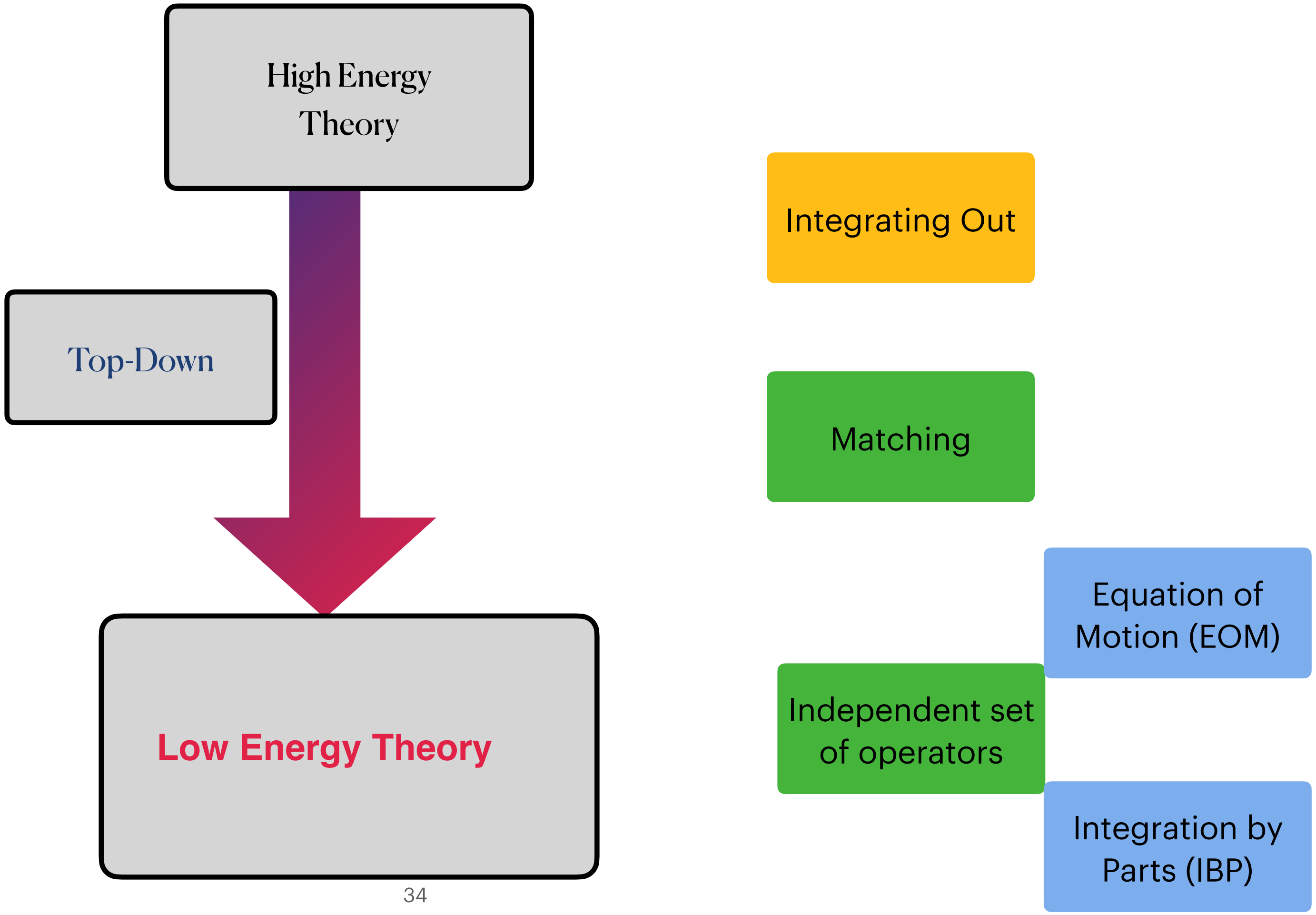
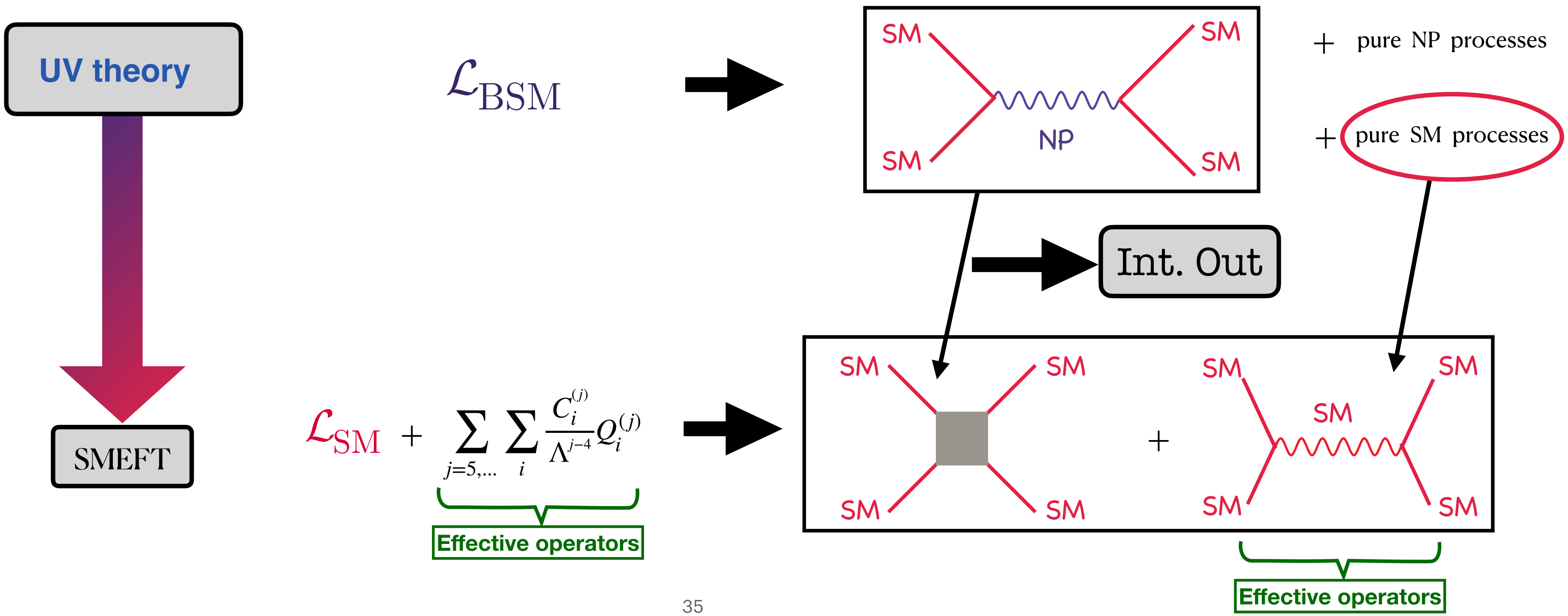

High Energy Theory
Top-Down
Low Energy Theory
Integrating Out
Matching
Independent set of operators
Equation of Motion (EOM)
Integration by Parts (IBP)

Top-Down approach: *SMEFT*

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

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



Integrating out heavy field

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

Φ - Heavy field $\qquad$ 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

Example - Scalar heavy field

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

$$\Rightarrow \Phi_c = \frac{1}{D^2 + m^2} B(\phi) \quad \textit{(leading order)}$$

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

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

} Dependent only on light fields

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

Λ : cut-off scale

Wilson coefficients

Effective operators

Mass dimension of effective operator

Model with Extra Scalar Doublet

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

$\tilde{H} = i\sigma_2 H^*$ — H : SM Higgs

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

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

Term quadratic in heavy field

Term linear in heavy field

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

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

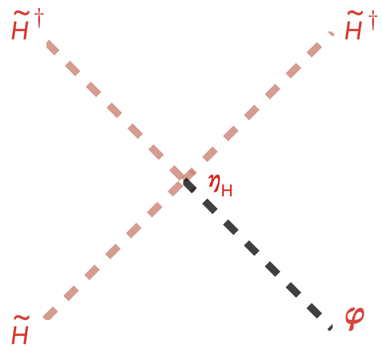
$$\eta_H|\tilde{H}|^2\tilde{H}^\dagger\varphi \to \eta_H|\tilde{H}|^2\tilde{H}^\dagger \times \frac{\eta_H|\tilde{H}|^2\tilde{H}}{m^2} = \frac{\eta_H^2}{m^2}\;|\tilde{H}|^6$$

$\frac{\eta_H^2}{m^2}$ → Wilson coefficients

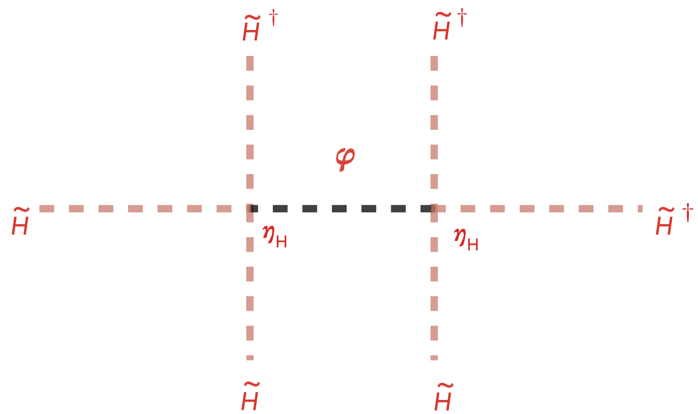
$|\tilde{H}|^6$ → Effective operator of mass dimension = 6

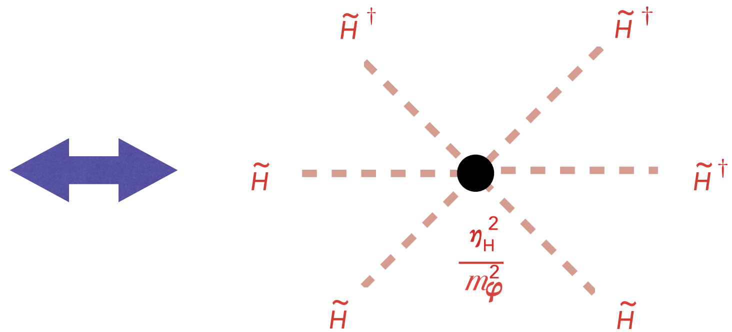
Feynman Diagrams

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



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

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

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

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

c: Numerical factor dependent on heavy field property

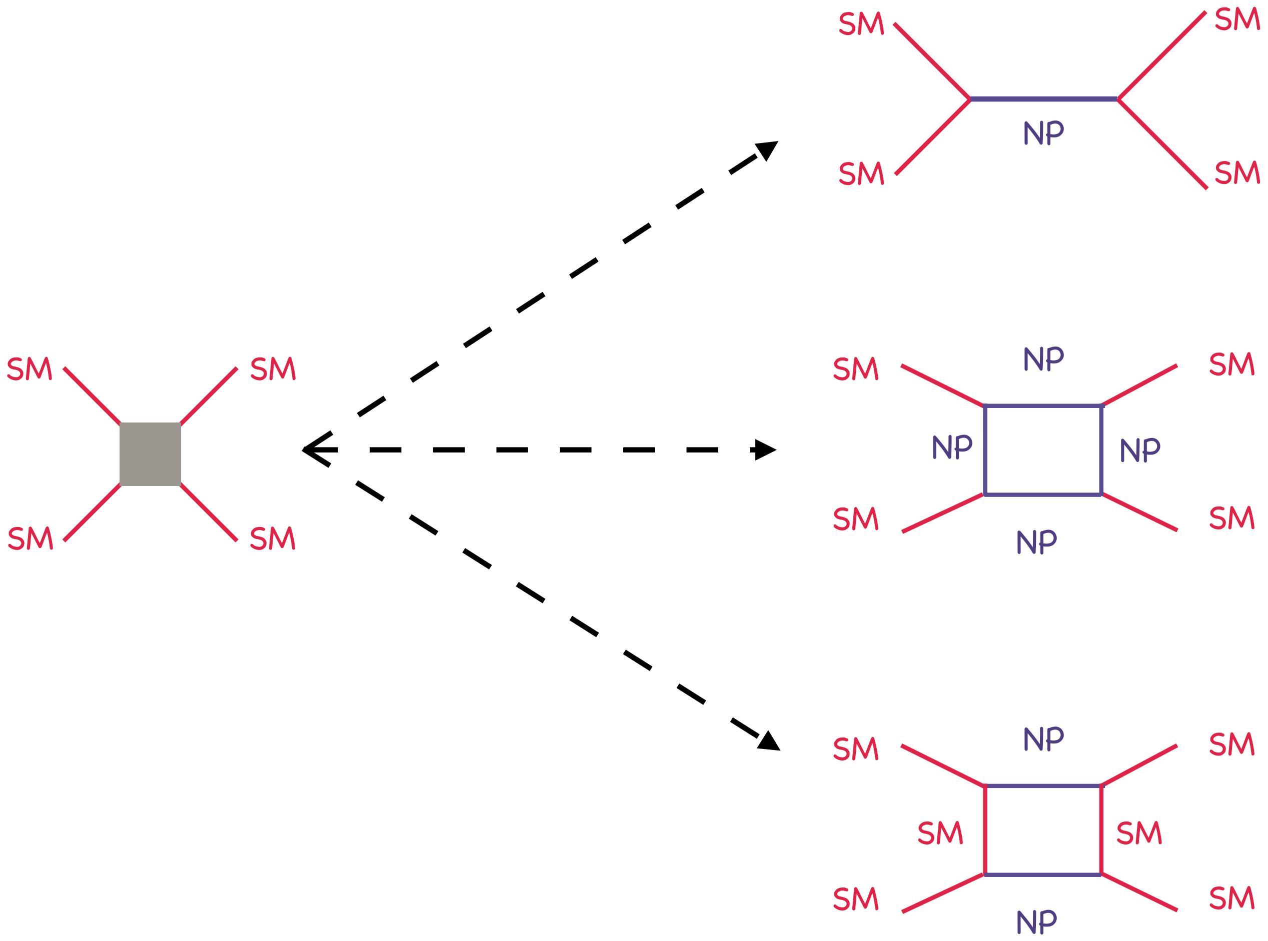
$\mathcal{D}^2$, m^2, U: Covariant Derivative, mass and quadratic terms in the Lagrangian for the heavy field

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

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

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

Henning et. al. JHEP01(2016)023



T — Tree-level effective operators

HH — Only heavy field propagator in the loop

HL — Both heavy and light field propagators in the loop

CoDEx : Wilson coefficient calculator

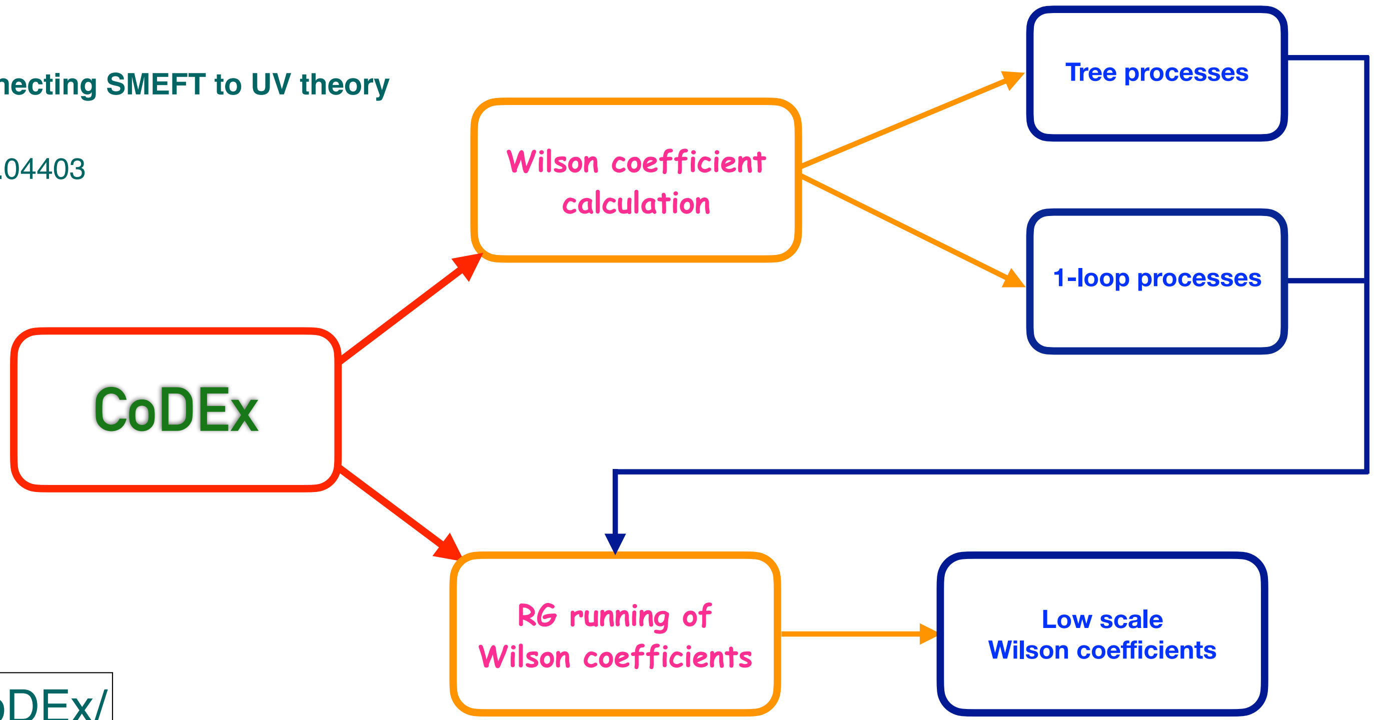
Complete 1-loop Wilson coefficients within seconds !

Manually matching BSMs to SMEFT is involved.

Package for automization is much needed.

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



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

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

SILH

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

Matching scale = mass of heavy field = mH2

Warsaw basis

$Q_{\mathrm{Hl}}{}^{(1)}$	$\frac{g_Y{}^4}{3840\pi^2 m_{\mathcal{H}_2}{}^2}$
$Q_{\mathrm{Hq}}{}^{(1)}$	$-\frac{g_Y{}^4}{11520\pi^2 m_{\mathcal{H}_2}{}^2}$
$Q_{\mathrm{ud}}{}^{(1)}$	$\frac{g_Y{}^4}{4320\pi^2 m_{\mathcal{H}_2}{}^2}$
$Q_{\mathrm{Hl}}{}^{(3)}$	$-\frac{g_W{}^4}{1920\pi^2 m_{\mathcal{H}_2}{}^2}$
$Q_{\mathrm{Hq}}{}^{(3)}$	$-\frac{g_W{}^4}{1920\pi^2 m_{\mathcal{H}_2}{}^2}$
$Q_{\mathrm{lq}}{}^{(3)}$	$-\frac{g_W{}^4}{3840\pi^2 m_{\mathcal{H}_2}{}^2}$
$Q_{\mathrm{qq}}{}^{(3)}$	$-\frac{g_W{}^4}{7680\pi^2 m_{\mathcal{H}_2}{}^2}$
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}	$\frac{3\lambda_{\mathcal{H}_2} Y^{(d)}_{\mathcal{H}_2} Y^{(e)}_{\mathcal{H}_2}}{64\pi^2 m_{\mathcal{H}_2}{}^2}$
$Q_{\mathrm{lequ}}{}^{(1)}$	$\frac{3\lambda_{\mathcal{H}_2} Y^{(e)}_{\mathcal{H}_2} Y^{(u)}_{\mathcal{H}_2}}{64\pi^2 m_{\mathcal{H}_2}{}^2}$
$Q_{\mathrm{quqd}}{}^{(1)}$	$-\frac{3\lambda_{\mathcal{H}_2} Y^{(d)}_{\mathcal{H}_2} Y^{(u)}_{\mathcal{H}_2}}{64\pi^2 m_{\mathcal{H}_2}{}^2}$

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

Contributions from heavy-light diagrams?

HL Wilson coefficients - 2HDM

(A) Warsaw basis

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

(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:

$$[D^a, G_{ab}]^\alpha = g_S \left(\bar{q}_L\, T^\alpha \gamma_b\, q_L + \bar{u}_R\, T^\alpha \gamma_b\, u_R + \bar{d}_R\, T^\alpha \gamma_b\, d_R\right)$$

$$[D^a, W_{ab}]^I = g_W \left(\frac{1}{2}\bar{q}_L\, \sigma^I \gamma_b\, q_L + \frac{1}{2}\bar{l}_L\, \sigma^I \gamma_b\, l_L + \frac{1}{2} H^\dagger i \overleftrightarrow{D}{}^I_b H\right)$$

$$D^a B_{ab} = g_Y \left(\frac{1}{6}\bar{q}_L\, \gamma_b\, q_L - \frac{1}{2}\bar{l}_L\, \gamma_b\, l_L + \frac{1}{2} H^\dagger i \overleftrightarrow{D}_b H + \frac{2}{3}\bar{u}_R\, \gamma_b\, u_R - \frac{1}{3}\bar{d}_R\, \gamma_b\, d_R - \bar{e}_R\, \gamma_b\, e_R\right)$$

$$H^\dagger i \overleftrightarrow{D}_b H = i H^\dagger (D_b H) - i (D_b H^\dagger) H,$$

$$H^\dagger i \overleftrightarrow{D}{}^I_b H = i H^\dagger \sigma^I (D_b H) - i (D_b H^\dagger) \sigma^I H.$$

Fermions:

$$i\not{D} q_L = Y_{\rm SM}^{(u)\dagger} u_R \widetilde{H} + Y_{\rm SM}^{(d)\dagger} d_R H,$$

$$i\not{D} l_L = Y_{\rm SM}^{(e)\dagger} e_R H,$$

$$i\not{D} e_R = Y_{\rm SM}^{(e)} l_L H^\dagger,$$

$$i\not{D} u_R = Y_{\rm SM}^{(u)} q_L \widetilde{H}^\dagger,$$

$$i\not{D} d_R = Y_{\rm SM}^{(d)} q_L H^\dagger$$

Scalars:

$$D^2 H + \mu_H |H|^2 + \lambda_H (H^\dagger H) H + \bar{q}_L i\sigma^2 Y_{\rm SM}^{(u)\dagger} u_R + \bar{d}_R Y_{\rm SM}^{(d)} q_L + \bar{e}_R Y_{\rm SM}^{(e)} l_L = 0$$

Operator identities

Gauge-invariant operators to SMEFT bases

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

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

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

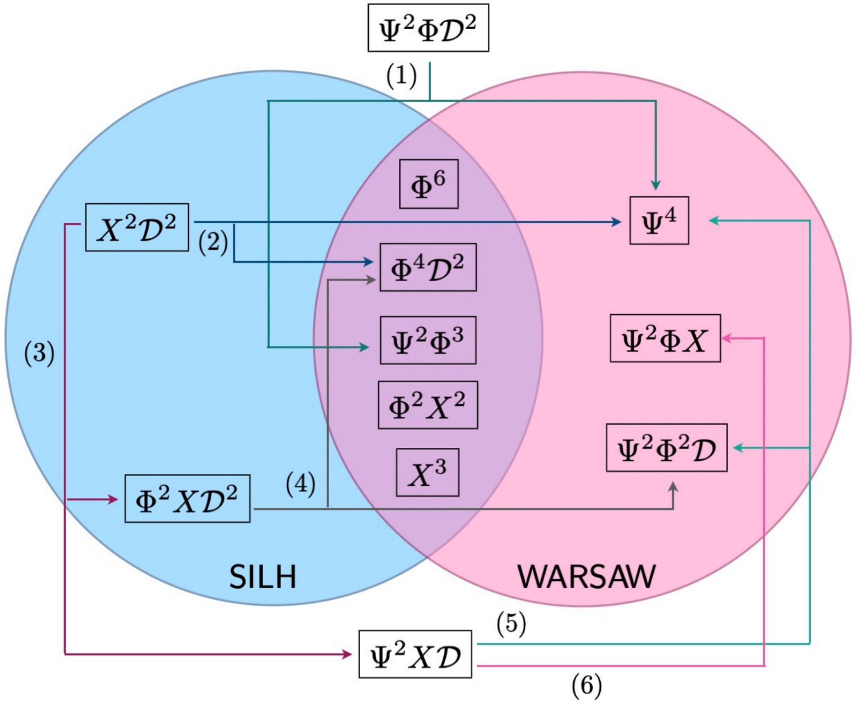
$$O_W = \frac{i}{2} g_W \left(H^\dagger \sigma^I \overleftrightarrow{D}_\mu H \right) D_\nu W^{\mu\nu} = g_W^2 \Big\{ \lambda_H Q_H + \frac{3}{4} Q_{H\Box} + \frac{1}{4} Q_{Hq}^{(3)} + \frac{1}{4} Q_{Hl}^{(3)} + \left(\frac{1}{2} Y_{\rm SM}^{(u)} Q_{uH} + \frac{1}{2} Y_{\rm SM}^{(d)} Q_{dH} + \frac{1}{2}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

Fierz identities:

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

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

Relations among different operator bases



(1) $\left(\overline{\Psi}_L\Psi_R\right)\mathcal{D}^2\Phi = c_1\left(\overline{\Psi}_L\Psi_R\Phi\right)\left(\Phi^\dagger\Phi\right) + c_2\left(\overline{\Psi}_L\Psi_R\Phi\right)\left(\overline{\Psi}_R\Psi_L\Phi\right)$

(2) $(\mathcal{D}_\mu X^{\mu\nu})^2 = c_3\left(\overline{\Psi}\gamma_\nu\Psi\right)\left(\overline{\Psi}\gamma^\nu\Psi\right) + c_4(\Phi^\dagger i\overleftrightarrow{D}_\nu\Phi)(\Phi^\dagger i\overleftrightarrow{D}^\nu\Phi) + c_5\left(\overline{\Psi}\gamma_\nu\Psi\right)(\Phi^\dagger i\overleftrightarrow{D}^\nu\Phi)$

(3) $(\mathcal{D}_\mu X^{\mu\nu})^2 = c_6\left(\overline{\Psi}\gamma_\nu\Psi\right)(\mathcal{D}_\mu X^{\mu\nu}) + c_7(\Phi^\dagger i\overleftrightarrow{D}_\nu\Phi)(\mathcal{D}_\mu X^{\mu\nu})$

(4) $(\Phi^\dagger i\overleftrightarrow{D}_\nu\Phi)(\mathcal{D}_\mu X^{\mu\nu}) = c_8(\Phi^\dagger i\overleftrightarrow{D}_\nu\Phi)(\Phi^\dagger i\overleftrightarrow{D}^\nu\Phi) + c_9(\Phi^\dagger i\overleftrightarrow{D}_\nu\Phi)\left(\overline{\Psi}\gamma^\nu\Psi\right)$

(5) $(\mathcal{D}_\mu X^{\mu\nu})\left(\overline{\Psi}_{L,R}\,\gamma^\nu\,\Psi_{L,R}\right) = c_{10}\Psi^4_{L,R}\,/\,\Psi^2_L\Psi^2_L + c_{11}\Psi_L\Psi_R\Phi^2\mathcal{D}$

(6) $X^{\mu\nu}\left(\overline{\Psi}_{L,R}\,\gamma_\mu\mathcal{D}_\nu\,\Psi_{L,R}\right) = c_{11}X^{\mu\nu}\left(\overline{\Psi}_{L,R}\,\sigma_{\mu\nu}\,\Psi_{R,L}\right)\Phi$

Paving the path to Phenomenology

❖ BSM Classifications

BSM Classifications

SM
+
Heavy Scalars

Color-singlets

BSMs	$\mathcal{S}$	$\mathcal{S}_2$	Δ	$\mathcal{H}_2$	Δ_1	Σ
$\mathcal{G}_{3,2,1}$	1,1,0	1,1,2	1,3,0	1,2,-1/2	1,3,1	1,4,1/2

Colored

BSMs	φ_1	φ_2	Θ_1	Θ_2	Ω	χ_1	χ_2	χ_3	χ_4
$\mathcal{G}_{3,2,1}$	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

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}

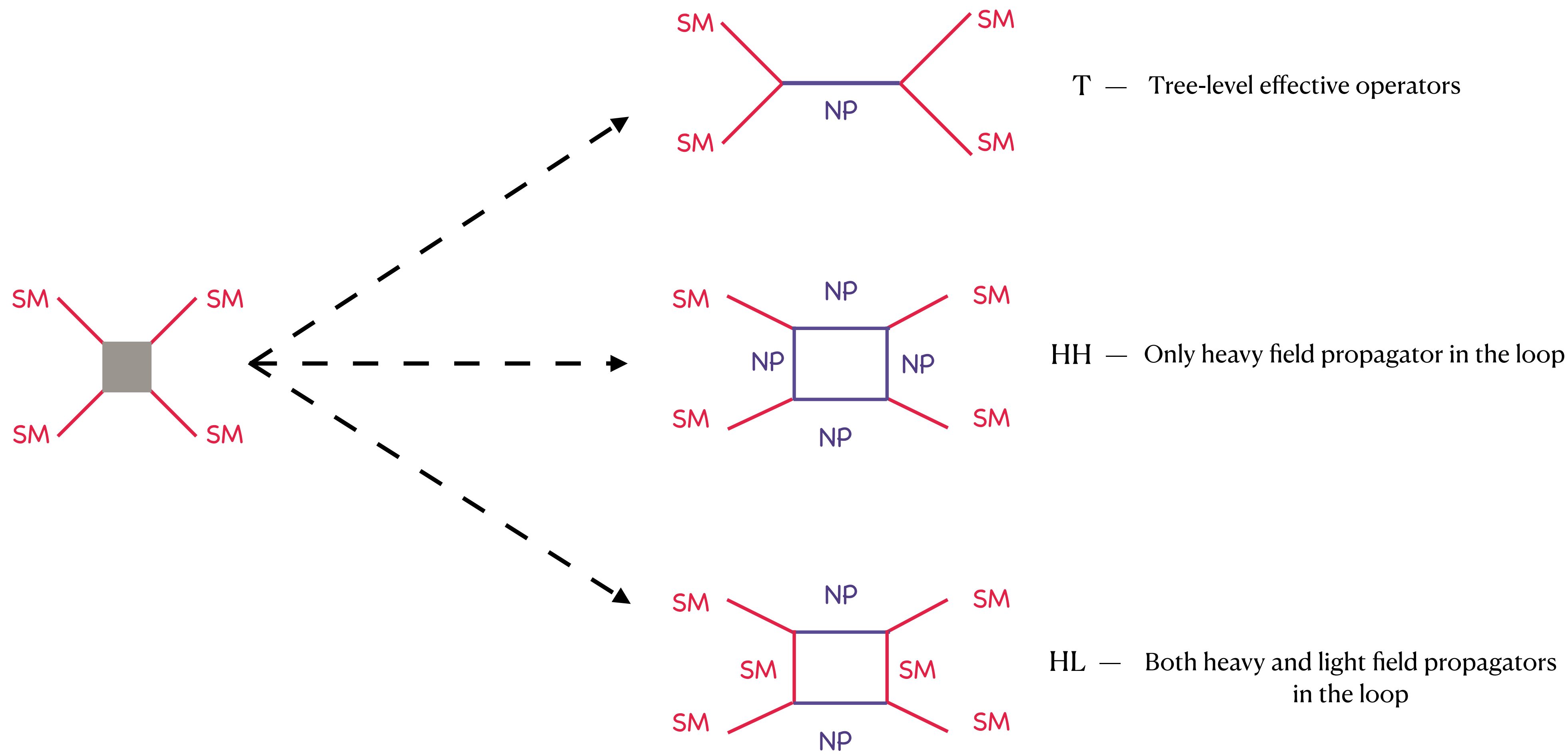
EWPO-LO

EWPO-NLO-I

EWPO-NLO-II

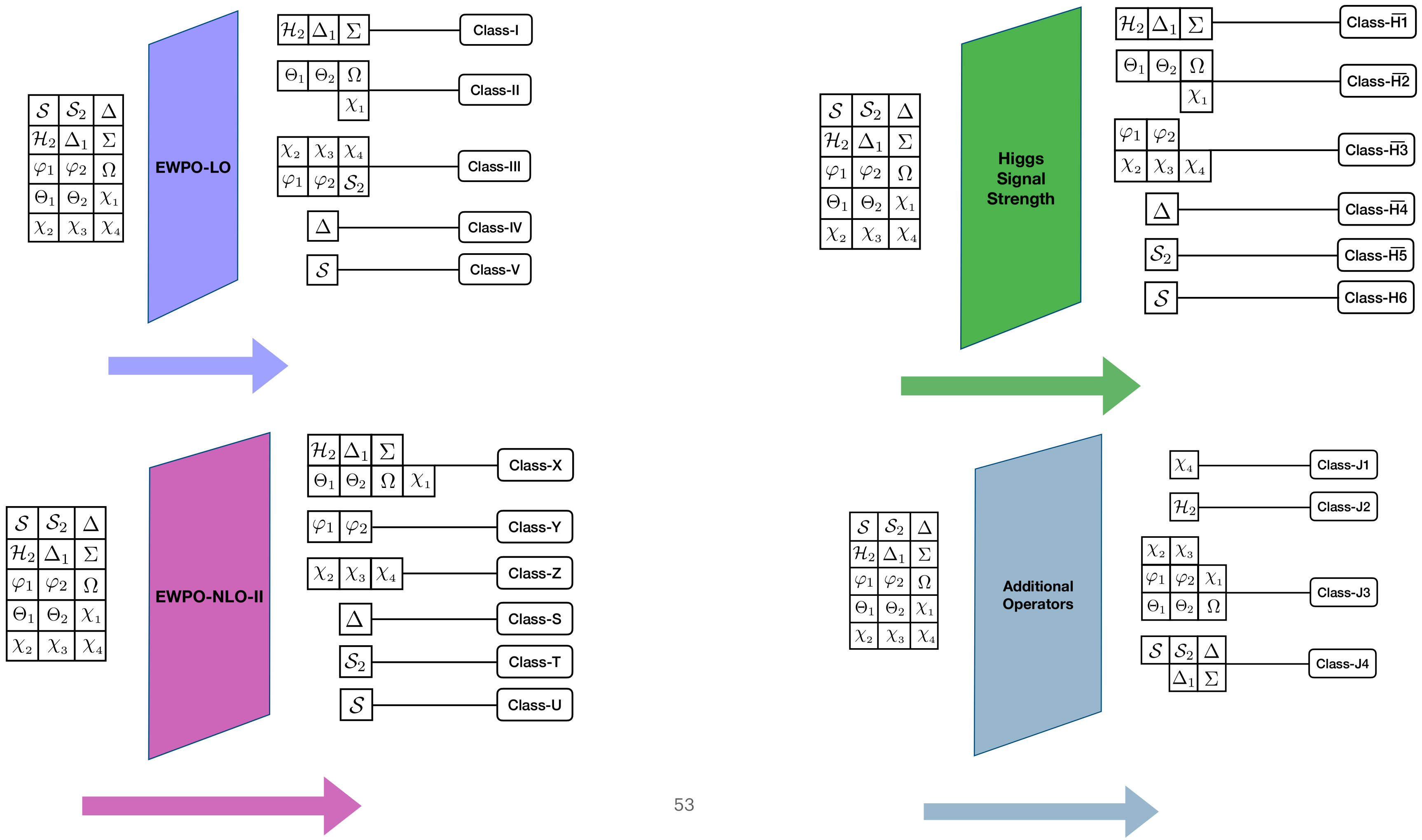
BSMs	Q_{HD}	Q_{ll}	Q_{Hu}	Q_{Hd}	Q_{He}	$Q_{Hq}^{(1)}$	$Q_{Hl}^{(1)}$	$Q_{Hl}^{(3)}$	$Q_{Hq}^{(3)}$	Q_{HWB}	$Q_{H\Box}$	Q_{HB}	Q_{HW}	Q_H	Q_G	Q_{HG}	Q_{eH}	Q_{uH}	Q_{dH}	$Q_{qq}^{(1)}$	$Q_{qq}^{(3)}$	Q_{uu}	Q_{dd}	$Q_{ud}^{(1)}$	$Q_{lq}^{(1)}$	Q_{ee}	Q_{eu}	Q_{ed}	Q_{le}	Q_{lu}	Q_{ld}	Q_{qe}	$Q_{qu}^{(1)}$	$Q_{qd}^{(1)}$	$Q_{lq}^{(3)}$	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	✗	✗

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

BSM Classification based on Observables

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



BSM Classification based on Observables