Constraining neutrino-quark scalar couplings from neutrino masses

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Outline

Neutrino in the SM

- Neutrinos are massless:
  - Assuming the Dirac nature of neutrinos

$$\mathcal{L}_{\rm Yukawa} = -y_\nu \bar{L}_L \tilde{H} \cancel{\nu_R} + \text{h.c.} \quad \Rightarrow \quad m_\nu = 0 \tag{1}$$

  - Assuming the Majorana nature of neutrinos

$$\mathcal{L}_{\rm Yukawa} = -\frac{1}{2} y_\nu \bar{L}_L^c \cancel{\Delta} L_L + \text{h.c.} \quad \Rightarrow \quad m_\nu = 0 \tag{2}$$

- However, the neutrino oscillations imply that neutrinos should have nonzero masses

$$\begin{aligned} P_{\alpha\to\beta} = \delta_{\alpha\beta} &- 4\sum_{i>j} \text{Re}\left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right) \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right) \\ &+ 2\sum_{i>j} \text{Im}\left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right) \sin\left(\frac{\Delta m^2_{ij} L}{2E}\right) \end{aligned} \tag{3}$$

Experimentally,

$$\text{NO}: \quad \Delta m^2_{21} = 7.41^{+0.21}_{-0.20} \times 10^{-5}\ \text{eV}^2, \qquad \Delta m^2_{21} = 2.437^{+0.028}_{-0.027} \times 10^{-3}\ \text{eV}^2$$

$$\text{IO}: \quad \Delta m^2_{21} = 7.41^{+0.21}_{-0.20} \times 10^{-5}\ \text{eV}^2, \qquad \Delta m^2_{21} = -2.498^{+0.032}_{-0.025} \times 10^{-3}\ \text{eV}^2$$

Possible neutrino mass origins: Seesaw Mechanisms

- Type-I: SM + heavy singlet right-handed neutrinos, N, with mass M_N;
- Type-II: SM + heavy triplet scalar, Δ, with mass M_Δ
- Type-III: SM + heavy triplet fermions, Σ with mass M_Σ
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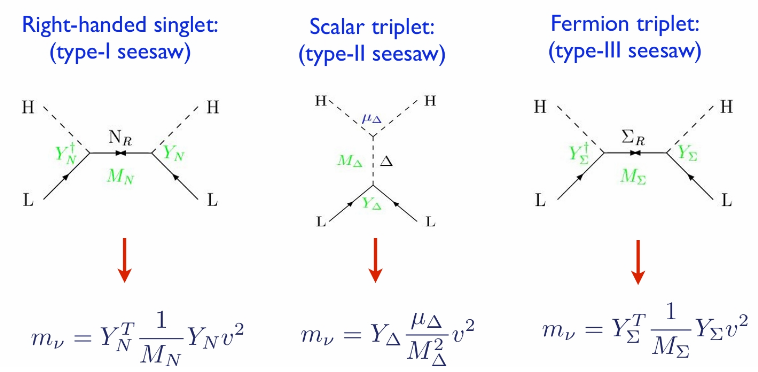


Neutrino mass from EFT

- The neutrino mass is well below the EW scale, so it may arise from low-energy effective interactions like neutrino-quark and/or neutrino-lepton four fermion interactions.
- In which way to produce a tiny neutrino mass with a given EFT operators?
- Focusing on neutrino and light quark scalar interactions, we will demonstrate that there are two ways to generate a neutrino mass: (1) loop corrections and (2) quark condensates.
- These effective interactions may also affect other low-energy processes like CEνNS and light pseudoscalar meson (π^0, η, η') invisible decays, so if the limits on the neutrino masses are stringent enough, they may have significant impacts on the later.

LNEFT

- An alternative and complementary way to search for new physics beyond the SM is to consider the low-energy EFT below the electroweak scale $\Lambda_{\rm EW}$;

- The LEFT is constructed by integrating out the particles that acquire masses of the order of the $\mu_{\rm EW}$ in the spontaneously broken high-energy theory, e.g., SM, SMEFT.

$$\mathcal{L}_{\rm LEFT} = \mathcal{L}_{\rm QED+QCD} + \mathcal{L}_{\not{L}}^{(3)} + \sum_i \sum_{d\geq 5} L_i^{(d)} \mathcal{O}_i^{(d)}$$

E. E. Jenkins, A. V. Manohar, and P. Stoffer, Low-Energy Effective Field Theory below the Electroweak Scale: Operators and Matching, JHEP 03 (2018) 016, [arXiv:1709.04486].
E. E. Jenkins, A. V. Manohar, and P. Stoffer, Low-Energy Effective Field Theory below the Electroweak Scale: Anomalous Dimensions, JHEP 01 (2018) 084, [arXiv:1711.05270]

  - $SU(3)_C \times U(1)_{em}$;
  - $\mu < \Lambda_{\rm EW}$;
  - Containing light SM particles excluding W, Z, t, h;
  - Wilson coefficient $L_i^{(d)}$ contains a suppression factor $1/v^{d-4}$.

- Augmenting LEFT with a light N_R forms a new EFT named LNEFT

$$\mathrm{LEFT} + N_R \longrightarrow \mathrm{LNEFT}$$

Neutrinos and light quarks scalar interactions

- Assuming the Dirac nature of the neutrinos (LNC, $|\Delta L| = 0$)

$$\mathcal{L}^{\rm LNC}_{\rm LNEFT} \supset L^{S,RR}_{\substack{\nu N u\\ prst}}(\bar{\nu}_{Lp}N_{Rr})(\bar{u}_{Ls}u_{Rt}) + L^{S,RL}_{\substack{\nu N u\\ prst}}(\bar{\nu}_{Lp}N_{Rr})(\bar{u}_{Rs}u_{Lt})$$
$$+ L^{S,RR}_{\substack{\nu N d\\ prst}}(\bar{\nu}_{Lp}N_{Rr})(\bar{d}_{Ls}d_{Rt}) + L^{S,RL}_{\substack{\nu N d\\ prst}}(\bar{\nu}_{Lp}N_{Rr})(\bar{d}_{Rs}d_{Lt}) + \text{h.c.}\,, \quad (4)$$

- Assuming the Majorana nature of the neutrinos (LNV, $|\Delta L| = 2$)

$$\mathcal{L}^{\rm LNV}_{\rm LNEFT} \supset L^{S,LR}_{\substack{\nu u\\ prst}}(\bar{\nu}^c_{Lp}\nu_{Lr})(\bar{u}_{Ls}u_{Rt}) + L^{S,LL}_{\substack{\nu u\\ prst}}(\bar{\nu}^c_{Lp}\nu_{Lr})(\bar{u}_{Rs}u_{Lt})$$
$$+ L^{S,LR}_{\substack{\nu d\\ prst}}(\bar{\nu}^c_{Lp}\nu_{Lr})(\bar{d}_{Ls}d_{Rt}) + L^{S,LL}_{\substack{\nu d\\ prst}}(\bar{\nu}^c_{Lp}\nu_{Lr})(\bar{d}_{Rs}d_{Lt})$$
$$+ L^{S,RR}_{\substack{Nu\\ prst}}(\bar{N}^c_{Rp}N_{Rr})(\bar{u}_{Ls}u_{Rt}) + L^{S,RL}_{\substack{Nu\\ prst}}(\bar{N}^c_{Rp}N_{Rr})(\bar{u}_{Rs}u_{Lt})$$
$$+ L^{S,RR}_{\substack{Nd\\ prst}}(\bar{N}^c_{Rp}N_{Rr})(\bar{d}_{Ls}d_{Rt}) + L^{S,RL}_{\substack{Nd\\ prst}}(\bar{N}^c_{Rp}N_{Rr})(\bar{d}_{Rs}d_{Lt}) + \text{h.c.}\,, \quad (5)$$

M. Chala and A. Titov, One-loop matching in the SMEFT extended with a sterile neutrino, JHEP 05 (2020) 139, [arXiv:2001.07732].

T. Li, X.-D. Ma, and M. A. Schmidt, General neutrino interactions with sterile neutrinos in light of coherent neutrino-nucleus scattering and meson invisible decays, JHEP 07 (2020) 152, [arXiv:2005.01543]

1. Neutrinos in the SM
   - Neutrino in the SM
   - Possible neutrino mass origin : Seesaw Mechanisms

2. Neutrino Mass from Effective Field Theory
   - Low-energy effective field theory with N_R (LNEFT)

3. Constraining neutrino-quark scalar couplings from neutrino masses
   - Neutrino mass from loop corrections
   - Neutrino mass from quark condensate
   - Numerical estimate

4. Conclusions

Neutrino mass from loop corrections

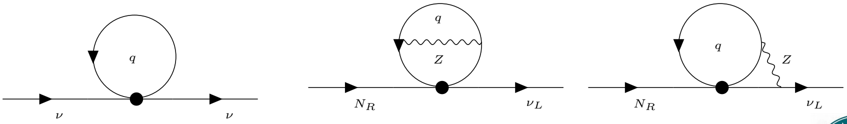
- One-loop correction (L_ν is short for $L^{S,AB}_{\substack{iq\\prst}}$, $i=\nu N,\nu,N$, $q=u,d,s$, $A,B=L,R$)

$$m_{\rm eff}^{(1)} \approx \frac{1}{2} L_\nu N_C \frac{m_q^3}{(4\pi)^2} \ln \frac{\mu^2}{m_q^2}, \tag{6}$$

- Two-loop correction (g is the $SU(2)_L$ coupling constant)

$$m_{\rm eff}^{(2)} \approx \frac{1}{2} g^2 L_\nu N_C \frac{m_q}{(4\pi)^4} m_Z^2 \left(\ln \frac{\mu^2}{m_Z^2}\right)^2, \tag{7}$$

  where μ is the renormalization scale, usually chosen to be the NP scale $\mu \sim 1$ TeV.
- Taking the RG running effect into account, there should multiply by a factor of about 2.
- $m_{\rm eff}^{(1)}/m_{\rm eff}^{(2)} \approx 50 m_q^2/m_Z^2 \quad \Rightarrow \quad m_{\rm eff}^{(1)}$ is negligible for all fermions except the top quark



G. Prezeau and A. Kurylov, Neutrino mass constraints on μ-decay and $\pi^0 \to \nu\bar{\nu}$, Phys. Rev. Lett. 95 (2005) 101802 [hep-ph/0409193]

T.M. Ito and G. Prezeau, Neutrino mass constraints on β decay, Phys. Rev. Lett. 94 (2005) 161802 [hep-ph/0410254]

Neutrino Mass from quark condensate

- After chiral symmetry breaking, the light quark develop a VEV, i.e., quark condensate (qc)

$$\langle q\bar{q}\rangle \approx \Lambda^3_{\mathrm{QCD}}/(16\pi^2) \tag{8}$$

Lattice results

$$\langle q\bar{q}\rangle^{\overline{\mathrm{MS}}}(2\ \mathrm{GeV}) = -(283(2)\ \mathrm{MeV})^3, \quad q = u, d, \quad \text{1211.6577 [hep-lat]} \tag{9}$$

$$\langle s\bar{s}\rangle^{\overline{\mathrm{MS}}}(2\ \mathrm{GeV}) = -(296(11)\ \mathrm{MeV})^3 \quad q = s, \quad \text{1811.04305 [hep-lat]} \tag{10}$$

- Quark condensate contribute to neutrino mass after chiral symmetry breaking, e.g.:

$$\begin{aligned}
L_\nu(\bar{\nu}_L N_R)(\bar{q}_L q_R) &\xrightarrow{\chi SB} \frac{1}{2}L_\nu\langle q\bar{q}\rangle(\bar{\nu}_L N_R), && \Rightarrow m^{qc}_{\mathrm{eff}} = \frac{1}{2}L_\nu\langle q\bar{q}\rangle \\
L_\nu(\bar{\nu}^C_L \nu_L)(\bar{q}_L q_R) &\xrightarrow{\chi SB} \frac{1}{2}L_\nu\langle q\bar{q}\rangle(\bar{\nu}^C_L \nu_L), && \Rightarrow m^{qc}_{\mathrm{eff}} = L_\nu\langle q\bar{q}\rangle \\
L_\nu(\bar{N}^C_R N_R)(\bar{q}_L q_R) &\xrightarrow{\chi SB} \frac{1}{2}L_\nu\langle q\bar{q}\rangle(\bar{N}^C_R N_R), && \Rightarrow m^{qc}_{\mathrm{eff}} = L_\nu\langle q\bar{q}\rangle
\end{aligned} \tag{11}$$

Scott Thomas, Rui-Ming Xu, Light neutrinos from the quark condensate, Physics Letters B 284 (1992) 341-346.
A. Babic, S. Kovalenko, M. I. Krivoruchenko, and F. Simkovic, Quark condensate seesaw mechanism for neutrino mass, Phys. Rev. D 103 no. 1, (2021) 015007, arXiv:1911.12189 [hep-ph]

Numerical estimate

- Experimental upper bounds on neutrino masses (90% CL)

$$m_{\nu_e}^{\rm eff} < 0.45\ \text{eV} \quad \text{KATRIN, Science 388 (2025) 6743, adq9592} \tag{12}$$

$$m_{ee}^{\rm eff} < 36 - 156\ \text{meV} \quad \text{KamLAND-Zen, Phys. Rev. Lett.130, 5, 051801 (2023)} \tag{13}$$

- Only radiative mass estimate ($\bar{m} = (m_u + m_d)/2 = 3.49(4)$ MeV, $m_s = 93.5(5)$ MeV)

$$m_{\rm eff}^{(2)}|_{q=u,d} \approx 0.041 L_{\nu_e} \quad \Rightarrow \quad |L_{\nu_e}| < 1.10 \times 10^{-8}\ \mathrm{GeV}^{-2} \tag{14}$$

$$m_{\rm eff}^{(2)}|_{q=s} \approx 1.10 L_{\nu_e} \quad \Rightarrow \quad |L_{\nu_e}| < 4.09 \times 10^{-10}\ \mathrm{GeV}^{-2} \tag{15}$$

- Only quark-condensate mass estimate

$$m_{\rm eff}^{qc}|_{q=u,d} \approx -0.011 L_{\nu_e} \quad \Rightarrow \quad |L_{\nu_e}| < 4.09 \times 10^{-8}\ \mathrm{GeV}^{-2} \tag{16}$$

$$m_{\rm eff}^{qc}|_{q=s} \approx -0.013 L_{\nu_e} \quad \Rightarrow \quad |L_{\nu_e}| < 3.46 \times 10^{-8}\ \mathrm{GeV}^{-2} \tag{17}$$

- Combination of radiative and quark-condensate contributions

$$m_{\rm eff}|_{q=u,d} \approx 0.030 L_{\nu_e} \quad \Rightarrow \quad |L_{\nu_e}| < 1.50 \times 10^{-8}\ \mathrm{GeV}^{-2} \tag{18}$$

$$m_{\rm eff}^{qc}|_{q=s} \approx 1.09 L_{\nu_e} \quad \Rightarrow \quad |L_{\nu_e}| < 4.13 \times 10^{-10}\ \mathrm{GeV}^{-2} \tag{19}$$

- Majorana neutrino cases

$$m_{\rm eff}|_{q=u,d} \approx 0.060 L_{\nu_e} \quad \Rightarrow \quad |L_{\nu_e}| < (6 - 26) \times 10^{-10}\ \mathrm{GeV}^{-2} \tag{20}$$

$$m_{\rm eff}^{qc}|_{q=s} \approx 2.18 L_{\nu_e} \quad \Rightarrow \quad |L_{\nu_e}| < (1.65 - 7.16) \times 10^{-11}\ \mathrm{GeV}^{-2} \tag{21}$$

CEνNS and light pseudoscalar meson invisible decays

- CEνNS

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{4\pi}\left[\xi_S^2 \frac{E_r}{E_r^{\max}} + \xi_V^2\left(1 - \frac{E_r}{E_r^{\max}}\right)\right], \tag{22}$$

$$\xi^2_{V,\mathrm{SM}} = [\mathbb{N} - (1 - 4\sin^2\theta_W)\mathbb{Z}]^2 F^2(q^2) \tag{23}$$

$$\xi_S^2 = \begin{cases} \sum\limits_{j;pr}\left|\frac{1}{\sqrt{2}G_F}\sum\limits_q (L^{S,RR}_{\substack{iq\\prqq}} + L^{S,RL}_{\substack{iq\\prqq}})\left(\mathbb{Z}_j\frac{m_p}{m_q}f^p_{T_q} + \mathbb{N}_j\frac{m_n}{m_q}f^n_{T_q}\right)\right|^2 F^2(q^2), & \text{for } i = \nu N \\ \sum\limits_{j;pr}\left|\frac{\sqrt{2}}{G_F}\sum\limits_q (L^{S,LR}_{\substack{iq\\prqq}} + L^{S,LL}_{\substack{iq\\prqq}})\left(\mathbb{Z}_j\frac{m_p}{m_q}f^p_{T_q} + \mathbb{N}_j\frac{m_n}{m_q}f^n_{T_q}\right)\right|^2 F^2(q^2), & \text{for } i = \nu \end{cases}, \tag{24}$$

- Light pseudoscalar meson (π^0, η, η') invisible decays

$$\begin{aligned} \mathcal{B}(P \to \mathrm{invible}) = \frac{\tau_P m_P}{16\pi}\sum_{q;pr}\Bigg[2\left|\frac{h_P^q}{4m_q}\left(L^{S,RR}_{\substack{\nu Nq\\prqq}} - L^{S,RL}_{\substack{\nu Nq\\prqq}}\right)\right|^2\left(1 - \frac{m^2_{N_R}}{m_P^2}\right)^2 \\ + \left|\frac{h_P^q}{2m_q}\left(L^{S,RL}_{\substack{Nq\\prqq}} - L^{S,RR}_{\substack{Nq\\prqq}}\right)\right|^2\left(1 - 2\frac{m^2_{N_R}}{m_P^2}\right)\left(1 - 4\frac{m^2_{N_R}}{m_P^2}\right)^{\frac{1}{2}} \\ + \left|\frac{h_P^q}{2m_q}\left(L^{S,LL}_{\substack{\nu q\\prqq}} - L^{S,LR}_{\substack{\nu q\\prqq}}\right)\right|^2, \end{aligned} \tag{25}$$

Comparison

表: Upper limits on LNC scalar LNEFT Wilson coefficients

L_ν [GeV^{-2}]	Neutrino mass	CEνNS	π^0 →inv.	η →inv.	η' →inv.
$L^{S,RR(L)}_{\substack{\nu Nu \\ eeuu}}$	1.50×10^{-8}	7.6×10^{-7}	3.2×10^{-6}	7.3×10^{-4}	1.9×10^{-2}
$L^{S,RR(L)}_{\substack{\nu Nd \\ eedd}}$	1.50×10^{-8}	8.8×10^{-7}	6.9×10^{-6}	1.6×10^{-3}	4.0×10^{-2}
$L^{S,RR(L)}_{\substack{\nu Nd \\ eess}}$	4.13×10^{-10}	9.4×10^{-6}	-	5.2×10^{-4}	8.9×10^{-3}

表: Upper limits on LNV scalar LNEFT Wilson coefficients

L_ν [GeV^{-2}]	Neutrino mass	CEνNS	π^0 →inv.	η →inv.	η' →inv.
$L^{S,LL(R)}_{\substack{\nu u \\ eeuu}}$	$(6 - 26) \times 10^{-10}$	3.8×10^{-7}	1.6×10^{-6}	3.7×10^{-4}	9.3×10^{-3}
$L^{S,LL(R)}_{\substack{\nu d \\ eedd}}$	$(6 - 26) \times 10^{-10}$	4.4×10^{-7}	3.5×10^{-6}	7.9×10^{-4}	2.0×10^{-2}
$L^{S,LL(R)}_{\substack{\nu d \\ eess}}$	$(1.65 - 7.16) \times 10^{-11}$	4.7×10^{-6}	-	2.6×10^{-4}	4.4×10^{-3}

Conclusions

1. The neutrino mass is generated by neutrino-quark scalar interactions;
2. The neutrino-quark scalar interactions is described by LNEFT;
3. The neutrino effective mass can be generated from two different ways: 1) loop corrections and 2) quark condensate;
4. For $q = u, d$, the radiative and quark-condensate contributions are comparable; while for $q = s$, the radiative contribution is dominant.
4. For either LNC or LNV LNEFT Wilson coefficients, electron neutrino mass provide the most stringent constraints.

Thank you !!