❖ CP-violation in SMEFT

Dimension-6 Gauge-Higgs SMEFT operators

Grzadkowski JHEP10(2010)085

CP-odd

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

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}	$(H^\dagger H)\,G_{\mu\nu}{}^{a}G^{a,\mu\nu}$
Q_{HW}	$(H^\dagger H)\,W_{\mu\nu}{}^{a}W^{a,\mu\nu}$
Q_{HB}	$(H^\dagger H)\,B_{\mu\nu}B^{\mu\nu}$
Q_{HWB}	$(H^\dagger\tau^a H)\,W_{\mu\nu}{}^{a}B^{\mu\nu}$

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

❖ **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 $Q_{\widetilde{G}}$

SM extended by heavy fermions

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

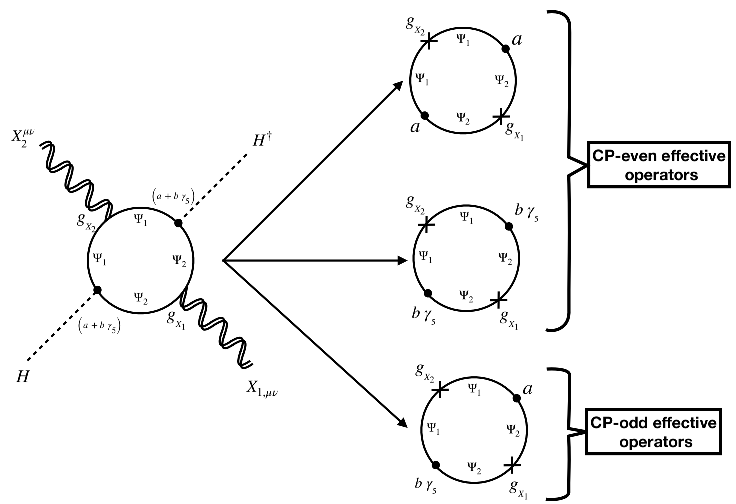
Vector-like lepton (VLL) model study

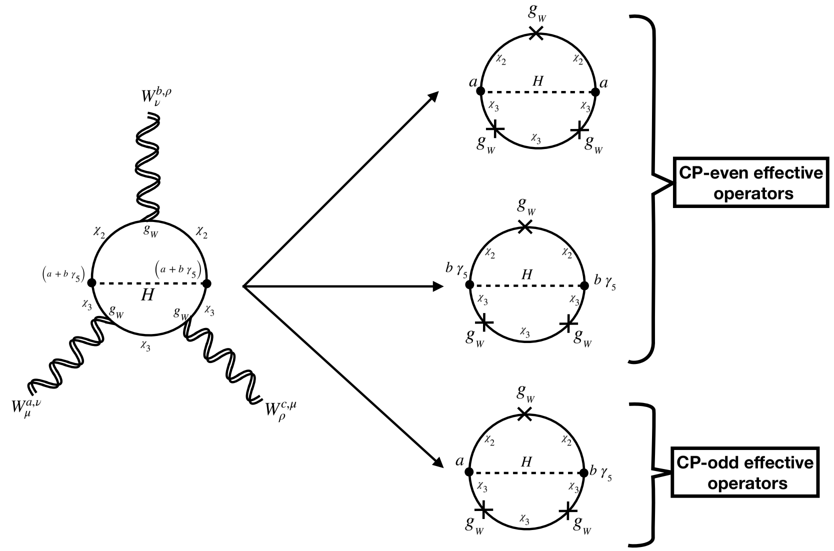
$$\Sigma_{L,R} = \begin{pmatrix} \eta \\ \xi \end{pmatrix}_{L,R} : (1, 2, \mathcal{Y}), \quad \eta'_{L,R} : (1, 1, \mathcal{Y} + \frac{1}{2}), \quad \xi'_{L,R} : (1, 1, \mathcal{Y} - \frac{1}{2}).$$

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

CPV operator diagrams

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





1-loop matching result

Operators	Wilson Coefficients $\left(\mathcal{C}_i \times \frac{1}{16\pi^2}\right)$
$Q_{H\widetilde{B}}$	$-\frac{g_Y^2}{12}\left[(1+6\mathcal{Y}+12\mathcal{Y}^2)\mathrm{Im}[Y_{\eta_L}Y^*_{\eta_R}]+(1-6\mathcal{Y}+12\mathcal{Y}^2)\mathrm{Im}[Y_{\xi_L}Y^*_{\xi_R}]\right]$
$Q_{H\widetilde{W}}$	$-\frac{g_W^2}{12}\mathrm{Im}[Y_{\eta_L}Y^*_{\eta_R}+Y_{\xi_L}Y^*_{\xi_R}]$
$Q_{H\widetilde{W}B}$	$\frac{g_W g_Y}{6}\left[(1+6\mathcal{Y})\mathrm{Im}[Y_{\eta_L}Y^*_{\eta_R}]+(1-6\mathcal{Y})\mathrm{Im}[Y_{\xi_L}Y^*_{\xi_R}]\right]$
Q_W	$g_W^3/180$
Q_H	$-\frac{2}{15}\left(\lvert\alpha_\eta\rvert^6+\lvert\alpha_\xi\rvert^6\right)+\frac{2}{3}\left(\lvert\beta_\eta\rvert^6+\lvert\beta_\xi\rvert^6\right)$ $+\frac{2}{3}\left(\lvert\alpha_\eta\rvert^4\lvert\beta_\eta\rvert^2+\lvert\alpha_\xi\rvert^4\lvert\beta_\xi\rvert^2\right)+2\left(\lvert\alpha_\eta\rvert^2\lvert\beta_\eta\rvert^4+\lvert\alpha_\xi\rvert^2\lvert\beta_\xi\rvert^4\right)$ $+\frac{2}{3}\left(\lvert\alpha_\eta\rvert^2\left((\alpha_\eta^*)^2\beta_\eta^2+\alpha_\eta^2(\beta_\eta^*)^2\right)+\lvert\alpha_\xi\rvert^2\left(\left(\alpha_\xi^*\right)^2\beta_\xi^2+\alpha_\xi^2\left(\beta_\xi^*\right)^2\right)\right)$ $+2\left(\lvert\beta_\eta\rvert^2\left((\alpha_\eta^*)^2\beta_\eta^2+\alpha_\eta^2(\beta_\eta^*)^2\right)+\lvert\beta_\xi\rvert^2\left(\left(\alpha_\xi^*\right)^2\beta_\xi^2+\alpha_\xi^2\left(\beta_\xi^*\right)^2\right)\right)$ $-2\lambda_H\mathcal{C}_F+\frac{4}{5}\lambda_H\left(\lvert\alpha_\xi\rvert^2+\lvert\alpha_\eta\rvert^2\right)+\frac{4}{3}\lambda_H\left(\lvert\beta_\xi\rvert^2+\lvert\beta_\eta\rvert^2\right)$
$Q_{H\Box}$	$-\frac{2}{5}\left(\lvert\alpha_\eta\rvert^2+\lvert\alpha_\xi\rvert^2\right)^2-\frac{1}{3}\left(\lvert\beta_\eta\rvert^2+\lvert\beta_\xi\rvert^2\right)^2$ $-\frac{1}{3}\left(\lvert\beta_\xi\rvert^2\lvert\alpha_\eta\rvert^2+\lvert\alpha_\xi\rvert^2\lvert\beta_\eta\rvert^2\right)-1\left(\lvert\alpha_\eta\rvert^2\lvert\beta_\eta\rvert^2+\lvert\alpha_\xi\rvert^2\lvert\beta_\xi\rvert^2\right)$ $-\frac{2}{3}\left(\alpha_\xi\beta_\xi^*\alpha_\eta^*\beta_\eta+\alpha_\xi^*\beta_\xi\alpha_\eta\beta_\eta^*\right)+\frac{1}{3}\left(\alpha_\eta^2(\beta_\eta^*)^2+(\alpha_\eta^*)^2\beta_\eta^2\right)$
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}	$-\frac{1}{2}\mathrm{Re}\left[\left(Y^e_{\rm SM}\right)^\dagger\right]\mathcal{C}_F+\frac{1}{2}\mathrm{Im}\left[\left(Y^e_{\rm SM}\right)^\dagger\right]\tilde{\mathcal{C}}_F+2\lambda_H\left(Y^e_{\rm SM}\right)^\dagger\left(Y^e_{\rm SM}\right)\mathcal{C}_{K4}$
Q_{uH}	$-\frac{1}{2}\mathrm{Re}\left[\left(Y^u_{\rm SM}\right)^\dagger\right]\mathcal{C}_F-\frac{1}{2}\mathrm{Im}\left[\left(Y^u_{\rm SM}\right)^\dagger\right]\tilde{\mathcal{C}}_F+2\lambda_H\left(Y^u_{\rm SM}\right)^\dagger\left(Y^u_{\rm SM}\right)\mathcal{C}_{K4}$
Q_{dH}	$-\frac{1}{2}\mathrm{Re}\left[\left(Y^d_{\rm SM}\right)^\dagger\right]\mathcal{C}_F+\frac{1}{2}\mathrm{Im}\left[\left(Y^d_{\rm SM}\right)^\dagger\right]\tilde{\mathcal{C}}_F+2\lambda_H\left(Y^d_{\rm SM}\right)^\dagger\left(Y^d_{\rm SM}\right)\mathcal{C}_{K4}$
Q_{ledq}	$\left\{\left(Y^e_{\rm SM}\right)\left(Y^d_{\rm SM}\right)^\dagger\mathcal{C}_{K4}+\text{h.c.}\right\}$
$Q^{(1)}_{quqd}$	$\left\{\left(Y^u_{\rm SM}\right)^\dagger\left(Y^d_{\rm SM}\right)^\dagger\mathcal{C}_{K4}+\text{h.c.}\right\}$
$Q^{(1)}_{lequ}$	$-\left\{\left(Y^e_{\rm SM}\right)^\dagger\left(Y^u_{\rm SM}\right)^\dagger\mathcal{C}_{K4}+\text{h.c.}\right\}$
Q_{le}	$-\frac{1}{2}\left(Y^e_{\rm SM}\right)^\dagger\left(Y^e_{\rm SM}\right)\mathcal{C}_{K4}$
$Q^{(1)}_{qu}$	$-\frac{1}{2}\left(Y^u_{\rm SM}\right)^\dagger\left(Y^u_{\rm SM}\right)\mathcal{C}_{K4}$
$Q^{(1)}_{qd}$	$-\frac{1}{2}\left(Y^d_{\rm SM}\right)^\dagger\left(Y^d_{\rm SM}\right)\mathcal{C}_{K4}$

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

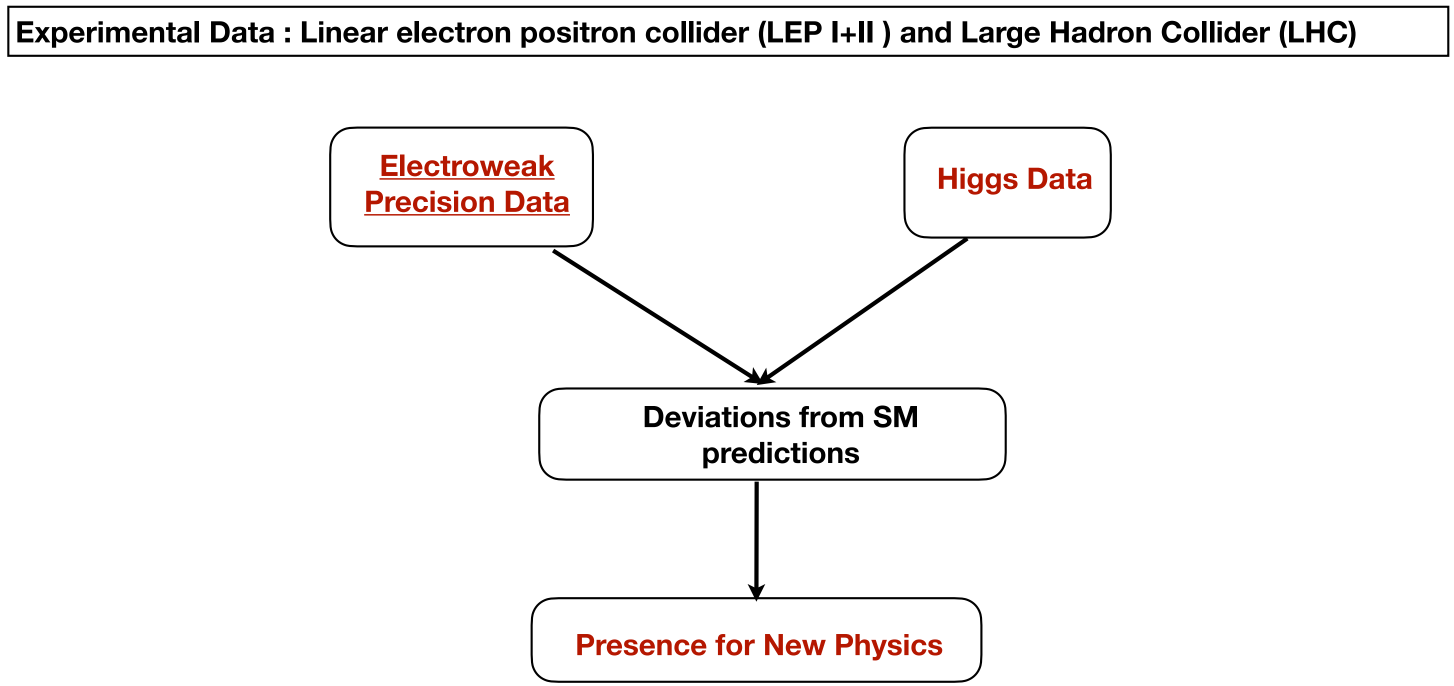
$$\begin{aligned}\mathcal{C}_F=&-\frac{2}{5}\left(|\alpha_\xi|^4-4|\alpha_\xi|^2|\alpha_\eta|^2+|\alpha_\eta|^4\right)+\frac{4}{3}\left(|\beta_\eta|^4+|\beta_\xi|^2|\beta_\eta|^2+|\beta_\xi|^4\right)\\&+2\left(|\alpha_\eta|^2|\beta_\eta|^2+|\alpha_\xi|^2|\beta_\xi|^2\right)+\frac{2}{3}\left(|\beta_\xi|^2|\alpha_\eta|^2+|\alpha_\xi|^2|\beta_\eta|^2\right)\\&+\fra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

$$\mathcal{C}_{K4}=\frac{1}{5}\left(|\alpha_\xi|^2+|\alpha_\eta|^2\right)+\frac{1}{3}\left(|\beta_\xi|^2+|\beta_\eta|^2\right),$$
$$\tilde{\mathcal{C}}_F=\frac{1}{3}\left[\left(|Y_{\xi_L}|^2+|Y_{\xi_R}|^2\right)\mathrm{Im}\left[Y_{\xi_L}Y^*_{\xi_R}\right]-\left(|Y_{\eta_L}|^2+|Y_{\eta_R}|^2\right)\mathrm{Im}\left[Y_{\eta_L}Y^*_{\eta_R}\right]\right].$$

Phenomenology

Hint For New Physics

There are a few unanswered questions which hint towards presence of New Physics:
Neutrino mass, dark matter, matter- antimatter asymmetry…etc.



Searching for New Physics

Theoretical ways

✤ Adding new particle(s)

- With the same SM gauge symmetry.
- Enlarge the SM gauge symmetry.

Experimental ways

✤ Detection of a new physics particle either directly or indirectly.

Theory + Experiment

↓

✤ Full theory to be known - to study different processes.

✤ Energy scale of colliders should be sufficient to detect new particle .

Searching for New Physics

Theoretical ways

✤Adding new particle(s)

- With the same SM gauge symmetry.
- Enlarge the SM gauge symmetry.

Experimental ways

✤ Detection of a new physics particle either directly or indirectly.

Theory + Experiment

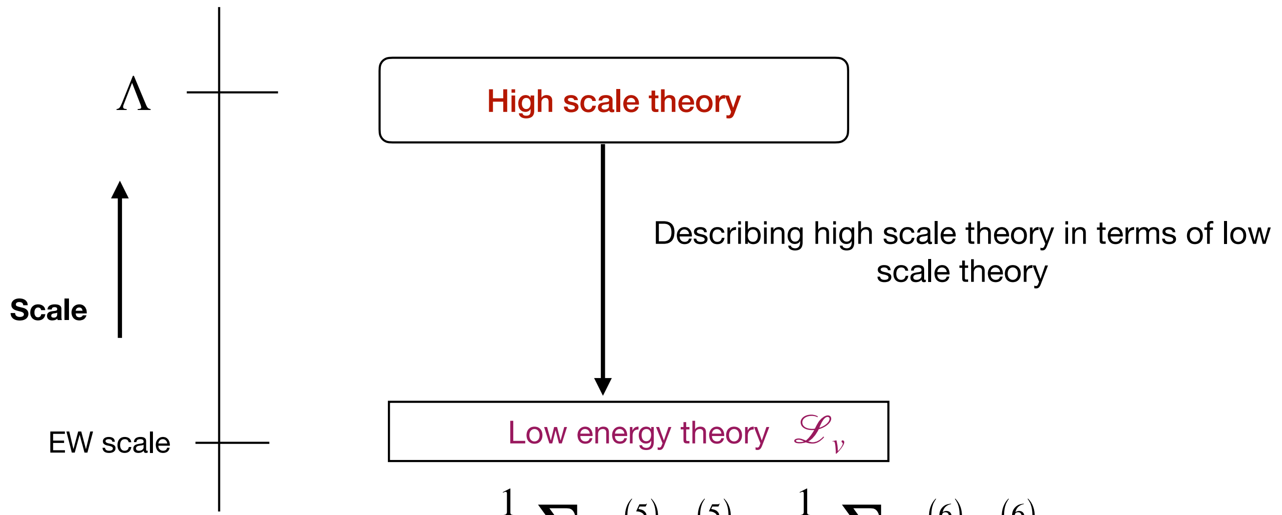
↓ **Problems**

✤No clue information about the full theory.

✤Energy scale in order to detect new particle is beyond the reach of ongoing colliders (LHC, etc.) .

Effective Field Theory: Solution to problems

EFT - Describe new physics in terms of Higher Dimensional Operators (HDO) each supplemented with Wilson Coefficients.

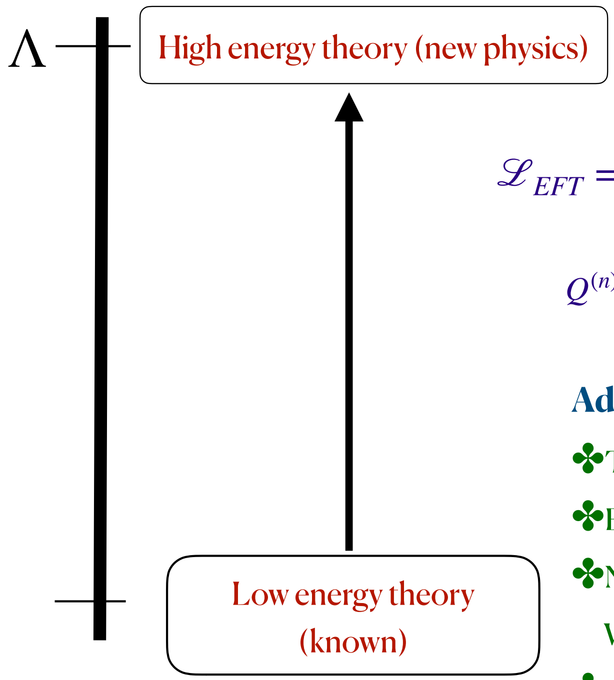


$$\mathscr{L}_{EFT} = \mathscr{L}_\nu + \frac{1}{\Lambda}\sum_i C_i^{(5)} Q_i^{(5)} + \frac{1}{\Lambda^2}\sum_i C_i^{(6)} Q_i^{(6)} + \ldots$$

$Q^{(n)}$ = **effective operators**

$C^{(n)}$ = **Wilson coefficients**

EFT path to New Physics



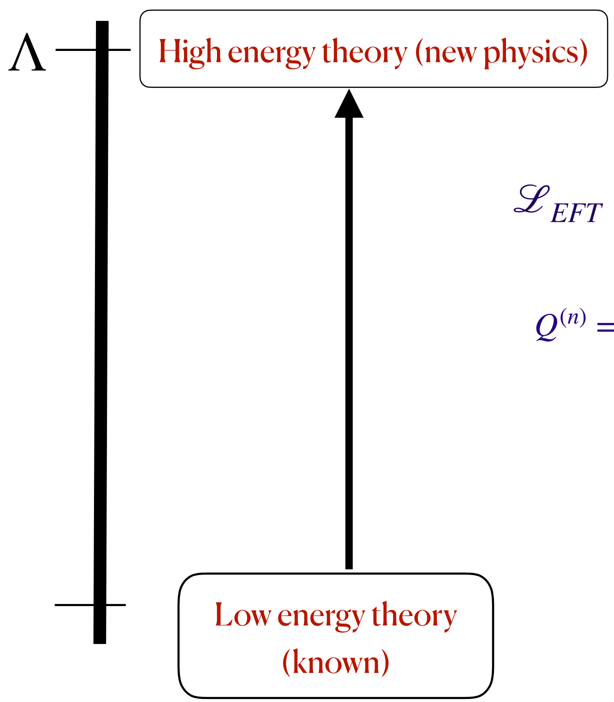
$$\mathscr{L}_{EFT} = \mathscr{L}_{\nu} + \frac{1}{\Lambda}\sum_i C_i^{(5)} Q_i^{(5)} + \frac{1}{\Lambda^2}\sum_i C_i^{(6)} Q_i^{(6)} + \dots$$

$Q^{(n)}$ = **effective operators** $C^{(n)}$ = **Wilson coefficients**

Advantages of EFT

- ✤There is **no need to know full theory**.
- ✤Explicit way of connecting with different mass scales.
- ✤NP information is encapsulated in HDO and their corresponding WCs (free parameters).
- ✤Effective operators are invariant under the gauge symmetry of low energy theory.
- ✤Efficient way to probe NP which is beyond the reach of current collider.

EFT path to New Physics



$$\mathscr{L}_{EFT} = \mathscr{L}_{\nu} + \frac{1}{\Lambda}\sum_i C_i^{(5)} Q_i^{(5)} + \frac{1}{\Lambda^2}\sum_i C_i^{(6)} Q_i^{(6)} + \ldots$$

$Q^{(n)}$ = **effective operators** $C^{(n)}$ = **Wilson coefficients**

Modification in the observables is written in a model independent manner are written as:

$$\Delta obs = obs^{Exp} - obs^{theory} = \frac{1}{\Lambda^2}\sum_i c_i^{(6)} \mathcal{O}_i^{(6)} + \ldots$$

Thus can affect as an efficient way for data interpretation.

Standard Model Effective Field Theory

- Using SM as low energy theory, the high energy theory is expressed in terms of effective operators constructed with SM fields and symmetry.

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\sum_i C_i^{(5)} Q_i^{(5)} + \frac{1}{\Lambda^2}\sum_i C_i^{(6)} Q_i^{(6)} + \dots$$

$Q^{(n)}$ = **SMEFT Warsaw Basis operators** $C^{(n)}$ = **Wilson coefficients**

- SMEFT describes any beyond SM physics lying at cut off Λ .
- At dim- 6, a total of 2499 independent and non-redundant operators are constructed with SM fields in a basis called Warsaw Basis in the most general case.

Grzadkowski et. al. JHEP 10(2010)085

- These can be reduced
  - assuming different flavor symmetries, CP .
  - for instance with single flavor and baryon no. conservation there are 59 operators.

Capturing New Physics effects in Observables

In order to account for deviations in experimental observations of the observables :

Observable →

$$\mathscr{L}_{SM(2HDM)} + \frac{1}{\Lambda}\sum_i C_i^{(5)} Q_i^{(5)} + \frac{1}{\Lambda^2}\sum_i C_i^{(6)} Q_i^{(6)}$$

8 different classes of operators

ϕ^6	$\phi^2 X^2$
$\psi^2 \phi X$	$\phi^4 D^2$
$\phi^2 \psi^2 D$	X^3
$\phi^3 \psi^2$	ψ^4

Modifications induced to mass spectrum due to dim-6 effective operators.

Modifications in mass spectrum

SMEFT

Redefining Kinetic terms → **Redefinitions of SM fields**

$\phi^4 D^2$

$$Q_{H\Box} = (H^\dagger H)\Box(H^\dagger H)$$

$$Q_{HD} = \left(H^\dagger D_\mu H\right)^* \left(H^\dagger D^\mu H\right)$$

→

$$h \to \left[h - \frac{1}{2\Lambda^2}\left(\frac{C_{HD}v^2}{2} - 2C_{H\Box}v^2\right)\right].$$

$\phi^2 X^2$

$$Q_{HW} = (H^\dagger H)\left(W^I_{\mu\nu}W^{I\mu\nu}\right)$$

$$Q_{HB} = (H^\dagger H)\left(B_{\mu\nu}B^{\mu\nu}\right)$$

$$Q_{HWB} = (H^\dagger \sigma^I H)\left(W^I_{\mu\nu}\sigma^I B^{\mu\nu}\right)$$

→

$$W^+_\mu \to W^+_\mu\left[1 + \frac{C_{HW}v^2}{\Lambda^2}\right],$$

$$Z_\mu \to Z_\mu\left[1 + \frac{1}{\Lambda^2}\Delta_{ZZ}\right],$$

$$A_\mu \to A_\mu\left[1 + \frac{1}{\Lambda^2}\Delta_{AA}\right] + \frac{Z_\mu}{\Lambda^2}\Delta_{AZ}.$$

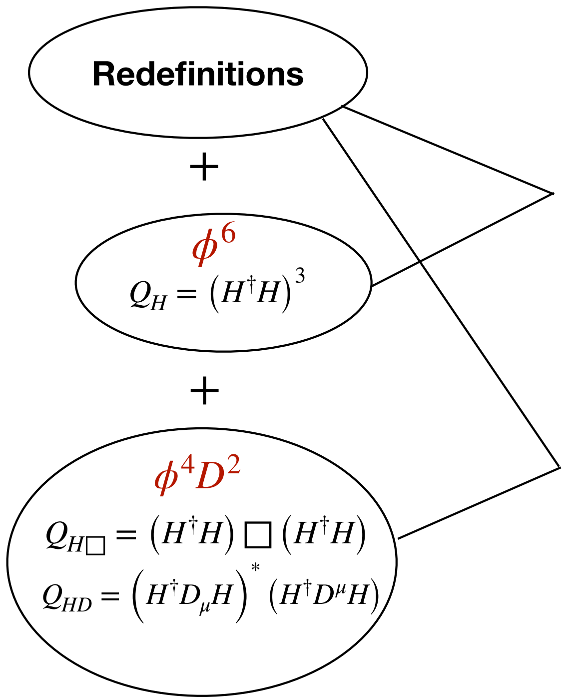
$$\Delta_{ZZ} = \left((\cos^2\theta_w)C_{HW}v^2 + (\cos\theta_w\sin\theta_w)C_{HWB}v^2 + C_{HB}(\sin^2\theta_w)v^2\right),$$

$$\Delta_{AA} = \left((\cos^2\theta_w)C_{HB}v^2 - (\cos\theta_w\sin\theta_w)C_{HWB}v^2 + C_{HW}\sin^2\theta_w v^2\right),$$

$$\Delta_{AZ} = \left(C_{HWB}v^2\left(\cos^2\theta_w - \sin^2\theta_w\right) + 2\cos\theta_w\sin\theta_w v^2(C_{HW} - C_{HB})\right).$$

Modifications in mass spectrum

Using redefinitions and operators



$$\mathscr{M}_H^2 = 2\lambda v^2 + \frac{1}{\Lambda^2}\left(\frac{15}{4}C_H v^4 - \lambda C_{HD} v^4 + 4\lambda C_{H\Box} v^4\right).$$

$$\mathscr{M}_W^2 = \frac{g_2^2 v^2}{4} + \frac{g_2^2 C_{HW} v^4}{2\Lambda^2},$$

$$\mathscr{M}_Z^2 = \frac{(g_1^2 + g_2^2)v^2}{4} + \frac{1}{2\Lambda^2}\left(\Delta_{ZZ} v^2 (g_1^2 + g_2^2) + \frac{C_{HD} v^4 (g_1^2 + g_2^2)}{4}\right).$$

Mass of charged fermions

$$-(H^{+j} d Y_d q_j + \tilde{H}^{+j} u Y_u q_j + H^{+j} e Y_e l_j + h.c.)$$

Considering single family of fermions

$$+$$

$$\phi^3\psi^2 + h.c.$$

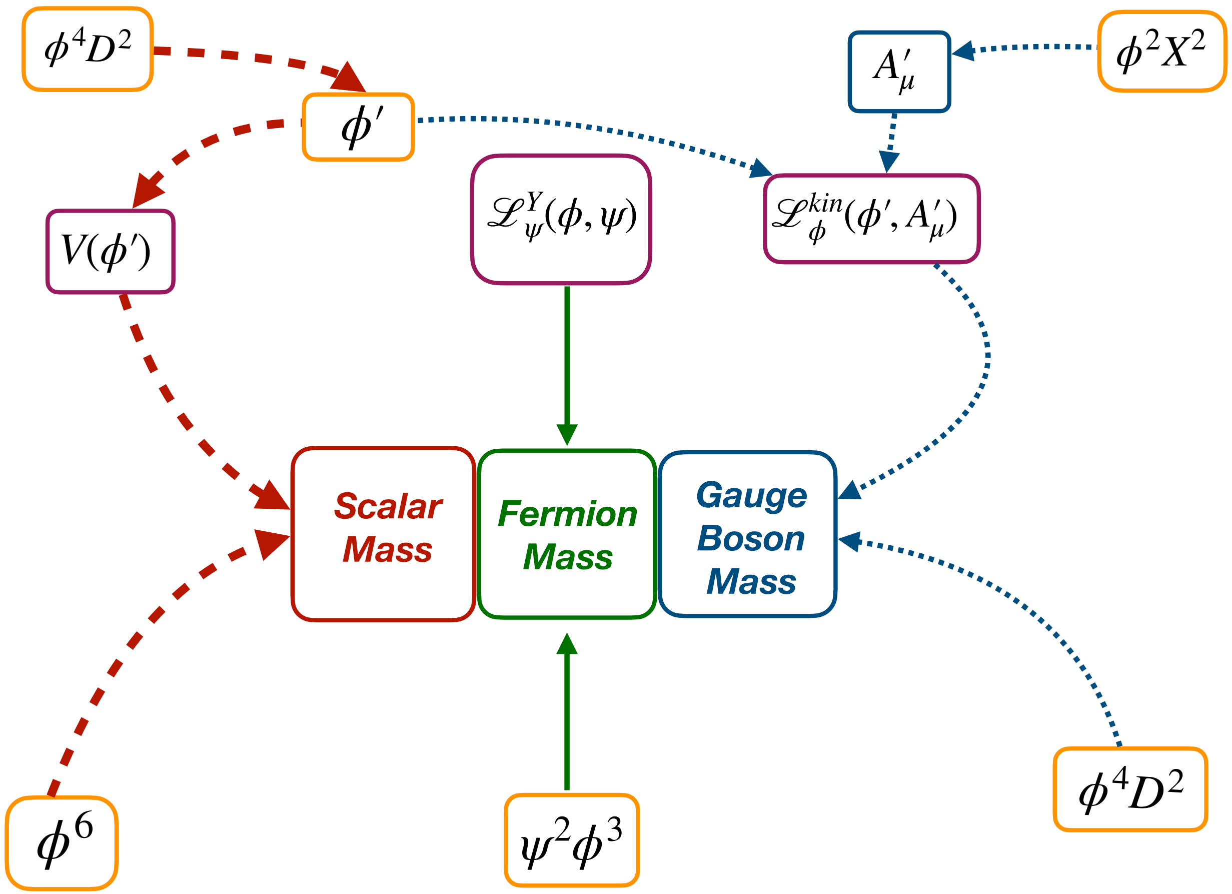
$$Q_{eH} = (H^\dagger H)(\bar{l} e H)$$

$$Q_{uH} = (H^\dagger H)(\bar{q} u \tilde{H})$$

$$Q_{dH} = (H^\dagger H)(\bar{q} d H)$$

$$\longrightarrow$$

$$\mathscr{M}_\psi \to \frac{v Y_\psi}{\sqrt{2}} - \frac{C_{\psi H} v^3}{2\sqrt{2}\Lambda^2}, \qquad \psi = \{u, d, e\}.$$



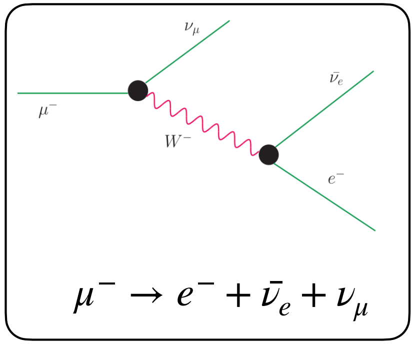
ϕ', A' are redefined scalar and gauge fields

✤ Modifications in low energy observables due to dim-6 effective operators.

Effect on Fermi Constant

SMEFT

$$(G_F)_{SM} = \frac{g_2^2}{4\sqrt{2}M_W^2} = \frac{1}{\sqrt{2}v^2}.$$



Modified vertex factor

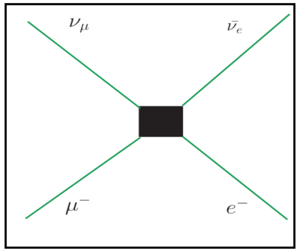
$\psi^2\phi^2 D$

$$\frac{g_2}{\sqrt{2}}\epsilon_{(e\nu)_L} = \frac{g_2}{\sqrt{2}}\left(1 + \frac{C_{Hl}^{(3)}v^2}{\Lambda^2}\right).$$

$Q_{Hl}^{[3]} = i(H^\dagger \overleftrightarrow{D}_\mu^I H)(\bar{l}\sigma^I\gamma^\mu l)$

Four point interactions

ψ^4



$Q_{ll} = (\bar{l}\gamma^\mu l)(\bar{l}\gamma^\mu l)$

$$\mathscr{G}_F = (G_F)_{SM}\left[1 + \frac{1}{\Lambda^2}\left(2C_{Hl}^{(3)}v^2 - C_{LL}v^2\right)\right].$$

Alonso, Jenkins, Manohar & Trott (JHEP04(2014)159)

New Physics in Weak mixing angle

Low energy neutrino nucleon scatterings experiments define

$$\widehat{R} = \frac{\sigma^{\nu NC} - \sigma^{\bar{\nu} NC}}{\sigma^{\nu CC} - \sigma^{\bar{\nu} CC}} = \frac{1}{2} - \sin^2\theta_w\,.$$

$$\mathscr{L}_{\nu q}^{CC} = \frac{g_2^2}{2M_W^2}\overline{e_L}\gamma^\mu\nu_L\left(\overline{u_L}\gamma^\mu d_L\right) + h.c.,$$

$$\mathscr{L}_{\nu q}^{NC} = \frac{g_2^2}{\cos^2\theta_w M_Z^2}\overline{\nu_L}\gamma^\mu\nu_L\left(\overline{u_L}\gamma^\mu u_L + \overline{u_R}\gamma^\mu u_R + \overline{d_L}\gamma^\mu d_L + \overline{d_R}\gamma^\mu d_R\right).$$

Due to inclusion of dim- 6 operators, the couplings of gauge bosons to fermions are redefined.

Buchmuller & Wyler Nucl.Phys.B 268 (1986) 621-653

$$\psi^2\phi^2 D + \mathscr{L}_{\psi}^{kin}$$

$$Q_{H\psi}^{[1]} = i(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{\psi}\gamma^\mu\psi)$$

$$Q_{H\psi}^{[3]} = i(H^\dagger \overleftrightarrow{D}^I_\mu H)(\bar{\psi}\sigma^I\gamma^\mu\psi)$$

$$\overline{\psi}\gamma_\mu\psi A^\mu$$

Example in case of SMEFT

$$\overline{u_L}\gamma_\mu d_L\,(W^\mu)^+ \rightarrow \frac{g_2}{\sqrt{2}}\left(1+\frac{C_{Hq}^{(3)}v^2}{\Lambda^2}\right),$$

$$\overline{\nu_L}\gamma^\mu e_L\,(W^\mu)^+ \rightarrow \frac{g_2}{\sqrt{2}}\left(1+\frac{C_{Hl}^{(3)}v^2}{\Lambda^2}\right),$$

$$\overline{\nu_L}\gamma_\mu\nu_L Z^\mu \rightarrow \frac{g_2}{2\cos\theta_w}\left[1+\left(\frac{\cos\theta_w}{g_2\Lambda^2}\left(-\frac{g_1^2C_{Hl}^{(1)}v^2}{2\sqrt{g_1^2+g_2^2}}-\frac{g_2^2C_{Hl}^{(1)}v^2}{2\sqrt{g_1^2+g_2^2}}+\frac{g_1^2C_{Hl}^{(3)}v^2}{2\sqrt{g_1^2+g_2^2}}+\frac{g_2^2C_{Hl}^{(3)}v^2}{2\sqrt{g_1^2+g_2^2}}\right)\right)\right].$$

$$(\overline{\psi}\gamma_\mu \psi A_\mu)_{NP} + \psi^4$$

Scattering matrix element gets redefined

$$\mathscr{L}_{\nu q}^{NC} = \frac{g_2^2}{\cos^2\theta_w \mathscr{M}_Z^2}\overline{\nu_L}\gamma^\mu \nu_L\left(\zeta_{\nu^* u_L}\overline{u_L}\gamma^\mu u_L + \zeta_{\nu^* u_R}\overline{u_R}\gamma^\mu u_R + \zeta_{\nu^* d_L}\overline{d_L}\gamma^\mu d_L + \zeta_{\nu^* d_R}\overline{d_R}\gamma^\mu d_R\right),$$

$$\mathscr{L}_{\nu q}^{CC} = \frac{g_2^2}{2\mathscr{M}_W^2}\overline{e_L}\gamma^\mu \nu_L\left(\epsilon_{\nu^*(ud)_L}\overline{u_L}\gamma^\mu d_L + (\epsilon_{\nu^*(ud)_R}\overline{u_R}\gamma^\mu d_R\right) + h.c.,$$

For SMEFT

$$\epsilon_{\nu^*(ud)_L} = -\left(1 + \frac{C_{Hl}^{(3)}v^2}{\Lambda^2}\right)\left(1 + \frac{C_{Hq}^{(3)}v^2}{\Lambda^2}\right) + \frac{4\mathscr{M}_W^2 C_{LQ}^3}{g_2^2\Lambda^2}.$$

$$\widehat{R} = \frac{\sigma^{\nu NC} - \sigma^{\bar{\nu}NC}}{\sigma^{\nu CC} - \sigma^{\bar{\nu}CC}} = \frac{1}{2} - \sin^2\bar{\theta}_w.$$

$$Q_{LQ}^{(3)} = (\bar{l}\gamma_\mu \sigma^I l)(\overline{q}\gamma^\mu \sigma^I q)$$

modified weak mixing angle can be calculated.

Overview of the modifications

$$O_{NP} = O_{SM} + \sum_i \frac{\mathscr{A}_i}{\Lambda^2} C_i .$$

EWPO

Using input parameter scheme $\{\alpha, G_F, M_Z\}$, tree level contributions are calculated.

$$\delta G_F = \frac{G_F}{\Lambda^2}\left(2v^2 C^3_{Hl} - v^2 C_{ll}\right),$$

$$\delta\alpha = \frac{2\,\alpha\, g_2 g_1 v^2}{(g_2^2 + g_1^2)}\frac{C_{HWB}}{\Lambda^2},$$

$$\delta m_Z^2 = \frac{1}{2\sqrt{2}}\frac{m_Z^2}{G_F}\frac{C_{HD}}{\Lambda^2} + \frac{2^{1/4}\sqrt{\pi\alpha}m_Z}{G_F^{3/2}}\frac{C_{HWB}}{\Lambda^2}.$$

$+$ $\phi^2\psi^2 D$

Assumed flavor independence

Higgs signal strength

Tree level contributions to the decay width and production cross-sections from Murphy (Phys.Rev.D 97 (2018)). These results were given in SILH basis, using basis translation, these were converted to Warsaw basis.

Relevant SMEFT dimension-6 operators

EWPO

$C_{Hl}^{(1)}$ $C_{Hl}^{(3)}$ C_{HWB}

$C_{Hq}^{(1)}$ $C_{Hq}^{(3)}$ C_{HD}

C_{He} C_{Hd} C_{Hu}

C_{H} $C_{H\Box}$ C_{ll}

Higgs

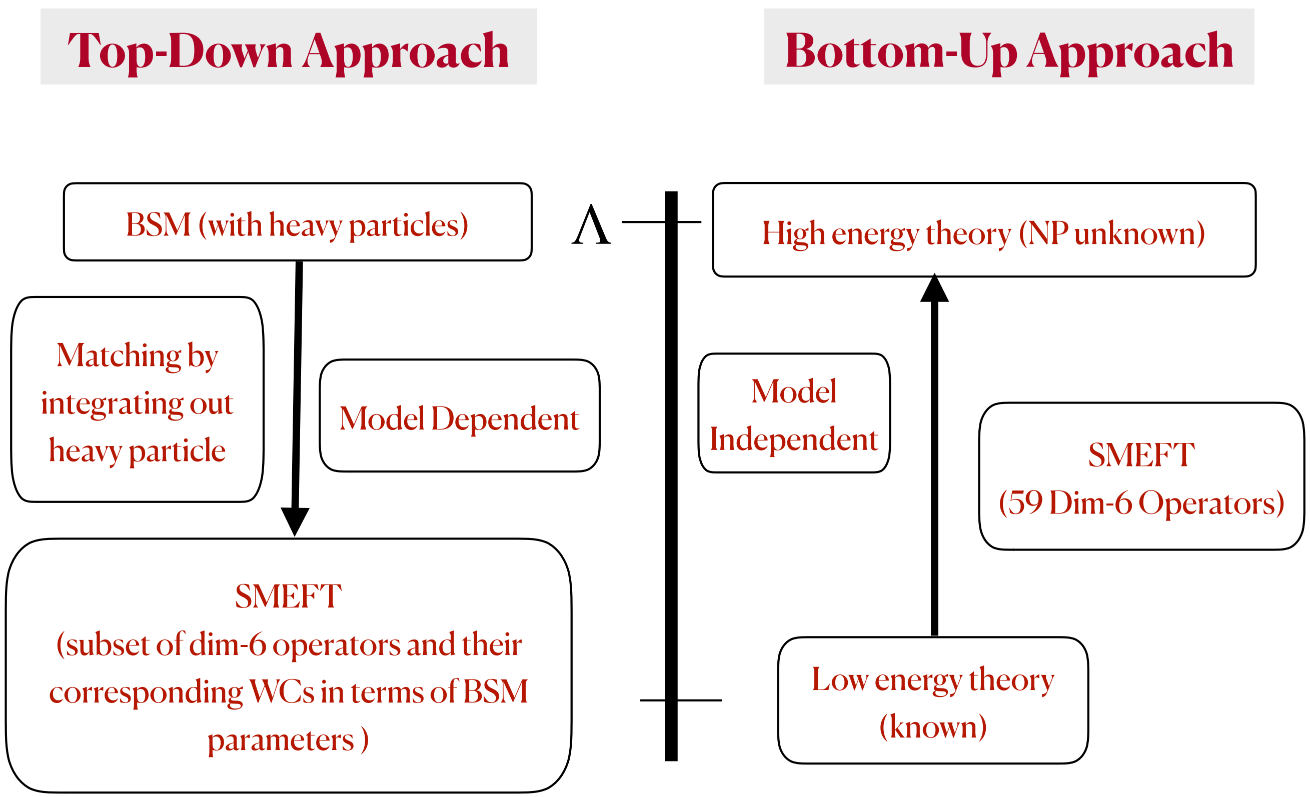
C_{HW} C_{eH}

C_{HG} C_{uH}

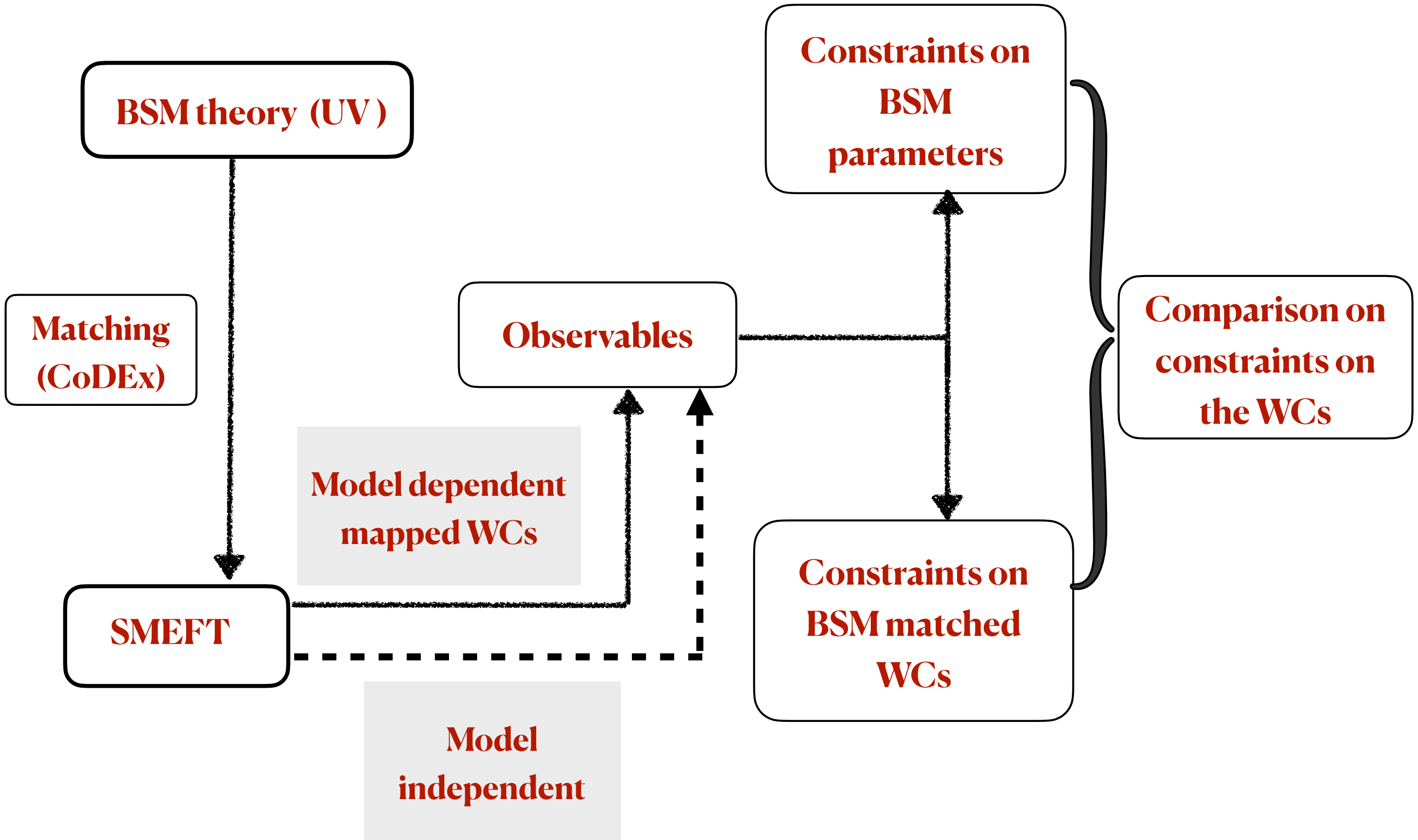
C_{HB} C_{dH}

Third generation couplings

Q_H	$(H^\dagger H)^3$	Q_{HG}	$(H^\dagger H)\, G_{\mu\nu}{}^a G^{a,\mu\nu}$	Q_{He}	$\left(H^\dagger i \overleftrightarrow{\mathcal{D}}_\mu H\right)(\bar{e}\gamma^\mu e)$
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	$Q_{Hl}^{(1)}$	$\left(H^\dagger i \overleftrightarrow{\mathcal{D}}_\mu H\right)(\bar{l}\gamma^\mu l)$	Q_{Hu}	$\left(H^\dagger i \overleftrightarrow{\mathcal{D}}_\mu H\right)(\bar{u}\gamma^\mu u)$
Q_{HD}	$(H^\dagger \mathcal{D}_\mu H)^*(H^\dagger \mathcal{D}^\mu H)$	$Q_{Hl}^{(3)}$	$\left(H^\dagger i\tau^I \overleftrightarrow{\mathcal{D}}_\mu H\right)(\bar{l}\tau^I\gamma^\mu l)$	Q_{Hd}	$\left(H^\dagger i \overleftrightarrow{\mathcal{D}}_\mu H\right)(\bar{d}\gamma^\mu d)$
Q_{HB}	$(H^\dagger H)\, B_{\mu\nu}B^{\mu\nu}$	$Q_{Hq}^{(1)}$	$\left(H^\dagger i \overleftrightarrow{\mathcal{D}}_\mu H\right)(\bar{q}\gamma^\mu q)$	Q_{eH}	$(H^\dagger H)(\bar{l}\ e\ H)$+h.c.
Q_{HW}	$(H^\dagger H)\, W_{\mu\nu}{}^I W^{I,\mu\nu}$	$Q_{Hq}^{(3)}$	$\left(H^\dagger i\tau^I \overleftrightarrow{\mathcal{D}}_\mu H\right)(\bar{q}\tau^I\gamma^\mu q)$	Q_{uH}	$(H^\dagger H)(\bar{q}\ u\ \tilde{H})$+h.c.
Q_{HWB}	$(H^\dagger \tau^I H)\, W_{\mu\nu}{}^I B^{\mu\nu}$	Q_{ll}	$(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l)$	Q_{dH}	$(H^\dagger H)(\bar{q}\ d\ H)$+h.c.


Top-Down Approach
Bottom-Up Approach
BSM (with heavy particles)
Λ
High energy theory (NP unknown)
Matching by integrating out heavy particle
Model Dependent
Model Independent
SMEFT (59 Dim-6 Operators)
SMEFT (subset of dim-6 operators and their corresponding WCs in terms of BSM parameters)
Low energy theory (known)

✤ Connecting Bottom-up approach with Top-down approach

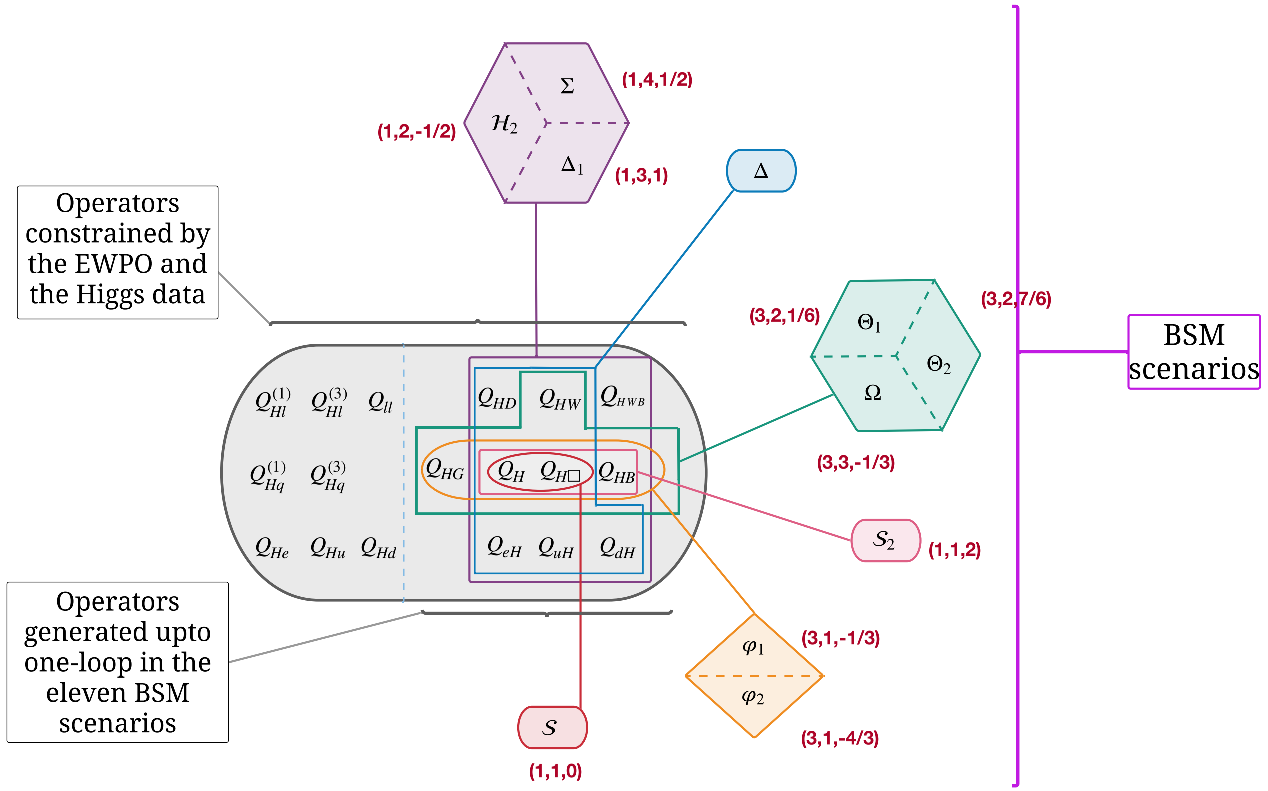


11 BSM scenarios

Heavy BSM fields	The SM Gauge quantum nos. (Color, Isospin, Hypercharge)	Q_H	$Q_{H\Box}$	Q_{HD}	Q_{HB}	Q_{HW}	Q_{HWB}	Q_{HG}	Q_{eH}	Q_{uH}	Q_{dH}
$\mathcal{S}$	(1,1,0)	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗
$\mathcal{S}_2$	(1,1,2)	✓	✓	✗	✓	✗	✗	✗	✗	✗	✗
Δ	(1,3,0)	✓	✓	✓	✗	✓	✗	✗	✓	✓	✓
$\mathcal{H}_2$	$(1,2,-\frac{1}{2})$	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓
Δ_1	(1,3,1)	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓
Σ	$(1,4,\frac{1}{2})$	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓
φ_1	$(3,1,-\frac{1}{3})$	✓	✓	✗	✓	✗	✗	✓	✗	✗	✗
φ_2	$(3,1,-\frac{4}{3})$	✓	✓	✗	✓	✗	✗	✓	✗	✗	✗
Θ_1	$(3,2,\frac{1}{6})$	✓	✓	✗	✓	✓	✗	✓	✗	✗	✗
Θ_2	$(3,2,\frac{7}{6})$	✓	✓	✗	✓	✓	✗	✓	✗	✗	✗
Ω	$(3,3,-\frac{1}{3})$	✓	✓	✗	✓	✓	✗	✓	✗	✗	✗

CoDEx- Bakshi, Chakrabortty, Patra EPJC 79 (2019) 1, 21

Out of 59 SMEFT operators, 18 operators contribute to EWPO & Higgs signal strength.



Model dependent analysis - Real singlet scalar

$$\mathscr{L}_S \supset \frac{1}{2} D_\mu S D^\mu S - \frac{1}{2} m_S^2 S^2 - c_{S,a} |H|^2 S - \frac{\kappa_S}{2} |H|^2 S^2 - \frac{\mu_S}{3!} S^3 - \frac{\lambda_S}{4!} S^4 .$$

CoDEx Results

Bakshi, Chakrabortty, Patra
EPJC 79 (2019) 1, 21

Effective operator	Wilson coefficient (SM + $\mathcal{S}$)
Q_H	$-\frac{c_{\mathcal{S},a}^2 \kappa_S \lambda_S}{32\pi^2 m_S^4} + \frac{c_{\mathcal{S},a}^2 \kappa_S \mu_S^2}{32\pi^2 m_S^6} - \frac{c_{\mathcal{S},a} \kappa_S^2 \mu_S}{64\pi^2 m_S^4} + \frac{c_{\mathcal{S},a}^3 \lambda_S \mu_S}{48\pi^2 m_S^6} - \frac{c_{\mathcal{S},a}^3 \mu_S^3}{96\pi^2 m_S^8} + \frac{c_{\mathcal{S},a}^3 \mu_S}{6 m_S^6} - \frac{c_{\mathcal{S},a}^2 \kappa_S}{2 m_S^4} - \frac{\kappa_S^3}{192\pi^2 m_S^2}$
$Q_{H\Box}$	$-\frac{5 c_{\mathcal{S},a} \kappa_S \mu_S}{192\pi^2 m_S^4} - \frac{c_{\mathcal{S},a}^2 \lambda_S}{32\pi^2 m_S^4} + \frac{11 c_{\mathcal{S},a}^2 \mu_S^2}{384\pi^2 m_S^6} - \frac{c_{\mathcal{S},a}^2}{2 m_S^4} - \frac{\kappa_S^2}{384\pi^2 m_S^2}$

Constraints on the model parameters

Uniform priors

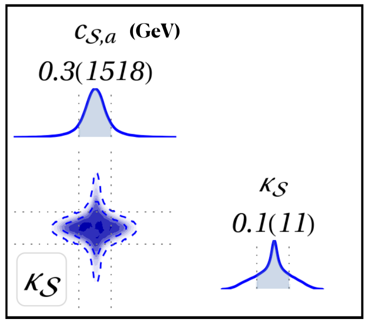
$c_{S,a}$ $\{-1,1\}$ TeV

κ_S $\{-4\pi,4\pi\}$

Insensitive parameters:

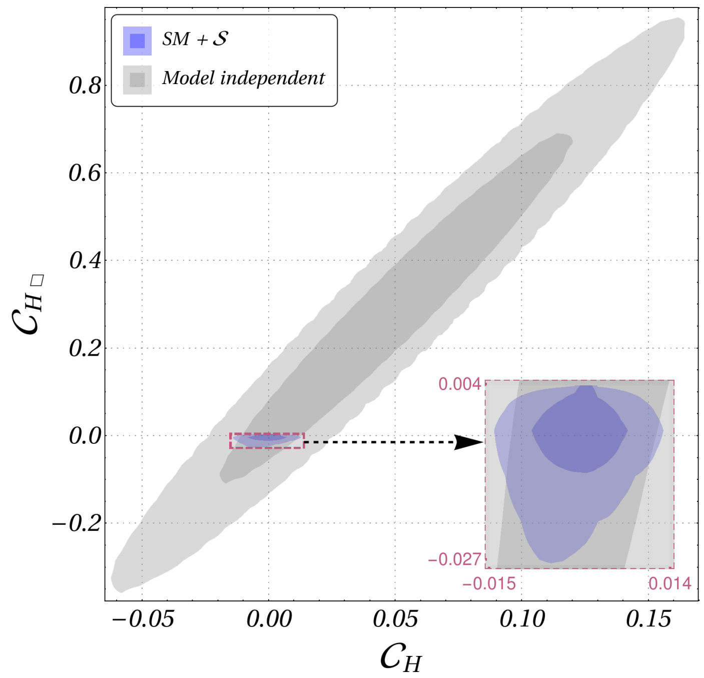
μ_S $\{-1,1\}$ TeV

λ_S $\{-4\pi,4\pi\}$

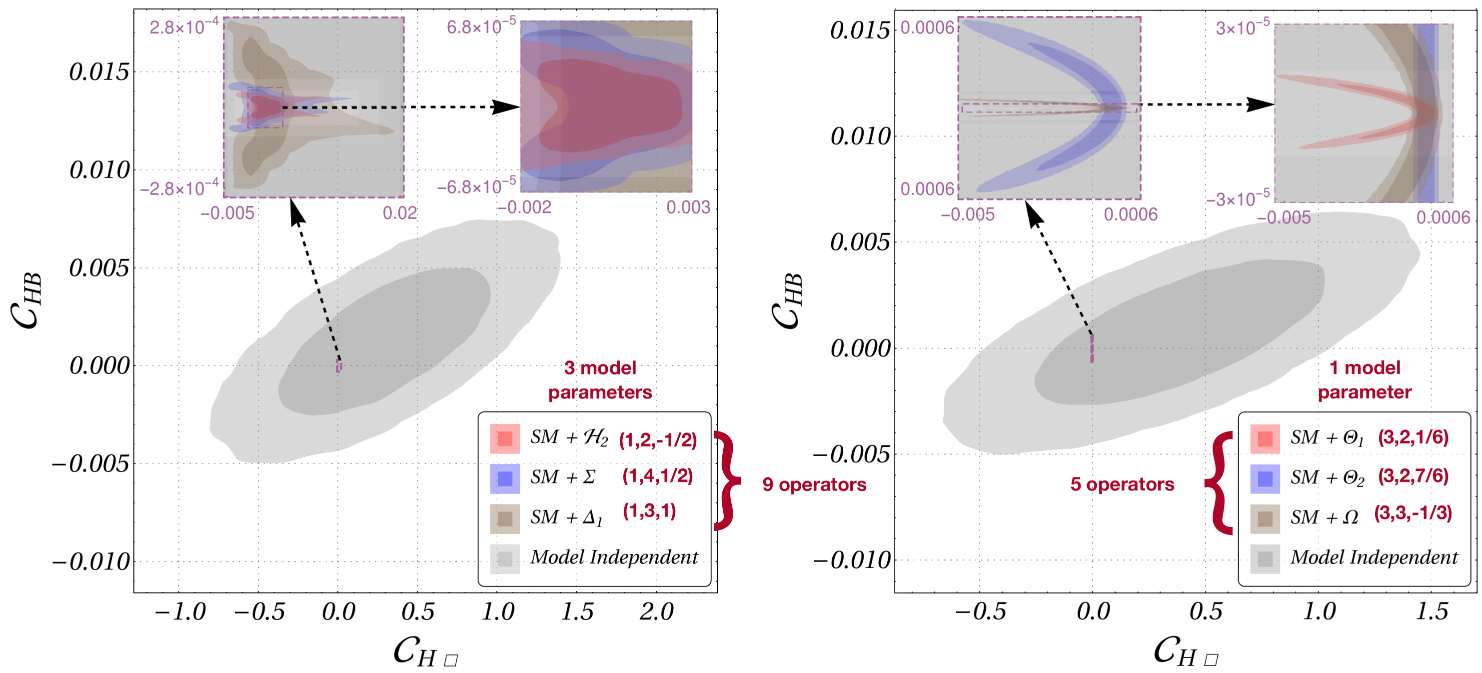


WC space : SMEFT vs BSM

Using the samples of points generated for $c_{s,a}$ and κ_S, the distributions for the C_H and $C_{H\Box}$ are obtained. These correspond to the bounds from the model information.



Comparison of the WC space for two classes



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

Theoretical constraints

Δ_1 (1,3,1)

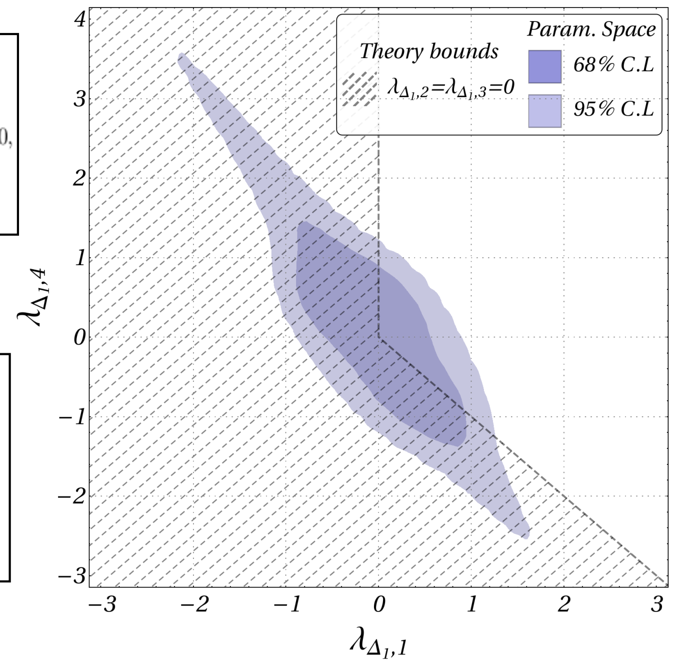
$$\mathscr{L}_{\Delta_1} \supset Tr[(D_\mu\Delta_1)^\dagger(D^\mu\Delta_1)] - m^2_{\Delta_1}\, Tr[\Delta_1^\dagger\Delta_1] - \left\{\mu_{\Delta_1}(H^T i\sigma_2\Delta_1^\dagger H) + h.c.\right\}$$
$$-\lambda_{\Delta_1,1}(H^\dagger H)\, Tr(\Delta_1^\dagger\Delta_1) - \lambda_{\Delta_1,2}\left[Tr(\Delta_1^\dagger\Delta_1)\right]^2 - \lambda_{\Delta_1,3}\, Tr\left[(\Delta_1^\dagger\Delta_1)^2\right] - \lambda_{\Delta_1,4}\, H^\dagger\Delta_1\Delta_1^\dagger H.$$

Vacuum stability bounds

$$\lambda_{\Delta_1,2}+\lambda_{\Delta_1,3}\geq 0,\quad \lambda_{\Delta_1,2}+\frac{\lambda_{\Delta_1,3}}{2}\geq 0,\quad \lambda_{\Delta_1,1}+\sqrt{4\lambda_H(\lambda_{\Delta_1,2}+\lambda_{\Delta_1,3})}\geq 0,$$
$$\lambda_{\Delta_1,1}+\sqrt{4\lambda_H(\lambda_{\Delta_1,2}+\frac{\lambda_{\Delta_1,3}}{2})}\geq 0,\quad \lambda_{\Delta_1,1}+\lambda_{\Delta_1,4}+\sqrt{4\lambda_H(\lambda_{\Delta_1,2}+\lambda_{\Delta_1,3})}\geq 0,$$
$$\lambda_{\Delta_1,1}+\lambda_{\Delta_1,4}+\sqrt{4\lambda_H(\lambda_{\Delta_1,2}+\frac{\lambda_{\Delta_1,3}}{2})}\geq 0.$$

Unitarity bounds

$$\lambda_{\Delta_1,2}+2\lambda_{\Delta_1,3}\leq 4\pi,\quad 4\lambda_{\Delta_1,2}+3\lambda_{\Delta_1,3}\leq 4\pi,\quad 2\lambda_{\Delta_1,2}-\lambda_{\Delta_1,3}\leq 8\pi,$$
$$|\lambda_{\Delta_1,1}+\lambda_{\Delta_1,4}|\leq 8\pi,\quad |\lambda_{\Delta_1,1}|\leq 8\pi,\quad |2\lambda_{\Delta_1,1}+3\lambda_{\Delta_1,4}|\leq 16\pi,$$
$$|2\lambda_{\Delta_1,1}-\lambda_{\Delta_1,4}|\leq 8\pi,\quad |\lambda_{\Delta_1,4}|\leq \min\sqrt{(4\lambda_H\pm 16\pi)(\lambda_{\Delta_1,2}+2\lambda_{\Delta_1,3}\pm 4\pi)},$$
$$|2\lambda_{\Delta_1,1}+\lambda_{\Delta_1,4}|\leq\sqrt{2(4\lambda_H-\frac{16}{3}\pi)(4\lambda_{\Delta_1,2}+3\lambda_{\Delta_1,3}-4\pi)}.$$



Arhrib et al PRD 84 (2011) 095005

A few queries:

Is D6 sufficient?

What are beyond D6?

How to compute beyond D6?

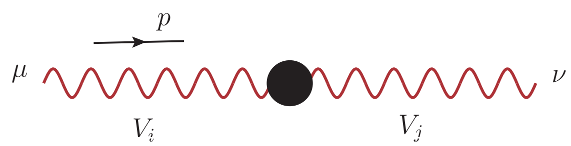
Decoupling!

EFT vs Full Theory!

EFT Truncation!

Effect on Oblique parameters

Parameters representing oblique corrections to propagators of gauge bosons.



$$i\Pi^{\mu\nu}_{V_iV_j}(p^2) = i\left(g^{\mu\nu} - \frac{p^\mu p^\nu}{p^2}\right)\Pi_{V_iV_j}(p^2) + \left(i\frac{p^\mu p^\nu}{p^2}\ term\right),$$

$$V_iV_j = \{WW, ZZ, \gamma\gamma, \gamma Z\} or \{W_1W_1,\ W_2W_2,\ W_3W_3,\ W_3B, BB\}\ .$$

$$\Pi_{V_iV_j}(p^2) = [\Pi_0 + \Pi_2 p^2 + \Pi_4 p^4 + O(p^6)]_{V_iV_j}\ .$$

$$S = -\frac{4\cos\theta_w \sin\theta_w}{\alpha}\Pi'_{3B}(0),$$

$$T = \frac{1}{\alpha m_W^2}\left(\Pi_{WW}(0) - \Pi_{33}(0)\right),$$

$$U = \frac{4\sin^2\theta_w}{\alpha}\left(\Pi'_{WW}(0) - \Pi'_{33}(0)\right).$$

Peskin & Takeuchi (PhysRevLett.65.964)

SMEFT

$$\mathscr{L}_A^{kin}\left(A'_\mu\right) + \mathscr{L}_\phi^{kin}\left(\phi', A'_\mu\right) + \phi^4 D^2 + \phi^2 X^2$$

↓ expanding in gauge fields

$$\mathscr{L}_{W_1W_1} = \frac{1}{2} W_{1\mu}\left(-\partial^2 g^{\mu\nu} + \partial^\mu \partial^\nu\right) W_{1\nu}\left(1 + \frac{2v^2 C_{HW}}{\Lambda^2}\right) + (\frac{1}{2} W_{1\mu} W_1^\mu)\left[\frac{1}{4} g_2^2 v_1^2 + 2 v_1^4 C_{HW}\right].$$

↓

$$i\Pi^{\mu\nu}_{V_iV_j}(p^2) = i\left(g^{\mu\nu} - \frac{p^\mu p^\nu}{p^2}\right)\Pi_{V_iV_j}(p^2), \qquad \Pi_{V_iV_j}(p^2) = A_2 p^2 + A_0\,.$$

$$\Pi_{W_1W_1}(p^2) = p^2\left(1 + \frac{2C_{HW}v^2}{\Lambda^2}\right) + \frac{1}{4} g_2^2 v^2 + \frac{g_2^2 C_{HW} v^4}{2\Lambda^2}\,.$$

↓ oblique parameters

$$S = \frac{4C_{HWB} v^2 \sin\theta_w \cos\theta_w}{\alpha\Lambda^2},$$

$$T = -\frac{g_2 v^2}{8\alpha\Lambda^2 m_W^2}\left(2g_1 C_{HWB} v^2 + g_2 C_{HD} v^2\right),$$

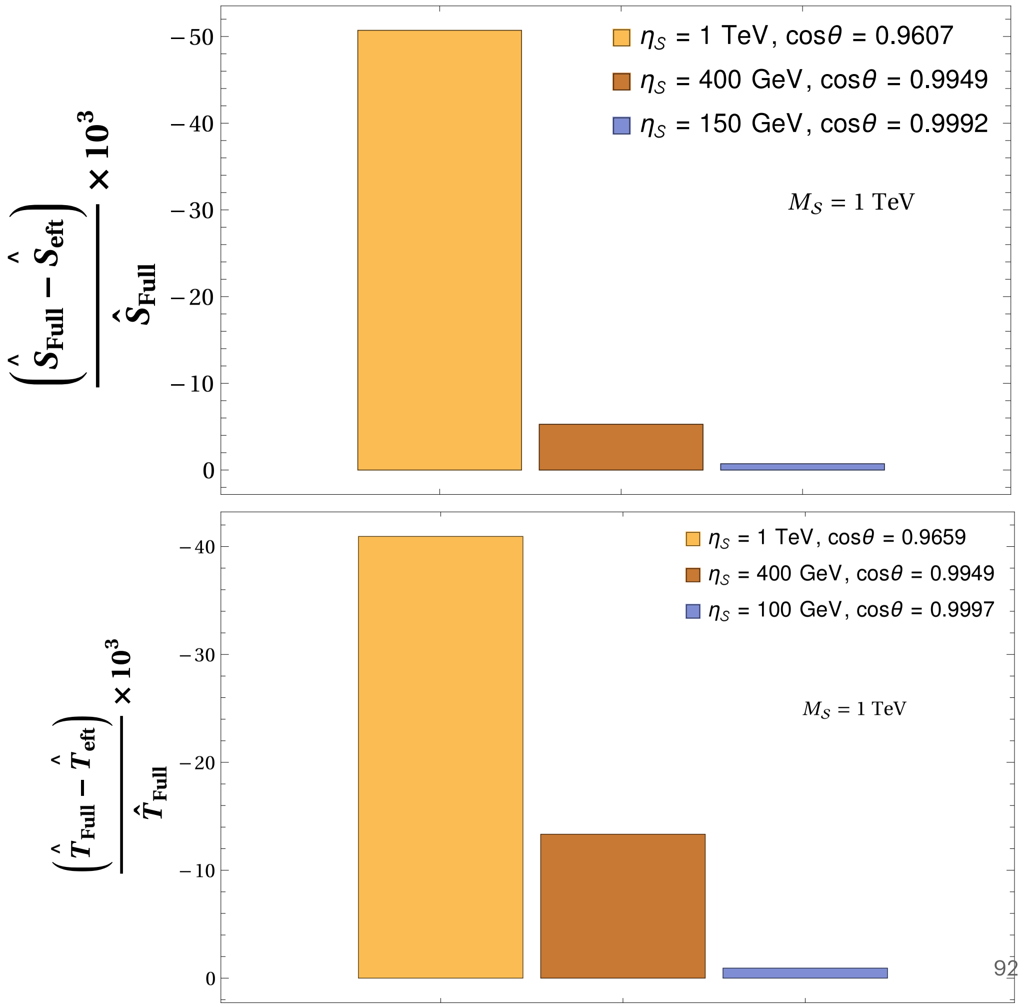
$$U = 0.$$

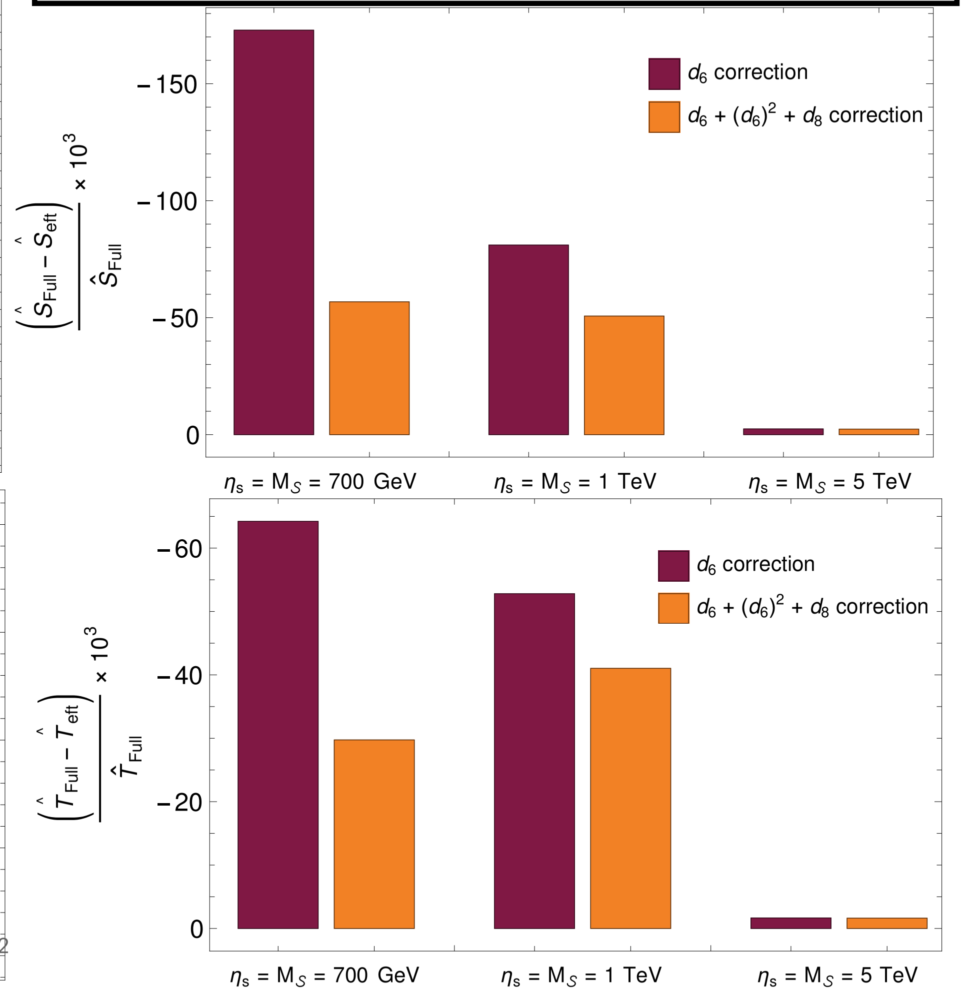
Henning et.al. JHEP 01 (2016)023

A Sample Toy Example: SM + Real Singlet scalar

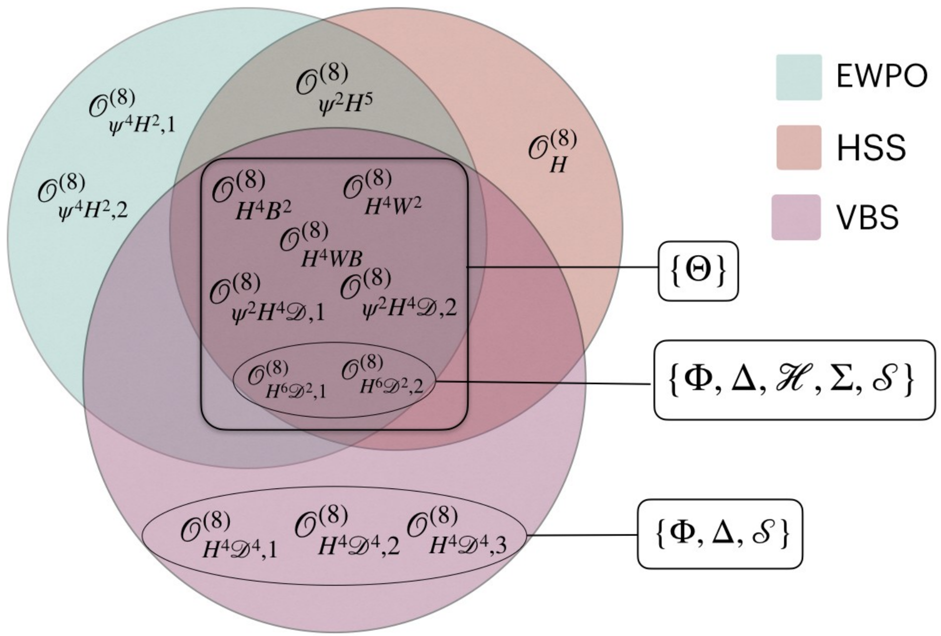
EFT, Decoupling, Higgs Mixing and All That Jazz; **arXiv:2303.05224**

Upalaparna Banerjee, JC, Christoph Englert, Wrishik Naskar, Shakeel Ur Rahaman, Michael Spannowsky





Impact of D8 on observables



❖ Take home messages

Effective Field Theory connects physics of different scales

It’s a very effective tool specially when new physics is unknown

Top-Down and Bottom-Up are two complementary aspects of EFT

Different UV theories can be brought into same footing “SMEFT”
— platform for a comparative analysis

EWPO and Higgs Observables play crucial role to estimate the room left for new physics

CP Violation may be the game changer: Scalar vs Fermion

Precision calculation: Higher loops and RGs will be in high demand