SMEFT Matching and Renormalisation

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24 August 2023

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SMEFT

$$\mathcal{L}_{\mathrm{SM}} + \underbrace{\sum_{j=5,\ldots} \sum_{i} \frac{C_i^{(j)}}{\Lambda^{j-4}} Q_i^{(j)}}_{\text{Effective operators}}$$

✤ **SMEFT is a well established idea.**

Dimension-5: S. Weinberg, PRL(**1979**), Baryon- and Lepton-Nonconserving Processes

Dimension-6:

(a) W. Buchmüller, D. Wyler, Nuc. Phy. B (**1986**),
Effective lagrangian analysis of new interactions and flavour conservation

(b) B. Grzadkowski, M. Iskrzynski, M. Misiak, J. Rosiek, JHEP (**2010**),
Dimension-Six Terms in the Standard Model Lagrangian

Recently, there is an uprise in SMEFT basis research: Dimension-7,8,9,…

D6: 2003.12525 (R), D7: 1410.4193 (P), 2005.08013 (R), D8: 2005.08013 (P), 2112.12724 (R)*, 2211.01420(R)

BSM scenarios and Effective theory

Beyond Standard Model scenarios

(1) Introduce new particles yet undiscovered

(2) Enlarge the underlying symmetry

Observation:

No clue about properties of new particles!

No clue about underlying gauge symmetry!

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Hint from history : Fermi's idea of four-fermion vertex

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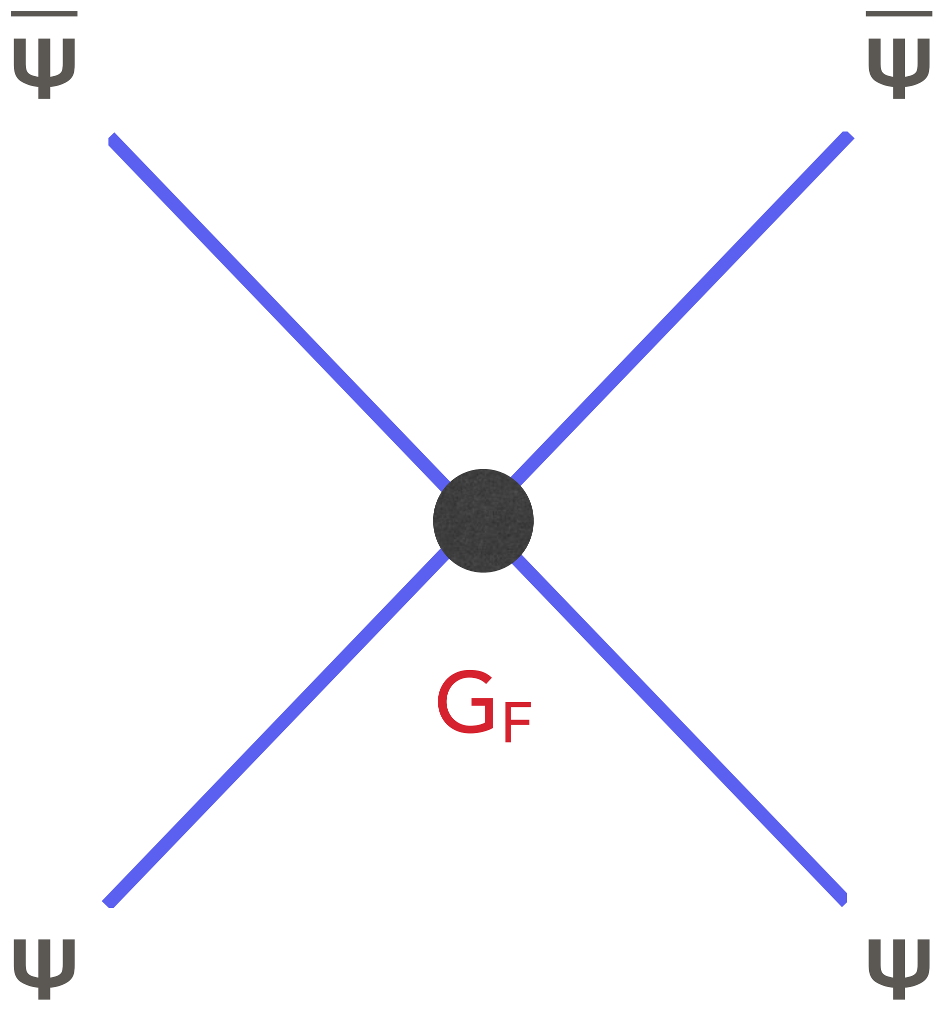

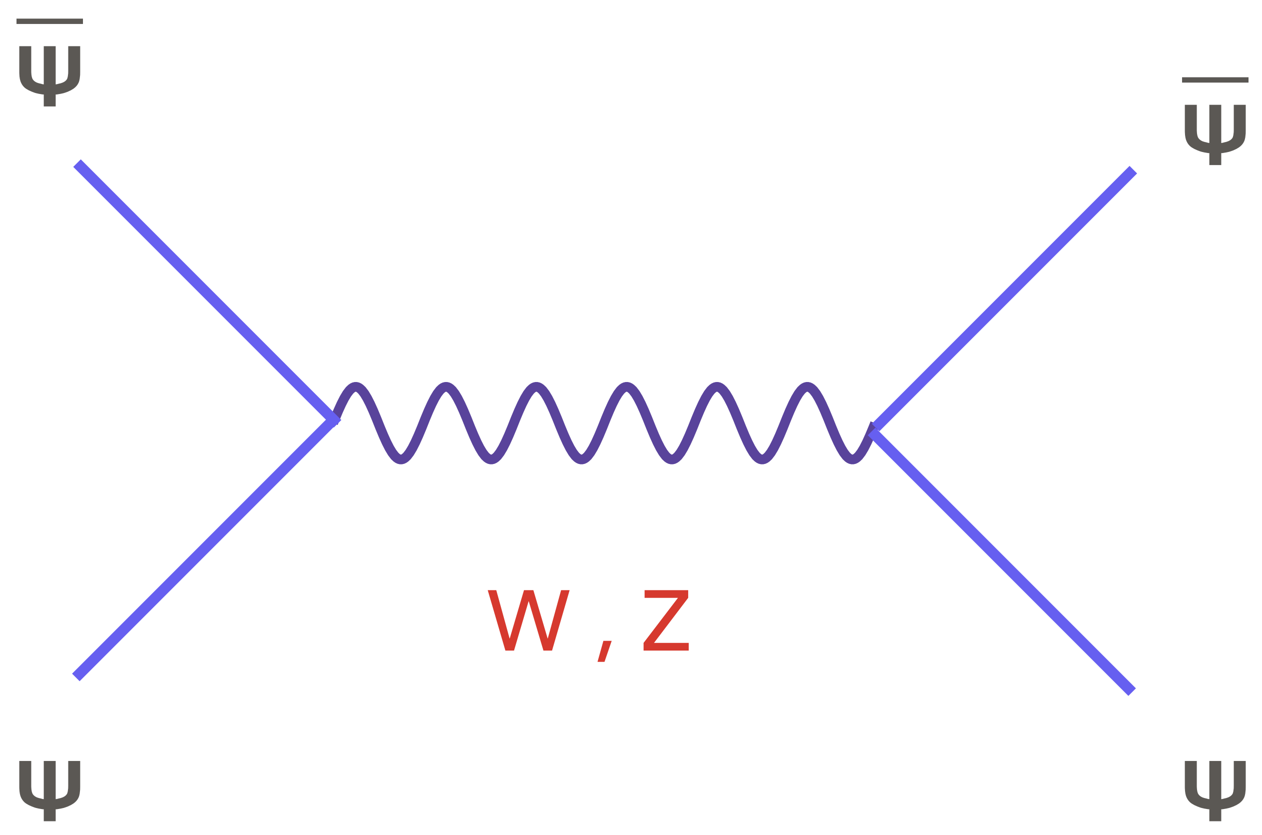

$$\frac{g_W^2}{p^2 - m_W^2} \simeq \frac{g_W^2}{-m_W^2} = -4\sqrt{2}\, G_F$$

BSM scenarios and Effective theory

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Higher mass dimension operators

$$\mathcal{L}_{\rm BSM} \to \mathcal{L}_{\rm SM} + \text{higher mass dimension operators}$$

Utility of EFTs :

If the energy scale of new physics is beyond the reach of recent experiments,

Parameterise lack of information in terms of higher mass dimension operators

- Study the relevant processes — no need to consider the full theory
- Resummation of large logarithms

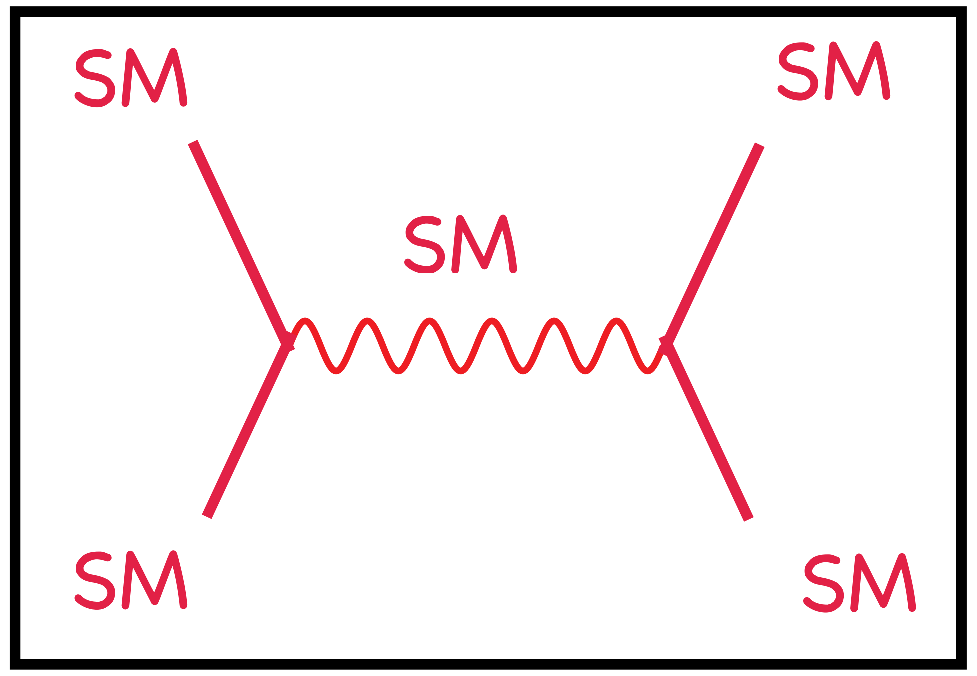
Georgi ARNPS 1993 43:209-52

Manohar arXiv:1804.05863

Falkowski Lectures on EFT Saclay'17

Bottom-Up approach: ***SMEFT***

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



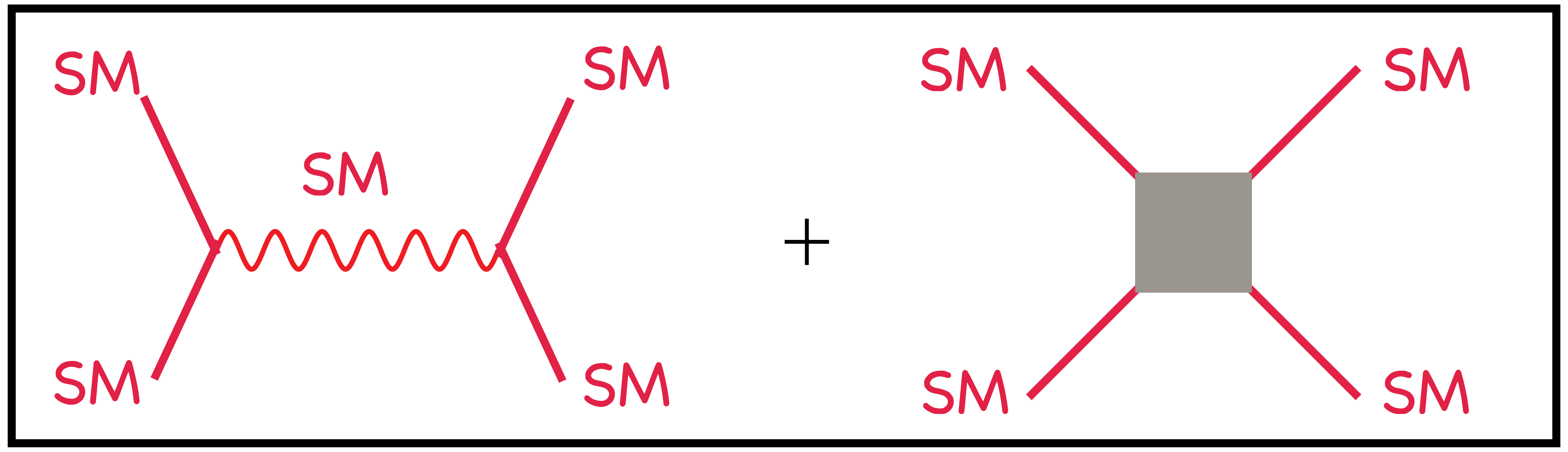
Low Energy Theory

Bottom-Up approach: *SMEFT*

★ **Knowledge of exact nature of new physics is not required**

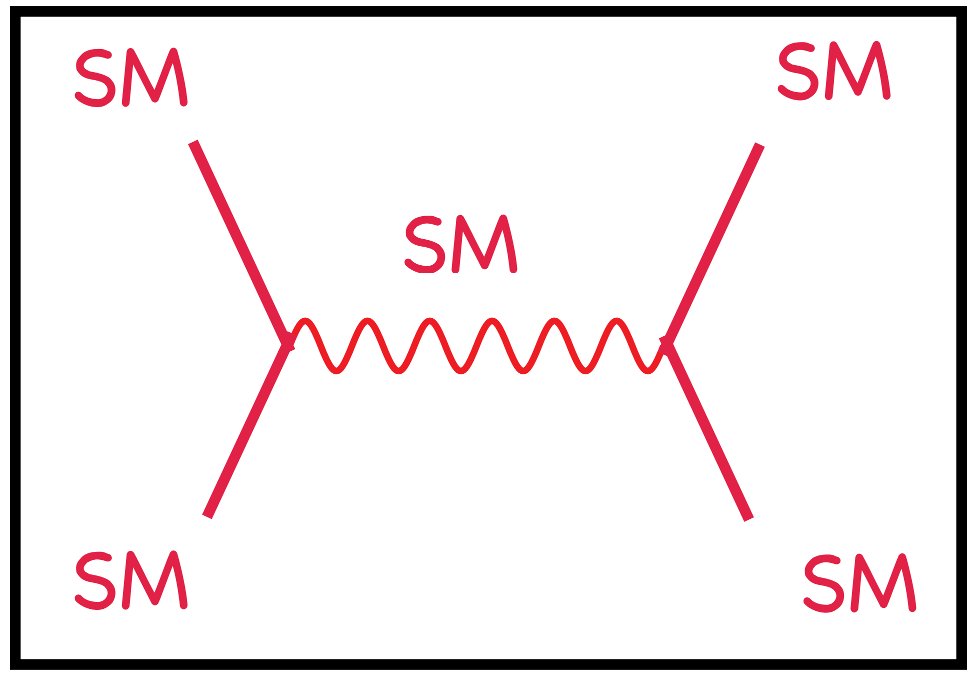
✤ **Wilson coefficients are free parameters: *origin-less***

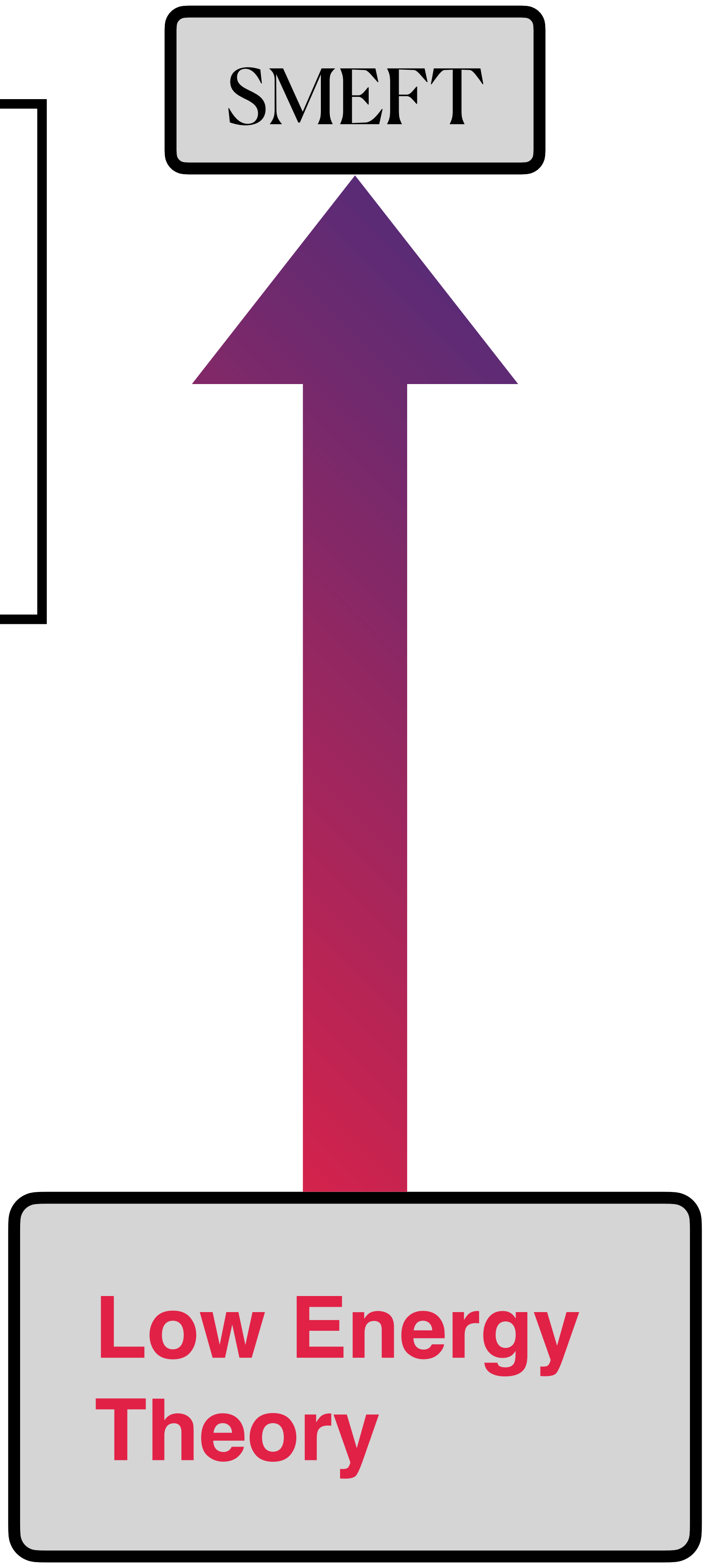
$$\mathcal{L}_{\rm SM} + \underbrace{\sum_{j=5,\ldots}\sum_{i}\frac{C_i^{(j)}}{\Lambda^{j-4}}Q_i^{(j)}}_{\text{Effective operators}} \rightarrow$$



Effective operators

$$\mathcal{L}_{\rm SM} \rightarrow$$

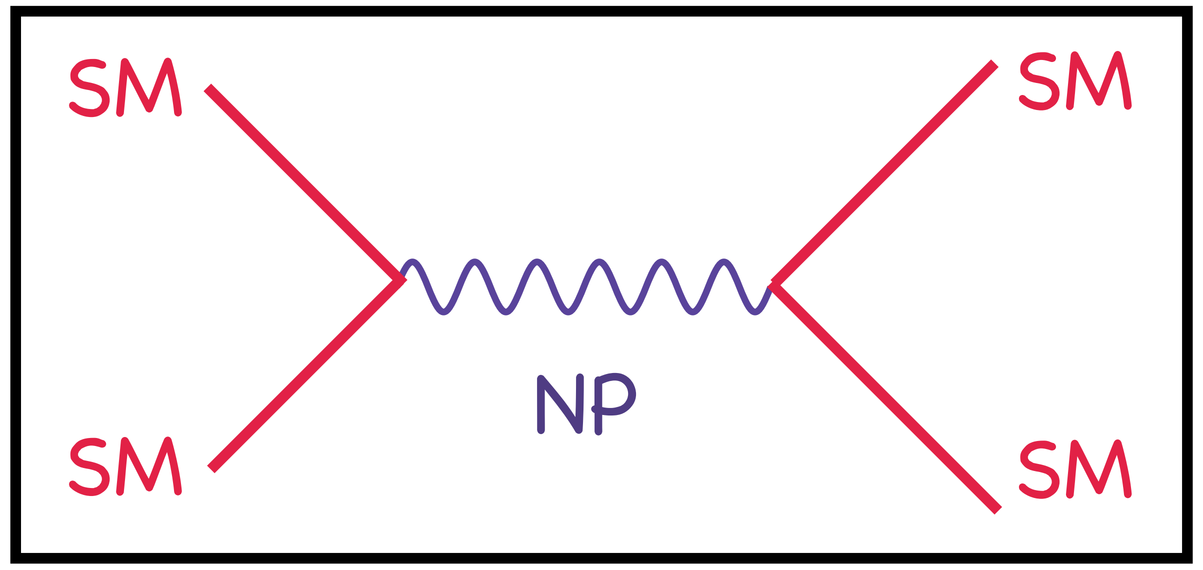




Top-Down approach: *SMEFT*

UV theory

$\mathcal{L}_{\rm BSM}$ →



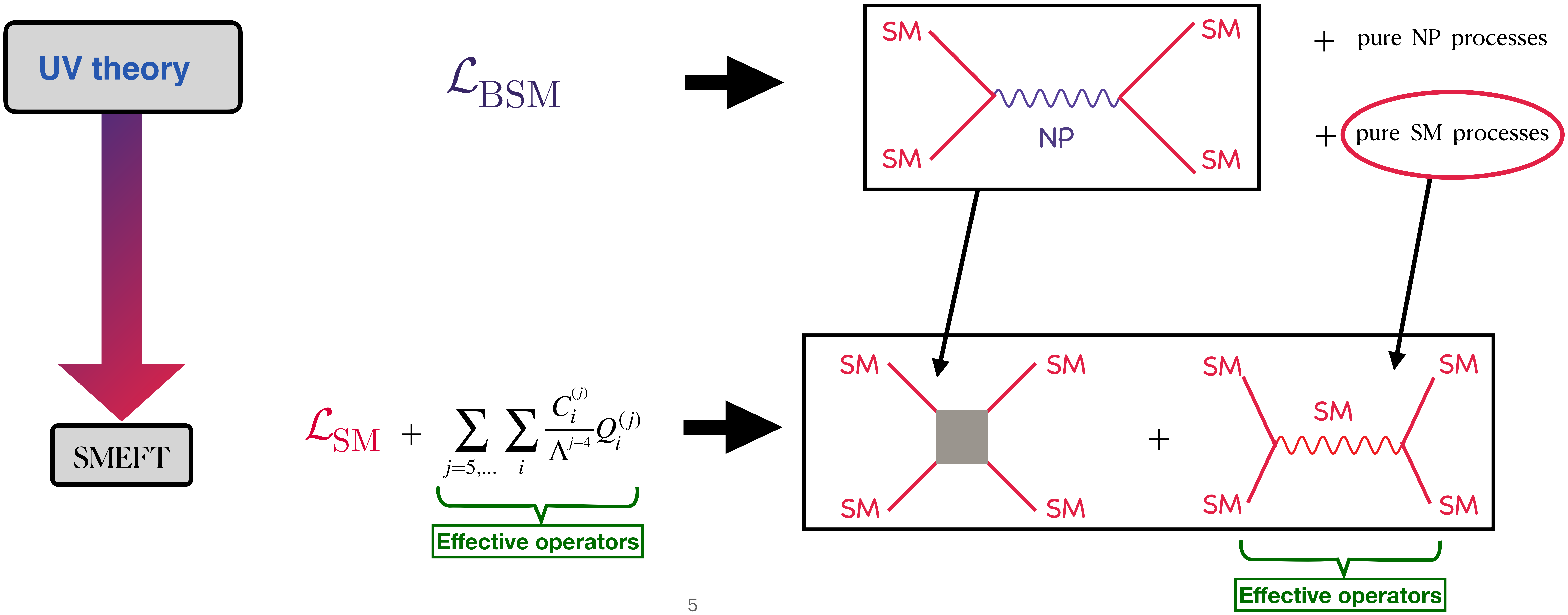
$+$ pure NP processes

$+$ pure SM processes

Top-Down approach: *SMEFT*

★ **The Wilson coefficients known in terms of BSM parameters**

✤ **The UV complete Lagrangian must be known**



Integrating out a heavy field

$$\mathcal{L}(\phi, \Phi) = \Phi_{kin} + \phi_{kin} + \Phi_{si} + \phi_{si} + (\phi * \Phi)_{int}$$

Φ - Heavy field ϕ - Light field

$$(\phi * \Phi)_{int} = B(\phi) * \Phi + U(\phi) * \Phi^2 + \mathcal{O}(\Phi^3)$$

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$$(\phi * \Phi)_{int} = B(\phi) * \Phi + U(\phi) * \Phi^2 + \mathcal{O}(\Phi^3)$$

$$D_\mu \frac{\partial}{\partial(D_\mu \Phi)} \mathcal{L}(\phi, \Phi) = \frac{\partial}{\partial \Phi} \mathcal{L}(\phi, \Phi)$$ *Euler - Lagrange equation*

Example - Scalar heavy field

$$(D^2 + m^2 - U(\phi))\Phi = B(\phi) + \mathcal{O}(\Phi^2) \qquad \Rightarrow \Phi_c = \frac{1}{(D^2 + m^2 - U(\phi))} B(\phi) \qquad \textit{(leading order)}$$

$$\approx \frac{1}{m^2} B(\phi) - \frac{1}{m^4}(D^2 - U(\phi))B(\phi)$$

$$B(\phi) * \Phi_c = B(\phi) \frac{1}{m^2} B(\phi) - B(\phi) \frac{(D^2 - U(\phi))}{m^4} B(\phi)$$ } Dependent only on light fields

Integrating out a heavy field

$$\mathcal{L}(\phi, \Phi) = \Phi_{kin} + \phi_{kin} + \Phi_{si} + \phi_{si} + (\phi * \Phi)_{int}$$

Φ - Heavy field ϕ - Light field

$$(\phi * \Phi)_{int} = B(\phi) * \Phi + U(\phi) * \Phi^2 + \mathcal{O}(\Phi^3)$$

$$D_\mu \frac{\partial}{\partial(D_\mu \Phi)} \mathcal{L}(\phi, \Phi) = \frac{\partial}{\partial \Phi} \mathcal{L}(\phi, \Phi)$$

Euler - Lagrange equation

Mass dimension of effective operator

$$\mathcal{L}_{BSM,eff} = \mathcal{L}_{SM} + \sum_j \frac{1}{\Lambda} c_j^{(5)} O_j^{(5)} + \sum_j \frac{1}{\Lambda^2} c_j^{(6)} O_j^{(6)} + \ldots$$

Λ : cut-off scale

Wilson coefficients

Effective operators

Example: Model with Extra Scalar Doublet

Heavy field φ → Color singlet, isospin doublet & hypercharge $-\frac{1}{2}$

BSM *Yukawas ignored!*

$\tilde{H} = i\sigma_2 H^*$

H : SM Higgs

$$\mathcal{L}_{BSM} = \mathcal{L}_{SM} + |\mathcal{D}_\mu \varphi|^2 - m_\varphi^2 |\varphi|^2 - \frac{\lambda_\varphi}{4}|\varphi|^4 + (\eta_H|\tilde{H}|^2 + \eta_\varphi|\varphi|^2)(\tilde{H}^\dagger\varphi + \varphi^\dagger\tilde{H})$$
$$- \lambda_1|\tilde{H}|^2|\varphi|^2 - \lambda_2|\tilde{H}^\dagger\varphi|^2 - \lambda_3\left[(\tilde{H}^\dagger\varphi)^2 + (\varphi^\dagger\tilde{H})^2\right]$$

Example: Model with Extra Scalar Doublet

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$$- \lambda_1|\tilde{H}|^2|\varphi|^2 - \lambda_2|\tilde{H}^\dagger\varphi|^2 - \lambda_3\left[(\tilde{H}^\dagger\varphi)^2 + (\varphi^\dagger\tilde{H})^2\right]$$

Term quadratic in heavy field

Term linear in heavy field

$$\varphi_c = \frac{1}{m^2}B - \frac{1}{m^4}(D^2 - U)B$$

$$\mathcal{L}_{BSM}(H,\varphi) \to \mathcal{L}_{BSM,eff}(H,\varphi_c)$$

$$\eta_H|\tilde{H}|^2\tilde{H}^\dagger\varphi \to \eta_H|\tilde{H}|^2\tilde{H}^\dagger \times \frac{\eta_H|\tilde{H}|^2\tilde{H}}{m^2} = \frac{\eta_H^2}{m^2}\,|\tilde{H}|^6$$

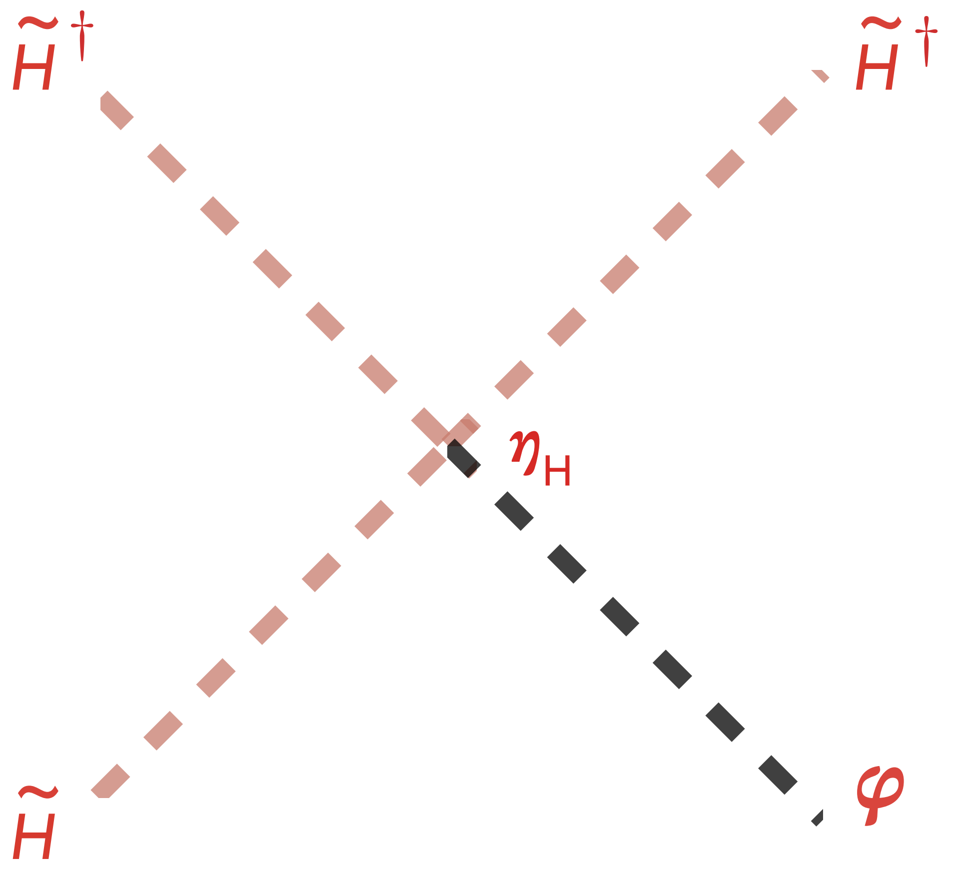
Effective operator of mass dimension = 6

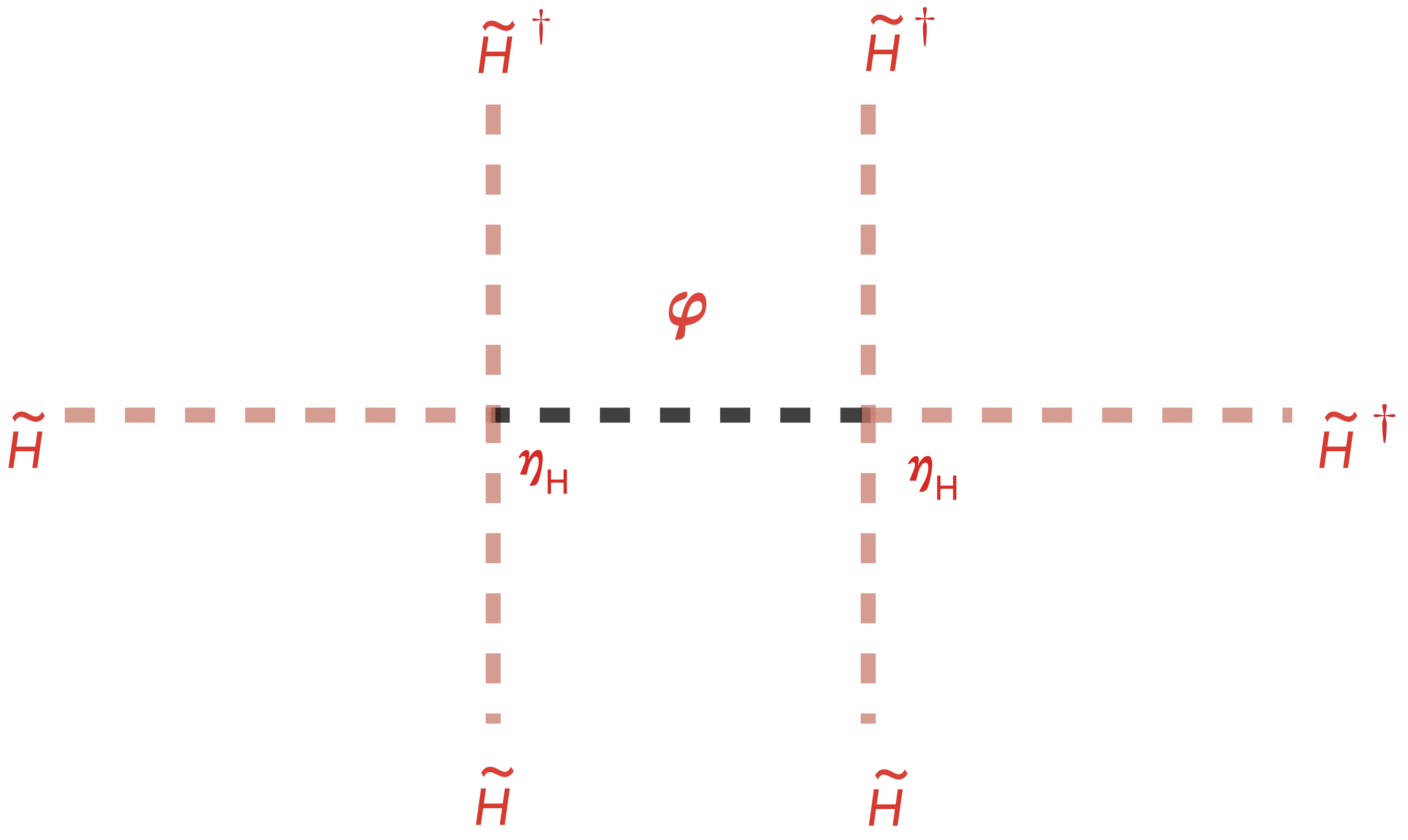
Wilson coefficients

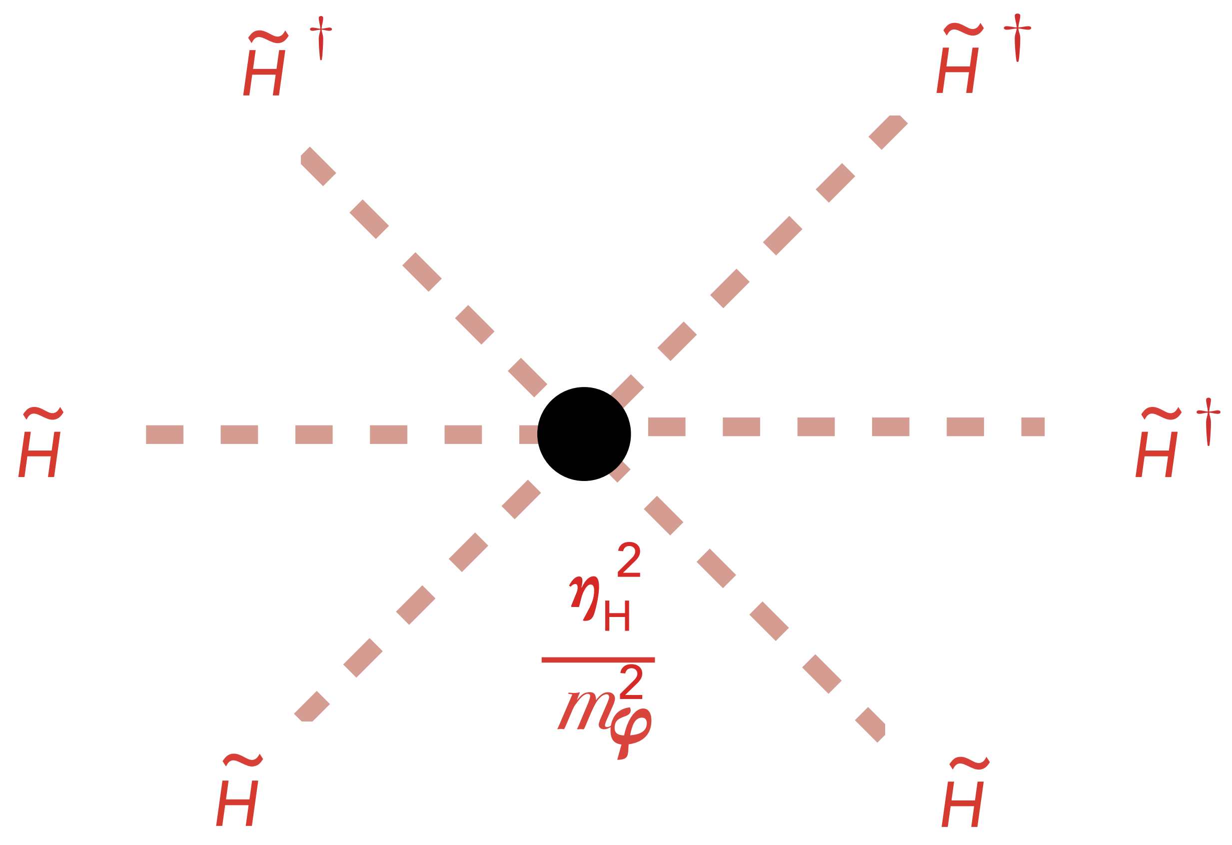
$m = m_\varphi$

Feynman Diagrams

$$\eta_H |\tilde{H}|^2 \tilde{H}^\dagger \varphi$$







$$\frac{1}{p^2 - m_\varphi^2}$$

$$m_\varphi^2 \gg p^2$$

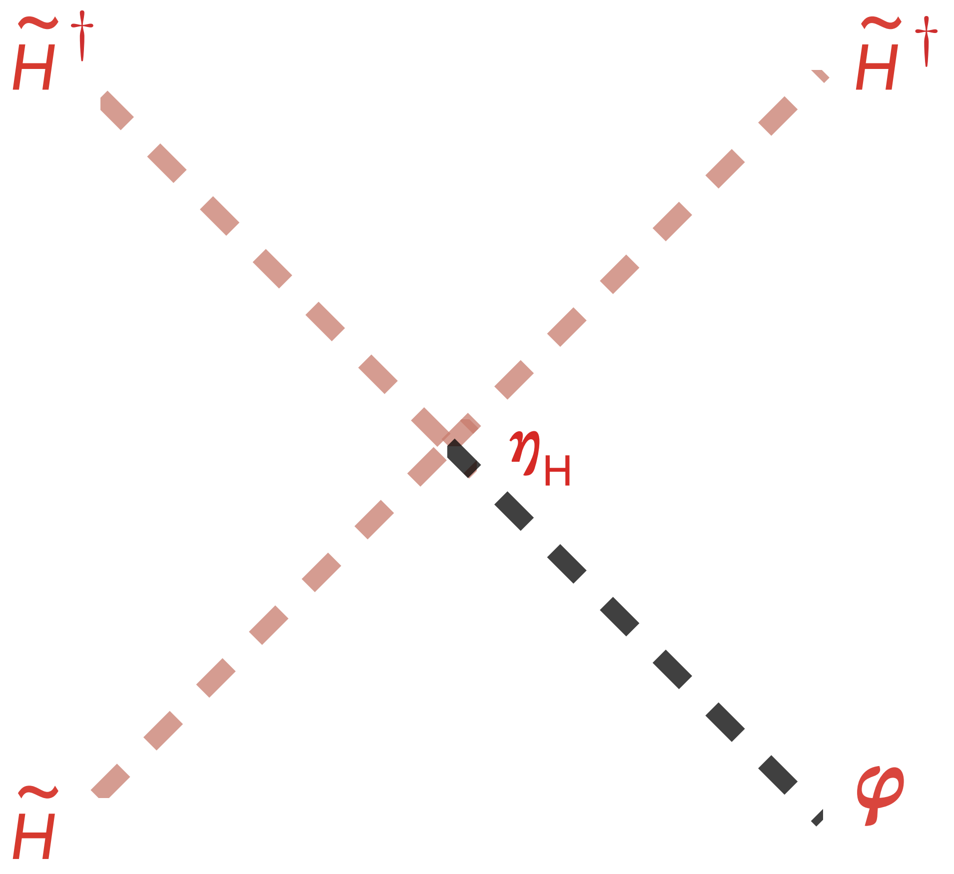
$$\frac{1}{m_\varphi^2}$$

Non-local

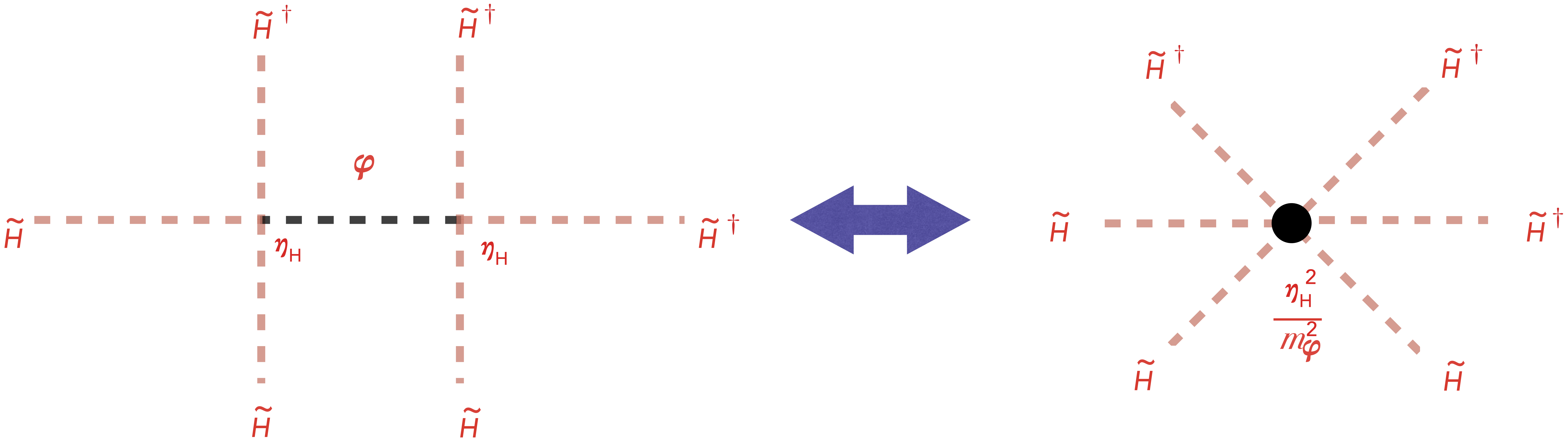
Local

Feynman Diagrams

$$\eta_H |\tilde{H}|^2 \tilde{H}^\dagger \varphi$$



Loop diagrams?



$$\frac{1}{p^2 - m_\varphi^2}$$

$$m_\varphi^2 \gg p^2$$

$$\frac{1}{m_\varphi^2}$$

Non-local

Local

Wilson Coefficients generated from 1 loop process

Action

$$S[\phi, \Phi_c + \eta] \quad = \quad S[\phi, \Phi_c] \quad + \quad \eta \frac{\delta S(\phi, \Phi)}{\delta \Phi}|_{\Phi=\Phi_c} \quad + \quad \frac{\eta^2}{2} \frac{\delta^2 S(\phi, \Phi)}{\delta \Phi^2}|_{\Phi=\Phi_c} \quad + \quad \mathcal{O}(\eta^3)$$

$$\Phi = \Phi_c + \eta$$

Wilson Coefficients generated from 1 loop process

Action

tree diagrams

0

loop diagrams

$$S[\phi, \Phi_c + \eta] \quad = \quad S[\phi, \Phi_c] \quad + \quad \eta \frac{\delta S(\phi, \Phi)}{\delta \Phi}|_{\Phi=\Phi_c} \quad + \quad \frac{\eta^2}{2} \frac{\delta^2 S(\phi, \Phi)}{\delta \Phi^2}|_{\Phi=\Phi_c} \quad + \quad \mathcal{O}(\eta^3)$$

Euler-Lagrange equation

$$\Phi = \Phi_c + \eta$$

Wilson Coefficients generated from 1 loop process

Action

tree diagrams — loop diagrams

$$S[\phi, \Phi_c + \eta] = \underbrace{S[\phi, \Phi_c]}_{\text{tree diagrams}} + \eta \frac{\delta S(\phi, \Phi)}{\delta \Phi}|_{\Phi=\Phi_c} + \frac{\eta^2}{2} \underbrace{\frac{\delta^2 S(\phi, \Phi)}{\delta \Phi^2}}_{\text{loop diagrams}}|_{\Phi=\Phi_c} + \mathcal{O}(\eta^3)$$

Euler-Lagrange equation → 0

$$\Phi = \Phi_c + \eta$$

Summing over all configurations :

$$e^{iS_{\text{eff}}[\phi]} = \int \mathcal{D}\Phi \; e^{iS[\phi,\Phi]}$$

$$S_{\text{eff}}[\phi, \Phi_c] = S[\phi, \Phi_c] + \frac{i}{2} \text{Tr} \log \left(-\frac{\delta^2 S(\phi, \Phi)}{\delta \Phi^2}|_{\Phi=\Phi_c} \right)$$

} Dependent only on light fields

Idea proposed by Gaillard (1986) and Cheyette (1988) and later adapted by Henning et. al. (2016)

$$S_{\text{eff,1-loop}} = i \; c \; \text{Tr} \log \left(\mathcal{D}^2 + m^2 + U \right)$$

- c: Numerical factor dependent on heavy field property
- $\mathcal{D}^2$, m^2, U: Covariant Derivative, mass and quadratic terms in the Lagrangian for the heavy field

Gaillard M.K. Nucl.Phys. B268 (1986) 669-692

Cheyette O. Nucl. Phys. B 297 (1988) 183

Henning et. al. JHEP01(2016)023

1-loop processes in EFT : Truncation

Where to truncate : In the expansion, succeeding terms are higher in mass dimension

$\mathcal{D}_\mu$: mass dimension $\longrightarrow$ 1

U : mass dimension $\longrightarrow$ 1 or 2

m : mass dimension $\longrightarrow$ 1

Henning et. al. JHEP01(2016)023

Drozd et. al. JHEP03(2016)180

Fuentes-Martin et. al. JHEP 09 (2016) 156

del Aguila et. al. Eur.Phys.J.C 76 (2016) 5, 244

Kramer et. al. JHEP 01 (2020) 079

and more (sorry for missing out)

For example: Effective operators upto mass dimension-six only:

$$\mathcal{L}_{1-loop}^{(dim-6)}[\phi,\Phi_c] = \frac{c}{(4\pi)^2}\,\mathrm{tr}\Bigg\{ m^2\left(1+\log\frac{\mu^2}{m^2}\right)\,U + m^0\left[\frac{1}{12}\left(1+\log\frac{\mu^2}{m^2}\right)G'^2_{\mu\nu} + \frac{1}{2}\log\frac{\mu^2}{m^2}U^2\right]$$
$$+\frac{1}{m^2}\left[-\frac{1}{60}\left(P_\mu G'_{\mu\nu}\right)^2 - \frac{1}{90}G'_{\mu\nu}G'_{\nu\sigma}G'_{\sigma\mu} - \frac{1}{12}\left(P_\mu U\right)^2 - \frac{1}{6}U^3\right.$$
$$\left.-\frac{1}{12}UG'_{\mu\nu}G'_{\mu\nu}\right] + \frac{1}{m^4}\left[\frac{1}{24}U^4 + \frac{1}{12}U\left(P_\mu U\right)^2 + \frac{1}{120}\left(P^2U\right)^2 + \frac{1}{24}\left(U^2G'_{\mu\nu}G'_{\mu\nu}\right)\right.$$
$$\left.-\frac{1}{120}\left[(P_\mu U),(P_\nu U)\right]G'_{\mu\nu} - \frac{1}{120}\left[U[U,G'_{\mu\nu}]\right]G'_{\mu\nu}\right] + \frac{1}{m^6}\left[-\frac{1}{60}U^5 - \frac{1}{20}U^2\left(P_\mu U\right)^2\right.$$
$$\left.-\frac{1}{30}\left(UP_\mu U\right)^2\right] + \frac{1}{m^8}\left[\frac{1}{120}U^6\right]\Bigg\}.$$

Eff. action : DR + MS-bar,

μ is the matching scale,

$P_\mu = i\mathcal{D}_\mu$

$G'_{\mu\nu} = [\mathcal{D}_\mu, \mathcal{D}_\nu] = -igF_{\mu\nu}$

Wilson coefficient calculator

CoDEx: Wilson coefficient calculator connecting SMEFT to UV theory

SDB, J Chakrabortty, S K Patra
Eur.Phys.J.C 79 (2019) 1, 21 • e-Print: 1808.04403

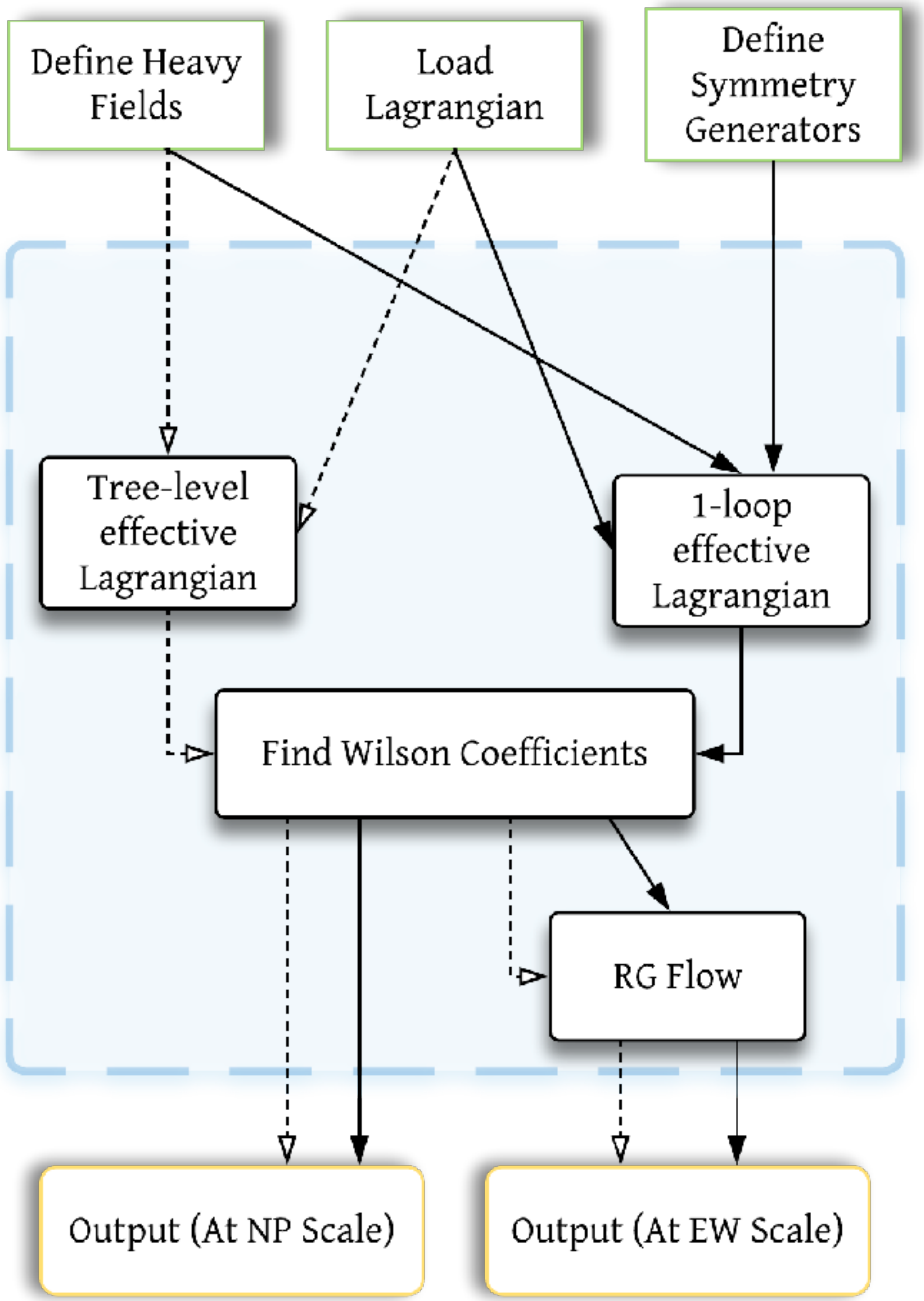
Also checkout:

Matchmakereft: automated tree-level and one-loop matching

Adrian Carmona, Achilleas Lazopoulos, Pablo Olgoso, Jose Santiago
SciPost Phys. 12 (2022) 6 • e-Print: 2112.10787

A Proof of Concept for Matchete: An Automated Tool for Matching Effective Theories

Javier Fuentes-Martín, Matthias König, Julie Pagès, Anders Eller Thomsen, Felix Wilsch
e-Print: 2212.04510



CoDEx: Extra Scalar Doublet

Heavy field properties

{Name, Color, Isospin, Hypercharge, Spin, Mass}

list = { hf, 1, 2, -1/2, 0, mH2}

Heavy field representation

φ = defineHeavyFields[list]

BSM Lagrangian

$$\begin{aligned}\mathcal{L}_{\mathcal{H}_2} &= \mathcal{L}_{SM} + |D_\mu \mathcal{H}_2|^2 - m^2_{\mathcal{H}_2}|\mathcal{H}_2|^2 - \frac{\lambda_{\mathcal{H}_2}}{4}|\mathcal{H}_2|^4 - (\eta_H|\widetilde{H}|^2 + \eta_{\mathcal{H}_2}|\mathcal{H}_2|^2)(\widetilde{H}^\dagger \mathcal{H}_2 + \mathcal{H}_2^\dagger \widetilde{H}) \\ &- \lambda_{\mathcal{H}_2,1}|\widetilde{H}|^2|\mathcal{H}_2|^2 - \lambda_{\mathcal{H}_2,2}|\widetilde{H}^\dagger \mathcal{H}_2|^2 - \lambda_{\mathcal{H}_2,3}\left[(\widetilde{H}^\dagger \mathcal{H}_2)^2 + (\mathcal{H}_2^\dagger \widetilde{H})^2\right] \\ &- \left\{ Y^{(e)}_{\mathcal{H}_2} \overline{L}_L \widetilde{\mathcal{H}}_2 e_R + Y^{(u)}_{\mathcal{H}_2} \overline{q}_L \mathcal{H}_2 u_R + Y^{(d)}_{\mathcal{H}_2} \overline{q}_L \widetilde{\mathcal{H}}_2 d_R + \text{h.c.} \right\}\end{aligned}$$

BSM Lagrangian

$$\mathcal{L}_{\mathcal{H}_2} = \mathcal{L}_{SM} + |D_\mu \mathcal{H}_2|^2 - m^2_{\mathcal{H}_2}|\mathcal{H}_2|^2 - \frac{\lambda_{\mathcal{H}_2}}{4}|\mathcal{H}_2|^4 - (\eta_H|\widetilde{H}|^2 + \eta_{\mathcal{H}_2}|\mathcal{H}_2|^2)(\widetilde{H}^\dagger \mathcal{H}_2 + \mathcal{H}_2^\dagger \widetilde{H})$$
$$- \lambda_{\mathcal{H}_2,1}|\widetilde{H}|^2|\mathcal{H}_2|^2 - \lambda_{\mathcal{H}_2,2}|\widetilde{H}^\dagger \mathcal{H}_2|^2 - \lambda_{\mathcal{H}_2,3}\left[(\widetilde{H}^\dagger \mathcal{H}_2)^2 + (\mathcal{H}_2^\dagger \widetilde{H})^2\right]$$
$$- \left\{ Y^{(e)}_{\mathcal{H}_2} \overline{L}_L \widetilde{\mathcal{H}}_2 e_R + Y^{(u)}_{\mathcal{H}_2} \overline{q}_L \mathcal{H}_2 u_R + Y^{(d)}_{\mathcal{H}_2} \overline{q}_L \widetilde{\mathcal{H}}_2 d_R + \text{h.c.} \right\}$$

```
LH2 = - λH2/4 (dag[φ].φ)^2 - (ηH dag[Ht].Ht + ηH2 dag[φ].φ) (dag[Ht].φ + dag[φ].Ht)

   -λH21 (dag[Ht].Ht) * (dag[φ].φ)  - λℋ22 (dag[Ht].φ) * (dag[φ].Ht) - λℋ23 ((dag[Ht].φ)^2 + (dag[φ].Ht)^2)

   -yH2e ((lepb[1][[1]] * φt[[1]] + lepb[1][[2]] * φt[[2]]).eR[1]
      + eRb[1].(hermitianConjugate[φtilde[[1]]] * lep[1][[1]] + hermitianConjugate[φtilde[[2]]] * lep[1][[2]]))
   +yH2u ((qdubb[1, 1][[1]] * φ[[1]] + qdubb[1, 1][[2]] * φ[[2]]).uR[1, 1]
      + uRb[1, 1].(hermitianConjugate[φ[[1]]] * qdub[1, 1][[1]] + hermitianConjugate[φ[[2]]] * qdub[1, 1][[2]]))
   +yH2d ((qdubb[1, 1][[1]] * φt[[1]] + qdubb[1, 1][[2]] * φt[[2]]).dR[1, 1]
      + dRb[1, 1].(hermitianConjugate[φt[[1]]] * qdub[1, 1][[1]] + hermitianConjugate[φt[[2]]] * qdub[1, 1][[2]]))
```

Tree-level Wilson coefficients

```
In[4]:    codexOutput[ LH2, list, model —> "2HDM", outRange —> "Tree", operBasis —> "Warsaw" ]

Out[4]:
```

Q_H	$(H^\dagger H)^3$	$\frac{\eta H^2}{\text{mH2}^2}$
Q_{eH}	$(H^\dagger H)(\bar{l}\ \text{e}\ H)$+h.c.	$-\frac{\eta\text{H yH2e}}{\text{mH2}^2}$
Q_{uH}	$(H^\dagger H)(\bar{q}\ \text{u}\ \tilde{H})$+h.c.	$\frac{\eta\text{H yH2u}}{\text{mH2}^2}$
Q_{dH}	$(H^\dagger H)(\bar{q}\ \text{d}\ H)$+h.c.	$-\frac{\eta\text{H yH2d}}{\text{mH2}^2}$
Q_{le}	$(\bar{l}\,\gamma_\mu\,\text{l})(\bar{e}\,\gamma_\mu\,\text{e})$	$-\frac{\text{yH2e}^2}{4\,\text{mH2}^2}$
$Q_{qu}{}^{(1)}$	$(\bar{q}\,\gamma^\mu\,\text{q})(\bar{u}\,\gamma_\mu\,\text{u})$	$-\frac{\text{yH2u}^2}{4\,\text{mH2}^2}$
$Q_{qd}{}^{(1)}$	$(\bar{q}\,\gamma_\mu\,\text{q})(\bar{d}\,\gamma_\mu\,\text{d})$	$-\frac{\text{yH2d}^2}{4\,\text{mH2}^2}$
Q_{ledq}	$(\bar{l}^j\ \text{e})(\bar{d}\ q_j)$+h.c.	$\frac{\text{yH2d yH2e}}{2\,\text{mH2}^2}$
$Q_{quqd}{}^{(1)}$	$(\bar{q}^j\ \text{u})\epsilon_{\text{jk}}(\bar{q}^k\ \text{d})$+h.c.	$-\frac{\text{yH2d yH2u}}{2\,\text{mH2}^2}$
$Q_{lequ}{}^{(1)}$	$(\bar{l}^j\ \text{e})\epsilon_{\text{jk}}(\bar{q}^k\ \text{u})$+h.c.	$\frac{\text{yH2e yH2u}}{2\,\text{mH2}^2}$

SILH

O_6	$(H^\dagger H)^3$	$\frac{\eta H^2}{\text{mH2}^2}$

Matching scale = mass of heavy field = mH2

1-loop level Wilson coefficients

```
In[5]:   initializeLoop[ "2HDM" , list]

In[6]:   codexOutput[ LH2, list, model —> "2HDM", outRange —> "Loop", operBasis —> "Warsaw" ]

Out[6]:
```

Warsaw basis

$Q_{\text{Hl}}{}^{(1)}$	$\frac{g_Y{}^4}{3840\pi^2 m_{\mathcal{H}_2}{}^2}$
$Q_{\text{Hq}}{}^{(1)}$	$-\frac{g_Y{}^4}{11520\pi^2 m_{\mathcal{H}_2}{}^2}$
$Q_{\text{ud}}{}^{(1)}$	$\frac{g_Y{}^4}{4320\pi^2 m_{\mathcal{H}_2}{}^2}$
$Q_{\text{Hl}}{}^{(3)}$	$-\frac{g_W{}^4}{1920\pi^2 m_{\mathcal{H}_2}{}^2}$
$Q_{\text{Hq}}{}^{(3)}$	$-\frac{g_W{}^4}{1920\pi^2 m_{\mathcal{H}_2}{}^2}$
$Q_{\text{lq}}{}^{(3)}$	$-\frac{g_W{}^4}{3840\pi^2 m_{\mathcal{H}_2}{}^2}$
$Q_{\text{qq}}{}^{(3)}$	$-\frac{g_W{}^4}{7680\pi^2 m_{\mathcal{H}_2}{}^2}$
Q_{dd}	$-\frac{g_Y{}^4}{17280\pi^2 m_{\mathcal{H}_2}{}^2}$
Q_{ed}	$-\frac{g_Y{}^4}{2880\pi^2 m_{\mathcal{H}_2}{}^2}$
Q_{ee}	$-\frac{g_Y{}^4}{1920\pi^2 m_{\mathcal{H}_2}{}^2}$
Q_{eu}	$\frac{g_Y{}^4}{1440\pi^2 m_{\mathcal{H}_2}{}^2}$
Q_{Hd}	$\frac{g_Y{}^4}{5760\pi^2 m_{\mathcal{H}_2}{}^2}$
Q_{He}	$\frac{g_Y{}^4}{1920\pi^2 m_{\mathcal{H}_2}{}^2}$
Q_{Hu}	$-\frac{g_Y{}^4}{2880\pi^2 m_{\mathcal{H}_2}{}^2}$
Q_{HWB}	$\frac{g_W g_Y \lambda^{(2)}_{\mathcal{H}_2}}{384\pi^2 m_{\mathcal{H}_2}{}^2}$
Q_{ld}	$-\frac{g_Y{}^4}{5760\pi^2 m_{\mathcal{H}_2}{}^2}$
Q_{lu}	$\frac{g_Y{}^4}{2880\pi^2 m_{\mathcal{H}_2}{}^2}$
Q_{qe}	$\frac{g_Y{}^4}{5760\pi^2 m_{\mathcal{H}_2}{}^2}$
Q_{uu}	$-\frac{g_Y{}^4}{4320\pi^2 m_{\mathcal{H}_2}{}^2}$
Q_W	$\frac{g_W{}^3}{5760\pi^2 m_{\mathcal{H}_2}{}^2}$
Q_{ledq}	$\frac{3\lambda_{\mathcal{H}_2} Y^{(d)}_{\mathcal{H}_2} Y^{(e)}_{\mathcal{H}_2}}{64\pi^2 m_{\mathcal{H}_2}{}^2}$
$Q_{\text{lequ}}{}^{(1)}$	$\frac{3\lambda_{\mathcal{H}_2} Y^{(e)}_{\mathcal{H}_2} Y^{(u)}_{\mathcal{H}_2}}{64\pi^2 m_{\mathcal{H}_2}{}^2}$
$Q_{\text{quqd}}{}^{(1)}$	$-\frac{3\lambda_{\mathcal{H}_2} Y^{(d)}_{\mathcal{H}_2} Y^{(u)}_{\mathcal{H}_2}}{64\pi^2 m_{\mathcal{H}_2}{}^2}$

Q_{dH}	$-\frac{3\eta_H \eta_{\mathcal{H}_2} Y_d^{\text{SM}}}{16\pi^2 m_{\mathcal{H}_2}{}^2} - \frac{3\eta_H \lambda_{\mathcal{H}_2} Y^{(d)}_{\mathcal{H}_2}}{32\pi^2 m_{\mathcal{H}_2}{}^2} - \frac{3\eta_{\mathcal{H}_2} \lambda_{\mathcal{H}_2,1} Y^{(d)}_{\mathcal{H}_2}}{16\pi^2 m_{\mathcal{H}_2}{}^2} - \frac{3\eta_{\mathcal{H}_2} \lambda_{\mathcal{H}_2,2} Y^{(d)}_{\mathcal{H}_2}}{16\pi^2 m_{\mathcal{H}_2}{}^2} + \frac{\lambda_{\mathcal{H}_2,3}{}^2 Y_d^{\text{SM}}}{48\pi^2 m_{\mathcal{H}_2}{}^2} + \frac{\lambda_{\mathcal{H}_2,2}{}^2 Y_d^{\text{SM}}}{192\pi^2 m_{\mathcal{H}_2}{}^2}$
$Q_{H\Box}$	$-\frac{g_W{}^4}{7680\pi^2 m_{\mathcal{H}_2}{}^2} - \frac{\lambda_{\mathcal{H}_2,1}{}^2}{96\pi^2 m_{\mathcal{H}_2}{}^2} - \frac{\lambda_{\mathcal{H}_2,1}\lambda_{\mathcal{H}_2,2}}{96\pi^2 m_{\mathcal{H}_2}{}^2} + \frac{\lambda_{\mathcal{H}_2,2}{}^2}{384\pi^2 m_{\mathcal{H}_2}{}^2} + \frac{\lambda_{\mathcal{H}_2,3}{}^2}{96\pi^2 m_{\mathcal{H}_2}{}^2}$
Q_{uH}	$\frac{3\eta_{\mathcal{H}_2} \lambda_{\mathcal{H}_2,1} Y^{(u)}_{\mathcal{H}_2}}{16\pi^2 m_{\mathcal{H}_2}{}^2} + \frac{3\eta_{\mathcal{H}_2} \lambda_{\mathcal{H}_2,2} Y^{(u)}_{\mathcal{H}_2}}{16\pi^2 m_{\mathcal{H}_2}{}^2} + \frac{\lambda_{\mathcal{H}_2,2}{}^2 Y_u^{\text{SM}}}{192\pi^2 m_{\mathcal{H}_2}{}^2} - \frac{3\eta_H \eta_{\mathcal{H}_2} Y_u^{\text{SM}}}{16\pi^2 m_{\mathcal{H}_2}{}^2} + \frac{3\eta_H \lambda_{\mathcal{H}_2} Y^{(u)}_{\mathcal{H}_2}}{32\pi^2 m_{\mathcal{H}_2}{}^2} + \frac{\lambda_{\mathcal{H}_2,3}{}^2 Y_u^{\text{SM}}}{48\pi^2 m_{\mathcal{H}_2}{}^2}$
Q_H	$\frac{3\eta_H \eta_{\mathcal{H}_2} \lambda_{\mathcal{H}_2,1}}{8\pi^2 m_{\mathcal{H}_2}{}^2} + \frac{3\eta_H \eta_{\mathcal{H}_2} \lambda_{\mathcal{H}_2,2}}{8\pi^2 m_{\mathcal{H}_2}{}^2} - \frac{\lambda_{\mathcal{H}_2,1}{}^3}{48\pi^2 m_{\mathcal{H}_2}{}^2} + \frac{\lambda_H^{\text{SM}} \lambda_{\mathcal{H}_2,2}{}^2}{96\pi^2 m_{\mathcal{H}_2}{}^2} - \frac{\lambda_{\mathcal{H}_2,1}{}^2 \lambda_{\mathcal{H}_2,2}}{32\pi^2 m_{\mathcal{H}_2}{}^2} - \frac{\lambda_{\mathcal{H}_2,1} \lambda_{\mathcal{H}_2,2}{}^2}{32\pi^2 m_{\mathcal{H}_2}{}^2} + \frac{\lambda_H^{\text{SM}} \lambda_{\mathcal{H}_2,3}{}^2}{24\pi^2 m_{\mathcal{H}_2}{}^2} - \frac{\lambda_{\mathcal{H}_2,1} \lambda_{\mathcal{H}_2,3}{}^2}{8\pi^2 m_{\mathcal{H}_2}{}^2} - \frac{\lambda_{\mathcal{H}_2,2}{}^3}{96\pi^2 m_{\mathcal{H}_2}{}^2} + \frac{3\eta_H{}^2 \lambda_{\mathcal{H}_2}}{32\pi^2 m_{\mathcal{H}_2}{}^2} - \frac{3\eta_H \eta_{\mathcal{H}_2} \lambda_H^{\text{SM}}}{8\pi^2 m_{\mathcal{H}_2}{}^2} - \frac{\lambda_{\mathcal{H}_2,2} \lambda_{\mathcal{H}_2,3}{}^2}{8\pi^2 m_{\mathcal{H}_2}{}^2}$
Q_{eH}	$-\frac{3\eta_H \eta_{\mathcal{H}_2} Y_e^{\text{SM}}}{16\pi^2 m_{\mathcal{H}_2}{}^2} - \frac{3\eta_H \lambda_{\mathcal{H}_2} Y^{(e)}_{\mathcal{H}_2}}{32\pi^2 m_{\mathcal{H}_2}{}^2} - \frac{3\eta_{\mathcal{H}_2} \lambda_{\mathcal{H}_2,1} Y^{(e)}_{\mathcal{H}_2}}{16\pi^2 m_{\mathcal{H}_2}{}^2} - \frac{3\eta_{\mathcal{H}_2} \lambda_{\mathcal{H}_2,2} Y^{(e)}_{\mathcal{H}_2}}{16\pi^2 m_{\mathcal{H}_2}{}^2} + \frac{\lambda_{\mathcal{H}_2,2}{}^2 Y_e^{\text{SM}}}{192\pi^2 m_{\mathcal{H}_2}{}^2} + \frac{\lambda_{\mathcal{H}_2,3}{}^2 Y_e^{\text{SM}}}{48\pi^2 m_{\mathcal{H}_2}{}^2}$
Q_{HD}	$-\frac{g_Y{}^4}{1920\pi^2 m_{\mathcal{H}_2}{}^2} - \frac{\lambda_{\mathcal{H}_2,2}{}^2}{96\pi^2 m_{\mathcal{H}_2}{}^2} + \frac{\lambda_{\mathcal{H}_2,3}{}^2}{24\pi^2 m_{\mathcal{H}_2}{}^2}$
Q_{le}	$-\frac{g_Y{}^4}{1920\pi^2 m_{\mathcal{H}_2}{}^2} - \frac{3\lambda_{\mathcal{H}_2} Y^{(e)2}_{\mathcal{H}_2}}{128\pi^2 m_{\mathcal{H}_2}{}^2}$
Q_{HB}	$\frac{g_Y{}^2 \lambda_{\mathcal{H}_2,1}}{384\pi^2 m_{\mathcal{H}_2}{}^2} + \frac{g_Y{}^2 \lambda_{\mathcal{H}_2,2}}{768\pi^2 m_{\mathcal{H}_2}{}^2}$
Q_{HW}	$\frac{g_W{}^2 \lambda_{\mathcal{H}_2,1}}{384\pi^2 m_{\mathcal{H}_2}{}^2} + \frac{g_W{}^2 \lambda_{\mathcal{H}_2,2}}{768\pi^2 m_{\mathcal{H}_2}{}^2}$
$Q_{\text{lq}}{}^{(1)}$	$\frac{g_Y{}^4}{11520\pi^2 m_{\mathcal{H}_2}{}^2} - \frac{g_W{}^4}{3840\pi^2 m_{\mathcal{H}_2}{}^2}$
$Q_{\text{qd}}{}^{(1)}$	$\frac{g_Y{}^4}{17280\pi^2 m_{\mathcal{H}_2}{}^2} - \frac{3\lambda_{\mathcal{H}_2} Y^{(d)2}_{\mathcal{H}_2}}{128\pi^2 m_{\mathcal{H}_2}{}^2}$
$Q_{\text{qq}}{}^{(1)}$	$\frac{g_W{}^4}{7680\pi^2 m_{\mathcal{H}_2}{}^2} - \frac{g_Y{}^4}{69120\pi^2 m_{\mathcal{H}_2}{}^2}$
$Q_{\text{qu}}{}^{(1)}$	$-\frac{g_Y{}^4}{8640\pi^2 m_{\mathcal{H}_2}{}^2} - \frac{3\lambda_{\mathcal{H}_2} Y^{(u)2}_{\mathcal{H}_2}}{128\pi^2 m_{\mathcal{H}_2}{}^2}$
Q_{ll}	$-\frac{g_W{}^4}{7680\pi^2 m_{\mathcal{H}_2}{}^2} - \frac{g_Y{}^4}{7680\pi^2 m_{\mathcal{H}_2}{}^2}$

SILH basis

O_H	$-\frac{3\eta_H \eta_{\mathcal{H}_2}}{8\pi^2 m^2_{\mathcal{H}_2}} + \frac{\lambda_{\mathcal{H}_2,1}\lambda_{\mathcal{H}_2,2}}{48\pi^2 m^2_{\mathcal{H}_2}} + \frac{\lambda^2_{\mathcal{H}_2,1}}{48\pi^2 m^2_{\mathcal{H}_2}} + \frac{\lambda^2_{\mathcal{H}_2,2}}{192\pi^2 m^2_{\mathcal{H}_2}} + \frac{\lambda^2_{\mathcal{H}_2,3}}{48\pi^2 m^2_{\mathcal{H}_2}}$
O_T	$\frac{\lambda^2_{\mathcal{H}_2,2}}{192\pi^2 m^2_{\mathcal{H}_2}} - \frac{\lambda^2_{\mathcal{H}_2,3}}{48\pi^2 m^2_{\mathcal{H}_2}}$
O_R	$-\frac{3\eta_H \eta_{\mathcal{H}_2}}{8\pi^2 m^2_{\mathcal{H}_2}} + \frac{\lambda^2_{\mathcal{H}_2,2}}{96\pi^2 m^2_{\mathcal{H}_2}} + \frac{\lambda^2_{\mathcal{H}_2,3}}{24\pi^2 m^2_{\mathcal{H}_2}}$
O_6	$\frac{3\eta_H \eta_{\mathcal{H}_2} \lambda_{\mathcal{H}_2,1}}{8\pi^2 m^2_{\mathcal{H}_2}} - \frac{\lambda_1^3}{48\pi^2 m^2_{\mathcal{H}_2}} + \frac{3\eta_H \eta_{\mathcal{H}_2} \lambda_{\mathcal{H}_2,2}}{8\pi^2 m^2_{\mathcal{H}_2}} - \frac{\lambda^2_{\mathcal{H}_2,1}\lambda_{\mathcal{H}_2,2}}{32\pi^2 m^2_{\mathcal{H}_2}} - \frac{\lambda_{\mathcal{H}_2,1}\lambda^2_{\mathcal{H}_2,2}}{32\pi^2 m^2_{\mathcal{H}_2}} - \frac{\lambda^3_{\mathcal{H}_2,2}}{96\pi^2 m^2_{\mathcal{H}_2}} - \frac{\lambda_{\mathcal{H}_2,1}\lambda^2_{\mathcal{H}_2,3}}{8\pi^2 m^2_{\mathcal{H}_2}} - \frac{\lambda_{\mathcal{H}_2,2}\lambda^2_{\mathcal{H}_2,3}}{8\pi^2 m^2_{\mathcal{H}_2}} + \frac{3\eta_H^2 \lambda_{\mathcal{H}_2}}{32\pi^2 m^2_{\mathcal{H}_2}}$
O_{WW}	$\frac{2\lambda_{\mathcal{H}_2,1}+\lambda_{\mathcal{H}_2,2}}{768\pi^2 m^2_{\mathcal{H}_2}}$
O_{2W}	$\frac{g_W^2}{960\pi^2 m^2_{\mathcal{H}_2}}$
O_{3W}	$\frac{g_W^2}{960\pi^2 m^2_{\mathcal{H}_2}}$
O_{WB}	$\frac{\lambda_{\mathcal{H}_2,2}}{384\pi^2 m^2_{\mathcal{H}_2}}$
O_{BB}	$\frac{2\lambda_{\mathcal{H}_2,1}+\lambda_{\mathcal{H}_2,2}}{768\pi^2 m^2_{\mathcal{H}_2}}$
O_{2B}	$\frac{g_Y^2}{960\pi^2 m^2_{\mathcal{H}_2}}$

Matching scale = heavy field mass

***1-loop processes involving only heavy propagators in the loop.**

Operator identities : gauge invariant structures to basis

Gauge-invariant operators to SMEFT bases

$$O_R = |H|^2 |D_\mu H|^2 = \lambda_H Q_H + \frac{1}{2} Q_{H\Box} + \left(\frac{1}{2} Y_{\rm SM}^{(u)} Q_{uH} + \frac{1}{2} Y_{\rm SM}^{(d)} Q_{dH} + \frac{1}{2} Y_{\rm SM}^{(e)} Q_{eH} + \text{h.c.} \right),$$

$$O_T = \frac{1}{2} \left(H^\dagger \overleftrightarrow{D}_\mu H \right)^2 = -2 Q_{HD} - \frac{1}{2} Q_{H\Box},$$

$$O_B = \frac{i}{2} g_Y \left(H^\dagger \overleftrightarrow{D}_\mu H \right) \partial_\nu B^{\mu\nu} = g_Y^2 \left(Q_{HD} + \frac{1}{4} Q_{H\Box} + \frac{1}{12} Q_{Hq}^{(1)} - \frac{1}{4} Q_{Hl}^{(1)} + \frac{1}{3} Q_{Hu} - \frac{1}{6} Q_{Hd} - \frac{1}{2} Q_{He} \right),$$

$$O_W = \frac{i}{2} g_W \left(H^\dagger \sigma^I \overleftrightarrow{D}_\mu H \right) D_\nu W^{\mu\nu} = g_W^2 \left\{ \lambda_H Q_H + \frac{3}{4} Q_{H\Box} + \frac{1}{4} Q_{Hq}^{(3)} + \frac{1}{4} Q_{Hl}^{(3)} + \left(\frac{1}{2} Y_{\rm SM}^{(u)} Q_{uH} + \frac{1}{2} Y_{\rm SM}^{(d)} Q_{dH} + \frac{1}{2} Y_{\rm SM}^{(e)} Q_{eH} + \text{h.c.} \right) \right\}.$$

Falkowski et. al. arXiv:1508.05895 – Rosetta

Fierz identities:

$$\left(\overline{\psi}_1 \Gamma^A \psi_2\right) \left(\overline{\psi}_3 \Gamma^B \psi_4\right) = \sum_{C,D} C_{CD}^{AB} \left(\overline{\psi}_1 \Gamma^C \psi_4\right) \left(\overline{\psi}_3 \Gamma^D \psi_2\right), \qquad C_{CD}^{AB} = \frac{1}{16} \text{tr}\left[\Gamma^C \Gamma^A \Gamma^D \Gamma^B\right]$$

Aebischer et. al. arXiv:2202.01225

Operator identities : gauge invariant structures to basis

Gauge-invariant operators to SMEFT bases

$$O_R = |H|^2|D_\mu H|^2 = \lambda_H Q_H + \frac{1}{2}Q_{H\Box} + \left(\frac{1}{2}Y^{(u)}_{\rm SM}Q_{uH} + \frac{1}{2}Y^{(d)}_{\rm SM}Q_{dH} + \frac{1}{2}Y^{(e)}_{\rm SM}Q_{eH} + {\rm h.c.}\right),$$

$$O_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2 = -2Q_{HD} - \frac{1}{2}Q_{H\Box},$$

$$O_B = \frac{i}{2}g_Y\left(H^\dagger \overleftrightarrow{D}_\mu H\right)\partial_\nu B^{\mu\nu} = g_Y^2\left(Q_{HD} + \frac{1}{4}Q_{H\Box} + \frac{1}{12}Q^{(1)}_{Hq} - \frac{1}{4}Q^{(1)}_{Hl} + \frac{1}{3}Q_{Hu} - \frac{1}{6}Q_{Hd} - \frac{1}{2}Q_{He}\right),$$

$$O_W = \frac{i}{2}g_W\left(H^\dagger \sigma^I \overleftrightarrow{D}_\mu H\right)D_\nu W^{\mu\nu} = g_W^2\left\{\lambda_H Q_H + \frac{3}{4}Q_{H\Box} + \frac{1}{4}Q^{(3)}_{Hq} + \frac{1}{4}Q^{(3)}_{Hl} + \left(\frac{1}{2}Y^{(u)}_{\rm SM}Q_{uH} + \frac{1}{2}Y^{(d)}_{\rm SM}Q_{dH} + \frac{1}{2}Y^{(e)}_{\rm SM}Q_{eH} + {\rm h.c.}\right)\right\}.$$

Falkowski et. al. arXiv:1508.05895 — Rosetta

Fierz identities:

$$(\overline{\psi_1}\gamma^\mu\psi_2)(\overline{\psi_3}\gamma_\mu\psi_4) = 2(\overline{\psi_1}\psi_3^C)(\overline{\psi_4^C}\psi_2),$$

$$(\overline{\psi_1}\gamma^\mu\psi_2)(\overline{\psi_3}\gamma_\mu\psi_4) = -2(\overline{\psi_1}\psi_4)(\overline{\psi_3}\psi_2).$$

Aebischer et. al. arXiv:2202.01225

❖ BSM Classifications

BSMs	$\mathcal{S}$	$\mathcal{S}_2$	Δ	$\mathcal{H}_2$	Δ_1	Σ	φ_1	φ_2	Θ_1	Θ_2	Ω	χ_1	χ_2	χ_3	χ_4
$\mathcal{G}_{3,2,1}$	**1,1,0**	**1,1,2**	**1,3,0**	**1,2,-1/2**	**1,3,1**	**1,4,1/2**	**3,1,-1/3**	**3,1,-4/3**	**3,2,1/6**	**3,2,7/6**	**3,3,-1/3**	**6,3,1/3**	**6,1,4/3**	**6,1,-2/3**	**6,1,1/3**

Higgs signal strengths + Q_{ll} (Q_{HD} … Q_{dH})

EWPO-LO (Q_{HD} … Q_{HWB})

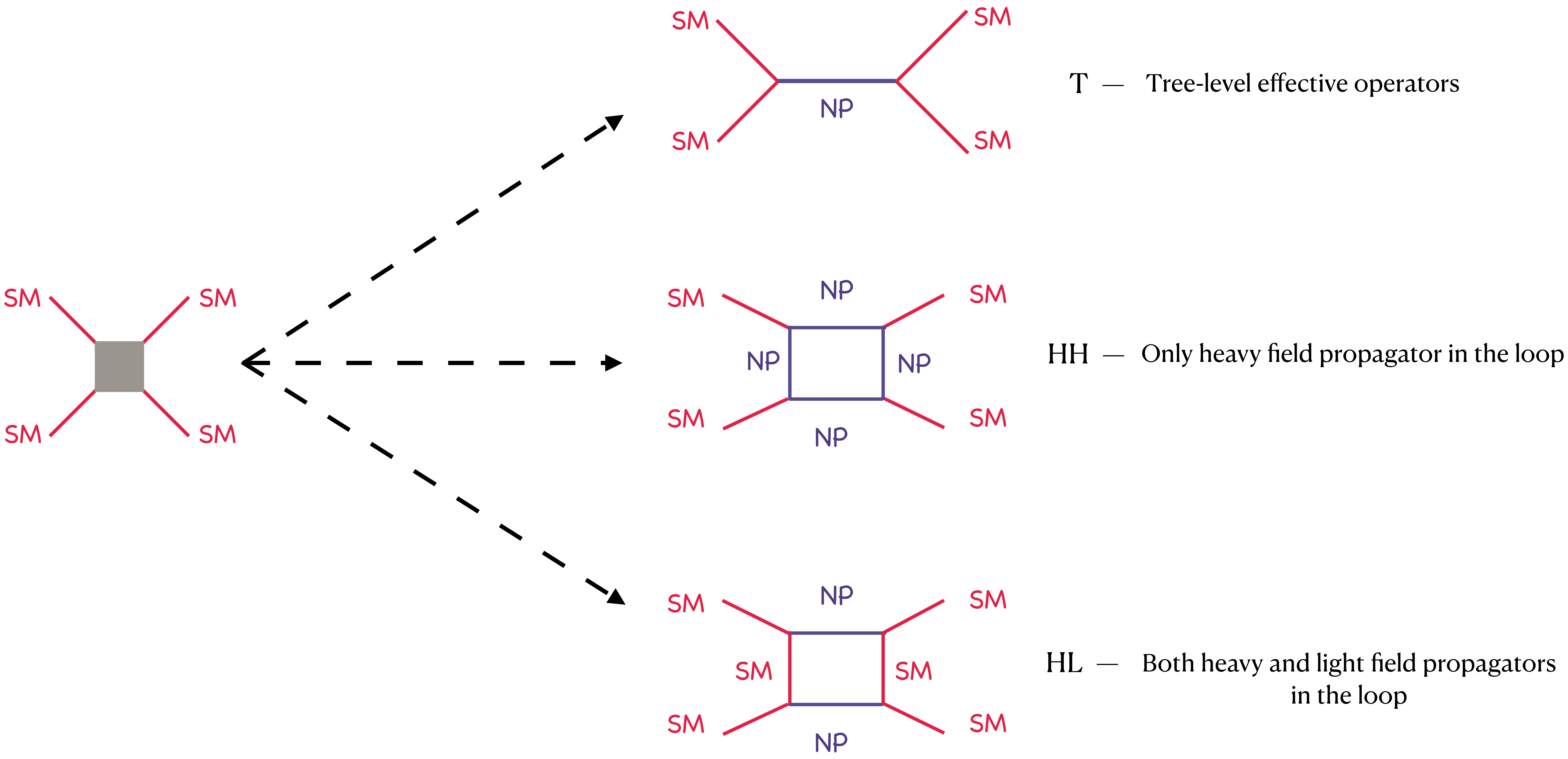
EWPO-NLO-I ($Q_{H\Box}$, Q_{HB}, Q_{HW})

EWPO-NLO-II ($Q_{qq}^{(1)}$ … Q_W)

BSMs	Q_{HD}	Q_{ll}	Q_{Hu}	Q_{Hd}	Q_{He}	$Q_{Hq}^{(1)}$	$Q_{Hl}^{(1)}$	$Q_{Hl}^{(3)}$	$Q_{Hq}^{(3)}$	Q_{HWB}	$Q_{H\Box}$	Q_{HB}	Q_{HW}	Q_H	Q_G	Q_{HG}	Q_{eH}	Q_{uH}	Q_{dH}
$\mathcal{S}$	HL	✗	✗	✗	✗	✗	✗	✗	✗	HL	T	HL	HL	T	✗	✗	HL	HL	HL
$\mathcal{S}_2$	HH	HH	HH	HH	HH	HH	HH	✗	✗	✗	HH	HH	✗	HH	✗	✗	✗	✗	✗
Δ	T	HH	✗	✗	✗	✗	✗	HH	HH	HL	T	HL	HH	T	✗	✗	T	T	T
$\mathcal{H}_2$	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	T	✗	✗	T	T	T
Δ_1	T	T	HH	HH	HH	HH	HH	HH	HH	HH	T	HH	HH	T	✗	✗	T	T	T
Σ	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	✗	✗	HH	HH	HH
φ_1	HH	HH	HH	HH	HH	HH	HH	✗	✗	✗	HH	HH	✗	HH	HH	HH	✗	✗	✗
φ_2	HH	HH	HH	HH	HH	HH	HH	✗	✗	✗	HH	HH	✗	HH	HH	HH	✗	✗	✗
Θ_1	HH	HH	HH	HH	HH	HH	HH	HH	HH	✗	HH	HH	HH	HH	HH	HH	✗	✗	✗
Θ_2	HH	HH	HH	HH	HH	HH	HH	HH	HH	✗	HH	HH	HH	HH	HH	HH	✗	✗	✗
Ω	HH	HH	HH	HH	HH	HH	HH	HH	HH	✗	HH	HH	HH	HH	HH	HH	✗	✗	✗
χ_1	HH	HH	HH	HH	HH	HH	HH	HH	HH	✗	HH	HH	HH	HH	HH	HH	✗	✗	✗
χ_2	HH	HH	HH	HH	HH	HH	HH	✗	✗	✗	HH	HH	✗	HH	HH	HH	✗	✗	✗
χ_3	HH	HH	HH	HH	HH	HH	HH	✗	✗	✗	HH	HH	✗	HH	HH	HH	✗	✗	✗
χ_4	HH	HH	HH	HH	HH	HH	HH	✗	✗	✗	HH	HH	✗	HH	HH	HH	✗	✗	✗

BSMs	$Q_{qq}^{(1)}$	$Q_{qq}^{(3)}$	Q_{uu}	Q_{dd}	$Q_{ud}^{(1)}$	$Q_{lq}^{(1)}$	Q_{ee}	Q_{eu}	Q_{ed}	Q_{le}	Q_{lu}	Q_{ld}	Q_{qe}	$Q_{qu}^{(1)}$	$Q_{qd}^{(1)}$	$Q_{lq}^{(3)}$	Q_W
$\mathcal{S}$	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
$\mathcal{S}_2$	HH	✗	HH	HH	HH	HH	T	HH	HH	HH	HH	HH	HH	HH	✗	✗	✗
Δ	✗	HH	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	HH	✗
$\mathcal{H}_2$	HH	HH	HH	HH	HH	HH	HH	HH	HH	T	HH	HH	HH	T	T	HH	HH
Δ_1	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH
Σ	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH
φ_1	HH	HH	HH	HH	HH	HH	HH	T	HH	HH	HH	HH	HH	HH	HH	T	✗
φ_2	HH	HH	HH	HH	HH	HH	HH	HH	T	HH	HH	HH	HH	HH	HH	HH	✗
Θ_1	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	T	HH	HH	HH	HH	HH
Θ_2	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	T	HH	T	HH	HH	HH	HH
Ω	HH	HH	HH	HH	HH	T	HH	HH	HH	HH	HH	HH	HH	HH	HH	T	HH
χ_1	T	T	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH
χ_2	HH	HH	T	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	✗	✗
χ_3	HH	HH	HH	T	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	✗	✗
χ_4	T	T	HH	HH	T	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	✗	✗

Tree-level (T), Heavy-loop (HH), Heavy-light-loop (HL)


SM
SM
SM
SM
SM
SM
NP
SM
SM
T — Tree-level effective operators
SM
NP
SM
NP
NP
SM
NP
SM
HH — Only heavy field propagator in the loop
SM
NP
SM
SM
SM
SM
NP
SM
HL — Both heavy and light field propagators in the loop

BSMs	$\mathcal{S}$	$\mathcal{S}_2$	Δ	$\mathcal{H}_2$	Δ_1	Σ	φ_1	φ_2	Θ_1	Θ_2	Ω	χ_1	χ_2	χ_3	χ_4
$\mathcal{G}_{3,2,1}$	**1,1,0**	**1,1,2**	**1,3,0**	**1,2,-1/2**	**1,3,1**	**1,4,1/2**	**3,1,-1/3**	**3,1,-4/3**	**3,2,1/6**	**3,2,7/6**	**3,3,-1/3**	**6,3,1/3**	**6,1,4/3**	**6,1,-2/3**	**6,1,1/3**

Higgs signal strengths + Q_{ll}

EWPO-LO: Q_{HD} to Q_{HWB}; EWPO-NLO-I: $Q_{H\Box}$, Q_{HB}, Q_{HW}; EWPO-NLO-II: $Q_{qq}^{(1)}$ to Q_W

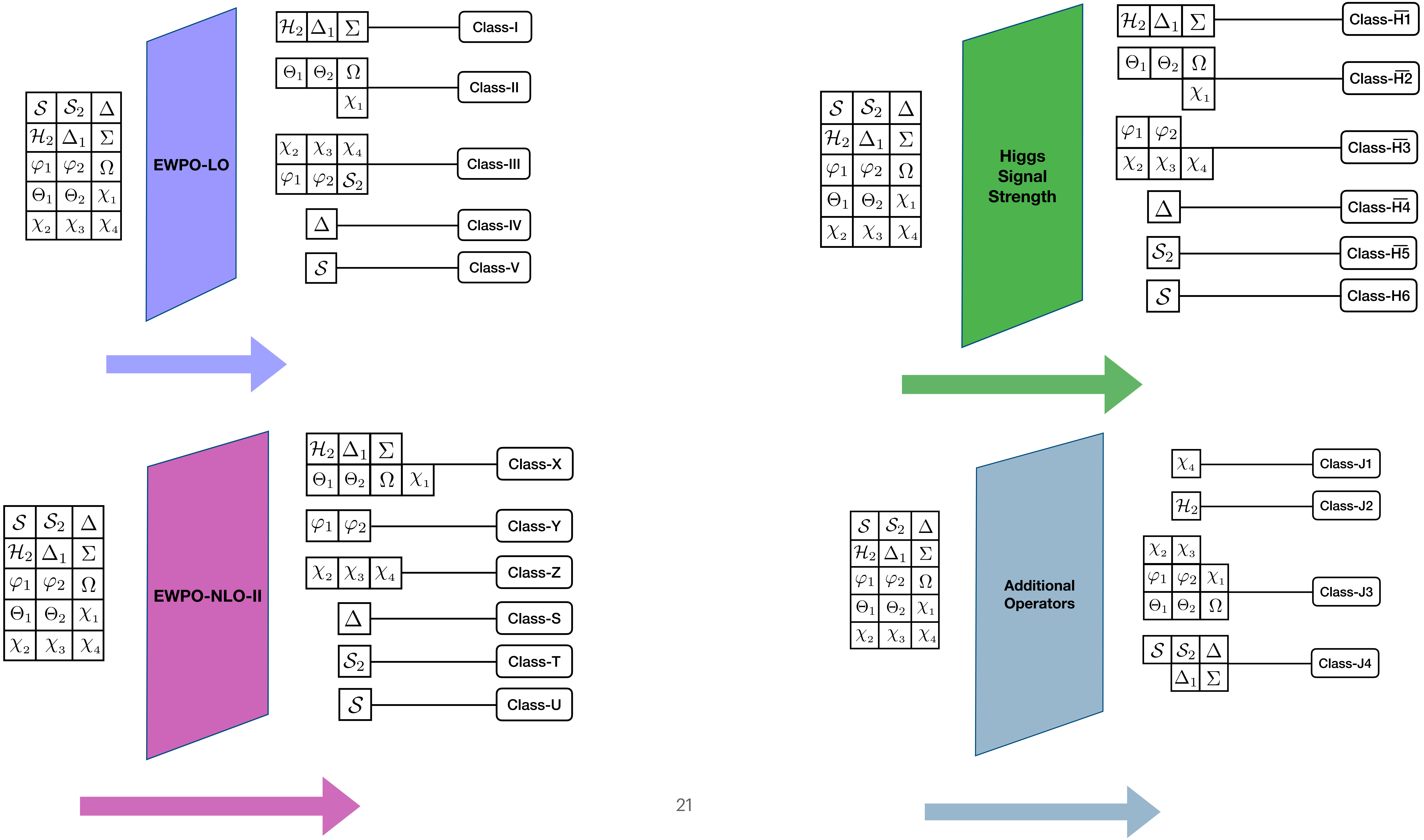
BSMs	Q_{HD}	Q_{ll}	Q_{Hu}	Q_{Hd}	Q_{He}	$Q_{Hq}^{(1)}$	$Q_{Hl}^{(1)}$	$Q_{Hl}^{(3)}$	$Q_{Hq}^{(3)}$	Q_{HWB}	$Q_{H\Box}$	Q_{HB}	Q_{HW}	Q_H	Q_G	Q_{HG}	Q_{eH}	Q_{uH}	Q_{dH}
$\mathcal{S}$	HL	✗	✗	✗	✗	✗	✗	✗	✗	HL	T	HL	HL	T	✗	✗	HL	HL	HL
$\mathcal{S}_2$	HH	HH	HH	HH	HH	HH	HH	✗	✗	✗	HH	HH	✗	HH	✗	✗	✗	✗	✗
Δ	T	HH	✗	✗	✗	✗	✗	HH	HH	HL	T	HL	HH	T	✗	✗	T	T	T
$\mathcal{H}_2$	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	T	✗	✗	T	T	T
Δ_1	T	T	HH	HH	HH	HH	HH	HH	HH	HH	T	HH	HH	T	✗	✗	T	T	T
Σ	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	✗	✗	HH	HH	HH
φ_1	HH	HH	HH	HH	HH	HH	HH	✗	✗	✗	HH	HH	✗	HH	HH	HH	✗	✗	✗
φ_2	HH	HH	HH	HH	HH	HH	HH	✗	✗	✗	HH	HH	✗	HH	HH	HH	✗	✗	✗
Θ_1	HH	HH	HH	HH	HH	HH	HH	HH	HH	✗	HH	HH	HH	HH	HH	HH	✗	✗	✗
Θ_2	HH	HH	HH	HH	HH	HH	HH	HH	HH	✗	HH	HH	HH	HH	HH	HH	✗	✗	✗
Ω	HH	HH	HH	HH	HH	HH	HH	HH	HH	✗	HH	HH	HH	HH	HH	HH	✗	✗	✗
χ_1	HH	HH	HH	HH	HH	HH	HH	HH	HH	✗	HH	HH	HH	HH	HH	HH	✗	✗	✗
χ_2	HH	HH	HH	HH	HH	HH	HH	✗	✗	✗	HH	HH	✗	HH	HH	HH	✗	✗	✗
χ_3	HH	HH	HH	HH	HH	HH	HH	✗	✗	✗	HH	HH	✗	HH	HH	HH	✗	✗	✗
χ_4	HH	HH	HH	HH	HH	HH	HH	✗	✗	✗	HH	HH	✗	HH	HH	HH	✗	✗	✗

BSMs	$Q_{qq}^{(1)}$	$Q_{qq}^{(3)}$	Q_{uu}	Q_{dd}	$Q_{ud}^{(1)}$	$Q_{lq}^{(1)}$	Q_{ee}	Q_{eu}	Q_{ed}	Q_{le}	Q_{lu}	Q_{ld}	Q_{qe}	$Q_{qu}^{(1)}$	$Q_{qd}^{(1)}$	$Q_{lq}^{(3)}$	Q_W
$\mathcal{S}$	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
$\mathcal{S}_2$	HH	✗	HH	HH	HH	HH	T	HH	HH	HH	HH	HH	HH	HH	✗	✗	✗
Δ	✗	HH	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	HH	✗
$\mathcal{H}_2$	HH	HH	HH	HH	HH	HH	HH	HH	HH	T	HH	HH	HH	T	T	HH	HH
Δ_1	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH
Σ	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH
φ_1	HH	HH	HH	HH	HH	HH	HH	T	HH	HH	HH	HH	HH	HH	HH	T	✗
φ_2	HH	HH	HH	HH	HH	HH	HH	HH	T	HH	HH	HH	HH	HH	HH	HH	✗
Θ_1	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	T	HH	HH	HH	HH	HH
Θ_2	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	T	HH	T	HH	HH	HH	HH
Ω	HH	HH	HH	HH	HH	T	HH	HH	HH	HH	HH	HH	HH	HH	HH	T	HH
χ_1	T	T	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH
χ_2	HH	HH	T	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	✗	✗
χ_3	HH	HH	HH	T	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	✗	✗
χ_4	T	T	HH	HH	T	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	✗	✗

Tree-level (T), Heavy-loop (HH), Heavy-light-loop (HL)

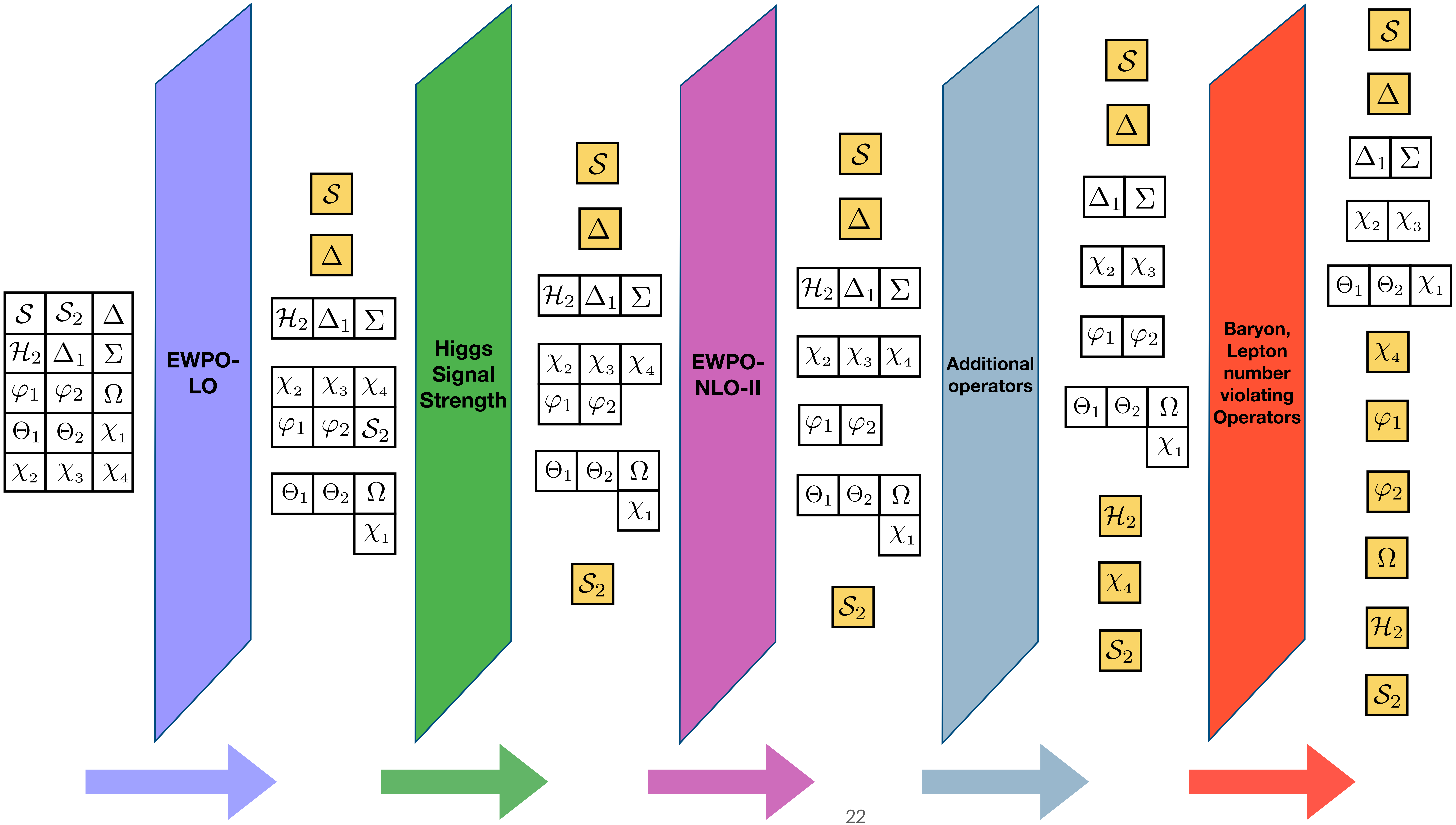
BSM Classification based on Observables

SDB, J Chakrabortty, M Spannowsky. **PhysRevD 103.056019**



BSM Classification based on Observables

Check out:
Anisha, SDB,
J Chakrabortty,
S Patra.
Phys.Rev.D 103 (2021) 7, 076007,
arxiv:2010.04088



❖ UV origin of CP-violation in SMEFT

Dimension-6 Gauge-Higgs SMEFT operators

CP-odd

$Q_{\widetilde{G}}$	$f^{ABC}\epsilon_{\mu\nu\alpha\beta}G^{A\alpha\beta}G^{B\nu}_{\rho}G^{C\rho\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK}\epsilon_{\mu\nu\alpha\beta}W^{I\alpha\beta}W^{J\nu}_{\rho}W^{K\rho\mu}$
$Q_{H\widetilde{G}}$	$\epsilon_{\mu\nu\alpha\beta}\left(H^\dagger H\right)G^{A\alpha\beta}G^{A\mu\nu}$
$Q_{H\widetilde{W}}$	$\epsilon_{\mu\nu\alpha\beta}\left(H^\dagger H\right)W^{I\alpha\beta}W^{I\mu\nu}$
$Q_{H\widetilde{B}}$	$\epsilon_{\mu\nu\alpha\beta}\left(H^\dagger H\right)B^{\alpha\beta}B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$\epsilon_{\mu\nu\alpha\beta}\left(H^\dagger\sigma^I H\right)W^{I\alpha\beta}B^{\mu\nu}$

CP-even

Q_{G}	$f^{ABC}G^{A,\mu}_{\nu}G^{B,\nu}_{\rho}G^{C,\rho}_{\mu}$
Q_{W}	$\epsilon^{IJK}W^{I,\mu}_{\nu}W^{J,\nu}_{\rho}W^{K,\rho}_{\mu}$
Q_{HG}	$\left(H^\dagger H\right)G_{\mu\nu}{}^{A}G^{A,\mu\nu}$
Q_{HW}	$\left(H^\dagger H\right)W_{\mu\nu}{}^{I}W^{I,\mu\nu}$
Q_{HB}	$\left(H^\dagger H\right)B_{\mu\nu}B^{\mu\nu}$
Q_{HWB}	$\left(H^\dagger\sigma^I H\right)W_{\mu\nu}{}^{I}B^{\mu\nu}$

ϵ is the anti-symmetric (Levi-Civita) tensor.

Grzadkowski et. al. JHEP10(2010)085

❖ **Heavy fermions :** $2i\sigma_{\rho\sigma}\gamma_5 = \epsilon_{\mu\nu\rho\sigma}\sigma^{\mu\nu}$

Integrating out heavy fermions generates the CPV operators at 1-loop except $Q_{\widetilde{W}}$ and $Q_{\widetilde{G}}$

Bélusca-Maïto et. al. 1710.05563

SM extended by heavy fermions

SDB, J Chakrabortty, C. Englert, M Spannowsky, P. Stylianou
PhyRevD 103.055008

Vector-like lepton (VLL) model study

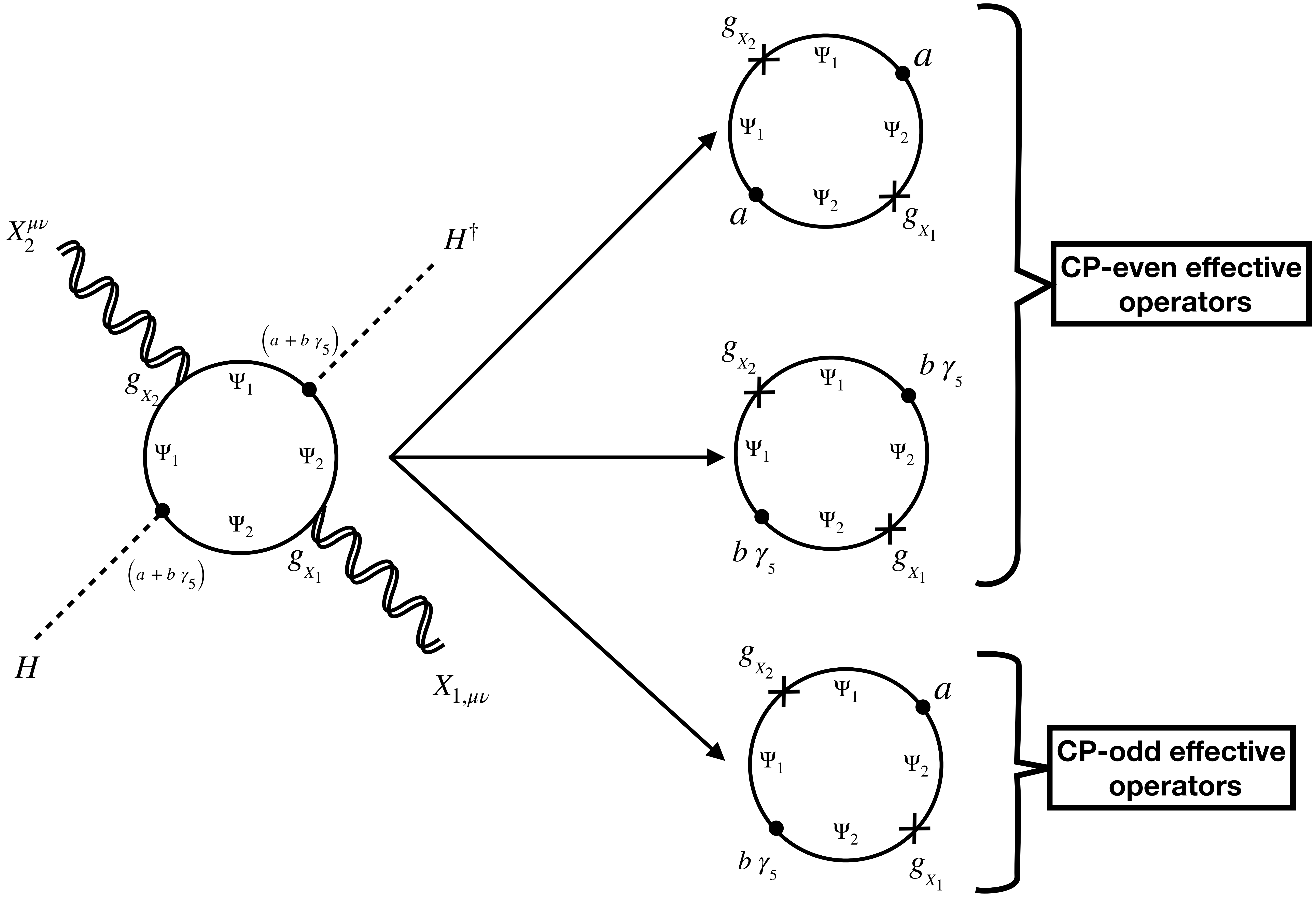
$$\Sigma_{L,R} = \begin{pmatrix} \eta \\ \xi \end{pmatrix}_{L,R} : (1,2,\mathcal{Y}), \;\; \eta'_{L,R} : (1,1,\mathcal{Y}+\frac{1}{2}), \;\; \xi'_{L,R} : (1,1,\mathcal{Y}-\frac{1}{2}).$$

$$\mathcal{L}_{\rm DS} = \bar{\Sigma}(iD_{\Sigma} - m_{\Sigma})\Sigma + \bar{\eta}'(iD_{\eta} - m_{\eta})\eta' + \bar{\xi}'(iD_{\xi} - m_{\xi})\xi'$$
$$- \left\{ \bar{\Sigma}\tilde{H}(Y_{\eta_L}\mathbb{P}_L + Y_{\eta_R}\mathbb{P}_R)\eta' + \bar{\Sigma}H(Y_{\xi_L}\mathbb{P}_L + Y_{\xi_R}\mathbb{P}_R)\xi' + \text{h.c.} \right\}$$

Angelescu et. al. arxiv:2006.16532

CPV operator diagrams

SDB, J Chakrabortty, C. Englert, M Spannowsky, P. Stylianou
arXiv:**2103.15861**



CPV operator diagrams

SDB, J Chakrabortty, C. Englert, M Spannowsky, P. Stylianou
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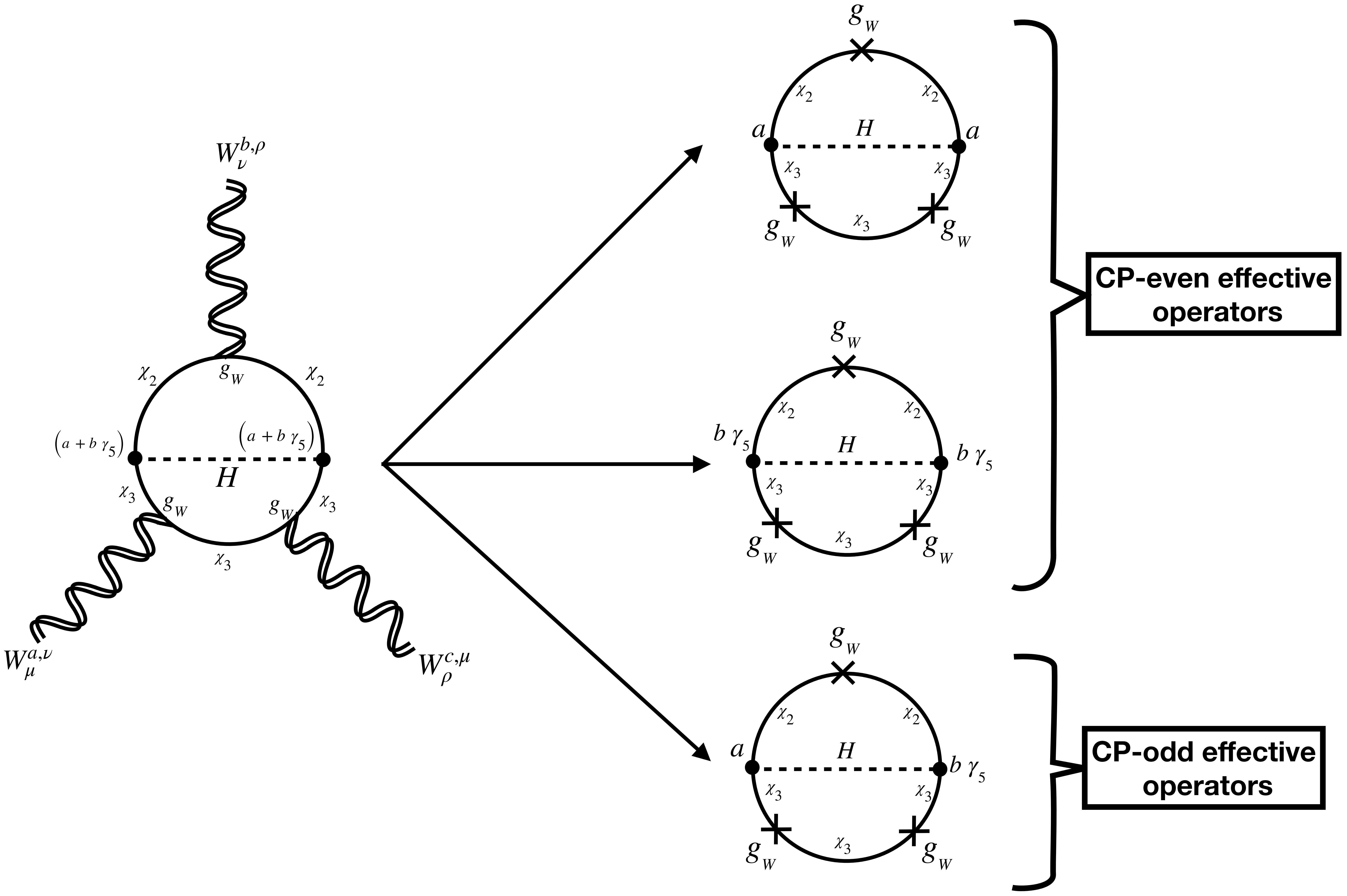


1-loop matching result

Operators	Wilson Coefficients $\left(\mathcal{C}_i \times \frac{1}{16\pi^2}\right)$
$Q_{H\tilde{B}}$	$-\frac{g_Y^2}{12}\left[(1+6\mathcal{Y}+12\mathcal{Y}^2)\mathrm{Im}[Y_{\eta_L}Y^*_{\eta_R}]+(1-6\mathcal{Y}+12\mathcal{Y}^2)\mathrm{Im}[Y_{\xi_L}Y^*_{\xi_R}]\right]$
$Q_{H\widetilde{W}}$	$-\frac{g_W^2}{12}\mathrm{Im}[Y_{\eta_L}Y^*_{\eta_R}+Y_{\xi_L}Y^*_{\xi_R}]$
$Q_{H\widetilde{W}B}$	$\frac{g_W g_Y}{6}\left[(1+6\mathcal{Y})\mathrm{Im}[Y_{\eta_L}Y^*_{\eta_R}]+(1-6\mathcal{Y})\mathrm{Im}[Y_{\xi_L}Y^*_{\xi_R}]\right]$
Q_W	$g_W^3/180$
Q_H	$-\frac{2}{15}\left(\lvert\alpha_\eta\rvert^6+\lvert\alpha_\xi\rvert^6\right)+\frac{2}{3}\left(\lvert\beta_\eta\rvert^6+\lvert\beta_\xi\rvert^6\right)$ $+\frac{2}{3}\left(\lvert\alpha_\eta\rvert^4\lvert\beta_\eta\rvert^2+\lvert\alpha_\xi\rvert^4\lvert\beta_\xi\rvert^2\right)+2\left(\lvert\alpha_\eta\rvert^2\lvert\beta_\eta\rvert^4+\lvert\alpha_\xi\rvert^2\lvert\beta_\xi\rvert^4\right)$ $+\frac{2}{3}\left(\lvert\alpha_\eta\rvert^2\left((\alpha_\eta^*)^2\beta_\eta^2+\alpha_\eta^2(\beta_\eta^*)^2\right)+\lvert\alpha_\xi\rvert^2\left(\left(\alpha_\xi^*\right)^2\beta_\xi^2+\alpha_\xi^2\left(\beta_\xi^*\right)^2\right)\right)$ $+2\left(\lvert\beta_\eta\rvert^2\left((\alpha_\eta^*)^2\beta_\eta^2+\alpha_\eta^2(\beta_\eta^*)^2\right)+\lvert\beta_\xi\rvert^2\left(\left(\alpha_\xi^*\right)^2\beta_\xi^2+\alpha_\xi^2\left(\beta_\xi^*\right)^2\right)\right)$ $-2\lambda_H\mathcal{C}_F+\frac{4}{5}\lambda_H\left(\lvert\alpha_\xi\rvert^2+\lvert\alpha_\eta\rvert^2\right)+\frac{4}{3}\lambda_H\left(\lvert\beta_\xi\rvert^2+\lvert\beta_\eta\rvert^2\right)$
$Q_{H\square}$	$-\frac{2}{5}\left(\lvert\alpha_\eta\rvert^2+\lvert\alpha_\xi\rvert^2\right)^2-\frac{1}{3}\left(\lvert\beta_\eta\rvert^2+\lvert\beta_\xi\rvert^2\right)^2$ $-\frac{1}{3}\left(\lvert\beta_\xi\rvert^2\lvert\alpha_\eta\rvert^2+\lvert\alpha_\xi\rvert^2\lvert\beta_\eta\rvert^2\right)-1\left(\lvert\alpha_\eta\rvert^2\lvert\beta_\eta\rvert^2+\lvert\alpha_\xi\rvert^2\lvert\beta_\xi\rvert^2\right)$ $-\frac{2}{3}\left(\alpha_\xi\beta_\xi^*\alpha_\eta^*\beta_\eta+\alpha_\xi^*\beta_\xi\alpha_\eta\beta_\eta^*\right)+\frac{1}{3}\left(\alpha_\eta^2(\beta_\eta^*)^2+(\alpha_\eta^*)^2\beta_\eta^2\right)$
Q_{HD}	$-\frac{4}{5}\left(\lvert\alpha_\xi\rvert^2-\lvert\alpha_\eta\rvert^2\right)^2-\frac{2}{3}\left(\lvert\beta_\xi\rvert^2-\lvert\beta_\eta\rvert^2\right)^2$ $+\frac{2}{3}\left(\lvert\beta_\xi\rvert^2\lvert\alpha_\eta\rvert^2+\lvert\alpha_\xi\rvert^2\lvert\beta_\eta\rvert^2\right)-2\left(\lvert\alpha_\eta\rvert^2\lvert\beta_\eta\rvert^2+\lvert\alpha_\xi\rvert^2\lvert\beta_\xi\rvert^2\right)$ $+\frac{2}{3}\left(\alpha_\eta^2(\beta_\eta^*)^2+(\alpha_\eta^*)^2\beta_\eta^2\right)+\frac{4}{3}\left(\alpha_\xi\beta_\xi^*\alpha_\eta^*\beta_\eta+\alpha_\xi^*\beta_\xi\alpha_\eta\beta_\eta^*\right)$
Q_{HB}	$\frac{g_Y^2}{120}\left[(-7+40\mathcal{Y}-80\mathcal{Y}^2)\lvert\alpha_\xi\rvert^2+(-7-40\mathcal{Y}-80\mathcal{Y}^2)\lvert\alpha_\eta\rvert^2\right.$ $\left.+(5-40\mathcal{Y}+80\mathcal{Y}^2)\lvert\beta_\xi\rvert^2+(5+40\mathcal{Y}+80\mathcal{Y}^2)\lvert\beta_\eta\rvert^2\right]$
Q_{HW}	$-\frac{7g_W^2}{120}\left(\lvert\alpha_\xi\rvert^2+\lvert\alpha_\eta\rvert^2\right)+\frac{g_W^2}{24}\left(\lvert\beta_\xi\rvert^2+\lvert\beta_\eta\rvert^2\right)$
Q_{HWB}	$\frac{g_W g_Y}{60}\left[(3-20\mathcal{Y})\lvert\alpha_\xi\rvert^2+(3+20\mathcal{Y})\lvert\alpha_\eta\rvert^2\right.$ $\left.+5(-1+4\mathcal{Y})\lvert\beta_\xi\rvert^2-5(1+4\mathcal{Y})\lvert\beta_\eta\rvert^2\right]$

Q_{eH}	$-\frac{1}{2}\mathrm{Re}\left[\left(Y^e_{\rm SM}\right)^\dagger\mathcal{C}_F+\frac{1}{2}\mathrm{Im}\left[\left(Y^e_{\rm SM}\right)^\dagger\tilde{\mathcal{C}}_F+2\lambda_H\left(Y^e_{\rm SM}\right)^\dagger\left(Y^e_{\rm SM}\right)\mathcal{C}_{K4}\right.\right.$
Q_{uH}	$-\frac{1}{2}\mathrm{Re}\left[\left(Y^u_{\rm SM}\right)^\dagger\mathcal{C}_F-\frac{1}{2}\mathrm{Im}\left[\left(Y^u_{\rm SM}\right)^\dagger\tilde{\mathcal{C}}_F+2\lambda_H\left(Y^u_{\rm SM}\right)^\dagger\left(Y^u_{\rm SM}\right)\mathcal{C}_{K4}\right.\right.$
Q_{dH}	$-\frac{1}{2}\mathrm{Re}\left[\left(Y^d_{\rm SM}\right)^\dagger\mathcal{C}_F+\frac{1}{2}\mathrm{Im}\left[\left(Y^d_{\rm SM}\right)^\dagger\tilde{\mathcal{C}}_F+2\lambda_H\left(Y^d_{\rm SM}\right)^\dagger\left(Y^d_{\rm SM}\right)\mathcal{C}_{K4}\right.\right.$
Q_{ledq}	$\left\{\left(Y^e_{\rm SM}\right)\left(Y^d_{\rm SM}\right)^\dagger\mathcal{C}_{K4}+\mathrm{h.c.}\right\}$
$Q^{(1)}_{quqd}$	$\left\{\left(Y^u_{\rm SM}\right)^\dagger\left(Y^d_{\rm SM}\right)^\dagger\mathcal{C}_{K4}+\mathrm{h.c.}\right\}$
$Q^{(1)}_{lequ}$	$-\left\{\left(Y^e_{\rm SM}\right)^\dagger\left(Y^u_{\rm SM}\right)^\dagger\mathcal{C}_{K4}+\mathrm{h.c.}\right\}$
Q_{le}	$-\frac{1}{2}\left(Y^e_{\rm SM}\right)^\dagger\left(Y^e_{\rm SM}\right)\mathcal{C}_{K4}$
$Q^{(1)}_{qu}$	$-\frac{1}{2}\left(Y^u_{\rm SM}\right)^\dagger\left(Y^u_{\rm SM}\right)\mathcal{C}_{K4}$
$Q^{(1)}_{qd}$	$-\frac{1}{2}\left(Y^d_{\rm SM}\right)^\dagger\left(Y^d_{\rm SM}\right)\mathcal{C}_{K4}$

$$|\alpha_i|^2=\frac{1}{4}\left(|Y_{i_L}|^2+|Y_{i_R}|^2+Y^*_{i_L}Y_{i_R}+Y_{i_L}Y^*_{i_R}\right),$$

$$|\beta_i|^2=\frac{1}{4}\left(|Y_{i_L}|^2+|Y_{i_R}|^2-Y^*_{i_L}Y_{i_R}-Y_{i_L}Y^*_{i_R}\right),$$

$$\begin{aligned}\mathcal{C}_F=&-\frac{2}{5}\left(|\alpha_\xi|^4-4|\alpha_\xi|^2|\alpha_\eta|^2+|\alpha_\eta|^4\right)+\frac{4}{3}\left(|\beta_\eta|^4+|\beta_\xi|^2|\beta_\eta|^2+|\beta_\xi|^4\right)\\&+2\left(|\alpha_\eta|^2|\beta_\eta|^2+|\alpha_\xi|^2|\beta_\xi|^2\right)+\frac{2}{3}\left(|\beta_\xi|^2|\alpha_\eta|^2+|\alpha_\xi|^2|\beta_\eta|^2\right)\\&+\frac{4}{3}\left((\alpha_\eta^*)^2\beta_\eta^2+\alpha_\eta^2(\beta_\eta^*)^2+(\alpha_\xi^*)^2\beta_\xi^2+\alpha_\xi^2(\beta_\xi^*)^2\right)+\frac{4}{3}\left(\alpha_\xi\beta_\xi^*\alpha_\eta^*\beta_\eta+\alpha_\xi^*\beta_\xi\alpha_\eta\beta_\eta^*\right),\end{aligned}$$

$$\mathcal{C}_{K4}=\frac{1}{5}\left(|\alpha_\xi|^2+|\alpha_\eta|^2\right)+\frac{1}{3}\left(|\beta_\xi|^2+|\beta_\eta|^2\right),$$

$$\tilde{\mathcal{C}}_F=\frac{1}{3}\left[\left(|Y_{\xi_L}|^2+|Y_{\xi_R}|^2\right)\mathrm{Im}\left[Y_{\xi_L}Y^*_{\xi_R}\right]-\left(|Y_{\eta_L}|^2+|Y_{\eta_R}|^2\right)\mathrm{Im}\left[Y_{\eta_L}Y^*_{\eta_R}\right]\right].$$

Dimension-8 SMEFT Renormalisation

SMEFT Renormalisation Status (2023)!

	d_5	d_5^2	d_6	d_5^3	$d_5 \times d_6$	d_7	d_5^4	$d_5^2 \times d_6$	d_6^2	$d_5 \times d_7$	d_8
$d_{\leq 4}$ (bosonic)			✓						✓		This talk
$d_{\leq 4}$ (fermionic)			✓						X		X
d_5	✓				✓	✓					
d_6 (bosonic)		✓	✓					X	✓	X	This talk
d_6 (fermionic)		✓	✓					X	X	X	X
d_7				✓	✓	✓					
d_8 (bosonic)							This talk	This talk	✓	This talk	This talk
d_8 (fermionic)							X	X	X	X	✓ (orange)

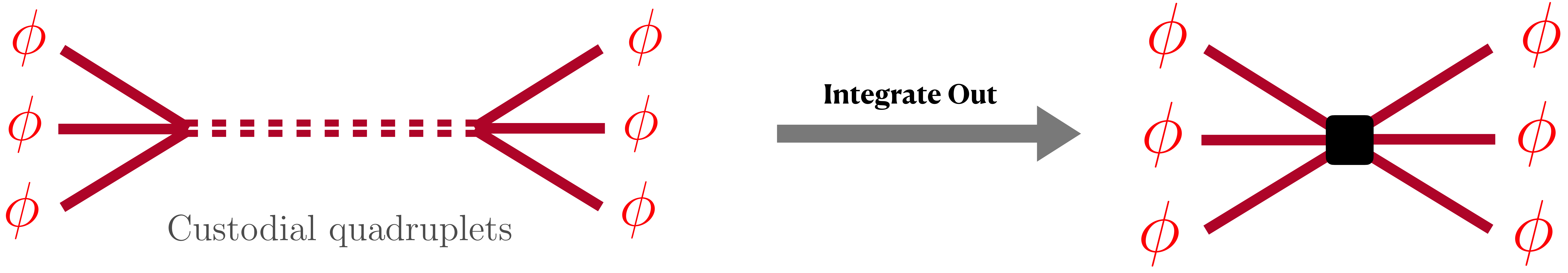
Blank entries vanish; ✓ (green) $\rightarrow$ known; ✓ (orange) $\rightarrow$ substantially known (not complete); X $\rightarrow$ nothing, or very little, is known. The contribution discussed in this talk is marked by ▬.

Table compiled from: arxiv:2106.05291, 2205.03301, 2301.07151 . Check these out for Refs.

Motivations :

- RGEs reveal restrictions on Dim-8 WC space imposed from positivity bounds.

- Custodial symmetry violation absent at tree-level dim-6, dim-8, and 1-loop dim-6.



Chala, Krause, Nardini, (2018); Durieux, McCullough, Salvioni (2022)

- Also, Dim-8 RGEs computed using multiple computational tools, with agreement in results. These establish validation among these tools.

SMEFT Dim-8 RGEs

Λ = EFT cut-off scale

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\sum_i c_i^{(5)} O_i^{(5)} + \frac{1}{\Lambda^2}\sum_i c_i^{(6)} O_i^{(6)} + \frac{1}{\Lambda^3}\sum_j c_j^{(7)} O_j^{(7)} + \frac{1}{\Lambda^4}\sum_j c_j^{(8)} O_j^{(8)} + \cdots$$

$$\dot{c}_i^{(8)} \equiv 16\pi^2 \tilde{\mu}\frac{dc_i^{(8)}}{d\tilde{\mu}} = \boxed{\gamma_{ij} c_j^{(8)}} + \gamma'_{ijk} c_j^{(7)} c_k^{(5)} + \gamma''_{ijklm} c_j^{(5)} c_k^{(5)} c_l^{(5)} c_m^{(5)} + \ldots$$

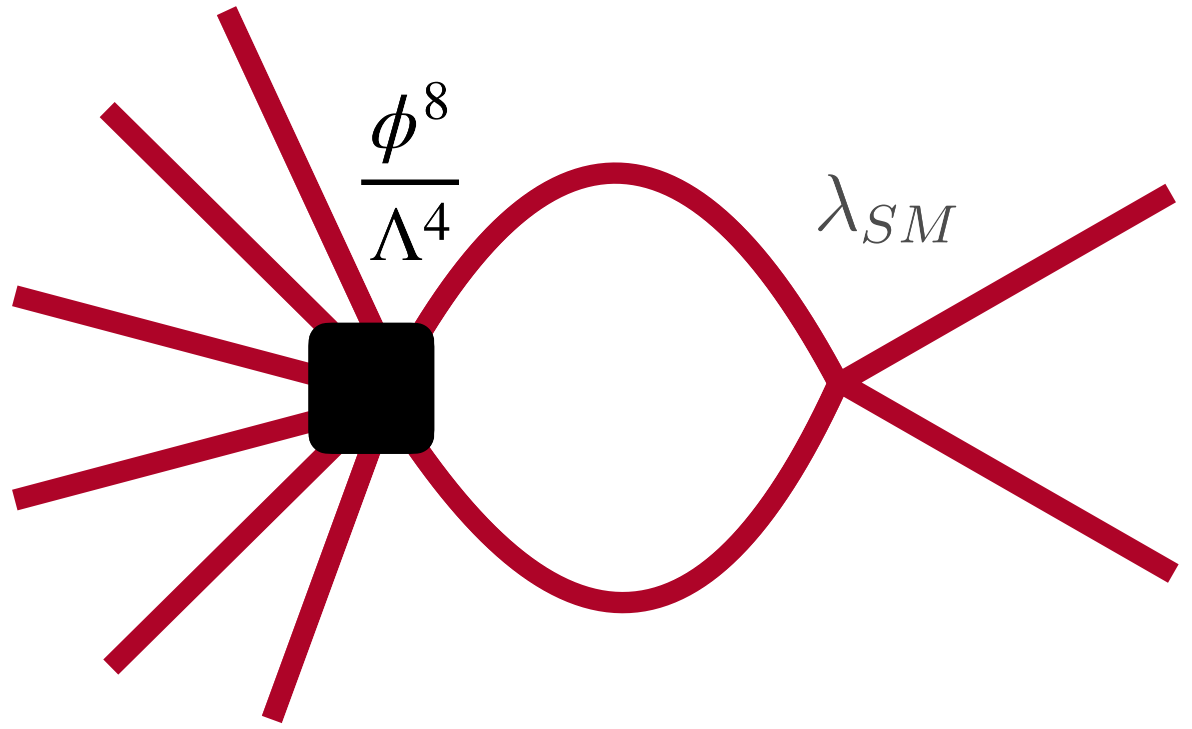
- ❖ One dim-8 operator insertion.

arXiv:2205.03301

Towards the renormalisation of the Standard Model effective field theory to dimension eight: Bosonic interactions II

- SDB, M Chala, Á Díaz-Carmona, G Guedes

e.g. :



Bosonic SMEFT Dim-8 RGEs

Λ = EFT cut-off scale

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\sum_i c_i^{(5)} O_i^{(5)} + \frac{1}{\Lambda^2}\sum_i c_i^{(6)} O_i^{(6)} + \frac{1}{\Lambda^3}\sum_j c_j^{(7)} O_j^{(7)} + \frac{1}{\Lambda^4}\sum_j c_j^{(8)} O_j^{(8)} + \cdots$$

$$\dot{c}_i^{(8)} \equiv 16\pi^2 \tilde{\mu}\frac{dc_i^{(8)}}{d\tilde{\mu}} = \gamma_{ij} c_j^{(8)} + \boxed{\gamma'_{ijk} c_j^{(7)} c_k^{(5)} + \gamma''_{ijklm} c_j^{(5)} c_k^{(5)} c_l^{(5)} c_m^{(5)}} + \ \ldots$$

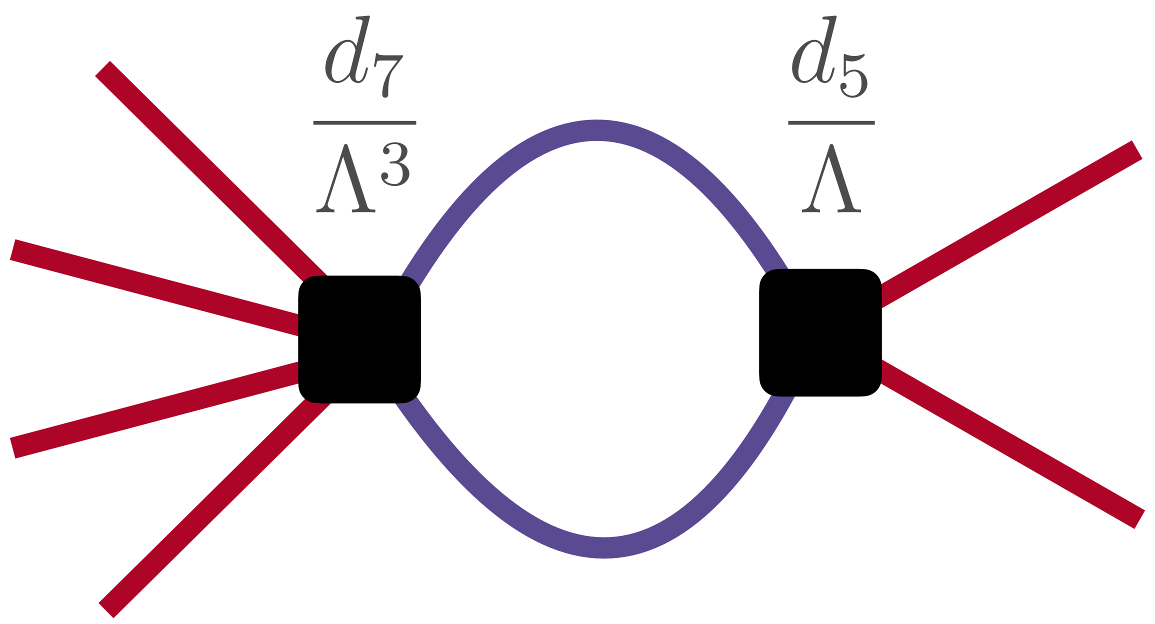
❖ Dim-7 and dim-5 operators insertions.

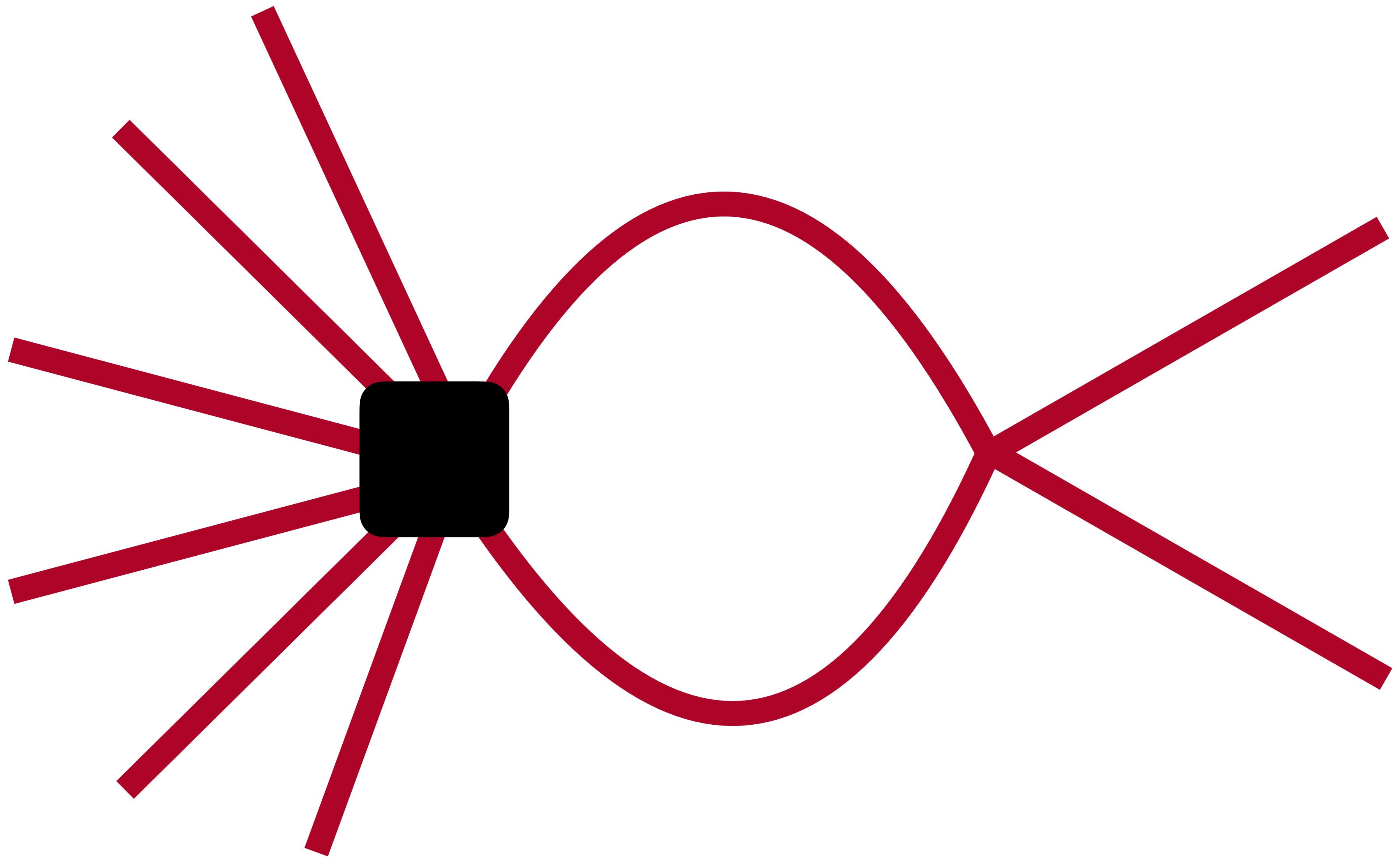
arXiv:2301.07151

Renormalisation of SMEFT bosonic interactions
up to dimension eight by LNV operators

- SDB, Á Díaz-Carmona

e.g. :





Part 1 : Dim-8 renormalisation by Dim-8

arXiv:2301.07151

SMEFT Operator Classes

$$\dot{c}_i^{(8)} \equiv 16\pi^2 \tilde{\mu} \frac{dc_i^{(8)}}{d\tilde{\mu}} = \boxed{\gamma_{ij} c_j^{(8)}} + \gamma'_{ijk} c_j^{(7)} c_k^{(5)} + \gamma''_{ijklm} c_j^{(5)} c_k^{(5)} c_l^{(5)} c_m^{(5)} + \ldots$$

- One **tree-level generated** dim-8 operator in one-loop.

arXiv:2001.00017
- Craig, Jiang, Li, Sutherland

Classes of operator that are tree-level generated:

Bosonic : $\{\phi^8, \phi^6 D^2, \phi^4 D^4, X^2 \phi^4, X \phi^4 D^2, X^2 H^2 D^2, X^3 H^2, X^4\}$

Fermionic : $\{\psi^2 X \phi^3,\ \psi^2 \phi^2 D^3,\ \psi^2 \phi^5,\ \psi^2 \phi^4 D,\ \psi^2 X \phi^2 D,\ \psi^2 \phi^3 D^2, \psi^2 X^2 \phi, \psi^2 X^2 D, \psi^2 X \phi D^2\}$

SMEFT Dim-8 **on-shell basis** : arXiv:2005.00059 — C. W. Murphy

SMEFT Dim-8 **Green's/off-shell basis** : arXiv:2112.12724 — M. Chala, Á Díaz-Carmona, G. Guedes

More on this : Alvaro's talk on Wednesday!

Divergences to RGEs, some details:

- Compute **1-PI loop diagrams**. Use **FeynRules, FeynARTs,** and **FormCalc** packages.

- Divergences are captured by the operators of **off-shell/Green's basis**.

arXiv:2112.12724
- M Chala, Á Díaz-Carmona, G Guedes

$$16\pi^2 \epsilon\, \mathcal{L}_{\rm DIV} = \tilde{K}_\phi (D_\mu \phi)^\dagger (D^\mu \phi) + \tilde{\mu}^2 |\phi|^2 - \tilde{\lambda} |\phi|^4 + \tilde{c}_i^{(6)} \frac{\mathcal{O}_i^{(6)}}{\Lambda^2} + \tilde{c}_j^{(8)} \frac{\mathcal{O}_j^{(8)}}{\Lambda^4}$$

[on RHS we have Green's basis]

- **Removing redundant operators** using on-shell relations.

arXiv:2106.05291
- M Chala, G Guedes, M Ramos, J Santiago

- **Cross-checks with MatchMakerEFT.** ✓
  H^8 topologies are computed in MM primarily.

arXiv:2112.10787
- A Carmona, A Lazopoulos, P Olgoso, J Santiago

- **Subset of our RGEs cross-validated** with arXiv:2108.03669 (on-shell amplitude methods). ✓

(at linear order in the Wilson coefficients and leading (quadratic) order in the renormalisable couplings)

arXiv:2108.03669
- M A Huber, S De Angelis.

Bosonic-bosonic RGE:

Classes of tree-generated bosonic operators

	$\phi^4 D^4$	$B\phi^4 D^2$	$W\phi^4 D^2$	$B^2\phi^4$	$W^2\phi^4$	$WB\phi^4$	$G^2\phi^4$	$\phi^6 D^2$	ϕ^8
$B^2\phi^2 D^2$	g_1^2	0	0	0	0	0	0	0	0
$W^2\phi^2 D^2$	g_2^2	0	0	0	0	0	0	0	0
$WB\phi^2 D^2$	$g_1 g_2$	0	0	0	0	0	0	0	0
$G^2\phi^2 D^2$	0	0	0	0	0	0	0	0	0
$W^3\phi^2$	0	0	0	0	0	0	0	0	0
$W^2B\phi^2$	0	0	0	0	0	0	0	0	0
$G^3\phi^2$	0	0	0	0	0	0	0	0	0
$\phi^4 D^4$	g_2^2	0	0	0	0	0	0	0	0
$B\phi^4 D^2$	$g_1 g_2^2$	λ	0	0	0	0	0	0	0
$W\phi^4 D^2$	g_2^3	0	g_2^2	0	0	0	0	0	0
$B^2\phi^4$	$g_1^2 g_2^2$	$g_1\lambda$	$g_1^2 g_2$	λ	0	$g_1 g_2$	0	0	0
$W^2\phi^4$	g_2^4	$g_1 g_2^2$	g_2^3	0	λ	$g_1 g_2$	0	0	0
$WB\phi^4$	$g_1 g_2^3$	$g_2\lambda$	$g_1\lambda$	$g_1 g_2$	$g_1 g_2$	λ	0	0	0
$G^2\phi^4$	0	0	0	0	0	0	g_3^2	0	0
$\phi^6 D^2$	g_2^4	$g_1\lambda$	$g_2\lambda$	0	0	0	0	λ	0
ϕ^8	λ^3	$g_1\lambda^2$	$g_2\lambda^2$	$g_1^2\lambda$	$g_2^2\lambda$	$g_1 g_2\lambda$	0	λ^2	λ

- **Largest contribution from each operator class is shown.**
- **Loop generated operators that are renormalised by tree-generated operators are in gray.**
- **Blue entries contribute larger than what expected from naive dimensional analysis.**

$$\tilde{\mu}\frac{dc_{\phi^8}}{d\tilde{\mu}} = \frac{1}{16\pi^2}\left(192\lambda - 6(g_1^2 + 3g_2^2) + \ldots\right) c_{\phi^8}$$

Fermionic-bosonic RGE:

Classes of tree-generated fermionic operators

	$\psi^2 B\phi^3$	$\psi^2 W\phi^3$	$\psi^2 G\phi^3$	$\psi^2\phi^2 D^3$	$\psi^2\phi^5$	$\psi^2\phi^4 D$	$\psi^2 B\phi^2 D$	$\psi^2 W\phi^2 D$	$\psi^2 G\phi^2 D$	$\psi^2\phi^3 D^2$
$B^2\phi^2 D^2$	0	0	0	g_1^2	0	0	0	0	0	0
$W^2\phi^2 D^2$	0	0	0	g_2^2	0	0	0	0	0	0
$WB\phi^2 D^2$	0	0	0	$g_1 g_2$	0	0	0	0	0	0
$G^2\phi^2 D^2$	0	0	0	g_3^2	0	0	0	0	0	0
$W^3\phi^2$	0	0	0	0	0	0	0	0	0	0
$W^2 B\phi^2$	0	0	0	0	0	0	0	0	0	0
$G^3\phi^2$	0	0	0	0	0	0	0	0	0	0
$\phi^4 D^4$	0	0	0	$\|y^t\|^2$	0	0	0	0	0	0
$B\phi^4 D^2$	0	0	0	$g_1\|y^t\|^2$	0	0	$\|y^t\|^2$	0	0	$g_1 y^t$
$W\phi^4 D^2$	0	0	0	$g_2\|y^t\|^2$	0	0	0	$\|y^t\|^2$	0	$g_2 y^t$
$B^2\phi^4$	$g_1 y^t$	0	0	$g_1^2\|y^t\|^2$	0	0	$g_1\|y^t\|^2$	0	0	$g_1^2 y^t$
$W^2\phi^4$	0	$g_2 y^t$	0	$g_2^2\|y^t\|^2$	0	g_2^2	0	$g_2\|y^t\|^2$	0	$g_2^2 y^t$
$WB\phi^4$	$g_2 y^t$	$g_1 y^t$	0	$g_1 g_2\|y^t\|^2$	0	$g_1 g_2$	$g_2\|y^t\|^2$	$g_1\|y^t\|^2$	0	$g_1 g_2 y^t$
$G^2\phi^4$	0	0	$g_3 y^t$	0	0	0	0	0	0	0
$\phi^6 D^2$	0	0	0	$g_2^2\|y^t\|^2$	0	$\|y^t\|^2$	$g_1\|y^t\|^2$	$g_2\|y^t\|^2$	0	$y^t\|y^t\|^2$
ϕ^8	0	0	0	$\lambda\|y^t\|^4$	$y^t\|y^t\|^2$	$\lambda\|y^t\|^2$	$g_1\lambda\|y^t\|^2$	$g_2\lambda\|y^t\|^2$	0	$\lambda y^t\|y^t\|^2$

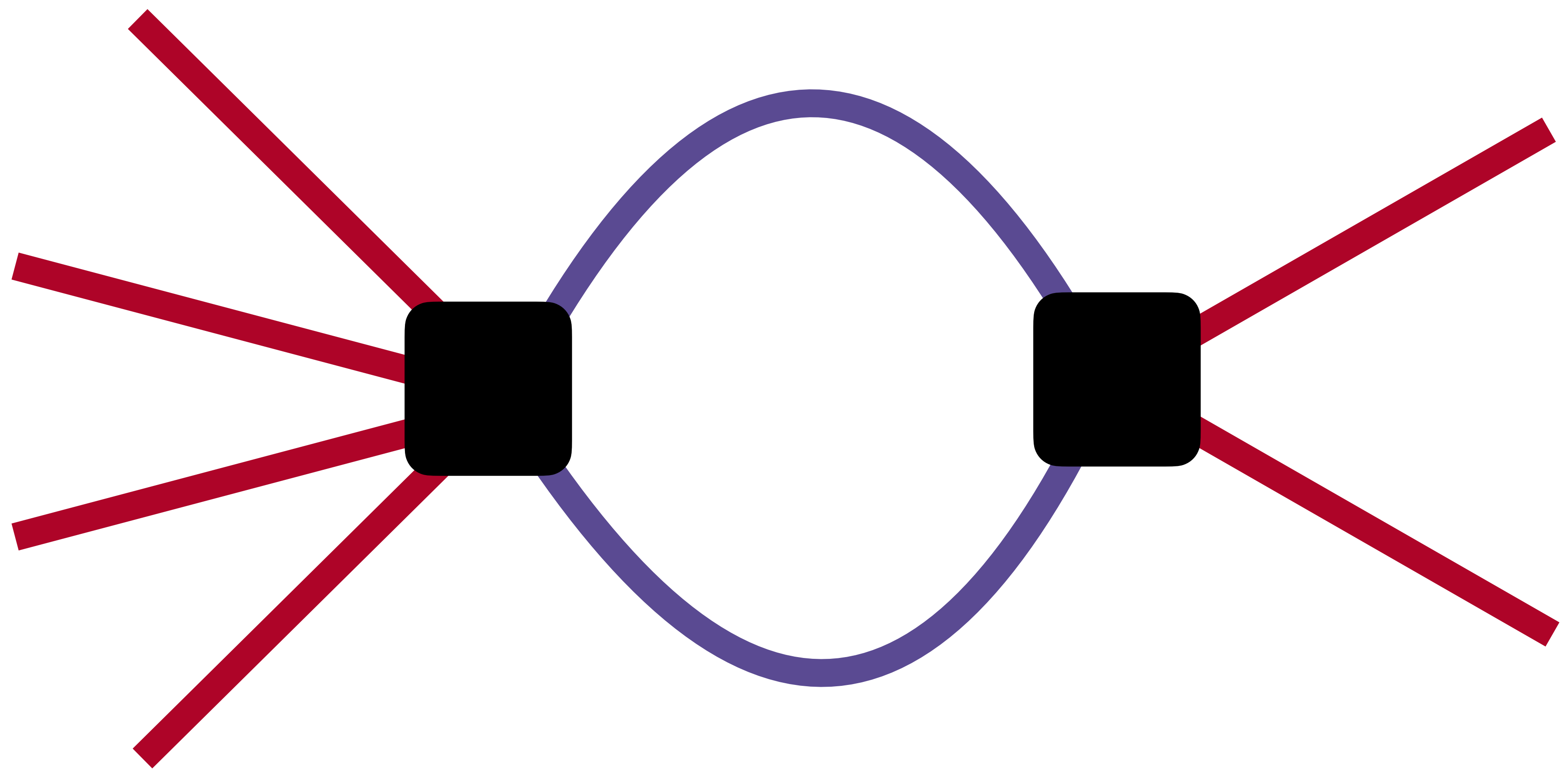
RGEs of Dim-6,4,2

- Dim-8 operators also induce running of dim-6, dim-4, dim-2 operators.

	$\phi^4 D^4$	$B\phi^4 D^2$	$W\phi^4 D^2$	$B^2\phi^4$	$W^2\phi^4$	$WB\phi^4$	$G^2\phi^4$	$\phi^6 D^2$	ϕ^8
ϕ^2	μ^6	0	0	0	0	0	0	0	0
ϕ^4	$\lambda\mu^4$	$g_1\mu^4$	$g_2\mu^4$	0	0	0	0	μ^4	0
$B^2\phi^2$	$g_1^2\mu^2$	$g_1\mu^2$	0	μ^2	0	0	0	0	0
$W^2\phi^2$	$g_2^2\mu^2$	0	$g_2\mu^2$	0	μ^2	0	0	0	0
$WB\phi^2$	$g_1 g_2\mu^2$	$g_2\mu^2$	$g_1\mu^2$	0	0	μ^2	0	0	0
$G^2\phi^2$	0	0	0	0	0	0	μ^2	0	0
$\phi^4 D^2$	$\lambda\mu^2$	$g_1\mu^2$	$g_2\mu^2$	0	0	0	0	μ^2	0
ϕ^6	$\lambda^2\mu^2$	$\lambda g_1\mu^2$	$\lambda g_2\mu^2$	$g_1^2\mu^2$	$g_2^2\mu^2$	$g_1 g_2\mu^2$	0	$\lambda\mu^2$	μ^2

μ^2 is the squared Higgs mass in the SMEFT.

Lower dim. classes renormalised by the bosonic dim-8 operators.
Similar contributions from two-fermionic dim-8 operators are also present.

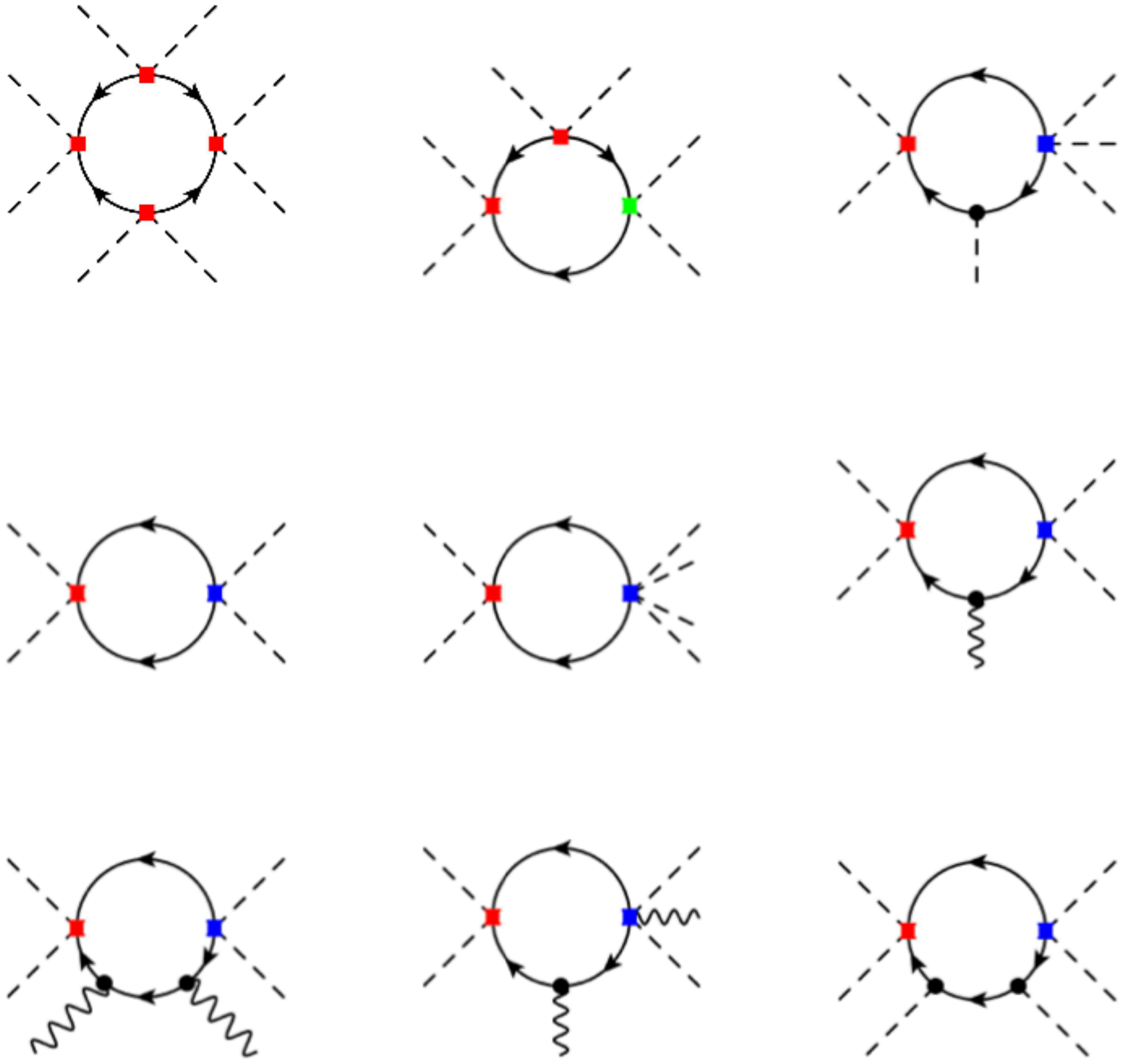


Part 2 : Dim-8 renormalisation by Dim-5 & Dim-7

arXiv:2301.07151

LNV contributions (1-loop) to bosonic SMEFT: D5, D6, D7 insertions

$1/\Lambda^4$	d_5^4	$d_5^2 \times d_6$	$d_5 \times d_7$
8-Higgs	✓	-	-
6-Higgs	-	✓	✓
4-Higgs	-	-	✓
2-Higgs	-	-	-
0-Higgs	-	-	-



The hyphen stands for the vanishing contributions from LNVs upto Λ^{-3} at 1-loop.

Bosonic SMEFT RGEs from LNVs :

	$(\alpha_{\ell\phi})^4$	$(\alpha_{\ell\phi})^2\beta_{\phi D}$	$(\alpha_{\ell\phi})^2\beta^{(1)}_{\phi\ell}$	$(\alpha_{\ell\phi})^2\beta^{(3)}_{\phi\ell}$	$\alpha_{\ell\phi}\omega_{\ell\phi}$	$\alpha_{\ell\phi}\omega^{(1)}_{\ell\phi D}$	$\alpha_{\ell\phi}\omega^{(2)}_{\ell\phi D}$	$\alpha_{\ell\phi}\omega_{\ell\phi De}$	$\alpha_{\ell\phi}\omega_{\ell\phi W}$
γ_{ϕ^8}	16	8λ	32λ	32λ	16λ	$2\lambda g_2^2$	λg_2^2	0	0
$\gamma^{(1)}_{\phi^6}$	0	4	48	64	16	$\frac{14}{3}g_2^2$	32λ	$4y^e$	0
$\gamma^{(2)}_{\phi^6}$	0	8	32	16	8	$\frac{1}{6}g_2^2$	16λ	$4y^e$	0
$\gamma^{(2)}_{\phi^4}$	0	0	0	0	0	$\emptyset$	8	0	0
$\gamma^{(1)}_{W\phi^4D^2}$	0	0	0	0	0	$8g_2$	$4g_2$	0	$\emptyset$
$\gamma^{(2)}_{W\phi^4D^2}$	0	0	0	0	0	$8g_2$	$4g_2$	0	$\emptyset$
$\gamma^{(3)}_{W\phi^4D^2}$	0	0	0	0	0	$4g_2$	$2g_2$	0	$\emptyset$
$\gamma^{(4)}_{W\phi^4D^2}$	0	0	0	0	0	$4g_2$	$2g_2$	0	$\emptyset$
$\gamma^{(1)}_{W^2\phi^4}$	0	0	0	0	0	$\frac{1}{2}g_2^2$	$\frac{1}{4}g_2^2$	0	$4g_2$
$\gamma^{(2)}_{W^2\phi^4}$	0	0	0	0	0	$\frac{1}{2}g_2^2$	$\frac{1}{4}g_2^2$	0	$4g_2$
$\gamma^{(3)}_{W^2\phi^4}$	0	0	0	0	0	$\frac{1}{2}g_2^2$	$\frac{1}{4}g_2^2$	0	$4g_2$
$\gamma^{(4)}_{W^2\phi^4}$	0	0	0	0	0	$\frac{1}{2}g_2^2$	$\frac{1}{4}g_2^2$	0	$4g_2$
$\gamma^{(1)}_{WB\phi^4}$	0	0	0	0	0	g_1g_2	$\frac{1}{2}g_1g_2$	0	$\emptyset$
$\gamma^{(2)}_{WB\phi^4}$	0	0	0	0	0	g_1g_2	$\frac{1}{2}g_1g_2$	0	$\emptyset$
γ_{ϕ}	0	$4\mu^2$	$16\mu^2$	$16\mu^2$	$8\mu^2$	$\mu^2g_2^2$	$16\mu^2\lambda$	0	0
$\gamma_{\phi\Box}$	0	0	0	0	0	0	$16\mu^2$	0	0
$\gamma_{\phi D}$	0	0	0	0	0	0	$16\mu^2$	0	0
γ_{λ}	0	0	0	0	0	0	$8\mu^4$	0	0

Summary

- Renormalisation of bosonic SMEFT dim-8 operators discussed.
  - By Tree-level generated dim-8 operators.
  - By dim-5 & dim-7 LNV operators.
- These operators also contribute to the running of lower dimensional operators.
- Certain elements contribute larger than what expected from naive dimensional analysis.
- T-parameter example: RGEs translate bounds to blind direction of LNV spaces.

Thanks for your attention!

Backup slides

Take trace and use BCH formula -

$$e^{B} A e^{-B} = \sum_{n=0}^{\infty} \frac{1}{n!} L_B^n A \ , \qquad L_B A = [B, A]$$

Henning et. al. JHEP01(2016)023

Integral :

$$S_{\text{eff,1-loop}} = i\ c \int d^4x \int \frac{d^4q}{(2\pi)^4} \text{tr} \log\left(-(\mathcal{P} - q)^2 + m^2 + U(x)\right)$$

Sandwich $e^{\pm P \cdot \frac{\partial}{\partial q}}$ on both sides of the integrand

$$S_{\text{eff,1-loop}} = i\ c \int d^4x \int \frac{d^4q}{(2\pi)^4} \text{tr} \log\left[-(q_\mu + \tilde{G}_{\nu\mu} \frac{\partial}{\partial q_\nu})^2 + m^2 + \tilde{U}\right]$$

$$\tilde{G}_{\nu\mu} = -\sum_{n=0}^{\infty} \frac{n+1}{(n+2)!} [P_{a_1}, [P_{a_2}, [\ldots [P_{a_n}, [P_\nu, P_\mu]]]]] \frac{\partial^n}{\partial q_{a_1} \partial q_{a_2} \ldots \partial q_{a_n}}$$

$$\tilde{U} = \sum_{n=0}^{\infty} \frac{1}{n!} [P_{a_1}, [P_{a_2}, [\ldots [P_{a_n}, U]]]] \frac{\partial^n}{\partial q_{a_1} \partial q_{a_2} \ldots \partial q_{a_n}}$$

1-loop processes in EFT

Idea proposed by Gaillard (1986) and Cheyette (1988) and later adapted by Henning et. al. (2016)

Gauge invariant higher dimension operators.

$$S_{\text{eff,1-loop}} = i\ c \int d^4x \int \frac{d^4q}{(2\pi)^4} \text{tr} \log\left[-(q_\mu + \tilde{G}_{\nu\mu}\frac{\partial}{\partial q_\nu})^2 + m^2 + \tilde{U}\right]$$

tr : over internal indices like gauge and spinor indices

Gaillard M.K. Nucl.Phys. B268 (1986) 669-692

Cheyette O. Nucl. Phys. B 297 (1988) 183

Henning et. al. JHEP01(2016)023

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tr : over internal indices like gauge and spinor indices

$$\log[x^2 - a^2] \rightarrow \int dx^2 \frac{1}{x^2 - a^2}$$

Expand the denominator in binomial series.

Terms in series are suppressed by the mass of the heavy field.

Gaillard M.K. Nucl.Phys. B268 (1986) 669-692

Cheyette O. Nucl. Phys. B 297 (1988) 183

Henning et. al. JHEP01(2016)023

Goto

RGFlow of the Wilson coefficients

In[7]: RGFlow[Wilson coefficients, mH2, μ]

Out[7]:

37 operators —RGFlow→ **48 operators** In Warsaw basis

The RGE on tree + 1loop 2HDM matching result available:

https://github.com/effExTeam/SMEFT-EWPO-Higgs

Wilson coefficient exchange format

```
In[2]:= Import["sample_result_1.json"]

Out[2]= {eft→SMEFT,basis→Warsaw,scale→246,values→{phil1_11→-3.53103*10^-12,phiD→-1.97003*10^-8,
        ephi_11→-2.12747*10^-16,phiu_11→4.70804*10^-12,phi→-5.26475*10^-7,uphi_11→-9.36088*10^-16,
        phiBox→3.53103*10^-11,dphi_11→-1.87218*10^-15,phie_11→-7.06206*10^-12,
        phiq1_11→1.17701*10^-12,phid_11→-2.35402*10^-12}}

In[3]:= wcxfIn[246 (*scale*),%(*wcxf data*) ]

Out[3]= {{q1Hl[1,1],-3.53103*10^-12},{qHD,-1.97003*10^-8},{qeH[1,1],-2.12747*10^-16},
        {qHu[1,1],4.70804*10^-12},{qH,-5.26475*10^-7},{quH[1,1],-9.36088*10^-16},
        {qHbox,3.53103*10^-11},{qdH[1,1],-1.87218*10^-15},{qHe[1,1],-7.06206*10^-12},
        {q1Hq[1,1],1.17701*10^-12},{qHd[1,1],-2.35402*10^-12}}
```

Wilson coefficient exchange format

Aebischer et. al. JCPC 2018.05.022

Matching, mapping, running packages for EFTs:

In[8]:=
```
result=codexresult/.numvalpar//N
```

Out[8]=
```
{{qH,-5.26475*10^-7},{qHbox,3.53103*10^-11},{qHD,-1.97003*10^-8},{qeH[1,1],-2.12747*10^-16},
{quH[1,1],-9.36088*10^-16},{qdH[1,1],-1.87218*10^-15},{q1Hl[1,1],-3.53103*10^-12},
{qHe[1,1],-7.06206*10^-12},{q1Hq[1,1],1.17701*10^-12},{qHu[1,1],4.70804*10^-12},
{qHd[1,1],-2.35402*10^-12}}
```

In[10]:=
```
wcxfOut[246 (*scale*),result (* Numerical Wilson coefficients*)]
```

Out[10]=
```
{eft→SMEFT,basis→Warsaw,scale→246,values →{phi→-5.26475*10^-7,phiBox→3.53103*10^-11,
phiD→-1.97003*10^-8,ephi_11→-2.12747*10^-16,uphi_11→-9.36088*10^-16,
dphi_11→-1.87218*10^-15,phil1_11→-3.53103*10^-12,phie_11→-7.06206*10^-12,
phiq1_11→1.17701*10^-12,phiu_11→4.70804*10^-12,phid_11→-2.35402*10^-12}}
```

SmeftFr 1904.03204,
MatchingTools 1710.06445,
SMEFiT 1901.05965,
DSixTools 1704.04504,
wilson 1804.05033,
smelli 2012.12211,
SMEFTsim 1709.06492,
Matchmakereft 2112.10787

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In Warsaw basis

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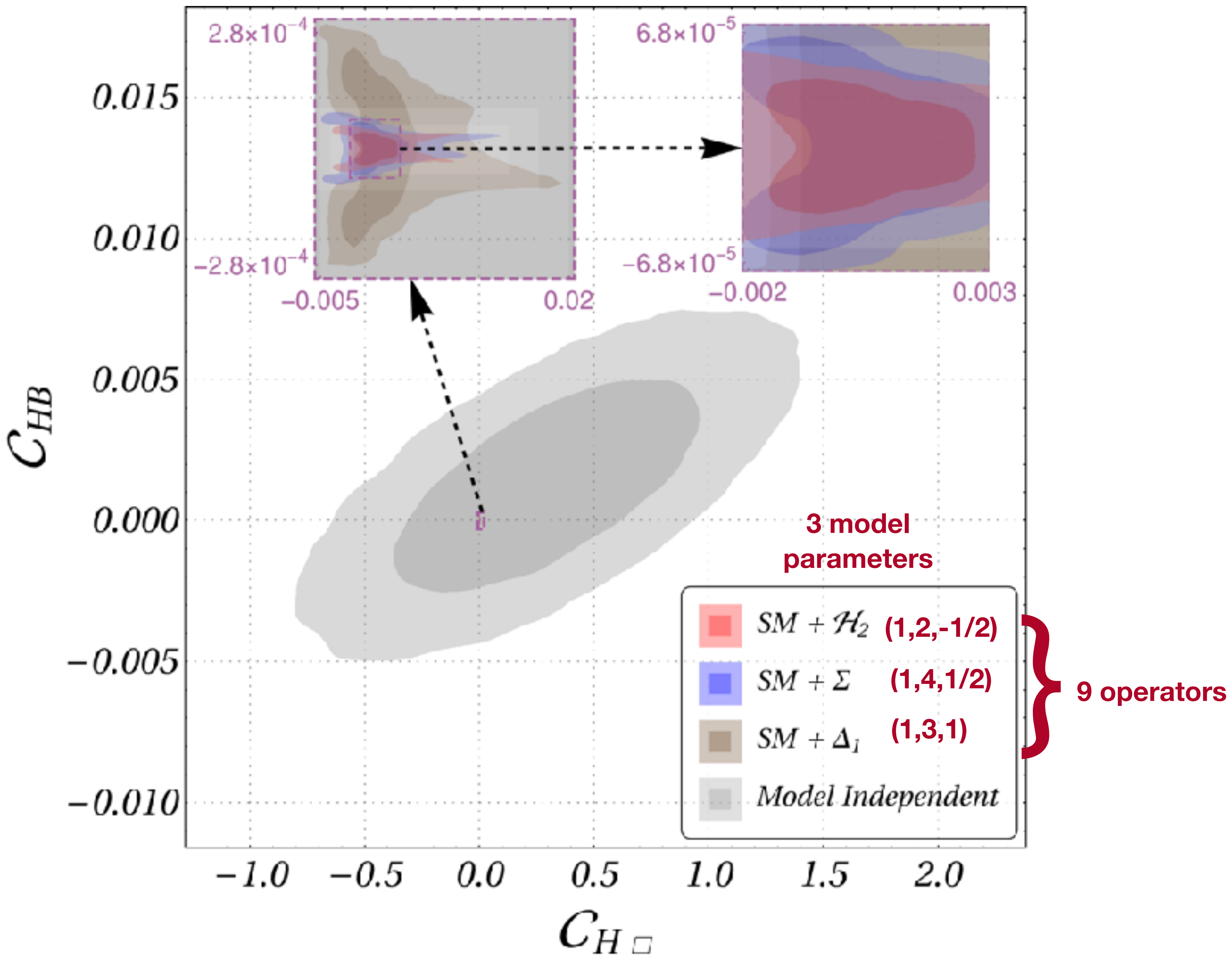
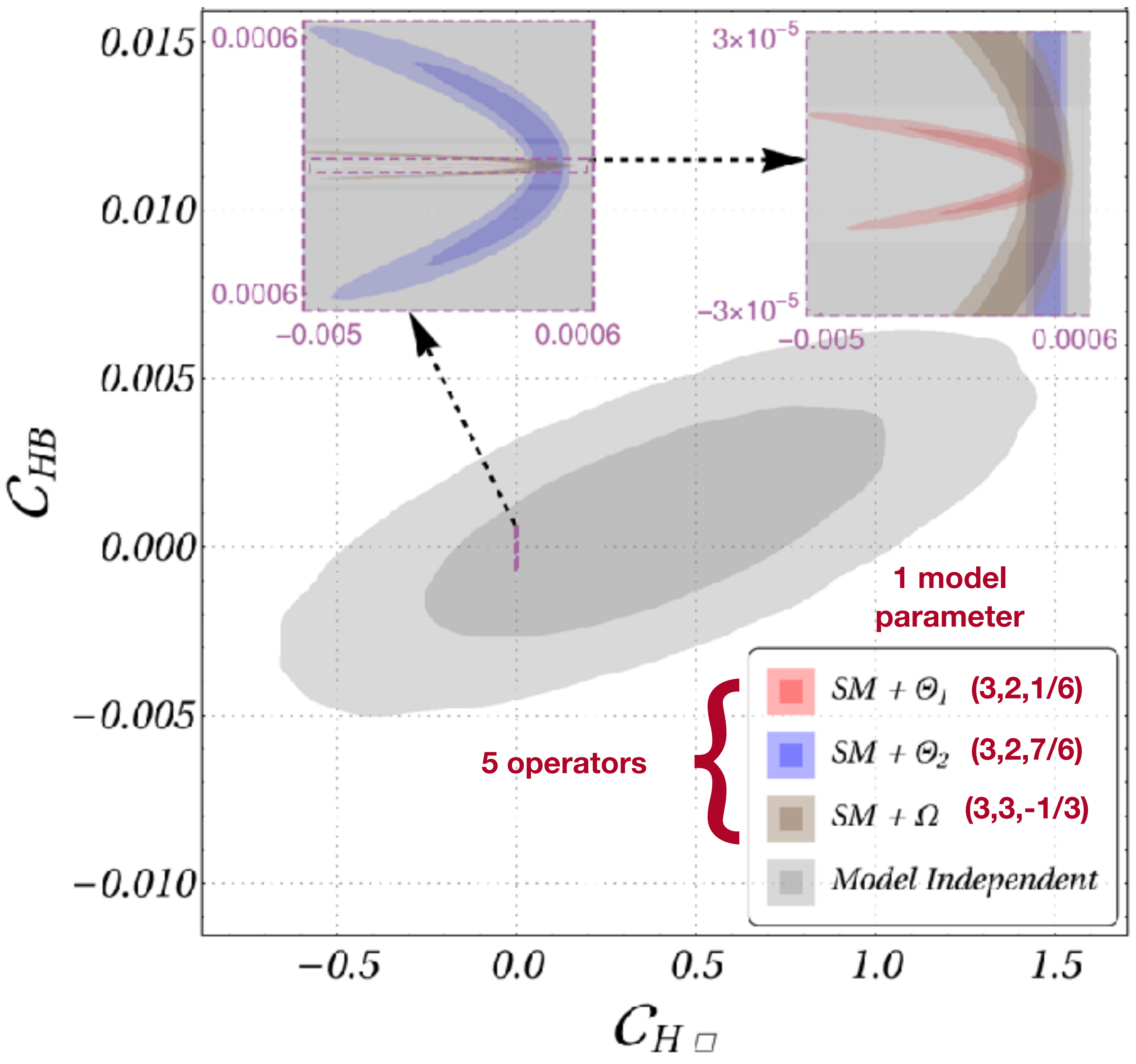
Proof of concept: Comparison of the WC space for two classes





Anisha, SDB, J Chakrabortty, S Patra.
***Phys.Rev.D* 103 (2021) 7, 076007, arxiv:2010.04088**

https://github.com/effExTeam/SMEFT-EWPO-Higgs