ M^0\,\frac{1}{2}\left[-\ln\left[\frac{M^2}{\mu^2}\right]U^2 - \frac{1}{6}\ln\left[\frac{M^2}{\mu^2}\right](G_{\mu\nu})^2\right]$$

$$+\frac{1}{M^2}\,\frac{1}{6}\left[-U^3 - \frac{1}{2}(P_\mu U)^2 - \frac{1}{2}U\,(G_{\mu\nu})^2 - \frac{1}{10}(J_\nu)^2 + \frac{1}{15}G^{\mu\nu}G_{\nu\rho}G^{\rho}{}_{\mu}\right]$$

$$+\frac{1}{M^4}\,\frac{1}{24}\Bigg[U^4 - U^2(P^2U) + \frac{4}{5}U^2(G_{\mu\nu})^2 + \frac{1}{5}(U\,G_{\mu\nu})^2 + \frac{1}{5}(P^2U)^2$$

$$-\frac{2}{5}U\,(P_\mu U)\,J^\mu + \frac{2}{5}U(J_\mu)^2 - \frac{2}{15}(P^2U)(G_{\rho\sigma})^2 + \frac{1}{35}(P_\nu J_\mu)^2$$

$$-\frac{4}{15}U\,G^{\mu\nu}G_{\nu\rho}G^{\rho}{}_{\mu} - \frac{8}{15}(P_\mu P^\nu U)\,G^{\rho\mu}G_{\rho\nu} + \frac{16}{105}G^{\mu\nu}J_\mu J_\nu$$

$$+\frac{16}{105}(P^\mu J_\nu)G^{\nu\sigma}G_{\sigma\mu} + \frac{1}{420}(G_{\mu\nu}G_{\rho\sigma})^2$$

$$+\frac{17}{210}(G_{\mu\nu})^2(G_{\rho\sigma})^2 + \frac{2}{35}(G_{\mu\nu}G_{\nu\rho})^2 + \frac{1}{105}G^{\mu\nu}G_{\nu\rho}G^{\rho\sigma}G_{\sigma\mu}\Bigg]$$

$$+\frac{1}{M^6}\,\frac{1}{60}\Bigg[-U^5 + 2U^3(P^2U) + U^2(P_\mu U)^2 - \frac{2}{3}U^2G_{\mu\nu}U\,G_{\mu\nu} - U^3(G_{\mu\nu})^2$$

$$+\frac{1}{3}U^2(P_\mu U)J_\mu - \frac{1}{3}U\,(P_\mu U)(P_\nu U)\,G_{\mu\nu} - \frac{1}{3}U^2J_\mu(P_\mu U)$$

$$-\frac{1}{3}U\,G_{\mu\nu}(P_\mu U)(P_\nu U) - U\,(P^2U)^2 - \frac{2}{3}(P^2U)(P_\nu U)^2 - \frac{1}{7}((P_\mu U)G_{\mu\alpha})^2$$

$$+\frac{2}{7}U^2G_{\mu\nu}G_{\nu\alpha}G_{\alpha\mu} + \frac{8}{21}U\,G_{\mu\nu}U\,G_{\nu\alpha}G_{\alpha\mu} - \frac{4}{7}U^2(J_\mu)^2 - \frac{3}{7}(U\,J_\mu)^2$$

$$+\frac{4}{7}U\,(P^2U)(G_{\mu\nu})^2 + \frac{4}{7}(P^2U)U(G_{\mu\nu})^2 - \frac{2}{7}U\,(P_\mu U)J_\nu G_{\mu\nu}$$

$$-\frac{2}{7}(P_\mu U)U\,G_{\mu\nu}J_\nu - \frac{4}{7}U\,(P_\mu U)G_{\mu\nu}J_\nu - \frac{4}{7}(P_\mu U)U\,J_\nu G_{\mu\nu}$$

$$+\frac{4}{21}U\,G_{\mu\nu}(P^2U)G_{\mu\nu} + \frac{11}{21}(P_\alpha U)^2(G_{\mu\nu})^2 - \frac{10}{21}(P_\mu U)J_\nu U\,G_{\mu\nu}$$

$$-\frac{10}{21}(P_\mu U)G_{\mu\nu}U\,J_\nu - \frac{2}{21}(P_\mu U)(P_\nu U)G_{\mu\alpha}G_{\alpha\nu} + \frac{10}{21}(P_\nu U)(P_\mu U)G_{\mu\alpha}G_{\alpha\nu}$$

$$+\frac{1}{M^8}\,\frac{1}{120}\Bigg[U^6 - 3U^4(P^2U) - 2U^3(P_\nu U)^2 + \frac{12}{7}U^2(P_\mu P_\nu U)(P_\nu P_\mu U)$$

$$+\frac{26}{7}(P_\mu P_\nu U)U\,(P_\mu U)(P_\nu U) + \frac{26}{7}(P_\mu P_\nu U)(P_\mu U)(P_\nu U)U + \frac{9}{7}(P_\mu U)^2(P_\nu U)^2$$

$$+\frac{9}{7}U\,(P_\mu P_\nu U)U\,(P_\nu P_\mu U) + \frac{17}{14}((P_\mu U)(P_\nu U))^2 + \frac{8}{7}U^3G_{\mu\nu}U\,G_{\mu\nu}$$

$$+\frac{5}{7}U^4(G_{\mu\nu})^2 + \frac{18}{7}G_{\mu\nu}(P_\mu U)U^2(P_\nu U) + \frac{9}{14}(U^2G_{\mu\nu})^2$$

$$+\frac{18}{7}G_{\mu\nu}U\,(P_\mu U)(P_\nu U)U + \frac{18}{7}(P_\mu P_\nu U)(P_\mu U)U\,(P_\nu U)$$

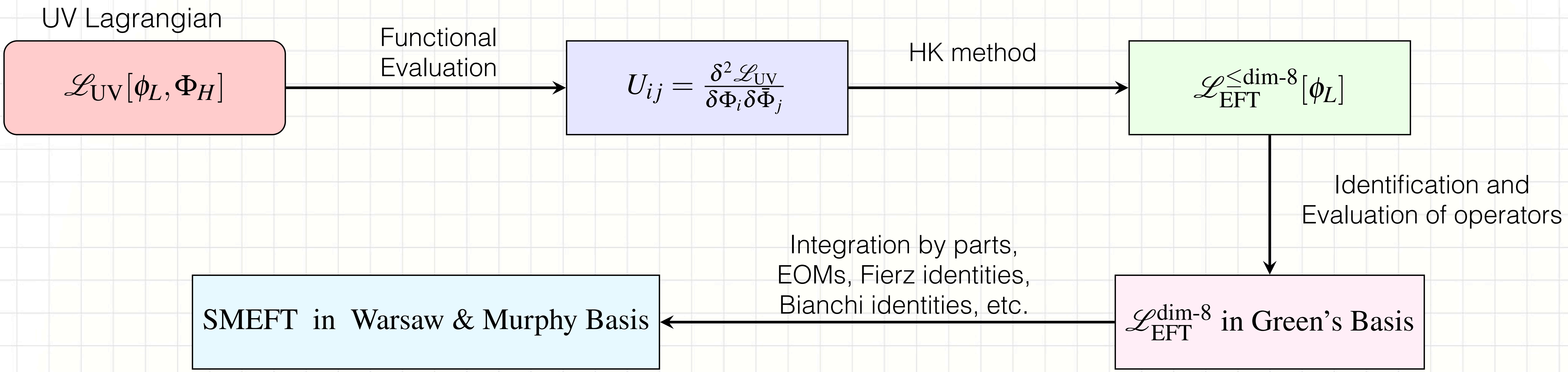
$$+\left(\frac{8}{7}G_{\mu\nu}U\,(P_\mu U)U\,(P_\nu U) + \frac{26}{7}G_{\mu\nu}(P_\mu U)U\,(P_\nu U)U\right)$$

$$+\left(\frac{24}{7}G_{\mu\nu}(P_\mu U)(P_\nu U)U^2 - \frac{2}{7}G_{\mu\nu}U^2(P_\mu U)(P_\nu U)\right)\Bigg]$$

$$+\frac{1}{M^{10}}\,\frac{1}{210}\left[-U^7 - 5U^4(P_\nu U)^2 - 8U^3(P_\mu U)U(P_\mu U) - \frac{9}{2}(U^2(P_\mu U))^2\right]$$

$$+\frac{1}{M^{12}}\,\frac{1}{336}\left[U^8\right]\Bigg\}.$$

# Complex Scalar Triplet upto Dimension-eight...




**SM + complex, triplet scalar,** $\Delta$ **:** Full Lagrangian for a complex scalar triplet with hypercharge $Y = 1$ is then given by

$$\mathscr{L}_{BSM} = \mathscr{L}_{SM} + \left( [(D_\mu \Delta)^\dagger (D^\mu \Delta)] - m_\Delta^2 [\Delta^\dagger \Delta] + \mathscr{L}_Y - V(H, \Delta) \right),$$

where the scalar potential is

$$V(H,\Delta) = \lambda_1 \left(H^\dagger H\right) \text{Tr}[\Delta^\dagger \Delta] + \lambda_2 \left(\text{Tr}[\Delta^\dagger \Delta]\right)^2 + \lambda_3 \text{Tr}\left[\left(\Delta^\dagger \Delta\right)^2\right] + \lambda_4 \left(H^\dagger \Delta \Delta^\dagger H\right) + \left[\mu_\Delta \left(H^T i\sigma^2 \Delta^\dagger H\right) + \text{h.c.}\right].$$

$$\mathscr{L}_Y = Y_{\Delta_{ab}} L_a^T C i\sigma^2 \Delta L_b + \text{h.c.},$$

where $C$ represents the charge conjugation matrix, and $a, b = e, \mu, \tau$ denote the flavor indices.

*[TB, Chakrabortty, Englert , Spannowsky (in prep)]*

# Complex Scalar Triplet upto Dimension-eight...

## Integrating out the heavy complex triplet up to one loop

$O_\phi^8 : (\phi^\dagger\phi)^4$

↓

Higgs trilinear & quartic couplings
Higgs pair & triple Higgs production

$O_{\phi^6}^{(1)} : (\phi^\dagger\phi)^2(D_\mu\phi)^\dagger(D^\mu\phi)$

↓

All Higgs couplings & Higgs $ZZ/WW$
Single Higgs production & decay

$X^2X'^2$ classes

↓

anomalous quartic gauge self-couplings

| EFT operators | Matching results at scale $M_\Delta(\gg v)$ |
|---|---|
| $\mathscr{O}_{\phi^8} = (\phi^\dagger\phi)^4$ | $\mathbb{C}_{\phi^8} = \frac{1}{16\pi^2}c_{\phi^8}^{\llbracket U\rrbracket} - \frac{1}{32\pi^2}\ln\left(\frac{M_\Delta^2}{\mu^2}\right)c_{\phi^8}^{\llbracket U^2\rrbracket} - \frac{1}{96\pi^2}c_{\phi^8}^{\llbracket U^3\rrbracket} + \frac{1}{384\pi^2}c_{\phi^8}^{\llbracket U^4\rrbracket}$ |
| $\mathscr{O}_{\phi^6}^{(1)} = (\phi^\dagger\phi)^2(D_\mu\phi^\dagger D^\mu\phi)$ | $\mathbb{C}_{\phi^6}^{(1)} = \frac{1}{16\pi^2}c_{\phi^6}^{(1),\llbracket U\rrbracket} - \frac{1}{384\pi^2}c_{\phi^6}^{(1),\llbracket U^2(P^2U)\rrbracket}$ |
| $\mathscr{O}_{\phi^6}^{(2)} = (\phi^\dagger\phi)(\phi^\dagger\sigma^I\phi)(D_\mu\phi^\dagger\sigma^I D^\mu\phi)$ | $\mathbb{C}_{\phi^6}^{(2)} = -\frac{1}{384\pi^2}c_{\phi^6}^{(2),\llbracket U^2(P^2U)\rrbracket}$ |
| $\mathscr{O}_{\phi^6}^{(3)} = (\phi^\dagger\phi)^2(\phi^\dagger D^2\phi + \text{h.c.})$ | $\mathbb{C}_{\phi^6}^{(3)} = \frac{1}{16\pi^2}c_{\phi^6}^{(3),\llbracket U\rrbracket} - \frac{1}{192\pi^2}c_{\phi^6}^{(3),\llbracket(P_\mu U)^2\rrbracket} - \frac{1}{384\pi^2}c_{\phi^6}^{(3),\llbracket U^2(P^2U)\rrbracket}$ |
| $\mathscr{O}_{W^2\phi^4}^{(1)} = (\phi^\dagger\phi)^2 W_{\mu\nu}^I W^{I\mu\nu}$ | $\mathbb{C}_{W^2\phi^4}^{(1)} = -\frac{1}{192\pi^2}c_{W^2\phi^4}^{(1),\llbracket U(G_{\mu\nu})^2\rrbracket} + \frac{1}{480\pi^2}c_{W^2\phi^4}^{(1),\llbracket U^2(G_{\mu\nu})^2\rrbracket} + \frac{1}{1920\pi^2}c_{W^2\phi^4}^{(1),\llbracket(UG_{\mu\nu})^2\rrbracket}$ |
| $\mathscr{O}_{W^2\phi^4}^{(3)} = (\phi^\dagger\sigma^I\phi)(\phi^\dagger\sigma^J\phi)W_{\mu\nu}^I W^{J\mu\nu}$ | $\mathbb{C}_{W^2\phi^4}^{(3)} = -\frac{1}{192\pi^2}c_{W^2\phi^4}^{(3),\llbracket U(G_{\mu\nu})^2\rrbracket} + \frac{1}{480\pi^2}c_{W^2\phi^4}^{(3),\llbracket U^2(G_{\mu\nu})^2\rrbracket} + \frac{1}{1920\pi^2}c_{W^2\phi^4}^{(3),\llbracket(UG_{\mu\nu})^2\rrbracket}$ |
| $\mathscr{O}_{B^2\phi^4}^{(1)} = (\phi^\dagger\phi)^2 B_{\mu\nu}B^{\mu\nu}$ | $\mathbb{C}_{B^2\phi^4}^{(1)} = -\frac{1}{192\pi^2}c_{B^2\phi^4}^{(1),\llbracket U(G_{\mu\nu})^2\rrbracket} + \frac{1}{480\pi^2}c_{B^2\phi^4}^{(1),\llbracket U^2(G_{\mu\nu})^2\rrbracket} + \frac{1}{1920\pi^2}c_{B^2\phi^4}^{(1),\llbracket(UG_{\mu\nu})^2\rrbracket} + \frac{1}{960\pi^2}c_{B^2\phi^4}^{(1),\llbracket U(J_\mu)^2\rrbracket}$ |
| $\mathscr{O}_{WB\phi^4}^{(1)} = (\phi^\dagger\phi)(\phi^\dagger\sigma^I\phi)W_{\mu\nu}^I B^{\mu\nu}$ | $\mathbb{C}_{WB\phi^4}^{(1)} = \frac{1}{480\pi^2}c_{WB\phi^4}^{(1),\llbracket U^2(G_{\mu\nu})^2\rrbracket} + \frac{1}{1920\pi^2}c_{WB\phi^4}^{(1),\llbracket(UG_{\mu\nu})^2\rrbracket}$ |
| $\mathscr{O}_{\phi^4}^{(3)} = (D^\mu\phi^\dagger D_\mu\phi)(D^\nu\phi^\dagger D_\nu\phi)$ | $\mathbb{C}_{\phi^4}^{(3)} = \frac{1}{16\pi^2}c_{\phi^6}^{(3),\llbracket U\rrbracket} + \frac{1}{1920\pi^2}c_{\phi^4}^{(3),\llbracket(P^2U)^2\rrbracket}$ |
| $\mathscr{O}_{\phi^4}^{(4)} = (D_\mu\phi^\dagger D^\mu\phi)(\phi^\dagger D^2\phi + \text{h.c.})$ | $\mathbb{C}_{\phi^4}^{(4)} = \frac{1}{16\pi^2}c_{\phi^4}^{(4),\llbracket U\rrbracket} + \frac{1}{1920\pi^2}c_{\phi^4}^{(4),\llbracket(P^2U)^2\rrbracket}$ |
| $\mathscr{O}_{\phi^4}^{(8)} = ((D^2\phi^\dagger\phi)(D^2\phi^\dagger\phi) + \text{h.c.})$ | $\mathbb{C}_{\phi^4}^{(8)} = \frac{1}{16\pi^2}c_{\phi^4}^{(8),\llbracket U\rrbracket} + \frac{1}{1920\pi^2}c_{\phi^4}^{(8),\llbracket(P^2U)^2\rrbracket}$ |
| $\mathscr{O}_{\phi^4}^{(10)} = (D^2\phi^\dagger D^2\phi)(\phi^\dagger\phi)$ | $\mathbb{C}_{\phi^4}^{(10)} = \frac{1}{16\pi^2}c_{\phi^4}^{(10),\llbracket U\rrbracket} + \frac{1}{1920\pi^2}c_{\phi^4}^{(10),\llbracket(P^2U)^2\rrbracket}$ |
| $\mathscr{O}_{\phi^4}^{(11)} = (\phi^\dagger D^2\phi)(D^2\phi^\dagger\phi)$ | $\mathbb{C}_{\phi^4}^{(11)} = \frac{1}{16\pi^2}c_{\phi^4}^{(11),\llbracket U\rrbracket} + \frac{1}{1920\pi^2}c_{\phi^4}^{(11),\llbracket(P^2U)^2\rrbracket}$ |
| $\mathscr{O}_{W\phi^4D^2}^{(6)} = (\phi^\dagger\phi)D_\nu W^{I\mu\nu}(D_\mu\phi^\dagger i\sigma^I\phi + \text{h.c.})$ | $\mathbb{C}_{W\phi^4D^2}^{(6)} = -\frac{1}{960\pi^2}c_{W\phi^4D^2}^{(6),\llbracket U(P_\mu U)J_\mu\rrbracket}$ |
| $\mathscr{O}_{W\phi^4D^2}^{(7)} = \varepsilon^{IJK}(D_\mu\phi^\dagger\sigma^I\phi)(\phi^\dagger\sigma^J D_\nu\phi)W^{K\mu\nu}$ | $\mathbb{C}_{W\phi^4D^2}^{(7)} = -\frac{1}{960\pi^2}c_{W\phi^4D^2}^{(7),\llbracket U(P_\mu U)J_\mu\rrbracket}$ |
| ⋮ | ⋮ |

| | |
|---|---|
| $c_{\phi^8}^{\llbracket U^4\rrbracket}$ | $\frac{3}{8}\lambda_4^4 + \frac{3}{4}\lambda_1^3\lambda_4 + \frac{15}{16}\lambda_1^2\lambda_4^2 + \frac{9}{16}\lambda_1\lambda_4^3 + \frac{17}{128}\lambda_4^4$ |
| $c_{\phi^6}^{(1),\llbracket U^2(P^2U)\rrbracket}$ | $\frac{3\lambda_1^3}{2} + \frac{9\lambda_1^2\lambda_4}{4} + \frac{11\lambda_1\lambda_4^2}{8} + \frac{5\lambda_4^3}{16}$ |
| $c_{\phi^6}^{(2),\llbracket U^2(P^2U)\rrbracket}$ | $\frac{\lambda_1\lambda_4^2}{2} + \frac{\lambda_4^3}{4}$ |
| $c_{\phi^6}^{(3),\llbracket U^2(P^2U)\rrbracket}$ | $\frac{3\lambda_1^3}{4} + \frac{9\lambda_1^2\lambda_4}{8} + \frac{15\lambda_1\lambda_4^2}{16} + \frac{9\lambda_4^3}{32}$ |
| $c_{W^2\phi^4}^{(1),\llbracket(UG_{\mu\nu})^2\rrbracket}$ | $-\frac{1}{4}g^2(2\lambda_1+\lambda_4)^2$ |
| $c_{W^2\phi^4}^{(3),\llbracket(UG_{\mu\nu})^2\rrbracket}$ | $-g^2\lambda_4^2$ |
| $c_{B^2\phi^4}^{(1),\llbracket(UG_{\mu\nu})^2\rrbracket}$ | $-\frac{1}{4}g^2\lambda_4^2 - \frac{3}{8}g'^2(2\lambda_1+\lambda_4)^2$ |
| $c_{WB\phi^4}^{(1),\llbracket(UG_{\mu\nu})^2\rrbracket}$ | $-2gg'\lambda_4(2\lambda_1+\lambda_4)$ |
| $c_{\phi^4}^{(3),\llbracket(P^2U)^2\rrbracket}$ | $6\lambda_1^2 + 6\lambda_1\lambda_4 + \frac{5}{2}\lambda_4^2$ |
| $c_{\phi^4}^{(4),\llbracket(P^2U)^2\rrbracket}$ | $6\lambda_1^2 + 6\lambda_1\lambda_4 + \frac{5}{2}\lambda_4^2$ |
| $c_{\phi^4}^{(8),\llbracket(P^2U)^2\rrbracket}$ | $\frac{3}{2}\lambda_1^2 + \frac{3}{2}\lambda_1\lambda_4 + \frac{5}{8}\lambda_4^2$ |
| $c_{\phi^4}^{(10),\llbracket(P^2U)^2\rrbracket}$ | $\lambda_4^2$ |
| $c_{\phi^4}^{(11),\llbracket(P^2U)^2\rrbracket}$ | $3\lambda_1^2 + 3\lambda_1\lambda_4 + \frac{1}{4}\lambda_4^2$ |
| ⋮ | ⋮ |

Matching results for dimension-eight operators in the SMEFT for the complex triplet model with the heavy triplet integrated up to one loop. The terms in blue, magenta, black and green denote the contributions from lower dimensional terms: $M_\Delta^{-4}, M_\Delta^{-2}, M_\Delta^0$, and $M_\Delta^2$, respectively.

# Complex Scalar Triplet upto Dimension-eight...

Incorporating the effect of fermionic interactions with the heavy scalar :

D5, D7 operators
↓
contribute to $\nu$ masses:
Type-II seesaw-mechanism

D6, D8 operators
↓
Strong constraints from lepton flavour violating decays

| Dim-8 EFT operators | Matching results at scale $M_\Delta (\gg v)$ |
|---|---|
| $\mathcal{O}^{(1)}_{l^4\phi^2} = \varepsilon_{ij}\varepsilon_{mn}(\ell^i C \ell^m)\phi^j\phi^n(\phi^\dagger\phi)$ | $\mathbb{C}^{(1)}_{l^4\phi^2} = -\frac{1}{32\pi^2} ln\frac{M_\Delta}{\mu^2} c^{(1),[\![U^2]\!]}_{l^4\phi^2} + \frac{1}{16\pi^2} c^{(1),[\![U]\!]}_{l^4\phi^2}$ |
| $\mathcal{O}^{(2)}_{l^4\phi^2} = \varepsilon_{ij}\varepsilon_{mn}(\ell^i C \ell^m)\phi^j\phi^n(\phi^\dagger\phi)$ | $\mathbb{C}^{(2)}_{l^4\phi^2} = -\frac{1}{32\pi^2} ln\frac{M_\Delta}{\mu^2} c^{(2),[\![U^2]\!]}_{l^4\phi^2} + \frac{1}{16\pi^2} c^{(2),[\![U]\!]}_{l^4\phi^2}$ |
| $\mathcal{O}^{(1)}_{l^4D^2} = D^\nu(\bar\ell_p\gamma^\mu\ell_r)D_\nu(\bar\ell_s\gamma_\mu\ell_t)$ | $\mathbb{C}^{(1)}_{l^4D^2} = \frac{1}{16\pi^2} c^{(1),[\![U]\!]}_{l^4D^2}$ |
| **Dim-7 EFT operators** | **Matching results at scale $M_\Delta (\gg v)$** |
| $\mathcal{O}^{(1)}_{L\phi D} = \varepsilon_{ij}\varepsilon_{mn}\ell^i C(D^\mu\ell^j)\phi^m(D_\mu\phi^n)$ | $\mathbb{C}^{(1)}_{L\phi D} = \frac{1}{16\pi^2} c^{(1),[\![U]\!]}_{L\phi D}$ |
| $\mathcal{O}^{(2)}_{L\phi D} = \varepsilon_{im}\varepsilon_{jn}\ell^i C(D^\mu\ell^j)\phi^m(D_\mu\phi^n)$ | $\mathbb{C}^{(2)}_{L\phi D} = \frac{1}{16\pi^2} c^{(2),[\![U]\!]}_{L\phi D}$ |
| $\mathcal{O}_{L\phi} = \varepsilon_{ij}\varepsilon_{mn}(\ell^i C \ell^m)\phi^j\phi^n(\phi^\dagger\phi)$ | $\mathbb{C}_{L\phi} = -\frac{1}{32\pi^2} ln\frac{M_\Delta}{\mu^2} c^{[\![U^2]\!]}_{L\phi}$ |
| **Dim-6 EFT operators** | **Matching results at scale $M_\Delta (\gg v)$** |
| $\mathcal{O}_{ll} = \left(\bar\ell^r_{L_\alpha}\gamma_\mu\ell^p_{L_\gamma}\right)_i\left(\bar\ell^s_{L_\beta}\gamma^\mu\ell^q_{L_\delta}\right)$ | $\mathbb{C}_{ll} = \frac{1}{16\pi^2} c^{[\![U]\!]}_{ll}$ |
| **Dim-5 EFT operators** | **Matching results at scale $M_\Delta (\gg v)$** |
| $\mathcal{O}_{\phi^2L^2} = \varepsilon_{ij}\varepsilon_{mn}\phi^i\phi^m(\ell^j_p)^T C\ell^n_r$ | $\mathbb{C}_{\phi^2L^2} = \frac{1}{16\pi^2} c^{[\![U]\!]}_{\phi^2L^2}$ |

| | |
|---|---|
| $c^{(1),[\![U]\!]}_{l^4\phi^2}$ | $\frac{-1}{4M^6} Y_{\Delta_{rt}} Y^*_{\Delta_{ps}} \left(10\lambda_1\lambda_2 + 6\lambda_1\lambda_3 + 5\lambda_2\lambda_4 + 3\lambda_3\lambda_4\right)$ |
| $c^{(2),[\![U]\!]}_{l^4\phi^2}$ | $\frac{-1}{4M^6} Y_{\Delta_{rt}} Y^*_{\Delta_{ps}} \left(6\lambda_1\lambda_4 + 2\lambda_2\lambda_4 + 3\lambda_3\lambda_4\right)$ |
| $c^{[\![U]\!]}_{l^4D^2}$ | $= \frac{-1}{4M^6} Y_{\Delta_{rt}} Y^*_{\Delta_{ps}} \left(20\lambda_2 + 12\lambda_3\right)$ |
| $c^{(1),[\![U^2]\!]}_{l^4\phi^2}$ | $\frac{1}{4M^6} Y_{\Delta_{rt}} Y^*_{\Delta_{ps}} \left(\frac{3}{2}\lambda_1\lambda_3 + \frac{3}{4}\lambda_3\lambda_4 + 2\lambda_1\lambda_2 + \lambda_2\lambda_4\right)$ |
| $c^{(2),[\![U^2]\!]}_{l^4\phi^2}$ | $\frac{-1}{8M^6} Y_{\Delta_{rt}} Y^*_{\Delta_{ps}} \lambda_4\lambda_2$ |
| $c^{(1),[\![U]\!]}_{L\phi D}$ | $\frac{-1}{2M^3}(4\lambda_2)\mu_\Delta Y_{\Delta_{ij}}$ |
| $c^{(2),[\![U]\!]}_{L\phi D}$ | $\frac{-1}{2M^3}(4\lambda_2)\mu_\Delta Y_{\Delta_{ij}}$ |
| $c^{[\![U]\!]}_{L\phi}$ | $\frac{-1}{2M^3}\mu_\Delta Y_{\Delta_{im}} \Big(\lambda_2\lambda_4 - \frac{3}{2}(\lambda_2+\lambda_3)\lambda_4 + \lambda_2(2\lambda_1+\lambda_4)$ |
| | $+\frac{3}{2}(\lambda_2+\lambda_3)(2\lambda_1+\lambda_4)\Big)$ |
| $c^{[\![U]\!]}_{ll}$ | $\frac{1}{4M^2} Y_{\Delta_{pq}} Y^*_{\Delta_{rs}} (4\lambda_2 + 3\lambda_3)^2$ |
| $c^{[\![U]\!]}_{\phi^2L^2}$ | $\frac{-1}{4M}\mu_\Delta Y_{\Delta_{pq}}(4\lambda_2 + 3\lambda_3)$ |

Matching for relevant dimension-eight, -seven, -six, -five operators in the SMEFT for the complex triplet model with the heavy triplet integrated up to one loop. The terms in blue, magenta, black and green denote the contributions from lower dimensional terms: $M_\Delta^{-4}, M_\Delta^{-2}, M_\Delta^{0}$, and $M_\Delta^{2}$, respectively.

# Complex Scalar Doublet upto Dimension-eight...

The full Lagrangian is given by:

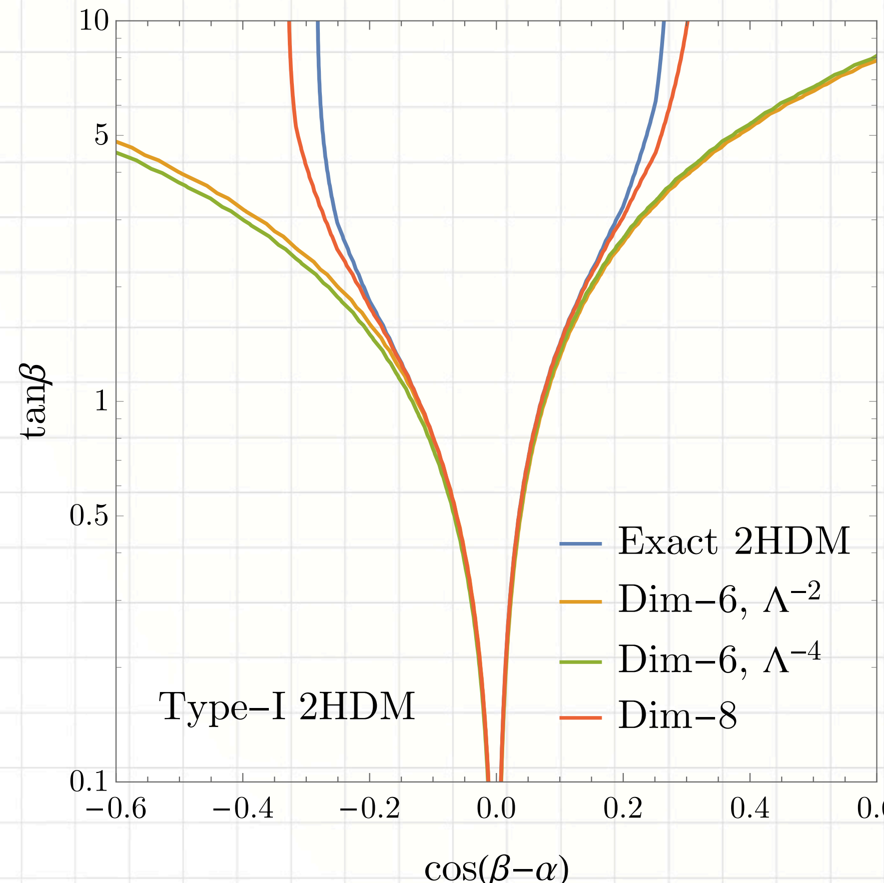
$$\mathscr{L}_{\mathscr{H}_2} = \mathscr{L}_{\rm SM} + |D_\mu \mathscr{H}_2|^2 - m^2_{\mathscr{H}_2}|\mathscr{H}_2|^2 + V_{\rm scalar} + \mathrm{L}_{\rm Yuk} \ ,$$

where $V_{\rm scalar}$ refers to the scalar potential part:

$$\begin{aligned} V_{\rm scalar} = &-\frac{\lambda_{\mathscr{H}_2}}{4}|\mathscr{H}_2|^4 - \left(\eta_H|\tilde{H}|^2 + \eta_{\mathscr{H}_2}|\mathscr{H}_2|^2\right)\left(\tilde{H}^\dagger \mathscr{H}_2 + \mathscr{H}_2^\dagger \tilde{H}\right) \\ &- \lambda_{\mathscr{H}_2,1}|\tilde{H}|^2|\mathscr{H}_2|^2 - \lambda_{\mathscr{H}_2,2}|\tilde{H}^\dagger \mathscr{H}_2|^2 - \lambda_{\mathscr{H}_2,3}\left[(\tilde{H}^\dagger \mathscr{H}_2)^2 + (\mathscr{H}_2^\dagger \tilde{H})^2\right] \ , \end{aligned}$$

and $\mathrm{L}_{\rm Yuk}$ is the Yukawa interactions of the fermions with the heavy scalar:

$$\mathrm{L}_{\rm Yuk} = -\left\{Y^{(e)}_{\mathscr{H}_2}\bar{\ell}_L \mathscr{H}_2 e_R + Y^{(u)}_{\mathscr{H}_2}\bar{q}_L \tilde{\mathscr{H}}_2 u_R + Y^{(d)}_{\mathscr{H}_2}\bar{q}_L \mathscr{H}_2 d_R + \text{h.c.}\right\}$$




Dawson, Fontes, Homiller, Sullivan 2205.01561

Exploring impact of dim-8 operators :

- Difficult to assess relevance when treated freely (e.g., in fits).
- when matched to specific models clarifies their natural scale and effects.

Dawson, Giardino, Homiller; PRD 103 (2021) 7, 075016
Dawson et al.; PRD 106 (2022) 5, 055012
Jiang et al.; JHEP 02 (2019) 031
Haisch et al.; JHEP 04 (2020) 164

# Complex Scalar Doublet upto Dimension-eight...

## Integrating out the heavy doublet up to one loop

| Dim-8 EFT operators | Matching results at scale $M_{\mathscr{H}_2}(\gg v)$ |
|---|---|
| $\mathscr{O}_{\phi^8} = (\phi^\dagger\phi)^4$ | $\mathbb{C}_{\phi^8} = \frac{1}{16\pi^2} c_{\phi^8}^{[\![U]\!]} - \frac{1}{32\pi^2}\ln\left(\frac{M^2_{\mathscr{H}_2}}{\mu^2}\right) c_{\phi^8}^{[\![U^2]\!]} - \frac{1}{96\pi^2} c_{\phi^8}^{[\![U^3]\!]} + \frac{1}{384\pi^2} c_{\phi^8}^{[\![U^4]\!]}$ |
| $\mathscr{O}^{(1)}_{\phi^6} = (\phi^\dagger\phi)^2(D_\mu\phi^\dagger D^\mu\phi)$ | $\mathbb{C}^{(1)}_{\phi^6} = -\frac{1}{192\pi^2} c_{\phi^6}^{(1),[\![(P_\mu U)^2]\!]}$ |
| $\mathscr{O}^{(3)}_{\phi^6} = (\phi^\dagger\phi)^2(\phi^\dagger D^2\phi + \text{h.c.})$ | $\mathbb{C}^{(3)}_{\phi^6} = \frac{1}{16\pi^2} c_{\phi^6}^{(3),[\![U]\!]} - \frac{1}{192\pi^2} c_{\phi^6}^{(3),[\![(P_\mu U)^2]\!]} - \frac{1}{384\pi^2} c_{\phi^6}^{(3),[\![U^2(P^2U)]\!]}$ |
| $\mathscr{O}^{(1)}_{W^2\phi^4} = (\phi^\dagger\phi)^2 W^I_{\mu\nu}W^{I\mu\nu}$ | $\mathbb{C}^{(1)}_{W^2\phi^4} = -\frac{1}{192\pi^2} c_{W^2\phi^4}^{(1),[\![U(G_{\mu\nu})^2]\!]} + \frac{1}{480\pi^2} c_{W^2\phi^4}^{(1),[\![U^2(G_{\mu\nu})^2]\!]} + \frac{1}{1920\pi^2} c_{W^2\phi^4}^{(1),[\![(UG_{\mu\nu})^2]\!]}$ |
| $\mathscr{O}^{(1)}_{B^2\phi^4} = (\phi^\dagger\phi)^2 B_{\mu\nu}B^{\mu\nu}$ | $\mathbb{C}^{(1)}_{B^2\phi^4} = -\frac{1}{192\pi^2} c_{B^2\phi^4}^{(1),[\![U(G_{\mu\nu})^2]\!]} + \frac{1}{480\pi^2} c_{B^2\phi^4}^{(1),[\![U^2(G_{\mu\nu})^2]\!]} + \frac{1}{1920\pi^2} c_{B^2\phi^4}^{(1),[\![(UG_{\mu\nu})^2]\!]}$ |
| $\mathscr{O}^{(1)}_{WB\phi^4} = (\phi^\dagger\phi)(\phi^\dagger\sigma^I\phi) W^I_{\mu\nu}B^{\mu\nu}$ | $\mathbb{C}^{(1)}_{WB\phi^4} = -\frac{1}{192\pi^2} c_{WB\phi^4}^{(1),[\![U(G_{\mu\nu})^2]\!]} + \frac{1}{480\pi^2} c_{WB\phi^4}^{(1),[\![U^2(G_{\mu\nu})^2]\!]} + \frac{1}{1920\pi^2} c_{WB\phi^4}^{(1),[\![(UG_{\mu\nu})^2]\!]}$ |
| $\mathscr{O}^{(3)}_{\phi^4} = (D^\mu\phi^\dagger D_\mu\phi)(D^\nu\phi^\dagger D_\nu\phi)$ | $\mathbb{C}^{(3)}_{\phi^4} = \frac{1}{16\pi^2} c_{\phi^6}^{(3),[\![U]\!]}$ |
| $\mathscr{O}^{(4)}_{\phi^4} = (D_\mu\phi^\dagger D^\mu\phi)(\phi^\dagger D^2\phi + \text{h.c.})$ | $\mathbb{C}^{(4)}_{\phi^4} = \frac{1}{16\pi^2} c_{\phi^4}^{(4),[\![U]\!]} + \frac{1}{1920\pi^2} c_{\phi^4}^{(4),[\![(P^2U)^2]\!]}$ |
| $\mathscr{O}^{(8)}_{\phi^4} = ((D^2\phi^\dagger\phi)(D^2\phi^\dagger\phi) + \text{h.c.})$ | $\mathbb{C}^{(8)}_{\phi^4} = \frac{1}{16\pi^2} c_{\phi^4}^{(8),[\![U]\!]} + \frac{1}{1920\pi^2} c_{\phi^4}^{(8),[\![(P^2U)^2]\!]}$ |
| $\mathscr{O}^{(10)}_{\phi^4} = (D^2\phi^\dagger D^2\phi)(\phi^\dagger\phi)$ | $\mathbb{C}^{(10)}_{\phi^4} = \frac{1}{16\pi^2} c_{\phi^4}^{(10),[\![U]\!]}$ |
| $\mathscr{O}^{(11)}_{\phi^4} = (\phi^\dagger D^2\phi)(D^2\phi^\dagger\phi)$ | $\mathbb{C}^{(11)}_{\phi^4} = \frac{1}{16\pi^2} c_{\phi^4}^{(11),[\![U]\!]} + \frac{1}{1920\pi^2} c_{\phi^4}^{(11),[\![(P^2U)^2]\!]}$ |
| ⋮ | ⋮ |

| | |
|---|---|
| $c_{\phi^8}^{[\![U^4]\!]}$ | $4\lambda_1^4 + 8\lambda_1^3\lambda_2 + 12\lambda_1^2\lambda_2^2 + 192\lambda_1^2\lambda_3^2 + 8\lambda_1\lambda_2^3 + 96\lambda_1\lambda_2\lambda_3^2 + 2\lambda_2^4 + 48\lambda_2^2\lambda_3^2 + 32\lambda_3^4$ |
| $c_{\phi^6}^{(3),[\![U^2(P^2U)]\!]}$ | $4\lambda_1^3 - 6\lambda_1^2\lambda_2 - 6\lambda_1\lambda_2^2 - 16\lambda_1\lambda_3^2 - 2\lambda_2^3 - 8\lambda_2\lambda_3^2.$ |
| $c_{W^2\phi^4}^{(1),[\![U^2(G_{\mu\nu})^2]\!]}$ | $-g^2\left(\lambda_1^2 + \lambda_1\lambda_2 + \frac{1}{2}\lambda_2^2\right)$ |
| $c_{B^2\phi^4}^{(1a),[\![U^2(G_{\mu\nu})^2]\!]}$ | $-2g'^2\left(2\lambda_1^2 + \lambda_2^2 + 2\lambda_1\lambda_2\right)$ |
| $c_{WB\phi^4}^{(1),[\![U^2(G_{\mu\nu})^2]\!]}$ | $-8gg'\lambda_1\lambda_2$ |
| $c_{W^2\phi^4}^{(1),[\![(UG_{\mu\nu})^2]\!]}$ | $-g^2\left(2\lambda_1^2 - \frac{1}{2}\lambda_2^2 - 2\lambda_1\lambda_2\right)$ |
| $c_{B^2\phi^4}^{(1),[\![(UG_{\mu\nu})^2]\!]}$ | $-g'^2\left(8\lambda_1^2 - 2\lambda_2^2 - 8\lambda_1\lambda_2\right)$ |
| $c_{WB\phi^4}^{(1),[\![(UG_{\mu\nu})^2]\!]}$ | $-4gg'\lambda_1\lambda_2$ |
| $c_{\phi^4}^{(4),[\![(P^2U)^2]\!]}$ | $8\left(4\lambda_1^2 + 4\lambda_1\lambda_2 + \lambda_2^2\right)$ |
| $c_{\phi^4}^{(8),[\![(P^2U)^2]\!]}$ | $2\left(4\lambda_1^2 + 4\lambda_1\lambda_2 + \lambda_2^2\right)$ |
| $c_{\phi^4}^{(11),[\![(P^2U)^2]\!]}$ | $4\left(4\lambda_1^2 + 4\lambda_1\lambda_2 + \lambda_2^2\right)$ |
| $c_{\phi^4}^{(12),[\![(P^2U)^2]\!]}$ | $-8\left(4\lambda_1^2 + 4\lambda_1\lambda_2 + \lambda_2^2\right)$ |
| $c_{B^2\phi^2D^2}^{(6),[\![U(J_\mu)^2]\!]}$ | $-4g'^2(2\lambda_1 + \lambda_2)$ |
| $c_{B^2\phi^2D^2}^{(8),[\![U(J_\mu)^2]\!]}$ | $-4g'^2(2\lambda_1 + \lambda_2)$ |
| $c_{WB\phi^2D^2}^{(10),[\![U(J_\mu)^2]\!]}$ | $-4gg'\lambda_2$ |
| $c_{W^2\phi^2D^2}^{(13),[\![U(J_\mu)^2]\!]}$ | $-g^2(2\lambda_1 + \lambda_2)$ |
| ⋮ | ⋮ |

Matching results for relevant dimension-eight operators in the SMEFT for the complex triplet model with the heavy triplet integrated up to one loop. The terms in blue, magenta, black and green denote the contributions from lower dimensional terms: $M^{-4}_{\mathscr{H}_2}, M^{-2}_{\mathscr{H}_2}, M^{0}_{\mathscr{H}_2}$ and $M^{2}_{\mathscr{H}_2}$, respectively.

# To Dimension-8

$O_{\phi}^{8} : (\phi^{\dagger}\phi)^4$

↓

Higgs trilinear & quartic couplings
Higgs pair & triple Higgs production

$O_{\phi^6}^{(1)} : (\phi^{\dagger}\phi)^2 (D_{\mu}\phi)^{\dagger}(D^{\mu}\phi)$

↓

All Higgs couplings & Higgs $ZZ/WW$
Single Higgs production & decay

$O_{u\phi^5} : (\phi^{\dagger}\phi)^2 \bar{Q}u\tilde{\phi}$

↓

Top quark Yukawa coupling
Gluon fusion & $t\bar{t}h$

| Dim-8 EFT operators | Matching results at scale $M_{\mathcal{H}_2}(\gg v)$ |
|---|---|
| $\mathcal{O}_{le\phi^5} = (\phi^{\dagger}\phi)^2(\bar{l}_p e_r \phi)$ | $\mathbb{C}_{le\phi^5} = \frac{-1}{96\pi^2} c_{le\phi^5}^{\llbracket U^3 \rrbracket} - \frac{1}{32\pi^2} ln\frac{M_{\mathcal{H}_2}}{\mu^2} c_{le\phi^5}^{\llbracket U^2 \rrbracket} + \frac{1}{16\pi^2} c_{le\phi^5}^{\llbracket U \rrbracket}$ |
| $\mathcal{O}_{le\phi^3D^2}^{(1)} = (D_{\mu}\phi^{\dagger}D^{\mu}\phi)(\bar{l}_p e_r \phi)$ | $\mathbb{C}_{le\phi^3D^2}^{(1)} = \frac{-1}{96\pi^2} c_{le\phi^3D^2}^{(1),\llbracket U^3 \rrbracket} - \frac{1}{32\pi^2} ln\frac{M_{\mathcal{H}_2}}{\mu^2} c_{le\phi^5}^{(1),\llbracket U^2 \rrbracket} + \frac{1}{16\pi^2} c_{le\phi^3D^2}^{(1),\llbracket U \rrbracket}$ |
| $\mathcal{O}_{le\phi^3D^2}^{(5)} = (\phi^{\dagger}D_{\mu}\phi)(\bar{l}_p e_r D^{\mu}\phi)$ | $\mathbb{C}_{le\phi^3D^2}^{(5)} = \frac{-1}{96\pi^2} c_{le\phi^3D^2}^{(5),\llbracket U^3 \rrbracket} - \frac{1}{32\pi^2} ln\frac{M_{\mathcal{H}_2}}{\mu^2} c_{le\phi^3D^2}^{(5),\llbracket U^2 \rrbracket} + \frac{1}{16\pi^2} c_{le\phi^3D^2}^{(5),\llbracket U \rrbracket}$ |
| $\mathcal{O}_{leW^2\phi}^{(1)} = (\bar{l}_p e_r)\phi W_{\mu\nu}^{I} W^{I\mu\nu}$ | $\mathbb{C}_{leW^2\phi}^{(1)} = \frac{-1}{96\pi^2} c_{leW^2\phi}^{(1),\llbracket U^3 \rrbracket}$ |
| $\mathcal{O}_{leB^2\phi}^{(1)} = (\bar{l}_p e_r)\phi B_{\mu\nu} B^{\mu\nu}$ | $\mathbb{C}_{leB^2\phi}^{(1)} = \frac{-1}{96\pi^2} c_{leB^2\phi}^{(1),\llbracket U^3 \rrbracket}$ |
| $\mathcal{O}_{leWB\phi}^{(1)} = (\bar{l}_p e_r)\tau^{I}\phi W_{\mu\nu}^{I} B^{\mu\nu}$ | $\mathbb{C}_{leWB\phi}^{(1)} = \frac{-1}{96\pi^2} c_{leWB\phi}^{(1),\llbracket U^3 \rrbracket}$ |
| $\mathcal{O}_{l^2e^2\phi^2}^{(1)} = (\bar{l}_p e_r \phi)(\bar{l}_s e_t \phi)$ | $\mathbb{C}_{l^2e^2\phi^2}^{(1)} = -\frac{1}{32\pi^2} ln\frac{M_{\mathcal{H}_2}}{\mu^2} c_{l^2e^2\phi^2}^{(1),\llbracket U^2 \rrbracket} + \frac{1}{16\pi^2} c_{l^2e^2\phi^2}^{(1),\llbracket U \rrbracket}$ |
| $\mathcal{O}_{l^2e^2\phi^2}^{(3)} = (\bar{l}_p \gamma_{\mu} l_r)(\bar{e}_s \gamma^{\mu} e_r)\phi^{\dagger}\phi$ | $\mathbb{C}_{l^2e^2\phi^2}^{(3)} = \frac{1}{16\pi^2} c_{l^2e^2\phi^2}^{(3),\llbracket U \rrbracket}$ |
| $\mathcal{O}_{lequ\phi^2}^{(1)} = (\bar{l}_p^{j} e_r)\varepsilon_{jk}(\bar{q}_s^{t} u_t)\phi^{\dagger}\phi$ | $\mathbb{C}_{lequ\phi^2}^{(1)} = -\frac{1}{32\pi^2} ln\frac{M_{\mathcal{H}_2}}{\mu^2} c_{le\phi^5}^{\llbracket U^2 \rrbracket} + \frac{1}{16\pi^2} c_{lequ\phi^2}^{\llbracket U \rrbracket}$ |
| $\mathcal{O}_{leqd\phi^2}^{(3)} = (\bar{l}_p e_r \phi)(\bar{q}_s d_t \phi)$ | $\mathbb{C}_{leqd\phi^2}^{(3)} = -\frac{1}{32\pi^2} ln\frac{M_{\mathcal{H}_2}}{\mu^2} c_{leqd\phi^2}^{(3),\llbracket U^2 \rrbracket} + \frac{1}{16\pi^2} c_{leqd\phi^2}^{(3),\llbracket U \rrbracket}$ |
| $\mathcal{O}_{l^2e^2D^2} = (\bar{l}_p e_r \phi)(\bar{q}_s d_t \phi)$ | $\mathbb{C}_{l^2e^2D^2} = \frac{1}{16\pi^2} c_{l^2e^2D^2}^{\llbracket U \rrbracket}$ |
| **Dim-6 EFT operators** | **Matching results at scale $M_{\mathcal{H}_2}(\gg v)$** |
| $\mathcal{O}_{e\phi} = (\phi^{\dagger}\phi)(\bar{l}_p e_r \phi)$ | $\mathbb{C}_{e\phi} = -\frac{1}{32\pi^2} ln\frac{M_{\mathcal{H}_2}}{\mu^2} c_{e\phi}^{\llbracket U^2 \rrbracket}(1+m_H^2) + \frac{1}{16\pi^2} c_{e\phi}^{\llbracket U \rrbracket}(1+m_H^2)$ |
| $\mathcal{O}_{le} = (\bar{l}_p \gamma_{\mu} l_r)(\bar{e}_s \gamma^{\mu} e_t)$ | $\mathbb{C}_{le} = \frac{1}{16\pi^2} c_{le}^{\llbracket U \rrbracket}$ |
| $\mathcal{O}_{ledq} = (\bar{l}_p^{j} e_r)(\bar{d}_s q_t^{j})$ | $\mathbb{C}_{ledq} = \frac{1}{16\pi^2} c_{ledq}^{(1),\llbracket U \rrbracket}$ |
| $\mathcal{O}_{lequ}^{(1)} = (\bar{l}_p^{j} e_r)\varepsilon_{jk}(\bar{q}_s^{k} u_t)$ | $\mathbb{C}_{lequ}^{(1)} = \frac{1}{16\pi^2} c_{lequ}^{(1),\llbracket U \rrbracket}$ |

| | |
|---|---|
| $c_{le\phi^5}^{\llbracket U^3 \rrbracket}$ | $\frac{-Y_{\mathcal{H}_2}^{(e)}}{M^2}\Big(18\eta_{\mathcal{H}_2}\lambda_1^2 + 36\eta_{\mathcal{H}_2}\lambda_1\lambda_2 + 16\eta_{\mathcal{H}_2}\lambda_3^2 + 12\lambda_3\eta_{\mathcal{H}_2}(\lambda_1+\lambda_2)\Big)$ |
| $c_{le\phi^3D^2}^{(1),\llbracket (P_{\mu}U)^2 \rrbracket}$ | $\frac{1}{M^2}\Big((6\lambda_1 + 4\lambda_2)\eta_{\mathcal{H}_2} Y_{\mathcal{H}_2}^{(e)}\Big)$ |
| $c_{le\phi^3D^2}^{(5),\llbracket (P_{\mu}U)^2 \rrbracket}$ | $\frac{1}{M^2}\Big((6\lambda_1 + 4\lambda_2)\eta_{\mathcal{H}_2} Y_{\mathcal{H}_2}^{(e)}\Big)$ |
| $c_{leW^2\phi}^{(1),\llbracket U(G_{\mu\nu})^2 \rrbracket}$ | $\frac{1}{M^2}\eta_{\mathcal{H}_2}\Big(g^2 Y_{\mathcal{H}_2}^{(e)} + \eta_{\mathcal{H}_2}\frac{g^2}{2} Y_{\mathcal{H}_2}^{(e)}\Big)$ |
| $c_{leB^2\phi}^{(1),\llbracket U(G_{\mu\nu})^2 \rrbracket}$ | $\frac{1}{M^2}\Big(6\eta_{\mathcal{H}_2} g'^2 Y_{\mathcal{H}_2}^{(e)}\Big)$ |
| $c_{leWB\phi}^{(1),\llbracket U(G_{\mu\nu})^2 \rrbracket}$ | $\frac{1}{M^2}\Big(\eta_{\mathcal{H}_2} g g' Y_{\mathcal{H}_2}^{(e)}\Big)$ |
| $c_{l^2e^2\phi^2}^{(1),\llbracket U \rrbracket}$ | $-\frac{1}{M^6}\Big((6\lvert Y_{\mathcal{H}_2}^{(e)}\rvert^2)\eta_{\mathcal{H}_2} + Y_{\mathcal{H}_2}^{(e)} Y_{\text{SM}}^{(e)}\eta_{\mathcal{H}_2}(\lambda_1-\lambda_2) + 3Y_{\mathcal{H}_2}^{(e)} Y_{\text{SM}}^{(e)}\eta_{\mathcal{H}_2}(2\lambda_1+\lambda_2)$ |
| | $-3\lambda_{\mathcal{H}_2}\lvert Y_{\mathcal{H}_2}^{(e)}\rvert^2(\lambda_1+\lambda_2) + 3Y_{\mathcal{H}_2}^{(e)} Y_{\text{SM}}^{(e)}\eta_{\mathcal{H}_2}\lambda_{\mathcal{H}_2}\Big)$ |
| $c_{l^2e^2\phi^2}^{(3),\llbracket U \rrbracket}$ | $-\frac{1}{M^6}\Big(6Y_{\mathcal{H}_2}^{(e)2}\eta_{\mathcal{H}_2} + Y_{\mathcal{H}_2}^{(e)} Y_{\text{SM}}^{(e)}\eta_{\mathcal{H}_2}(\lambda_1-\lambda_2)\Big)$ |
| $c_{lequ\phi^2}^{(1),\llbracket U \rrbracket}$ | $\frac{1}{M^6}\Big(-7Y_{\mathcal{H}_2}^{(e)} Y_{\text{SM}}^{(u)}\eta_{\mathcal{H}_2}\lambda_1 - 2Y_{\mathcal{H}_2}^{(e)} Y_{\text{SM}}^{(u)}\eta_{\mathcal{H}_2}\lambda_2 - 3Y_{\mathcal{H}_2}^{(e)} Y_{\text{SM}}^{(u)}\eta_{\mathcal{H}_2}\lambda_{\mathcal{H}_2}\Big)$ |
| $c_{leqd\phi^2}^{(3),\llbracket U \rrbracket}$ | $\frac{1}{M^6}\Big(-Y_{\mathcal{H}_2}^{(e)} Y_{\text{SM}}^{(d)}\eta_{\mathcal{H}_2}(\lambda_1+\lambda_2) - 3Y_{\mathcal{H}_2}^{(e)} Y_{\text{SM}}^{(d)*}\eta_{\mathcal{H}_2}(2\lambda_1+\lambda_2)$ |
| | $+3Y_{\mathcal{H}_2}^{(e)} Y_{\text{SM}}^{(d)}\eta_{\mathcal{H}_2}\lambda_{\mathcal{H}_2}\Big)$ |
| $c_{l^2e^2D^2}^{\llbracket U \rrbracket}$ | $\frac{3}{M^6}\lambda_{H_2}\lvert Y_{\mathcal{H}_2}^{(e)}\rvert^2$ |
| $c_{le\phi^3D^2}^{(5),\llbracket U^2 \rrbracket}$ | $\frac{1}{M^6}\Big(-6Y_{\mathcal{H}_2}^{(e)}\eta_{\mathcal{H}_2}^{(e)}\lambda_{\mathcal{H}_2}\Big)$ |
| $c_{le\phi^5}^{\llbracket U \rrbracket}$ | $\frac{1}{M^6}\Big(-3Y_{\mathcal{H}_2}^{(e)*}\eta_{\mathcal{H}_2}\lambda_1^2 - 6Y_{\mathcal{H}_2}^{(e)*}\eta_{\mathcal{H}_2}\lambda_1\lambda_2 - 3Y_{\mathcal{H}_2}^{(e)*}\eta_{\mathcal{H}_2}\lambda_2^2$ |
| | $-3Y_{\mathcal{H}_2}^{(e)}\eta_{\mathcal{H}_2}(2\lambda_1+\lambda_2)\lambda_{\text{SM}} - 2{Y_{\mathcal{H}_2}^{(e)}}^2\eta_{\mathcal{H}_2}(\lambda_1+\lambda_2)\lambda_{\text{SM}} + 6Y_{\mathcal{H}_2}^{(e)}\lambda_{\mathcal{H}_2}\lambda_1$ |
| | $+6Y_{\mathcal{H}_2}^{(e)}\lambda_{\mathcal{H}_2}\lambda_2 + 9Y_{\mathcal{H}_2}^{(e)}\eta_{\mathcal{H}_2}\lambda_{\mathcal{H}_2}\lambda_{\text{SM}}\Big)$ |
| $c_{e\phi}^{\llbracket U \rrbracket}$ | $\frac{1}{M^6}\Big(m_H^2 Y_{\mathcal{H}_2}^{(e)}\eta_{\mathcal{H}_2}(8\lambda_1+\lambda_2) - 9m_H^2 Y_{\mathcal{H}_2}^{(e)}\eta_{\mathcal{H}_2}\lambda_{\mathcal{H}_2}\Big)$ |
| $c_{e\phi}^{\llbracket U \rrbracket}$ | $\frac{1}{M^2}\Big(-3\eta_{\mathcal{H}_2}\lambda_{\text{SM}} Y_{\mathcal{H}_2}^{(e)} + 3\eta_{\mathcal{H}_2}(\lambda_1+\lambda_2)\Big)$ |
| $c_{le}^{\llbracket U \rrbracket}$ | $\frac{1}{M^2}\Big(-3\eta_{\mathcal{H}_2} Y_{\text{SM}}^{(e)} Y_{\mathcal{H}_2}^{(e)} - \frac{3}{2}\lambda_{\mathcal{H}_2} Y_{\mathcal{H}_2}^{(e)} Y_{\mathcal{H}_2}^{(e)*}\Big)$ |
| $c_{ledq}^{\llbracket U \rrbracket}$ | $-\frac{1}{M^2}\Big(-3\eta_{\mathcal{H}_2} Y_{\text{SM}}^{(d)*} Y_{\mathcal{H}_2}^{(e)}\Big)$ |
| $c_{lequ}^{(1),\llbracket U \rrbracket}$ | $\frac{1}{M^2}\Big(-3\eta_{\mathcal{H}_2} Y_{\text{SM}}^{(u)} Y_{\mathcal{H}_2}^{(e)}\Big)$ |

Matching results for relevant dimension-eight and dimension-six operators in the SMEFT for the complex triplet model with the heavy triplet integrated up to one loop. The terms in blue, magenta, black and green denote the contributions from lower dimensional terms: $M_{\mathcal{H}_2}^{-4}, M_{\mathcal{H}_2}, M_{\mathcal{H}_2}^{0}$, and $M_{\mathcal{H}_2}^{2}$, respectively.

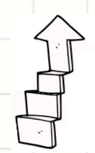
# Summary and Outlook

- The SMEFT is a well-defined, general framework to parametrize BSM effects.
- Given the prowess and potential of LHC as a precision machine, matching EFT with the UV-model is imperative especially if the new physics is lurking outside the LHC reach.
- Matching mismatch sometimes require the introduction of higher order operators.

- UOLEA up to dimension 8 It is universal, i.e., does not depend on the specific form of the UV theory as well as IR DoFs.
- Equally applicable for SMEFT or any other effective theory at any scale
- We performed matching for complex triplet scalar and doublet scalar models.
- Will be implemented in matching tools like CoDEx to get the WCs.

- Dimension-8 effects are phenomenologically interesting.
- NTGC searches provide important tests for the gauge structure of the SM, clean channel that improves with higher luminosity.
- Identify regions where the EFT expansion may be breaking down.

- We have lots to do to enable discovery of new Physics, by improving analysis techniques, looking for unconventional signatures, increasing precision and assessing validity.



**Thank you for your attention**