CoDEx: Matching BSMs to SMEFT

SMEFT Tools 2022

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Based on arxiv:1808:04403, in collaboration with
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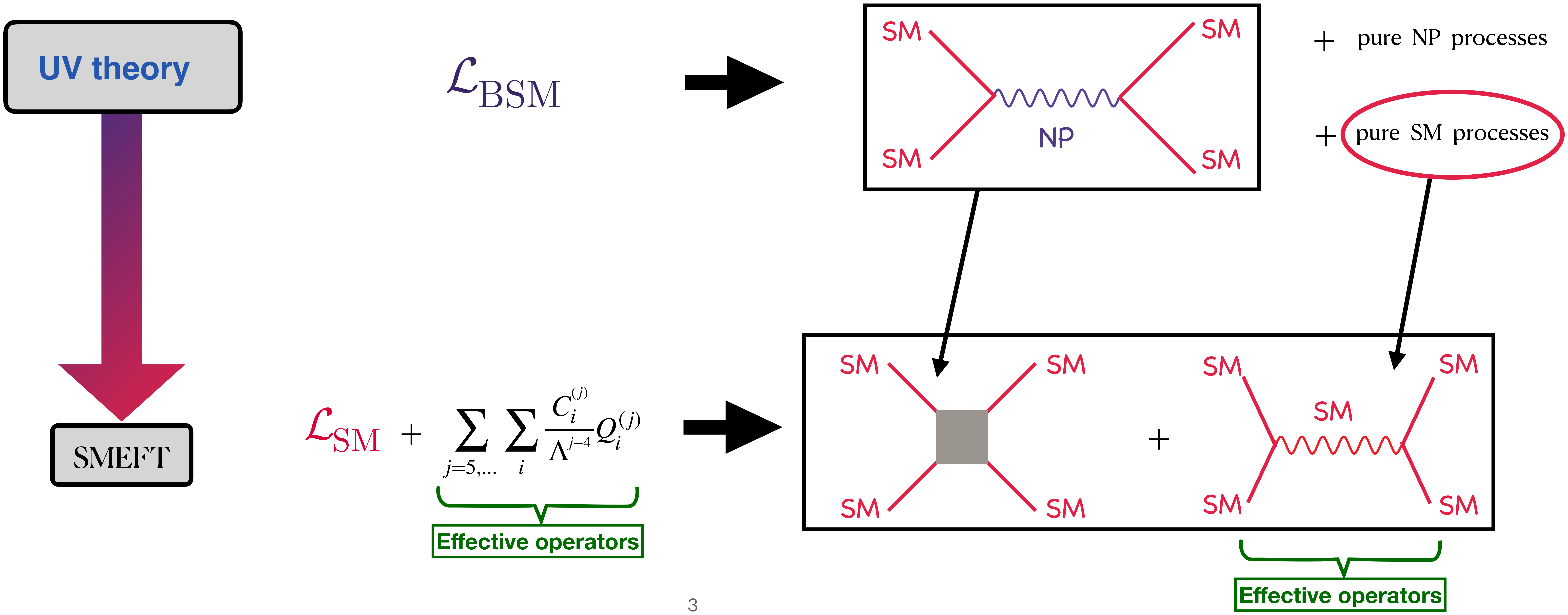
BSMs to SMEFT

- The Standard Model is the most accurate description of the sub-atomic physics (known to us yet), but it's not complete.
- Existence of new physics is supported by phenomena like neutrino oscillation, dark matter, baryon asymmetry, …
- Numerous BSM scenarios account for these phenomenon: e.g. seesaw models (new particle/field), Left-Right symmetry models (particle ext. + enlarged gauge symm.), …
- Standard Model EFT provides a platform to compare among these models, using simultaneously Top-down & Bottom-up approach.
- CoDEx is a mathematica package that automatises the matching procedure, i.e. to create the SMEFT for each BSM.

Matching

- ✤ **Input → BSM Lagrangian, Output → Wilson coefficients**



UV theory

SMEFT

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

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

$+$ pure NP processes

$+$ pure SM processes

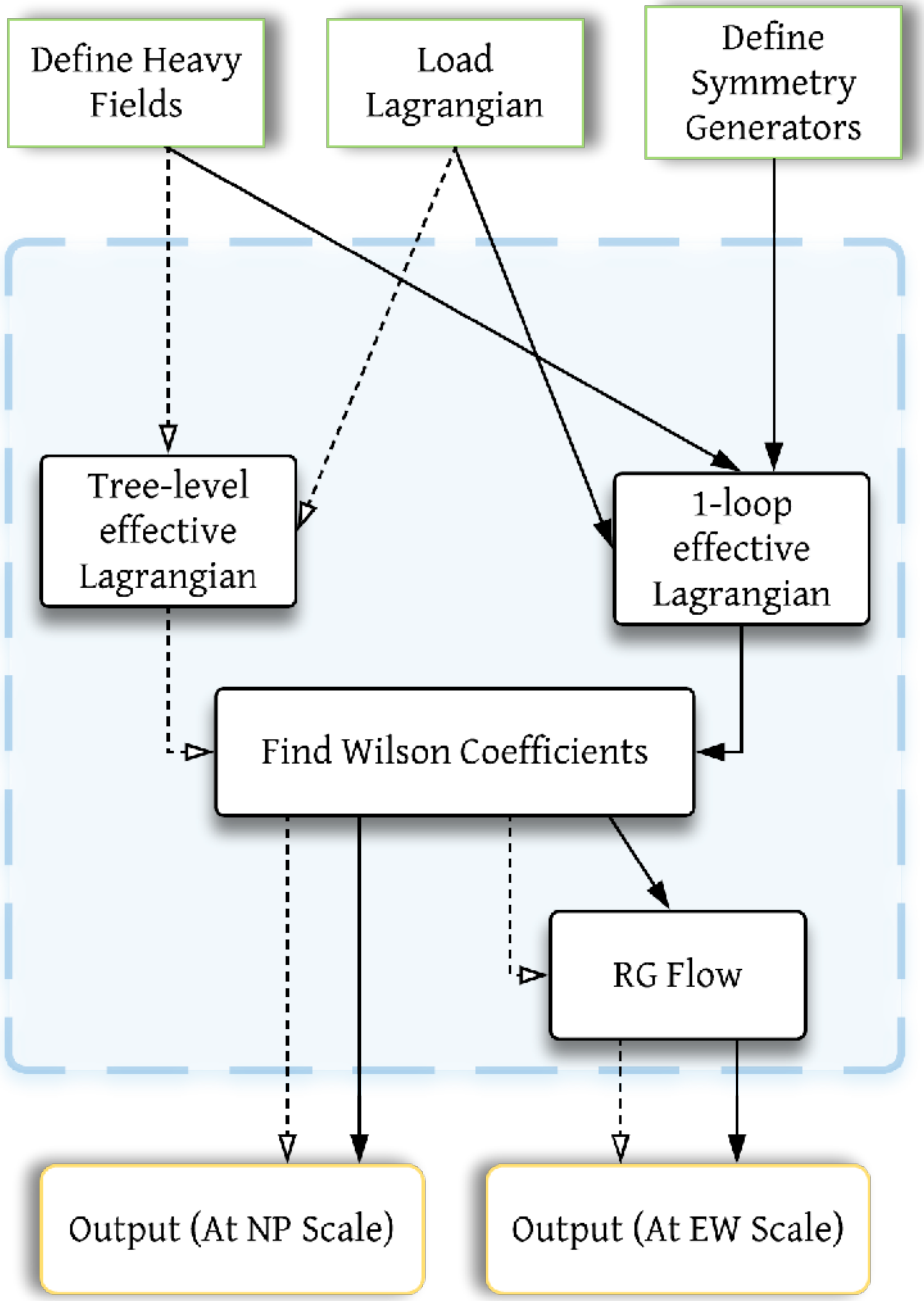
Effective operators

CoDEx: Wilson coefficient calculator connecting SMEFT to UV theory

https://effexteam.github.io/CoDEx/

Construction of:

- Tree-level effective lagrangian
- 1-Loop-level effective lagrangian
- Coefficients bases: Warsaw and SILH (SMEFT Dim-6)
- Operator identity implementations
- RG Flow in Warsaw



Integrating out a heavy field at tree-level

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

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 (real) heavy field

$$(D^2 + m^2 - U(\phi))\Phi = B(\phi) + \mathcal{O}(\Phi^2)$$

$$\Rightarrow \Phi_c^{(0)} = \frac{1}{D^2 + m^2 - U(\phi)} B(\phi)$$

Leading order

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

Substitution:

$$B(\phi) * \Phi_c^{(0)} = B(\phi)\frac{1}{m^2} B(\phi) - \frac{1}{m^2} B(\phi)(D^2 - U(\phi))\frac{1}{m^2} B(\phi) \quad \Big\}$$

Dependent only on light fields

Integrating out a heavy field at tree-level

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

Φ — **Heavy field**

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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

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

Λ: cut-off scale

$c_j^{(n)}$: Wilson coefficients

$O_j^{(n)}$: Operators of mass dimension ’n’

SM + Real singlet heavy scalar Φ

Φ → Color singlet, isospin singlet & hypercharge = 0

H : SM Higgs

$$\mathcal{L}_\Phi = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu \Phi)^2 - \frac{1}{2}m_\Phi^2\Phi^2 \boxed{- \eta|H|^2\Phi} \boxed{- \frac{1}{2}\kappa|H|^2\Phi^2} - \frac{1}{3!}\mu\Phi^3 - \frac{1}{4!}\lambda_\Phi\Phi^4$$

Term linear in heavy field

Term quadratic in heavy field

Solution

$$\Phi_c = \Phi_c^{(0)} + \Phi_c^{(1)} + \Phi_c^{(2)} + \ldots$$

Substitution

$$\mathcal{L}_\Phi(\Phi, H) \rightarrow \mathcal{L}_\Phi(\Phi_c, H)$$

$$\Phi_c^{(0)} = \frac{1}{D^2 + m_\Phi^2 + \kappa|H|^2}(-\eta|H|^2)$$

$$\Phi_c^{(1)} = \frac{1}{D^2 + m_\Phi^2 + \kappa|H|^2}(-\frac{\mu}{2}(\Phi_c^{(0)})^2 - \frac{\lambda_\Phi}{6}(\Phi_c^{(0)})^3)$$

$$\Phi_c^{(2)} = \frac{1}{D^2 + m_\Phi^2 + \kappa|H|^2}(-\mu(\Phi_c^{(0)})(\Phi_c^{(1)}) - \frac{\lambda_\Phi}{2}(\Phi_c^{(0)})^2\Phi_c^{(1)})$$

***SMEFT Basis:* *Warsaw* (arxiv:1008.4884)**

Q_H	$(H^\dagger H)^3$	$-\frac{\eta^2\kappa}{2m_\Phi^4} + \frac{\eta^3\mu}{6m_\Phi^6}$
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	$-\frac{\eta^2}{2m_\Phi^4}$

Truncate for dimension-6 EFT !

More on this: 1811.08878, 2003.05936

SM + Heavy Scalar Doublet φ

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

H : SM Higgs

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

Couplings with fermions suppressed

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

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

Term quadratic in heavy field

Term linear in heavy field

$$\varphi_c^{(0)} \approx \frac{1}{m^2}B - \frac{1}{m^2}(D^2 - U)\frac{1}{m^2}B$$

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

Term linear in Heavy field :

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

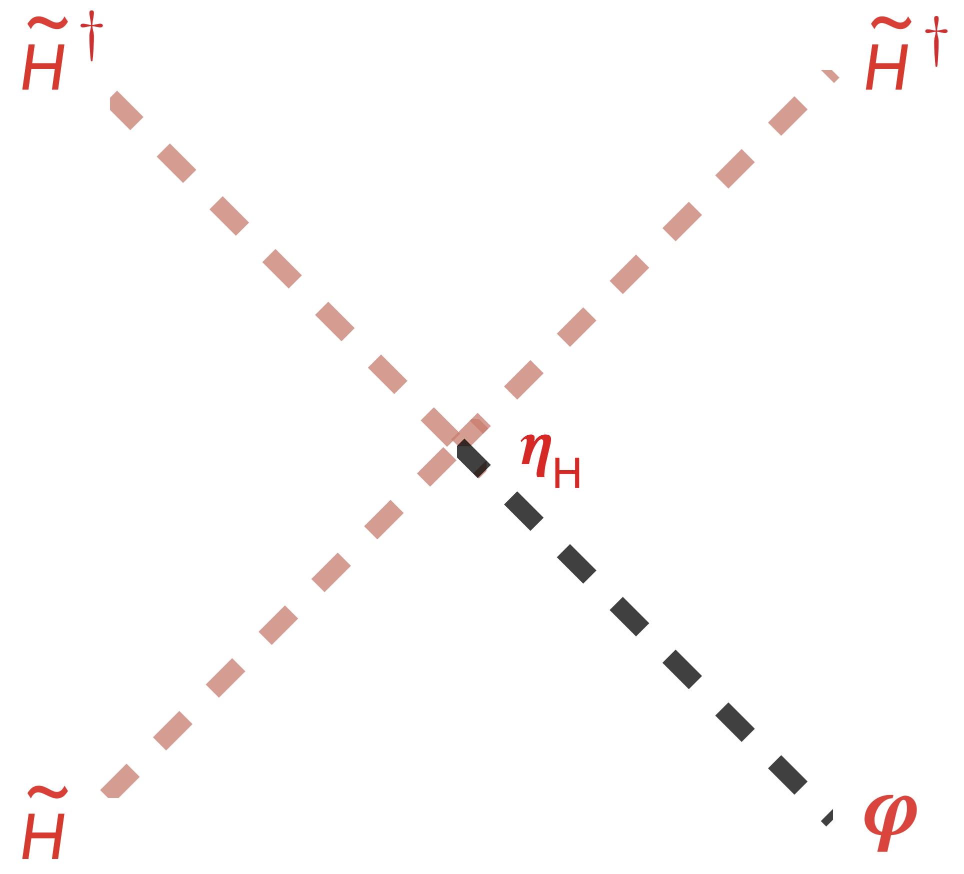
Effective operator of mass dimension = 6

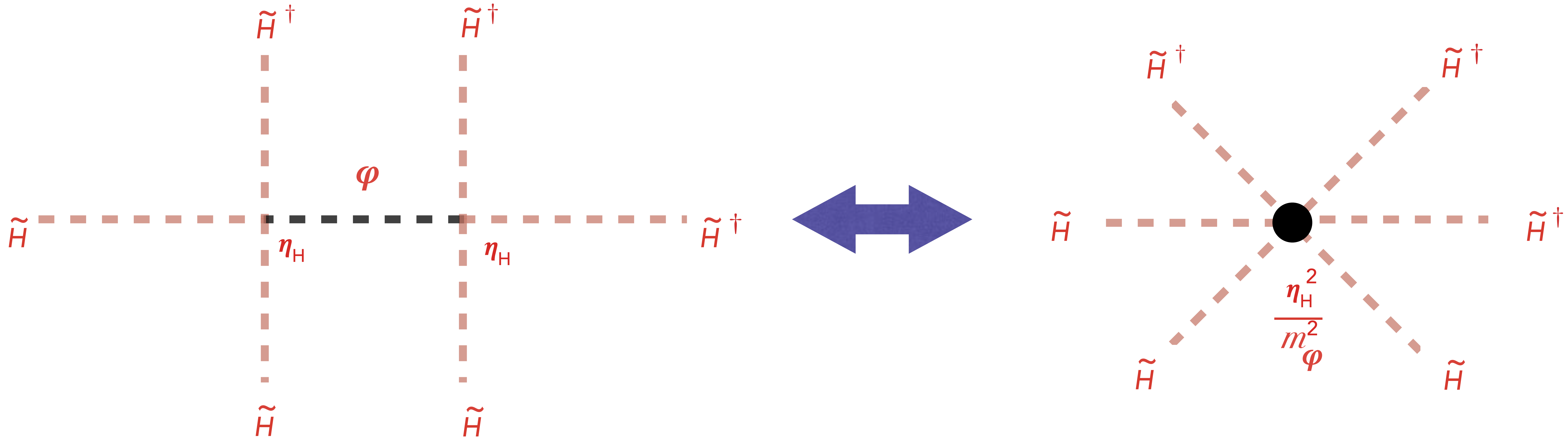
Wilson coefficients

$$m = m_\varphi$$

Feynman Diagrams

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





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

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

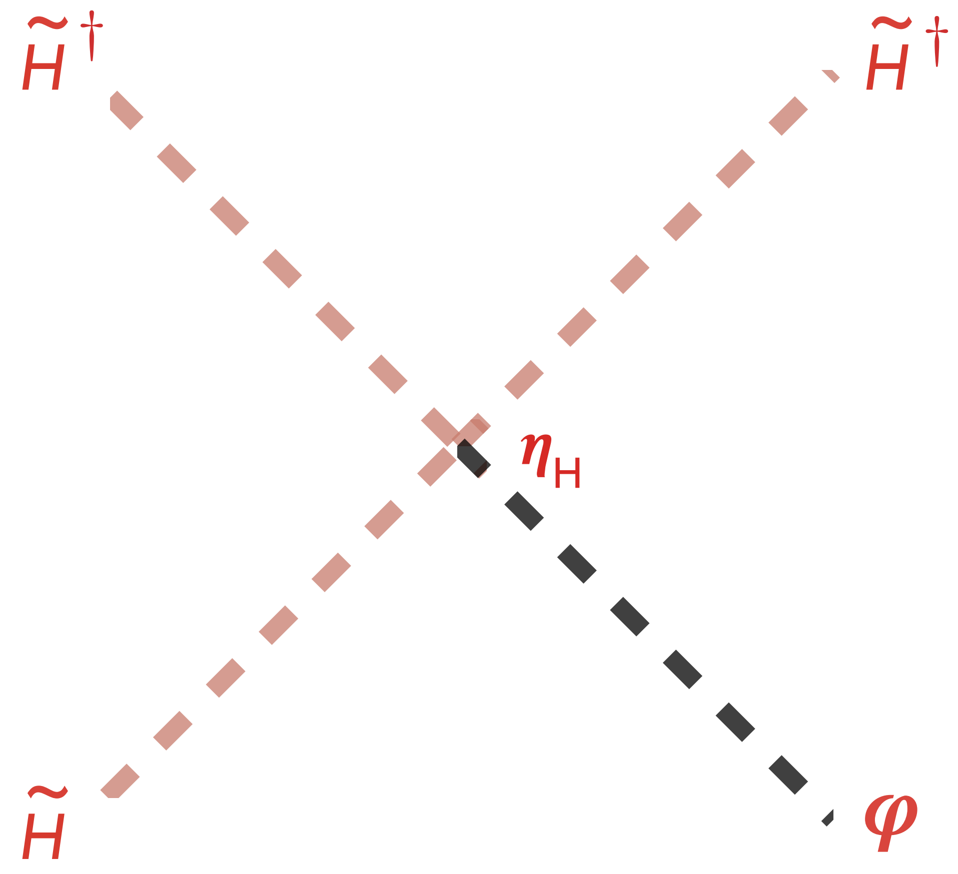
$$\frac{1}{m_\varphi^2}$$

Non-local

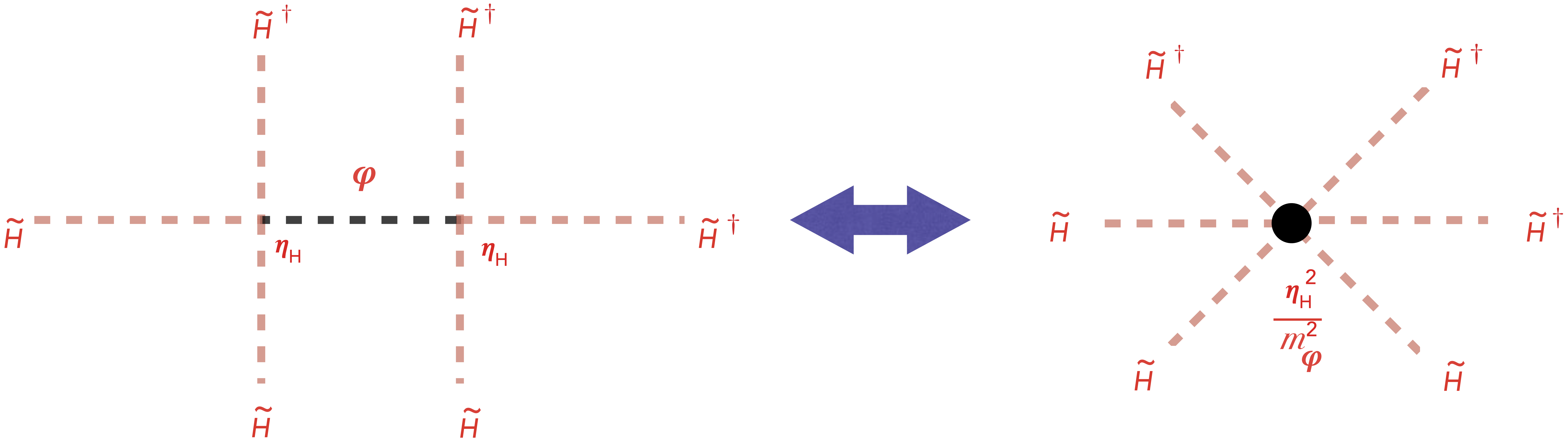
Local

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

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

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

Derivative expansion refs:

Wilson Coefficients generated from 1 loop process

Action

$$S[\phi, \Phi_c + \eta] \quad = \quad \overbrace{S[\phi, \Phi_c]}^{\text{tree diagrams}} \; + \; \eta \cancelto{0}{\frac{\delta S(\phi, \Phi)}{\delta \Phi}} |_{\Phi=\Phi_c} \; + \; \frac{\eta^2}{2} \overbrace{\frac{\delta^2 S(\phi, \Phi)}{\delta \Phi^2}}^{\text{loop diagrams}} |_{\Phi=\Phi_c} \; + \; \mathcal{O}(\eta^3)$$

Euler-Lagrange equation

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

Derivative expansion refs:

Wilson Coefficients generated from 1 loop process

Action

$$S[\phi, \Phi_c + \eta] \quad = \quad \overbrace{S[\phi, \Phi_c]}^{\text{tree diagrams}} \; + \; \eta \cancelto{0}{\frac{\delta S(\phi, \Phi)}{\delta \Phi}} |_{\Phi = \Phi_c} \; + \; \frac{\eta^2}{2} \frac{\overbrace{\delta^2 S}^{\text{loop diagrams}}(\phi, \Phi)}{\delta \Phi^2} |_{\Phi = \Phi_c} \; + \; \mathcal{O}(\eta^3)$$

Euler-Lagrange equation

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

Summing over all configurations :

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

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

Dependent only on light fields

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

Numerical factor dependent on heavy field property

Covariant Derivative, mass and quadratic terms in the Lagrangian for the heavy field

Derivative expansion refs:

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

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

1-loop processes in EFT : Truncation

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

$\mathcal{D}_\mu$: mass dimension ⟶ 1

U : mass dimension ⟶ 1 or 2

m : mass dimension ⟶ 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

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

Eff. action : DR + MS-bar,

μ is the matching scale,

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

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

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

CoDEx: Extra Scalar Doublet

Heavy field properties

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

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

Heavy field representation

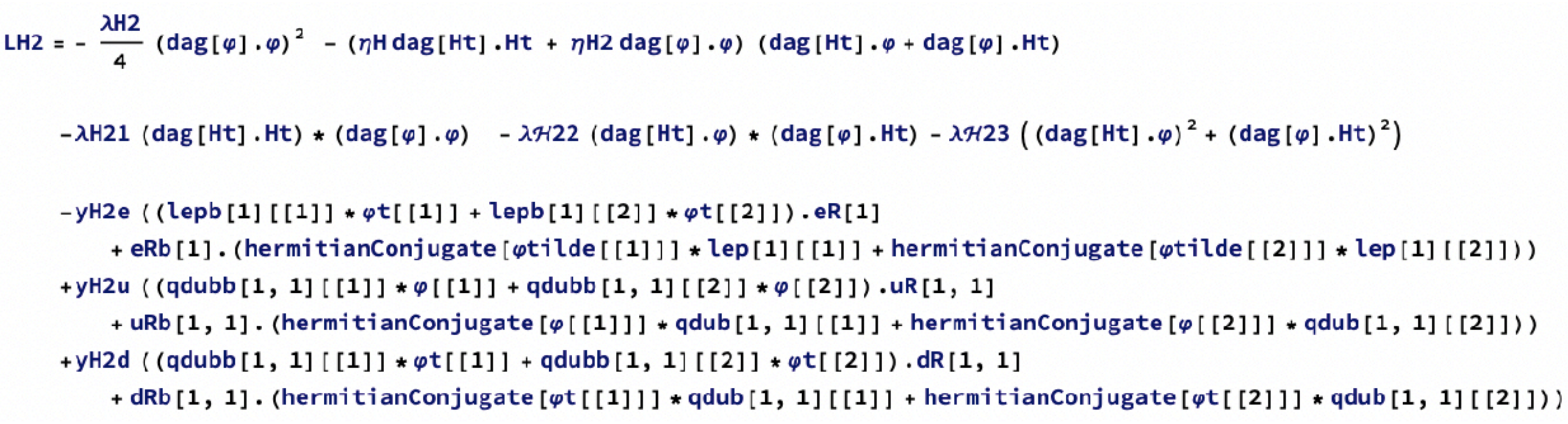
φ = defineHeavyFields[list]

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

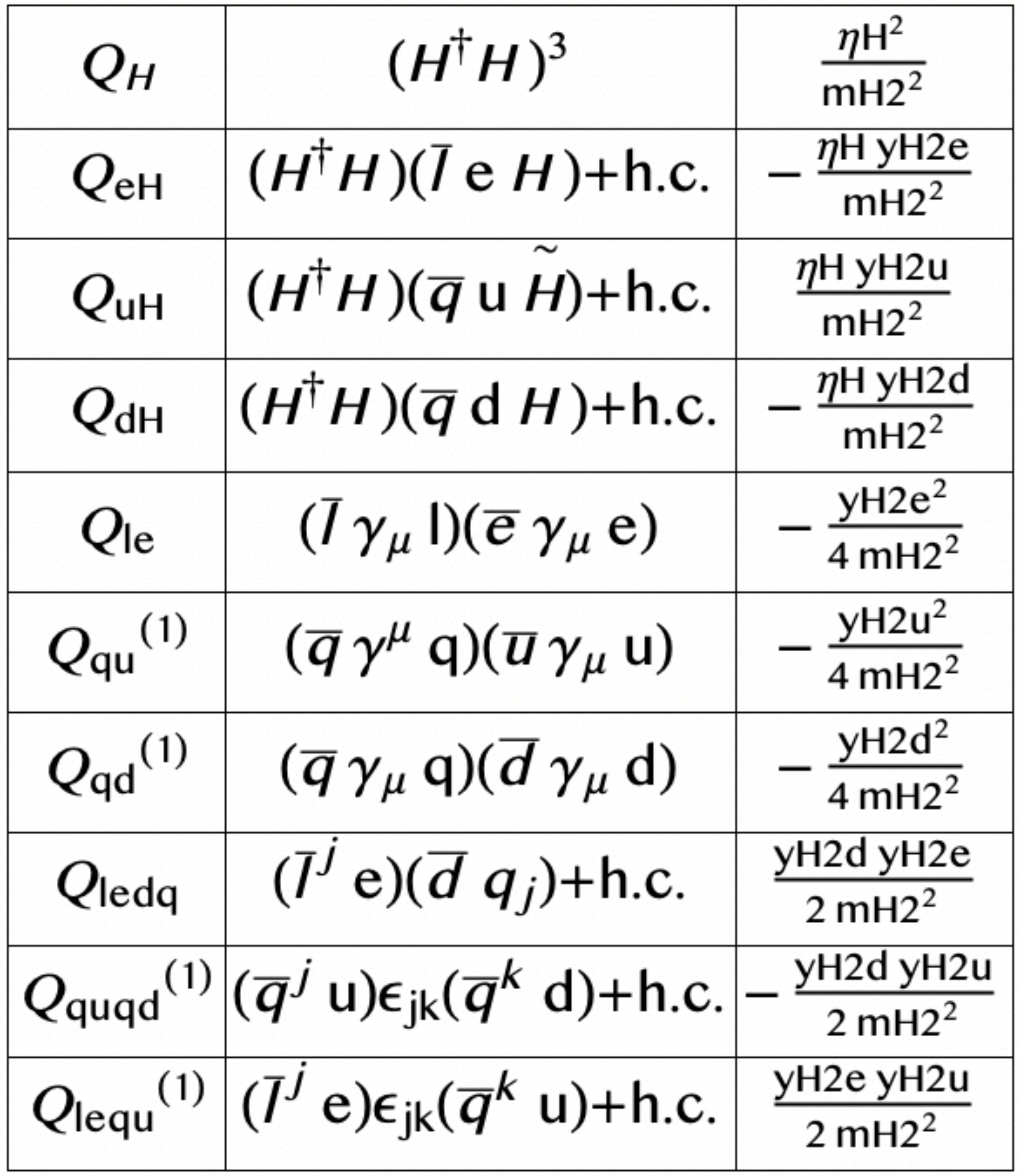
$$
\begin{aligned}
\mathcal{L}_{\mathcal{H}_2} = \mathcal{L}_{SM} + |D_\mu \mathcal{H}_2|^2 - m^2_{\mathcal{H}_2}|\mathcal{H}_2|^2 - \frac{\lambda_{\mathcal{H}_2}}{4}|\mathcal{H}_2|^4 - (\eta_H|\widetilde{H}|^2 + \eta_{\mathcal{H}_2}|\mathcal{H}_2|^2)(\widetilde{H}^\dagger \mathcal{H}_2 + \mathcal{H}_2^\dagger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



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

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

SILH

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

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

${Q_{\rm Hl}}^{(1)}$	$\frac{{g_Y}^4}{3840\pi^2{m_{\mathcal{H}_2}}^2}$
${Q_{\rm Hq}}^{(1)}$	$-\frac{{g_Y}^4}{11520\pi^2{m_{\mathcal{H}_2}}^2}$
${Q_{\rm ud}}^{(1)}$	$\frac{{g_Y}^4}{4320\pi^2{m_{\mathcal{H}_2}}^2}$
${Q_{\rm Hl}}^{(3)}$	$-\frac{{g_W}^4}{1920\pi^2{m_{\mathcal{H}_2}}^2}$
${Q_{\rm Hq}}^{(3)}$	$-\frac{{g_W}^4}{1920\pi^2{m_{\mathcal{H}_2}}^2}$
${Q_{\rm lq}}^{(3)}$	$-\frac{{g_W}^4}{3840\pi^2{m_{\mathcal{H}_2}}^2}$
${Q_{\rm qq}}^{(3)}$	$-\frac{{g_W}^4}{7680\pi^2{m_{\mathcal{H}_2}}^2}$
$Q_{\rm dd}$	$-\frac{{g_Y}^4}{17280\pi^2{m_{\mathcal{H}_2}}^2}$
$Q_{\rm ed}$	$-\frac{{g_Y}^4}{2880\pi^2{m_{\mathcal{H}_2}}^2}$
$Q_{\rm ee}$	$-\frac{{g_Y}^4}{1920\pi^2{m_{\mathcal{H}_2}}^2}$
$Q_{\rm eu}$	$\frac{{g_Y}^4}{1440\pi^2{m_{\mathcal{H}_2}}^2}$
$Q_{\rm Hd}$	$\frac{{g_Y}^4}{5760\pi^2{m_{\mathcal{H}_2}}^2}$
$Q_{\rm He}$	$\frac{{g_Y}^4}{1920\pi^2{m_{\mathcal{H}_2}}^2}$
$Q_{\rm Hu}$	$-\frac{{g_Y}^4}{2880\pi^2{m_{\mathcal{H}_2}}^2}$
$Q_{\rm HWB}$	$\frac{g_W\,g_Y\,\lambda_{\mathcal{H}_2}^{(2)}}{384\pi^2{m_{\mathcal{H}_2}}^2}$
$Q_{\rm ld}$	$-\frac{{g_Y}^4}{5760\pi^2{m_{\mathcal{H}_2}}^2}$
$Q_{\rm lu}$	$\frac{{g_Y}^4}{2880\pi^2{m_{\mathcal{H}_2}}^2}$
$Q_{\rm qe}$	$\frac{{g_Y}^4}{5760\pi^2{m_{\mathcal{H}_2}}^2}$
$Q_{\rm uu}$	$-\frac{{g_Y}^4}{4320\pi^2{m_{\mathcal{H}_2}}^2}$
Q_W	$\frac{{g_W}^3}{5760\pi^2{m_{\mathcal{H}_2}}^2}$
$Q_{\rm ledq}$	$\frac{3\lambda_{\mathcal{H}_2}Y_{\mathcal{H}_2}^{(d)}Y_{\mathcal{H}_2}^{(e)}}{64\pi^2{m_{\mathcal{H}_2}}^2}$
${Q_{\rm lequ}}^{(1)}$	$\frac{3\lambda_{\mathcal{H}_2}Y_{\mathcal{H}_2}^{(e)}Y_{\mathcal{H}_2}^{(u)}}{64\pi^2{m_{\mathcal{H}_2}}^2}$
${Q_{\rm quqd}}^{(1)}$	$-\frac{3\lambda_{\mathcal{H}_2}Y_{\mathcal{H}_2}^{(d)}Y_{\mathcal{H}_2}^{(u)}}{64\pi^2{m_{\mathcal{H}_2}}^2}$
$Q_{\rm dH}$	$-\frac{3\eta_H\eta_{\mathcal{H}_2}Y_d^{\rm SM}}{16\pi^2{m_{\mathcal{H}_2}}^2}-\frac{3\eta_H\lambda_{\mathcal{H}_2}Y_{\mathcal{H}_2}^{(d)}}{32\pi^2{m_{\mathcal{H}_2}}^2}-\frac{3\eta_{\mathcal{H}_2}\lambda_{\mathcal{H}_2,1}Y_{\mathcal{H}_2}^{(d)}}{16\pi^2{m_{\mathcal{H}_2}}^2}-\frac{3\eta_{\mathcal{H}_2}\lambda_{\mathcal{H}_2,2}Y_{\mathcal{H}_2}^{(d)}}{16\pi^2{m_{\mathcal{H}_2}}^2}+\frac{{\lambda_{\mathcal{H}_2,3}}^2Y_d^{\rm SM}}{48\pi^2{m_{\mathcal{H}_2}}^2}+\frac{{\lambda_{\mathcal{H}_2,2}}^2Y_d^{\rm SM}}{192\pi^2{m_{\mathcal{H}_2}}^2}$
$Q_{H\Box}$	$-\frac{{g_W}^4}{7680\pi^2{m_{\mathcal{H}_2}}^2}-\frac{{\lambda_{\mathcal{H}_2,1}}^2}{96\pi^2{m_{\mathcal{H}_2}}^2}-\frac{\lambda_{\mathcal{H}_2,1}\lambda_{\mathcal{H}_2,2}}{96\pi^2{m_{\mathcal{H}_2}}^2}+\frac{{\lambda_{\mathcal{H}_2,2}}^2}{384\pi^2{m_{\mathcal{H}_2}}^2}+\frac{{\lambda_{\mathcal{H}_2,3}}^2}{96\pi^2{m_{\mathcal{H}_2}}^2}$
$Q_{\rm uH}$	$\frac{3\eta_{\mathcal{H}_2}\lambda_{\mathcal{H}_2,1}Y_{\mathcal{H}_2}^{(u)}}{16\pi^2{m_{\mathcal{H}_2}}^2}+\frac{3\eta_{\mathcal{H}_2}\lambda_{\mathcal{H}_2,2}Y_{\mathcal{H}_2}^{(u)}}{16\pi^2{m_{\mathcal{H}_2}}^2}+\frac{{\lambda_{\mathcal{H}_2,2}}^2Y_u^{\rm SM}}{192\pi^2{m_{\mathcal{H}_2}}^2}-\frac{3\eta_H\eta_{\mathcal{H}_2}Y_u^{\rm SM}}{16\pi^2{m_{\mathcal{H}_2}}^2}+\frac{3\eta_H\lambda_{\mathcal{H}_2}Y_{\mathcal{H}_2}^{(u)}}{32\pi^2{m_{\mathcal{H}_2}}^2}+\frac{{\lambda_{\mathcal{H}_2,3}}^2Y_u^{\rm SM}}{48\pi^2{m_{\mathcal{H}_2}}^2}$
Q_H	$\frac{3\eta_H\eta_{\mathcal{H}_2}\lambda_{\mathcal{H}_2,1}}{8\pi^2{m_{\mathcal{H}_2}}^2}+\frac{3\eta_H\eta_{\mathcal{H}_2}\lambda_{\mathcal{H}_2,2}}{8\pi^2{m_{\mathcal{H}_2}}^2}-\frac{{\lambda_{\mathcal{H}_2,1}}^3}{48\pi^2{m_{\mathcal{H}_2}}^2}+\frac{\lambda_H^{\rm SM}{\lambda_{\mathcal{H}_2,2}}^2}{96\pi^2{m_{\mathcal{H}_2}}^2}-\frac{{\lambda_{\mathcal{H}_2,1}}^2\lambda_{\mathcal{H}_2,2}}{32\pi^2{m_{\mathcal{H}_2}}^2}-\frac{\lambda_{\mathcal{H}_2,1}{\lambda_{\mathcal{H}_2,2}}^2}{32\pi^2{m_{\mathcal{H}_2}}^2}+\frac{\lambda_H^{\rm SM}{\lambda_{\mathcal{H}_2,3}}^2}{24\pi^2{m_{\mathcal{H}_2}}^2}-\frac{\lambda_{\mathcal{H}_2,1}{\lambda_{\mathcal{H}_2,3}}^2}{8\pi^2{m_{\mathcal{H}_2}}^2}-\frac{{\lambda_{\mathcal{H}_2,2}}^3}{96\pi^2{m_{\mathcal{H}_2}}^2}+\frac{3{\eta_H}^2\lambda_{\mathcal{H}_2}}{32\pi^2{m_{\mathcal{H}_2}}^2}-\frac{3\eta_H\eta_{\mathcal{H}_2}\lambda_H^{\rm SM}}{8\pi^2{m_{\mathcal{H}_2}}^2}-\frac{\lambda_{\mathcal{H}_2,2}{\lambda_{\mathcal{H}_2,3}}^2}{8\pi^2{m_{\mathcal{H}_2}}^2}$
$Q_{\rm eH}$	$-\frac{3\eta_H\eta_{\mathcal{H}_2}Y_e^{\rm SM}}{16\pi^2{m_{\mathcal{H}_2}}^2}-\frac{3\eta_H\lambda_{\mathcal{H}_2}Y_{\mathcal{H}_2}^{(e)}}{32\pi^2{m_{\mathcal{H}_2}}^2}-\frac{3\eta_{\mathcal{H}_2}\lambda_{\mathcal{H}_2,1}Y_{\mathcal{H}_2}^{(e)}}{16\pi^2{m_{\mathcal{H}_2}}^2}-\frac{3\eta_{\mathcal{H}_2}\lambda_{\mathcal{H}_2,2}Y_{\mathcal{H}_2}^{(e)}}{16\pi^2{m_{\mathcal{H}_2}}^2}+\frac{{\lambda_{\mathcal{H}_2,2}}^2Y_e^{\rm SM}}{192\pi^2{m_{\mathcal{H}_2}}^2}+\frac{{\lambda_{\mathcal{H}_2,3}}^2Y_e^{\rm SM}}{48\pi^2{m_{\mathcal{H}_2}}^2}$
$Q_{\rm HD}$	$-\frac{{g_Y}^4}{1920\pi^2{m_{\mathcal{H}_2}}^2}-\frac{{\lambda_{\mathcal{H}_2,2}}^2}{96\pi^2{m_{\mathcal{H}_2}}^2}+\frac{{\lambda_{\mathcal{H}_2,3}}^2}{24\pi^2{m_{\mathcal{H}_2}}^2}$
$Q_{\rm le}$	$-\frac{{g_Y}^4}{1920\pi^2{m_{\mathcal{H}_2}}^2}-\frac{3\lambda_{\mathcal{H}_2}Y_{\mathcal{H}_2}^{(e)\,2}}{128\pi^2{m_{\mathcal{H}_2}}^2}$
$Q_{\rm HB}$	$\frac{{g_Y}^2\lambda_{\mathcal{H}_2,1}}{384\pi^2{m_{\mathcal{H}_2}}^2}+\frac{{g_Y}^2\lambda_{\mathcal{H}_2,2}}{768\pi^2{m_{\mathcal{H}_2}}^2}$
$Q_{\rm HW}$	$\frac{{g_W}^2\lambda_{\mathcal{H}_2,1}}{384\pi^2{m_{\mathcal{H}_2}}^2}+\frac{{g_W}^2\lambda_{\mathcal{H}_2,2}}{768\pi^2{m_{\mathcal{H}_2}}^2}$
${Q_{\rm lq}}^{(1)}$	$\frac{{g_Y}^4}{11520\pi^2{m_{\mathcal{H}_2}}^2}-\frac{{g_W}^4}{3840\pi^2{m_{\mathcal{H}_2}}^2}$
${Q_{\rm qd}}^{(1)}$	$\frac{{g_Y}^4}{17280\pi^2{m_{\mathcal{H}_2}}^2}-\frac{3\lambda_{\mathcal{H}_2}Y_{\mathcal{H}_2}^{(d)\,2}}{128\pi^2{m_{\mathcal{H}_2}}^2}$
${Q_{\rm qq}}^{(1)}$	$\frac{{g_W}^4}{7680\pi^2{m_{\mathcal{H}_2}}^2}-\frac{{g_Y}^4}{69120\pi^2{m_{\mathcal{H}_2}}^2}$
${Q_{\rm qu}}^{(1)}$	$-\frac{{g_Y}^4}{8640\pi^2{m_{\mathcal{H}_2}}^2}-\frac{3\lambda_{\mathcal{H}_2}Y_{\mathcal{H}_2}^{(u)\,2}}{128\pi^2{m_{\mathcal{H}_2}}^2}$
$Q_{\rm ll}$	$-\frac{{g_W}^4}{7680\pi^2{m_{\mathcal{H}_2}}^2}-\frac{{g_Y}^4}{7680\pi^2{m_{\mathcal{H}_2}}^2}$

SILH basis

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

Matching scale = heavy field mass

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

Contributions from heavy-light diagrams?

RG Flow?

In Warsaw basis

RGFlow of the Wilson coefficients

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

Out[7]:
```

37 operators $\xrightarrow{\text{RGFlow}}$ 48 operators

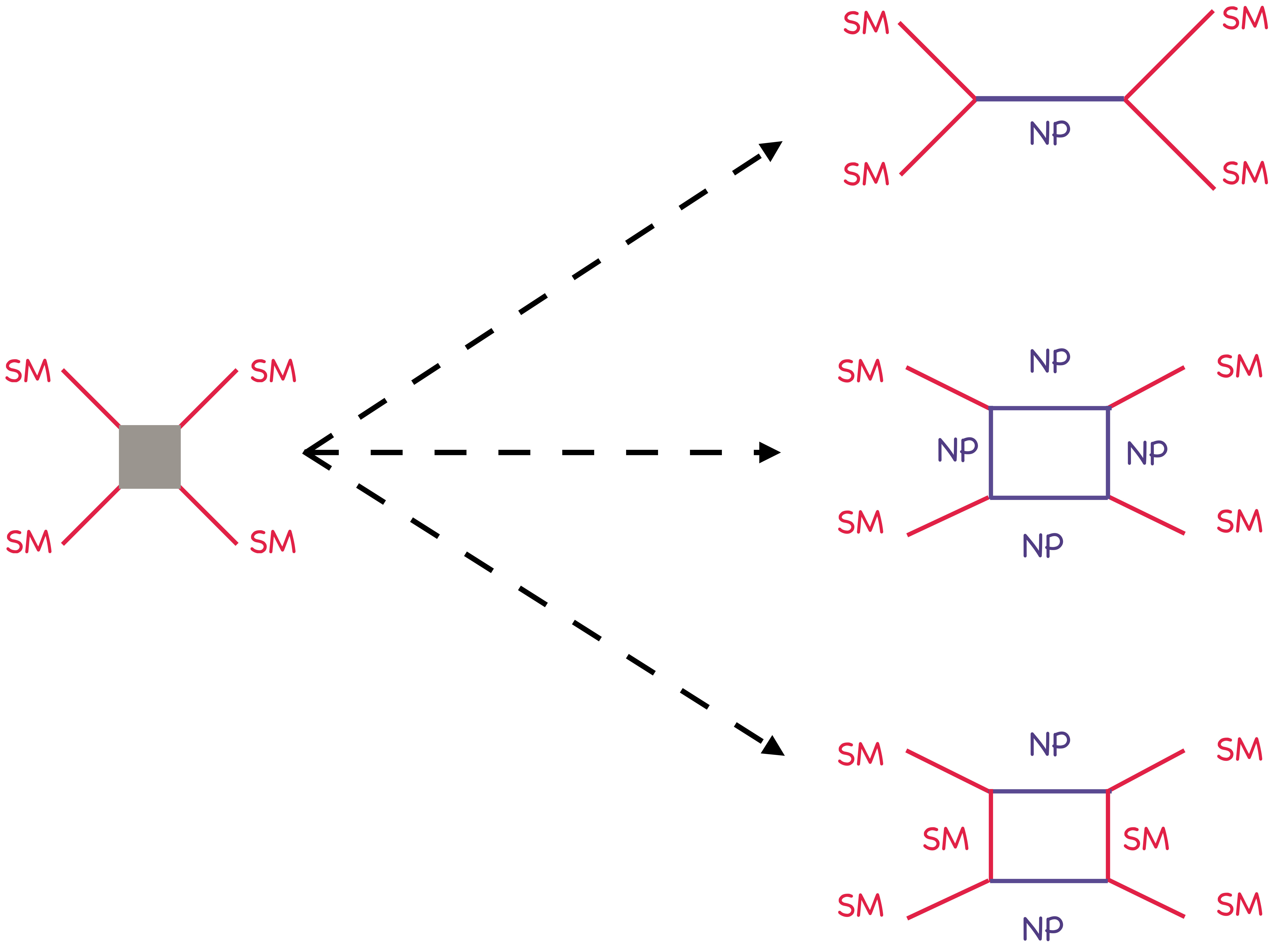
Jenkins et. al.
arxiv:1308.2627
arxiv:1310.4838
arxiv:1312.2014

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

https://github.com/effExTeam/Precision-Observables-and-Higgs-Signals-Effective-passageto-select-BSM/blob/main/rgTHDM_d6.m

Partial cross-checks with DSixTools done, found agreement!

DSixTools
arxiv:1704.04504
arxiv:2010.16341



T — Tree-level effective operators

HH — Only heavy field propagator in the loop

HL — Both heavy and light field propagators in the loop

NP (New Physics) — Heavy field propagators
SM (Standard Model) — Light field propagators

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

Heavy-light mixed propagators in loop

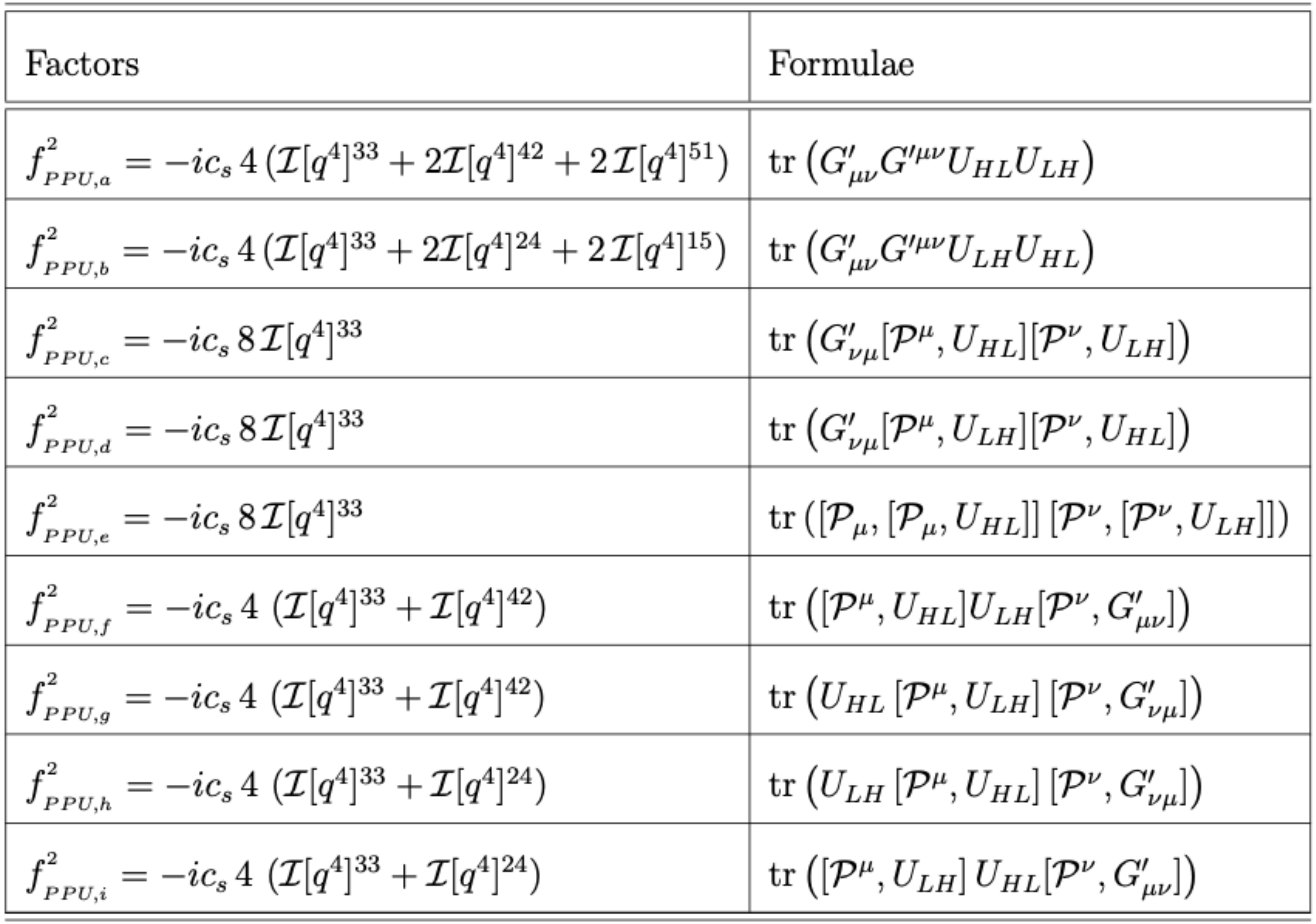
Zhang arxiv:1610.00710

Ellis et. al. arxiv:1706.07765

$$U = \frac{\delta^2 \mathcal{L}_{UV}}{\delta\{\Phi,\phi\}^2} = \begin{bmatrix} U_H & U_{HL} \\ U_{LH} & U_L \end{bmatrix}$$

$$D_\mu = \begin{bmatrix} D_{H\mu} & 0 \\ 0 & D_{L\mu} \end{bmatrix}$$

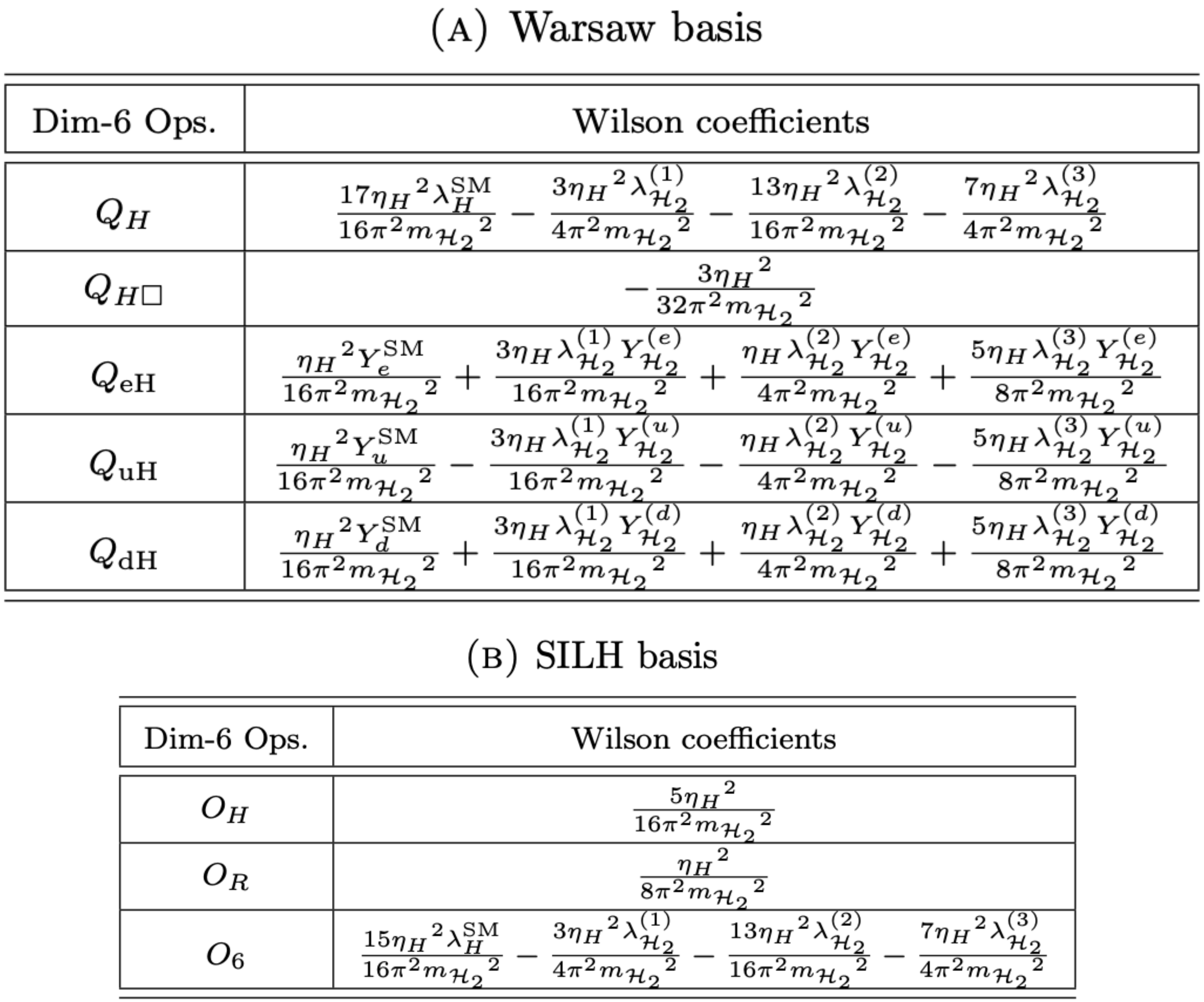
$$G_{\mu\nu} = \begin{bmatrix} G^{(H)}_{\mu\nu} & 0 \\ 0 & G^{(L)}_{\mu\nu} \end{bmatrix}$$



Factors	Formulae
$f^2_{PPU,a} = -ic_s\,4\,(\mathcal{I}[q^4]^{33} + 2\mathcal{I}[q^4]^{42} + 2\,\mathcal{I}[q^4]^{51})$	$\mathrm{tr}\left(G'_{\mu\nu}G'^{\mu\nu}U_{HL}U_{LH}\right)$
$f^2_{PPU,b} = -ic_s\,4\,(\mathcal{I}[q^4]^{33} + 2\mathcal{I}[q^4]^{24} + 2\,\mathcal{I}[q^4]^{15})$	$\mathrm{tr}\left(G'_{\mu\nu}G'^{\mu\nu}U_{LH}U_{HL}\right)$
$f^2_{PPU,c} = -ic_s\,8\,\mathcal{I}[q^4]^{33}$	$\mathrm{tr}\left(G'_{\nu\mu}[\mathcal{P}^\mu, U_{HL}][\mathcal{P}^\nu, U_{LH}]\right)$
$f^2_{PPU,d} = -ic_s\,8\,\mathcal{I}[q^4]^{33}$	$\mathrm{tr}\left(G'_{\nu\mu}[\mathcal{P}^\mu, U_{LH}][\mathcal{P}^\nu, U_{HL}]\right)$
$f^2_{PPU,e} = -ic_s\,8\,\mathcal{I}[q^4]^{33}$	$\mathrm{tr}\left([\mathcal{P}_\mu, [\mathcal{P}_\mu, U_{HL}]]\,[\mathcal{P}^\nu, [\mathcal{P}^\nu, U_{LH}]]\right)$
$f^2_{PPU,f} = -ic_s\,4\,\left(\mathcal{I}[q^4]^{33} + \mathcal{I}[q^4]^{42}\right)$	$\mathrm{tr}\left([\mathcal{P}^\mu, U_{HL}]U_{LH}[\mathcal{P}^\nu, G'_{\mu\nu}]\right)$
$f^2_{PPU,g} = -ic_s\,4\,\left(\mathcal{I}[q^4]^{33} + \mathcal{I}[q^4]^{42}\right)$	$\mathrm{tr}\left(U_{HL}\,[\mathcal{P}^\mu, U_{LH}]\,[\mathcal{P}^\nu, G'_{\nu\mu}]\right)$
$f^2_{PPU,h} = -ic_s\,4\,\left(\mathcal{I}[q^4]^{33} + \mathcal{I}[q^4]^{24}\right)$	$\mathrm{tr}\left(U_{LH}\,[\mathcal{P}^\mu, U_{HL}]\,[\mathcal{P}^\nu, G'_{\nu\mu}]\right)$
$f^2_{PPU,i} = -ic_s\,4\,\left(\mathcal{I}[q^4]^{33} + \mathcal{I}[q^4]^{24}\right)$	$\mathrm{tr}\left([\mathcal{P}^\mu, U_{LH}]\,U_{HL}[\mathcal{P}^\nu, G'_{\mu\nu}]\right)$

… more terms …

HL Wilson coefficients - 2HDM



(A) Warsaw basis

Dim-6 Ops.	Wilson coefficients
Q_H	$\frac{17{\eta_H}^2\lambda_H^{\rm SM}}{16\pi^2{m_{\mathcal{H}_2}}^2} - \frac{3{\eta_H}^2\lambda_{\mathcal{H}_2}^{(1)}}{4\pi^2{m_{\mathcal{H}_2}}^2} - \frac{13{\eta_H}^2\lambda_{\mathcal{H}_2}^{(2)}}{16\pi^2{m_{\mathcal{H}_2}}^2} - \frac{7{\eta_H}^2\lambda_{\mathcal{H}_2}^{(3)}}{4\pi^2{m_{\mathcal{H}_2}}^2}$
$Q_{H\Box}$	$-\frac{3{\eta_H}^2}{32\pi^2{m_{\mathcal{H}_2}}^2}$
$Q_{\rm eH}$	$\frac{{\eta_H}^2 Y_e^{\rm SM}}{16\pi^2{m_{\mathcal{H}_2}}^2} + \frac{3\eta_H\lambda_{\mathcal{H}_2}^{(1)}Y_{\mathcal{H}_2}^{(e)}}{16\pi^2{m_{\mathcal{H}_2}}^2} + \frac{\eta_H\lambda_{\mathcal{H}_2}^{(2)}Y_{\mathcal{H}_2}^{(e)}}{4\pi^2{m_{\mathcal{H}_2}}^2} + \frac{5\eta_H\lambda_{\mathcal{H}_2}^{(3)}Y_{\mathcal{H}_2}^{(e)}}{8\pi^2{m_{\mathcal{H}_2}}^2}$
$Q_{\rm uH}$	$\frac{{\eta_H}^2 Y_u^{\rm SM}}{16\pi^2{m_{\mathcal{H}_2}}^2} - \frac{3\eta_H\lambda_{\mathcal{H}_2}^{(1)}Y_{\mathcal{H}_2}^{(u)}}{16\pi^2{m_{\mathcal{H}_2}}^2} - \frac{\eta_H\lambda_{\mathcal{H}_2}^{(2)}Y_{\mathcal{H}_2}^{(u)}}{4\pi^2{m_{\mathcal{H}_2}}^2} - \frac{5\eta_H\lambda_{\mathcal{H}_2}^{(3)}Y_{\mathcal{H}_2}^{(u)}}{8\pi^2{m_{\mathcal{H}_2}}^2}$
$Q_{\rm dH}$	$\frac{{\eta_H}^2 Y_d^{\rm SM}}{16\pi^2{m_{\mathcal{H}_2}}^2} + \frac{3\eta_H\lambda_{\mathcal{H}_2}^{(1)}Y_{\mathcal{H}_2}^{(d)}}{16\pi^2{m_{\mathcal{H}_2}}^2} + \frac{\eta_H\lambda_{\mathcal{H}_2}^{(2)}Y_{\mathcal{H}_2}^{(d)}}{4\pi^2{m_{\mathcal{H}_2}}^2} + \frac{5\eta_H\lambda_{\mathcal{H}_2}^{(3)}Y_{\mathcal{H}_2}^{(d)}}{8\pi^2{m_{\mathcal{H}_2}}^2}$

(B) SILH basis

Dim-6 Ops.	Wilson coefficients
O_H	$\frac{5{\eta_H}^2}{16\pi^2{m_{\mathcal{H}_2}}^2}$
O_R	$\frac{{\eta_H}^2}{8\pi^2{m_{\mathcal{H}_2}}^2}$
O_6	$\frac{15{\eta_H}^2\lambda_H^{\rm SM}}{16\pi^2{m_{\mathcal{H}_2}}^2} - \frac{3{\eta_H}^2\lambda_{\mathcal{H}_2}^{(1)}}{4\pi^2{m_{\mathcal{H}_2}}^2} - \frac{13{\eta_H}^2\lambda_{\mathcal{H}_2}^{(2)}}{16\pi^2{m_{\mathcal{H}_2}}^2} - \frac{7{\eta_H}^2\lambda_{\mathcal{H}_2}^{(3)}}{4\pi^2{m_{\mathcal{H}_2}}^2}$

The SM equations of motion

Gauge fields:

$$[D^a, G_{ab}]^\alpha = g_{\scriptscriptstyle S}\left(\bar{q}_{\scriptscriptstyle L}\, T^\alpha \gamma_b\, q_{\scriptscriptstyle L} + \bar{u}_{\scriptscriptstyle R}\, T^\alpha \gamma_b\, u_{\scriptscriptstyle R} + \bar{d}_{\scriptscriptstyle R}\, T^\alpha \gamma_b\, d_{\scriptscriptstyle R}\right)$$

$$[D^a, W_{ab}]^I = g_{\scriptscriptstyle W}\left(\frac{1}{2}\bar{q}_{\scriptscriptstyle L}\, \sigma^I \gamma_b\, q_{\scriptscriptstyle L} + \frac{1}{2}\bar{l}_{\scriptscriptstyle L}\, \sigma^I \gamma_b\, l_{\scriptscriptstyle L} + \frac{1}{2} H^\dagger i \overleftrightarrow{D}{}^I_b H\right)$$

$$\begin{aligned} D^a B_{ab} = g_{\scriptscriptstyle Y} \Bigg(& \frac{1}{6}\bar{q}_{\scriptscriptstyle L}\, \gamma_b\, q_{\scriptscriptstyle L} - \frac{1}{2}\bar{l}_{\scriptscriptstyle L}\, \gamma_b\, l_{\scriptscriptstyle L} + \frac{1}{2} H^\dagger i \overleftrightarrow{D}_b H \\ & + \frac{2}{3}\bar{u}_{\scriptscriptstyle R}\, \gamma_b\, u_{\scriptscriptstyle R} - \frac{1}{3}\bar{d}_{\scriptscriptstyle R}\, \gamma_b\, d_{\scriptscriptstyle R} - \bar{e}_{\scriptscriptstyle R}\, \gamma_b\, e_{\scriptscriptstyle R} \Bigg) \end{aligned}$$

$$\begin{aligned} H^\dagger i \overleftrightarrow{D}_b H &= i H^\dagger (D_b H) - i (D_b H^\dagger) H, \\ H^\dagger i \overleftrightarrow{D}{}^I_b H &= i H^\dagger \sigma^I (D_b H) - i (D_b H^\dagger) \sigma^I H. \end{aligned}$$

Fermions:

$$\begin{aligned} i \not{D} q_{\scriptscriptstyle L} &= Y_{\rm SM}^{(u)\dagger} u_{\scriptscriptstyle R} \widetilde{H} + Y_{\rm SM}^{(d)\dagger} d_{\scriptscriptstyle R} H, \\ i \not{D} l_{\scriptscriptstyle L} &= Y_{\rm SM}^{(e)\dagger} e_{\scriptscriptstyle R} H, \\ i \not{D} e_{\scriptscriptstyle R} &= Y_{\rm SM}^{(e)} l_{\scriptscriptstyle L} H^\dagger, \\ i \not{D} u_{\scriptscriptstyle R} &= Y_{\rm SM}^{(u)} q_{\scriptscriptstyle L} \widetilde{H}^\dagger, \\ i \not{D} d_{\scriptscriptstyle R} &= Y_{\rm SM}^{(d)} q_{\scriptscriptstyle L} H^\dagger \end{aligned}$$

Scalars:

$$D^2 H + \mu_H |H|^2 + \lambda_H (H^\dagger H) H + \bar{q}_{\scriptscriptstyle L} i \sigma^2 Y_{\rm SM}^{(u)\dagger} u_{\scriptscriptstyle R} + \bar{d}_{\scriptscriptstyle R} Y_{\rm SM}^{(d)} q_{\scriptscriptstyle L} + \bar{e}_{\scriptscriptstyle R} Y_{\rm SM}^{(e)} l_{\scriptscriptstyle L} = 0$$

Operator identities

Gauge-invariant operators to SMEFT bases

$$
\begin{aligned}
O_R &= |H|^2|D_\mu H|^2 = \lambda_H Q_H + \frac{1}{2}Q_{H\Box} + \left(\frac{1}{2}Y_{\rm SM}^{(u)}Q_{uH} + \frac{1}{2}Y_{\rm SM}^{(d)}Q_{dH} + \frac{1}{2}Y_{\rm SM}^{(e)}Q_{eH} + \text{h.c.}\right),\\
O_T &= \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2 = -2Q_{HD} - \frac{1}{2}Q_{H\Box},\\
O_B &= \frac{i}{2}g_Y\left(H^\dagger \overleftrightarrow{D}_\mu H\right)\partial_\nu B^{\mu\nu} = g_Y^2\left(Q_{HD} + \frac{1}{4}Q_{H\Box} + \frac{1}{12}Q_{Hq}^{(1)} - \frac{1}{4}Q_{Hl}^{(1)} + \frac{1}{3}Q_{Hu} - \frac{1}{6}Q_{Hd} - \frac{1}{2}Q_{He}\right),\\
O_W &= \frac{i}{2}g_W\left(H^\dagger \sigma^I \overleftrightarrow{D}_\mu H\right)D_\nu W^{\mu\nu} = g_W^2\left\{\lambda_H Q_H + \frac{3}{4}Q_{H\Box} + \frac{1}{4}Q_{Hq}^{(3)} + \frac{1}{4}Q_{Hl}^{(3)}\right.\\
&\qquad\qquad\left. + \left(\frac{1}{2}Y_{\rm SM}^{(u)}Q_{uH} + \frac{1}{2}Y_{\rm SM}^{(d)}Q_{dH} + \frac{1}{2}Y_{\rm SM}^{(e)}Q_{eH} + \text{h.c.}\right)\right\}.
\end{aligned}
$$

Falkowski et. al. arXiv:1508.05895 – Rosetta

Fierz identities:

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

Evanescent operators !!

Aebischer et. al. arXiv:2202.01225
2208.10513

Operator identities

Gauge-invariant operators to SMEFT bases

$$
\begin{aligned}
O_R &= |H|^2 |D_\mu H|^2 = \lambda_H Q_H + \frac{1}{2} Q_{H\Box} + \left(\frac{1}{2} Y^{(u)}_{\rm SM} Q_{uH} + \frac{1}{2} Y^{(d)}_{\rm SM} Q_{dH} + \frac{1}{2} Y^{(e)}_{\rm SM} Q_{eH} + \text{h.c.} \right), \\
O_T &= \frac{1}{2} \left(H^\dagger \overleftrightarrow{D}_\mu H \right)^2 = -2 Q_{HD} - \frac{1}{2} Q_{H\Box}, \\
O_B &= \frac{i}{2} g_Y \left(H^\dagger \overleftrightarrow{D}_\mu H \right) \partial_\nu B^{\mu\nu} = g_Y^2 \left(Q_{HD} + \frac{1}{4} Q_{H\Box} + \frac{1}{12} Q^{(1)}_{Hq} - \frac{1}{4} Q^{(1)}_{Hl} + \frac{1}{3} Q_{Hu} - \frac{1}{6} Q_{Hd} - \frac{1}{2} Q_{He} \right), \\
O_W &= \frac{i}{2} g_W \left(H^\dagger \sigma^I \overleftrightarrow{D}_\mu H \right) D_\nu W^{\mu\nu} = g_W^2 \left\{ \lambda_H Q_H + \frac{3}{4} Q_{H\Box} + \frac{1}{4} Q^{(3)}_{Hq} + \frac{1}{4} Q^{(3)}_{Hl} \right. \\
&\qquad \left. + \left(\frac{1}{2} Y^{(u)}_{\rm SM} Q_{uH} + \frac{1}{2} Y^{(d)}_{\rm SM} Q_{dH} + \frac{1}{2} Y^{(e)}_{\rm SM} Q_{eH} + \text{h.c.} \right) \right\}.
\end{aligned}
$$

Falkowski et. al. arXiv:1508.05895 – Rosetta

Fierz identities:

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

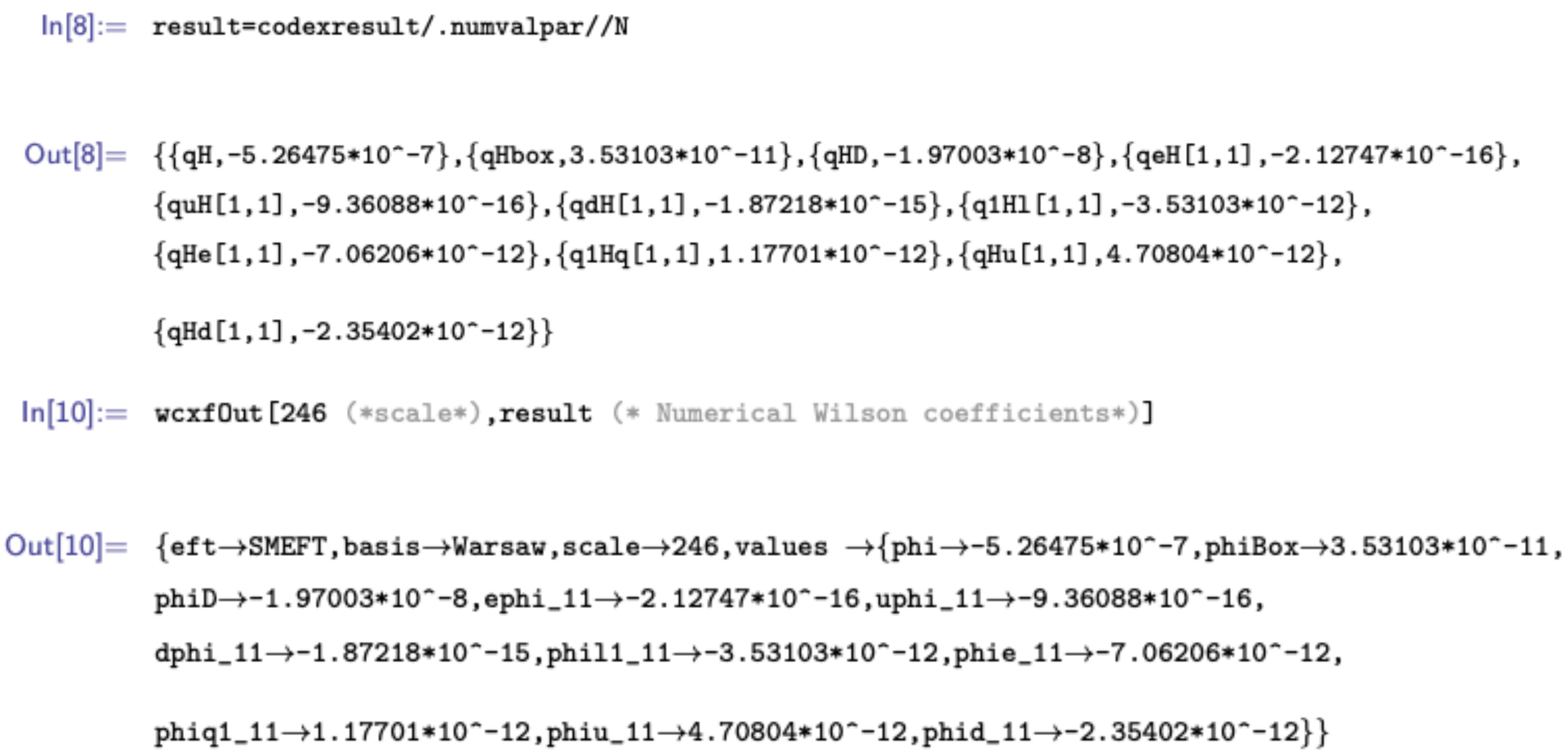
Evanescent operators !!

Aebischer et. al. arXiv:2202.01225
2208.10513

Wilson coefficient exchange format — wcxfIn , wcxfOut

Matching, mapping, running packages for EFTs:

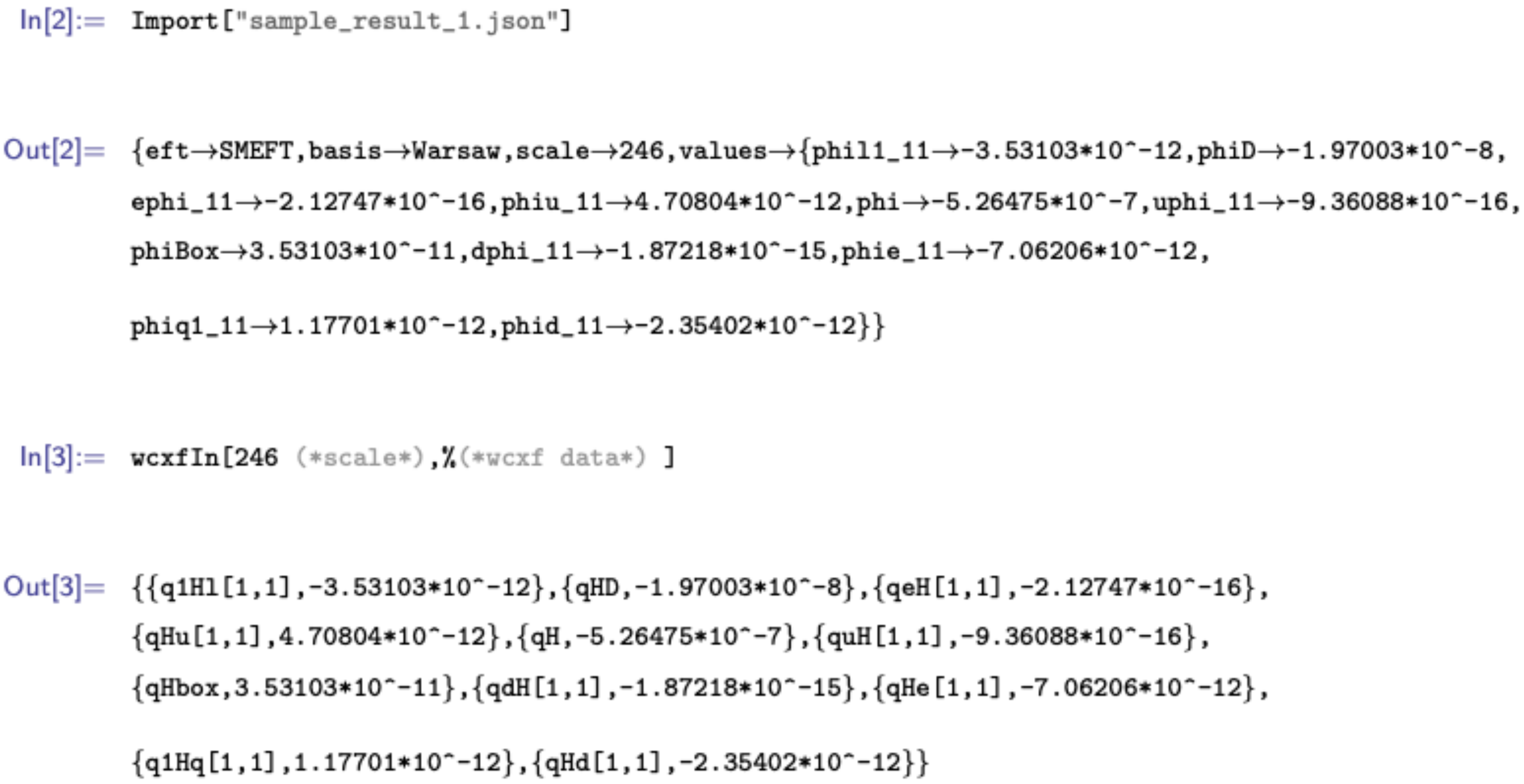
Aebischer et. al. JCPC 2018.05.022



```
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

Wilson coefficient exchange format — wcxfIn , wcxfOut



```
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}}
```

Applications:

- **Single heavy scalar extensions of SM**

https://github.com/effExTeam/Precision-Observables-and-Higgs-Signals-Effective-passageto-select-BSM

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**

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

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}	$Q_{qq}^{(1)}$	$Q_{qq}^{(3)}$	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
$\mathcal{S}$	HL	✗	✗	✗	✗	✗	✗	✗	✗	HL	T	HL	HL	T	✗	✗	HL	HL	HL	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗
$\mathcal{S}_2$	HH	HH	HH	HH	HH	HH	HH	✗	✗	✗	HH	HH	✗	HH	✗	✗	✗	✗	✗	HH	✗	HH	HH	HH	HH	T	HH	HH	HH	HH	HH	HH	HH	✗	✗	✗
Δ	T	HH	✗	✗	✗	✗	✗	HH	HH	HL	T	HL	HH	T	✗	✗	T	T	T	✗	HH	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	HH	✗
$\mathcal{H}_2$	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	T	✗	✗	T	T	T	HH	HH	HH	HH	HH	HH	HH	HH	HH	T	HH	HH	HH	T	T	HH	HH
Δ_1	T	T	HH	HH	HH	HH	HH	HH	HH	HH	T	HH	HH	T	✗	✗	T	T	T	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	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	✗	✗	✗	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	HH	✗	HH	HH	HH	✗	✗	✗	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	HH	HH	HH	HH	✗	✗	✗	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	HH	HH	HH	HH	HH	✗	✗	✗	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	T	HH	T	HH	HH	HH	HH
Ω	HH	HH	HH	HH	HH	HH	HH	HH	HH	✗	HH	HH	HH	HH	HH	HH	✗	✗	✗	HH	HH	HH	HH	HH	T	HH	HH	HH	HH	HH	HH	HH	HH	HH	T	HH
χ_1	HH	HH	HH	HH	HH	HH	HH	HH	HH	✗	HH	HH	HH	HH	HH	HH	✗	✗	✗	T	T	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	✗	✗	✗	HH	HH	T	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	✗	✗	✗	HH	HH	HH	T	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	✗	✗	✗	T	T	HH	HH	T	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	✗	✗

Matching result for these BSMs: https://github.com/effExTeam/Precision-Observables-and-Higgs-Signals-Effective-passageto-select-BSM

More on this: arxiv:2012.03839, arxiv:2111.05876

Summary & Future directions

- ❖ Matching using functional methods: Effective action formulae, implementation
  - Model implementation in CoDEx: Tree-level, 1-loop-level WCs and RGEs.
  - 15 scalar extension of the SM

Features in upcoming releases:

- ❖ Fermions at 1-loop. ✓
- ❖ 1-loop-level WCs from mixed statistics loops. ✓
- ❖ Multiple heavy fields at 1-loop with non-degenerate mass.
- ❖ Open sourcing and benchmarking models with other packages.

Thanks for your attention!

CoDEx web-documentation https://effexteam.github.io/CoDEx/html/tutorial/CoDExOverview.html

Backup slides

Take trace and use BCH formula -

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

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

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

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

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

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

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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