Neutrino masses in the Standard Model effective field theory

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Outline

- Motivation
- One-loop renormalisation of the operators contributing to the neutrino mass matrix at $d \leq 7$
- Leading-log correction to the neutrino mass matrix
- Some implications

Motivation

Tiny neutrino masses suggest that the new physics scale

$$\Lambda \gg \mathrm{v} \approx 246 \text{ GeV}$$

This justifies using the Standard Model effective field theory (SMEFT) to describe physics at low energies

At $d \leq 7$, the only operators contributing to the neutrino mass matrix M_ν at tree level are

$$\mathcal{O}^{(5)}_{LH} = \epsilon_{ij}\epsilon_{mn}\left(L^i C L^m\right) H^j H^n$$

Weinberg, PRL **43** (1979) 1566

$$\mathcal{O}^{(7)}_{LH} = \epsilon_{ij}\epsilon_{mn}\left(L^i C L^m\right) H^j H^n \left(H^\dagger H\right)$$

$$M_\nu^{\mathtt{tree}} = -\frac{\mathrm{v}^2}{\Lambda}\left(\alpha^{(5)}_{LH} + \alpha^{(7)}_{LH}\frac{\mathrm{v}^2}{2\Lambda^2}\right)$$

Motivation

At one loop, M_ν gets corrections due to

- dim-4 SM interactions (gauge couplings, λ_H, Yukawas)
- dim-6 interactions
- dim-7 interactions

$$M_\nu = M_\nu^{\texttt{tree}} + \delta M_\nu$$

Aim: compute δM_ν in the leading-log (LL) approximation to order v^3/Λ^3

- Important if *e.g.* $\alpha_{LH}^{(7)}\mathrm{v}^2/\Lambda^2$ partially cancels $\alpha_{LH}^{(5)}$ in $M_\nu^{\texttt{tree}}$
- Potential new probe of dim-6 operators
- One step forward towards the one-loop renormalisation of the SMEFT to order v^3/Λ^3

Technical details

Approximations:

- vanishing down-type quark and charged lepton Yukawas
- up-type quark Yukawa matrix Y_u real and diagonal

EFT operator bases:

- $d = 6$, independent on shell   Grzadkowski, Iskrzynski, Misiak, Rosiek, 1008.4884
- $d = 6$, independent off shell   Gherardi, Marzocca, Venturini, 2003.12525
- $d = 7$, independent on shell   Lehman, 1410.4193;   Liao and Ma, 1607.07309
- $d = 7$, independent off shell   (can be inferred from Lehman, 1410.4193)

To fix the divergences of the relevant Wilson coefficients (WCs), we compute all necessary 1PI diagrams off shell with the help of `FeynRules` + `FeynArts` + `Formcalc`

Operators potentially affecting δM_ν

$d = 6$

$\mathcal{O}_H$	$(H^\dagger H)^3$
$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
$\mathcal{O}_{HD}$	$(H^\dagger D^\mu H)^*(H^\dagger D_\mu H)$
$\mathcal{O}_{HB}$	$(H^\dagger H)B_{\mu\nu}B^{\mu\nu}$
$\mathcal{O}_{HW}$	$(H^\dagger H)W^I_{\mu\nu}W^{I\mu\nu}$,
$\mathcal{O}_{HWB}$	$(H^\dagger\sigma^I H)W^I_{\mu\nu}B^{\mu\nu}$
$\mathcal{O}_{3W}$	$\epsilon^{IJK}W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$
$\mathcal{O}_{H\tilde{B}}$	$(H^\dagger H)\widetilde{B}_{\mu\nu}B^{\mu\nu}$,
$\mathcal{O}_{H\widetilde{W}}$	$(H^\dagger H)\widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$
$\mathcal{O}_{H\widetilde{W}B}$	$(H^\dagger\sigma^I H)\widetilde{W}^I_{\mu\nu}B^{\mu\nu}$
$\mathcal{O}_{uH}$	$(\overline{Q}\tilde{H}u)(H^\dagger H)$
$\mathcal{O}^{(1)}_{HL}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\overline{L}\gamma^\mu L)$
$\mathcal{O}^{(3)}_{HL}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\overline{L}\gamma^\mu\sigma^I L)$
$\mathcal{O}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\overline{e}\gamma^\mu e)$
$\mathcal{O}^{(1)}_{HQ}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\overline{Q}\gamma^\mu Q)$
$\mathcal{O}^{(3)}_{HQ}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\overline{Q}\gamma^\mu\sigma^I Q)$
$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\overline{u}\gamma^\mu u)$
$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\overline{d}\gamma^\mu d)$
$\mathcal{O}_{LL}$	$(\overline{L}\gamma_\mu L)(\overline{L}\gamma^\mu L)$

11 dim-6 operators will contribute to δM_ν

(operators in grey won't contribute)

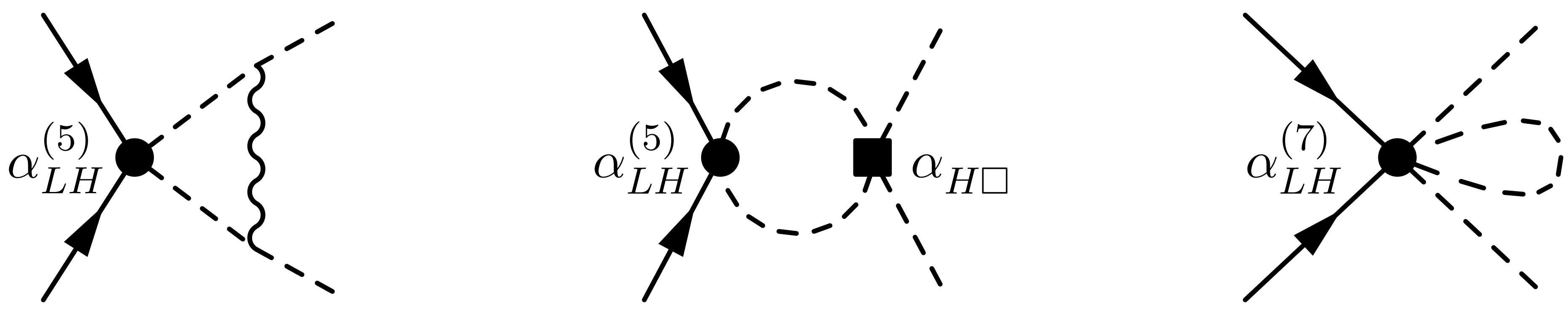
$d = 7$

$\mathcal{O}_{LHD1}$	$\epsilon_{ij}\epsilon_{mn}(L^iCD^\mu L^j)H^m(D_\mu H^n)$
$\mathcal{O}_{LHD2}$	$\epsilon_{im}\epsilon_{jn}(L^iCD^\mu L^j)H^m(D_\mu H^n)$
$\mathcal{O}_{LHW}$	$\epsilon_{ij}(\epsilon\sigma)_{mn}(L^iC\sigma_{\mu\nu}L^m)H^jH^nW^{I\mu\nu}$
$\mathcal{O}_{QuLLH}$	$\epsilon_{ij}(\overline{Q}u)(LCL^i)H^j$
$\mathcal{O}^{(7)}_{LH}$	$\epsilon_{ij}\epsilon_{mn}(L^iCL^m)H^jH^n(H^\dagger H)$

5 lepton number violating (LNV) dim-7 operators will contribute to δM_ν

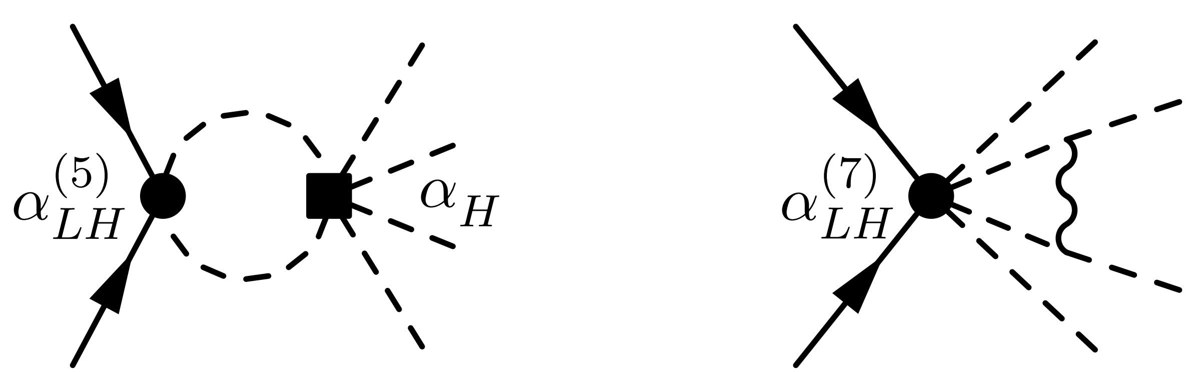
Direct renormalisation of the Weinberg operators

- Direct renormalisation of $\alpha_{LH}^{(5)}$



(a) (b) (c)

- Direct renormalisation of $\alpha_{LH}^{(7)}$



(d) (e)

Direct renormalisation of the Weinberg operators

Result of the direct renormalisation:

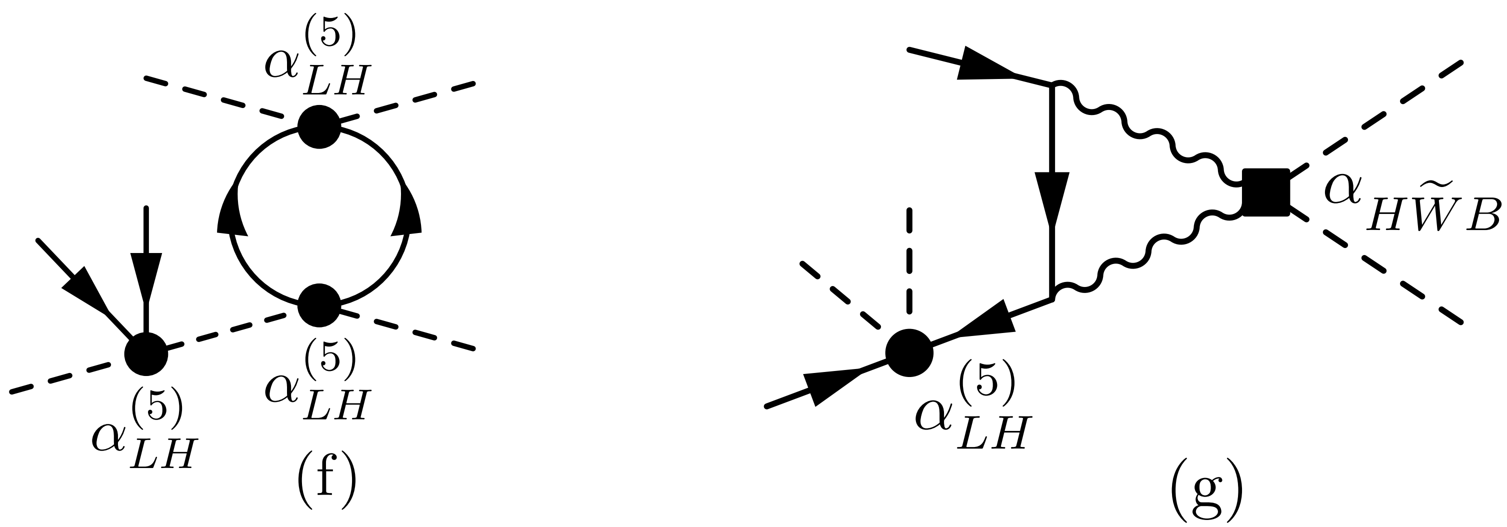
$$
\begin{aligned}
(\tilde{\alpha}_{LH}^{(5)})^{pq} = -\frac{1}{64\pi^2\epsilon}\bigg\{ & \left(g_1^2 - 3g_2^2 + 4\lambda_H\right)\left(\alpha_{LH}^{(5)}\right)^{pq} - 16\left(\alpha_{LH}^{(5)}\right)^{pq}\alpha_{H\Box}\frac{\mu_H^2}{\Lambda^2} \\
& - 8\left[\left(\alpha_{LH}^{(5)}\right)^{pr}\left(\alpha_{HL}^{(1)}\right)^{rq} - 2\left(\alpha_{LH}^{(5)}\right)^{pr}\left(\alpha_{HL}^{(3)}\right)^{rq} + p \leftrightarrow q\right]\frac{\mu_H^2}{\Lambda^2} - 16\left(\alpha_{LH}^{(7)}\right)^{pq}\frac{\mu_H^2}{\Lambda^2}\bigg\},
\end{aligned}
$$

$$
\begin{aligned}
(\tilde{\alpha}_{LH}^{(7)})^{pq} = \frac{1}{256\pi^2\epsilon}\bigg\{ & 16\left(\alpha_{LH}^{(5)}\right)^{pq}\left[6\alpha_H - 12\lambda_H\alpha_{H\Box} + 2\lambda_H\alpha_{HD} - 3g_1^2\alpha_{HB} - 3g_2^2\alpha_{HW} - 3g_1g_2\alpha_{HWB}\right] \\
& + 24\left(g_1^2 + g_2^2\right)\left[\left(\alpha_{LH}^{(5)}\right)^{pr}\left(\alpha_{HL}^{(1)}\right)^{rq} - \left(\alpha_{LH}^{(5)}\right)^{pr}\left(\alpha_{HL}^{(3)}\right)^{rq} + p \leftrightarrow q\right] \\
& - 32\lambda_H\left[\left(\alpha_{LH}^{(5)}\right)^{pr}\left(\alpha_{HL}^{(1)}\right)^{rq} - 2\left(\alpha_{LH}^{(5)}\right)^{pr}\left(\alpha_{HL}^{(3)}\right)^{rq} + p \leftrightarrow q\right] \\
& + 8\left(3g_2^2 - 20\lambda_H\right)\left(\alpha_{LH}^{(7)}\right)^{pq} + 6g_2^3\left[4\alpha_{LHW}^{pq} + g_2\alpha_{LHD1}^{pq} + p \leftrightarrow q\right] \\
& + 3\left(g_1^4 + 3g_2^4 + 2g_1^2g_2^2\right)\left[\alpha_{LHD2}^{pq} + p \leftrightarrow q\right] + 48Y_u^{rt}Y_u^{us}Y_u^{ut}\left[\alpha_{QuLLH}^{rspq} + p \leftrightarrow q\right]\bigg\},
\end{aligned}
$$

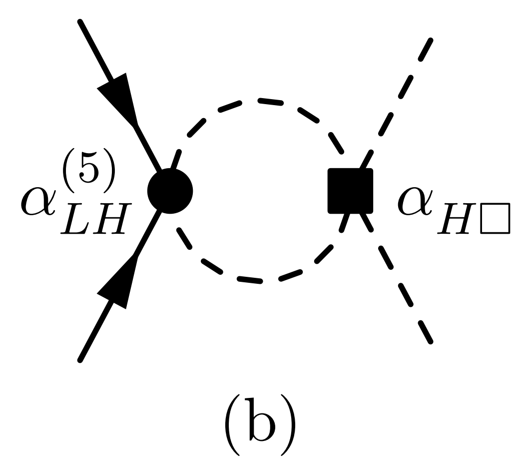
In the second equation, the terms proportional to dim-7 operators have been cross-checked against Liao and Ma, 1901.10302

Indirect renormalisation of the Weinberg operators

- Renormalisation of redundant dim-6 interactions that on shell contribute to the Weinberg operators



- Renormalisation of redundant dim-7 interactions that on shell contribute to the Weinberg operators



Relevant redundant operators

$d=6$	$\mathcal{O}_{2B}$	$-\frac{1}{2}(\partial_\mu B^{\mu\nu})(\partial^\rho B_{\rho\nu})$
	$\mathcal{O}_{2W}$	$-\frac{1}{2}(D_\mu W^{I\mu\nu})(D^\rho W^I_{\rho\nu})$
	$\mathcal{O}_{BDH}$	$\partial_\nu B^{\mu\nu}(H^\dagger i\overleftrightarrow{D}_\mu H)$
	$\mathcal{O}_{WDH}$	$D_\nu W^{I\mu\nu}(H^\dagger i\overleftrightarrow{D}^I_\mu H)$
	$\mathcal{O}_{DH}$	$(D_\mu D^\mu H)^\dagger(D_\nu D^\nu H)$
	$\mathcal{O}'_{HD}$	$(H^\dagger H)(D_\mu H)^\dagger(D^\mu H)$
	$\mathcal{O}''_{HD}$	$(H^\dagger H)D_\mu(H^\dagger i\overleftrightarrow{D}^\mu H)$
	$\mathcal{O}_{LD}$	$\frac{i}{2}\overline{L}\{D_\mu D^\mu, \not{D}\}L$
	$\mathcal{O}'^{(1)}_{HL}$	$(H^\dagger H)(\overline{L}i\overleftrightarrow{\not{D}}L)$
	$\mathcal{O}''^{(1)}_{HL}$	$\partial_\mu(H^\dagger H)(\overline{L}\gamma^\mu L)$
	$\mathcal{O}'^{(3)}_{HL}$	$(H^\dagger\sigma^I H)(\overline{L}i\overleftrightarrow{\not{D}}^I L)$
	$\mathcal{O}''^{(3)}_{HL}$	$D_\mu(H^\dagger\sigma^I H)(\overline{L}\gamma^\mu\sigma^I L)$
$d=7$	$\mathcal{O}^{(R)}_{LHD}$	$\epsilon_{ij}\epsilon_{mn}L^iCL^mH^j\Box H^n$

On-shell projections onto the Weinberg operators

Upon using the SMEFT equations of motion to $\mathcal{O}(1/\Lambda)$, in particular,

$$D^2 H^i = \mu_H^2 H^i - \lambda_H (H^\dagger H) H^i + Y_u^{pq} \epsilon^{ij} \overline{Q_p^j} u_q - \frac{\left(\alpha_{LH}^{(5)}\right)^*_{pq}}{\Lambda} \epsilon^{ij} \left[\overline{L_q^j} (\widetilde{H}^T L_p^c) + (\overline{L_q} \widetilde{H}) L_p^{c,j} \right],$$

$$i \not{D} L_q^i = -2 \frac{\left(\alpha_{LH}^{(5)}\right)^*_{pq}}{\Lambda} \widetilde{H}^i (\widetilde{H}^T L_p^c),$$

Barzinji, Trott, Vasudevan, 1806.06354

we get the following on-shell projections onto the Weinberg operators:

$$\mathcal{O}_{2W} \supset \frac{g_2^2}{2\Lambda} (\alpha_{LH}^{(5)})^{pq} (\mathcal{O}_{LH}^{(7)})^{pq} + \text{h.c.},$$

$$\mathcal{O}_{WDH} \supset -\frac{2 g_2}{\Lambda} (\alpha_{LH}^{(5)})^{pq} (\mathcal{O}_{LH}^{(7)})^{pq} + \text{h.c.},$$

$$\mathcal{O}'_{HD} \supset -\frac{1}{\Lambda} (\alpha_{LH}^{(5)})^{pq} (\mathcal{O}_{LH}^{(7)})^{pq} + \text{h.c.},$$

$$\mathcal{O}''_{HD} \supset -\frac{2i}{\Lambda} (\alpha_{LH}^{(5)})^{pq} (\mathcal{O}_{LH}^{(7)})^{pq} + \text{h.c.},$$

$$\delta^{pq} (\mathcal{O}''^{(1)}_{HL})^{pq} \supset \frac{2i}{\Lambda} (\alpha_{LH}^{(5)})^{rp} (\mathcal{O}_{LH}^{(7)})^{rp} + \text{h.c.},$$

$$\delta^{pq} (\mathcal{O}''^{(3)}_{HL})^{pq} \supset -\frac{2i}{\Lambda} (\alpha_{LH}^{(5)})^{rp} (\mathcal{O}_{LH}^{(7)})^{rp} + \text{h.c.}$$

$$(\mathcal{O}_{LHD}^{(R)})^{pq} \supset \mu_H^2 (\mathcal{O}_{LH}^{(5)})^{pq} - \lambda_H (\mathcal{O}_{LH}^{(7)})^{pq}$$

Renormalisation of the redundant operators

The divergencies of the redundant dim-6 operators:

$$\widetilde{\alpha}_{2W} = -\frac{3g_2}{4\pi^2\epsilon}\alpha_{3W}\,,$$

$$\widetilde{\alpha}_{WDH} = -\frac{g_2}{96\pi^2\epsilon}\left[\alpha_{H\Box} + 18g_2\alpha_{3W} + 4(\alpha_{HL}^{(3)})^{pp} + 12(\alpha_{HQ}^{(3)})^{pp}\right],$$

$$\widetilde{\alpha}'_{HD} = -\frac{1}{32\pi^2\epsilon}\Big[6\left(g_1^2\alpha_{HB} + g_1g_2\alpha_{HWB} + 3g_2^2\alpha_{HW}\right) + \left(3g_1^2 - 3g_2^2 + 2\lambda_H\right)\alpha_{HD} + \left(6g_2^2 - 4\lambda_H\right)\alpha_{H\Box}$$
$$+ 6Y_u^{pq}\left(\alpha_{uH}^{pq} + \alpha_{uH}^{pq*}\right) - 24Y_u^{pr}Y_u^{qr}(\alpha_{HQ}^{(3)})^{pq} - 8(\alpha_{LH}^{(5)})^{pq}(\alpha_{LH}^{(5)})^*_{pq}\Big],$$

$$\widetilde{\alpha}''_{HD} = -\frac{3i}{32\pi^2\epsilon}Y_u^{pq}\left(\alpha_{uH}^{pq} - \alpha_{uH}^{pq*}\right),$$

$$(\widetilde{\alpha}''^{(1)}_{HL})^{pq} = \frac{3}{32\pi^2\epsilon}\left(g_1^2\alpha_{H\widetilde{B}} + 3g_2^2\alpha_{H\widetilde{W}}\right)\delta^{pq}\,,$$

$$(\widetilde{\alpha}''^{(3)}_{HL})^{pq} = -\frac{3}{32\pi^2\epsilon}g_1g_2\alpha_{H\widetilde{W}B}\delta^{pq}\,.$$

The divergency of the redundant dim-7 operator:

$$(\widetilde{\alpha}^{(R)}_{LHD})^{pq} = \frac{1}{128\pi^2\epsilon}\Big\{16(\alpha_{LH}^{(5)})^{pq}\alpha_{H\Box} - 16\left[(\alpha_{LH}^{(5)})^{pr}(\alpha_{HL}^{(1)})^{rq} - 2(\alpha_{LH}^{(5)})^{pr}(\alpha_{HL}^{(3)})^{rq} + p\leftrightarrow q\right]$$
$$+ 3\left[2g_2^2\alpha_{LHD1}^{pq} + g_2^2\alpha_{LHD2}^{pq} + 4Y_u^{rs}\alpha_{QuLLH}^{rspq} + p\leftrightarrow q\right]\Big\},$$

Renormalisation group equation

Divergencies of the kinetic terms (wave function renormalisation):

$$K_H = -\frac{1}{32\pi^2\epsilon}\left[g_1^2 + 3g_2^2 - 6\,\mathrm{Tr}\left(Y_u^2\right) + 2\left(2\alpha_{H\Box} - \alpha_{HD}\right)\frac{\mu_H^2}{\Lambda^2}\right],$$
$$K_L = \frac{1}{64\pi^2\epsilon}\left(g_1^2 + 3g_2^2\right)\,.$$

Canonical normalisation of the kinetic terms:

$$H \to \left(1 - K_H/2\right)H \qquad \text{and} \qquad L \;\to \left(1 - K_L/2\right)L$$

Bare and renormalised quantities:

$$\left(\alpha_{LH}^{(5)}\right)^0 = \mu^{2\epsilon} Z_{LH}^{(5)} \alpha_{LH}^{(5)} \qquad \text{with} \qquad Z_{LH}^{(5)} = 1 - \widetilde{\alpha}_{LH}^{(5)}/\alpha_{LH}^{(5)}$$

RGE:

$$\mu\,\frac{\mathrm{d}\left(\alpha_{LH}^{(5)}\right)^0}{\mathrm{d}\mu} = 0 \qquad \Rightarrow \qquad \mu\,\frac{\mathrm{d}\alpha_{LH}^{(5)}}{\mathrm{d}\mu} = \epsilon\,\alpha_{LH}^{(5)}\,\frac{\partial Z_{LH}^{(5)}}{\partial g_k} n_k g_k$$

g_k are all Lagrangian couplings, renormalisable and not

n_k are tree-level anomalous dimensions of g_k

LL correction to neutrino mass matrix

Solving the RGEs to LL approximation, and upon EWSB, we obtain

$$
\begin{aligned}
\delta M_\nu^{pq} = -\frac{v^2}{16\pi^2\Lambda}\log\frac{\Lambda}{v}\Bigg\{ & \left[3g_2^2 - 2\lambda_H - 6\,\mathrm{Tr}\left(Y_u^2\right)\right]\left(\alpha_{LH}^{(5)}\right)^{pq} \\
& + \frac{v^2}{\Lambda^2}\left(\alpha_{LH}^{(5)}\right)^{pq}\Bigg[-4\left(\alpha_{LH}^{(5)}\right)^{st}\left(\alpha_{LH}^{(5)}\right)^*_{st} + 6\alpha_H + \frac{2}{3}\left(5g_2^2 - 12\lambda_H\right)\alpha_{H\Box} + \frac{1}{2}\left(3g_1^2 - 3g_2^2 + 4\lambda_H\right)\alpha_{HD} + 6g_2^2\alpha_{HW} \\
& + 3ig_1^2\alpha_{H\widetilde{B}} + 9ig_2^2\alpha_{H\widetilde{W}} + 3ig_1g_2\alpha_{H\widetilde{W}B} + 6Y_u^{st}\alpha_{uH}^{st*} + \frac{4}{3}g_2^2\left(\alpha_{HL}^{(3)}\right)^{rr} + 4g_2^2\left(\alpha_{HQ}^{(3)}\right)^{rr} - 12Y_u^{su}Y_u^{tu}\left(\alpha_{HQ}^{(3)}\right)^{st}\Bigg] \\
& + \frac{v^2}{\Lambda^2}\frac{3}{2}\left(g_1^2 + g_2^2\right)\left[\left(\alpha_{LH}^{(5)}\right)^{pr}\left(\alpha_{HL}^{(1)}\right)^{rq} - \left(\alpha_{LH}^{(5)}\right)^{pr}\left(\alpha_{HL}^{(3)}\right)^{rq} + p \leftrightarrow q\right] + \frac{v^2}{\Lambda^2}\frac{3}{4}\left[g_1^2 + 5g_2^2 - 8\lambda_H - 8\,\mathrm{Tr}\left(Y_u^2\right)\right]\left(\alpha_{LH}^{(7)}\right)^{pq} \\
& + \frac{v^2}{\Lambda^2}\left[\frac{3}{8}g_2^4\alpha_{LHD1}^{pq} + \frac{3}{16}\left(g_1^4 + 2g_1^2g_2^2 + 3g_2^4\right)\alpha_{LHD2}^{pq} + \frac{3}{2}g_2^3\alpha_{LHW}^{pq} + 3Y_u^{rt}Y_u^{us}Y_u^{ut}\alpha_{QuLLH}^{rspq} + p \leftrightarrow q\right]\Bigg\}
\end{aligned}
$$

1 dim-5, 11 dim-6 and 5 dim-7 operators contribute to δM_ν

The first line (renormalisation of $\alpha_{LH}^{(5)}$ by the SM interactions) agrees with the previous well-known result

Chankowski and Pluciennik, hep-ph/9306333
Babu, Leung, Pantaleone, hep-ph/9309223
Antusch et al., hep-ph/0108005

Implications

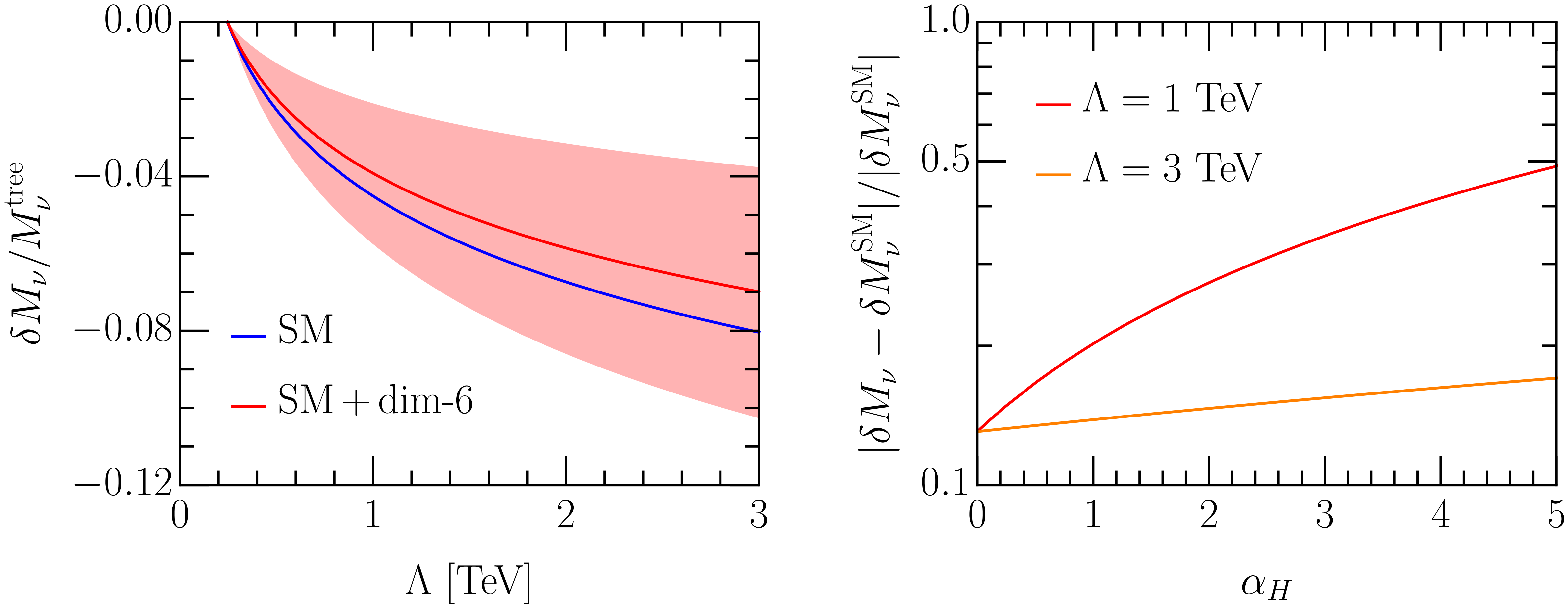
- $\alpha_{LH}^{(5)} = \alpha_{LH}^{(7)} = 0 \quad \Rightarrow \quad M_\nu^{\mathtt{tree}} = 0 \quad \Rightarrow$
  neutrino masses are induced by the dim-7 operators other than $\mathscr{O}_{LH}^{(7)}$ at $\Lambda \sim 10^3$ TeV (for order 1 WCs)

- $\alpha_{LH}^{(7)} \mathrm{v}^2/\Lambda^2$ partially cancels $\alpha_{LH}^{(5)}$ in $M_\nu^{\mathtt{tree}}$

- Certain combinations of the operators lead to $\delta M_\nu = 0$,
  e.g. $g_2^2 O_H - O_{HW}$ or $g_2 O_{LHW} - 4 O_{LHD1}$

- If the LNV and dim-6 operators are suppressed by different scales, $\Lambda_{\mathrm{LNV}} \gg \Lambda_{\mathrm{LNC}}$, then the $\mathrm{v}^3/(\Lambda_{\mathrm{LNV}}\Lambda_{\mathrm{LNC}}^2)$ provides the first correction to the renormalisation of the SMEFT obtained in
  Jenkins, Manohar, Trott, 1308.2627, 1310.4838 and Alonso, Jenkins, Manohar, Trott, 1312.2014

Impact of dim-6 operators



$\alpha_{LH}^{(5)}$ is such that $M_\nu^{\mathrm{tree}} = 0.01$ eV

$\delta M_\nu^{\mathrm{SM}}$: WCs of all dim-6 and dim-7 operators set to zero

δM_ν : WCs of dim-6 operators are fixed according to
the marginalised fit of Ellis et al., 2012.02779;
other dim-6 and dim-7 WCs are set to zero

Backup slides

SM Lagrangian and conventions

$$\begin{aligned}\mathcal{L}_{\rm ren} = &-\frac{1}{4}G^A_{\mu\nu}G^{A\mu\nu} - \frac{1}{4}W^I_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} \\ &+ (D_\mu H)^\dagger (D^\mu H) + \mu_H^2 H^\dagger H - \frac{1}{2}\lambda_H \left(H^\dagger H\right)^2 \\ &+ i\left(\overline{Q}\not{D}Q + \overline{u}\not{D}u + \overline{d}\not{D}d + \overline{L}\not{D}L + \overline{e}\not{D}e\right) \\ &- \left(\overline{Q}Y_d H d + \overline{Q}Y_u \tilde{H} u + \overline{L}Y_e H e + \text{h.c.}\right) . \qquad (3)\end{aligned}$$

$$\tilde{H} = \epsilon H^*$$

$$D_\mu = \partial_\mu - ig_1 Y B_\mu - ig_2 \frac{\sigma^I}{2} W^I_\mu - ig_s \frac{\lambda^A}{2} G^A_\mu ,$$

$$\begin{aligned}B_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu , \\ W^I_{\mu\nu} &= \partial_\mu W^I_\nu - \partial_\nu W^I_\mu + g_2 \varepsilon^{IJK} W^J_\mu W^K_\nu , \\ G^A_{\mu\nu} &= \partial_\mu G^A_\nu - \partial_\nu G^A_\mu + g_s f^{ABC} G^B_\mu G^C_\nu ,\end{aligned}$$

Results of the global fit

Ellis et al., 2012.02779

	Individual			Marginalised		
SMEFT Coeff.	Best fit $[\Lambda = 1$ TeV$]$	95% CL range	Scale $\frac{\Lambda}{\sqrt{C}}$ [TeV]	Best fit $[\Lambda = 1$ TeV$]$	95% CL range	Scale $\frac{\Lambda}{\sqrt{C}}$ [TeV]
$C_{H\Box}$	-0.27	[-1, +0.47]	1.2	-0.9	[-3, +1.2]	0.69
C_{HD}	-0.01	[-0.023, +0.0027]	8.8	-0.39	[-1.6, +0.81]	0.91
C_{HW}	0.00	[-0.012, +0.006]	11.0	0.12	[-0.38, +0.62]	1.4
C_{tH}	-0.09	[-1, +0.84]	1.0	1.5	[-2.8, +5.7]	0.48
$C_{Hl}^{(1)}$	0.00	[-0.0044, +0.013]	11.0	0.11	[-0.19, +0.41]	1.8
$C_{Hl}^{(3)}$	0.00	[-0.01, +0.003]	12.0	-0.03	[-0.13, +0.055]	3.3
$C_{HQ}^{(3)}$	0.01	[-0.032, +0.048]	5.0	-0.1	[-0.67, +0.46]	1.3

The WCs of dim-6 operators contributing to δM_ν and not constrained by the fit:

$$\alpha_H\,, \quad \alpha_{H\widetilde{B}}\,, \quad \alpha_{H\widetilde{W}}\,, \quad \alpha_{H\widetilde{W}B}$$