Probing neutrino-light-quark effective scalar interactions from neutrino masses

报 告 人： 陈丰之

暨南大学

2026 年 7 月 16 日

中国物理学会高能物理分会第十二届全国会员代表大会暨学术年会，华南师范大学，广州

based on Phys.Rev.D 113 (2026) 5, 5, arXiv: 2512.01947 [hep-ph]

Outline

Neutrino oscillations

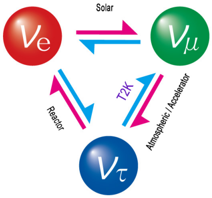
- The SM: neutrinos are massless

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

- Neutrino Oscillations: neutrinos are massive

$$\begin{aligned} P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right) \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right) \\ +2\sum_{i>j} \mathrm{Im}\left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}\right) \sin\left(\frac{\Delta m^2_{ij} L}{2E}\right) \end{aligned} , \quad \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \tag{2}$$

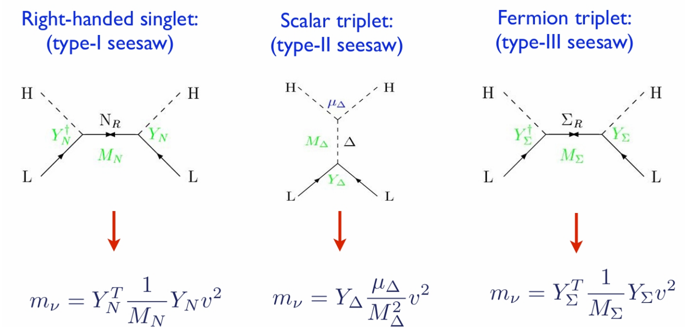
- Neutrinos mass origin: new physics beyond the SM!

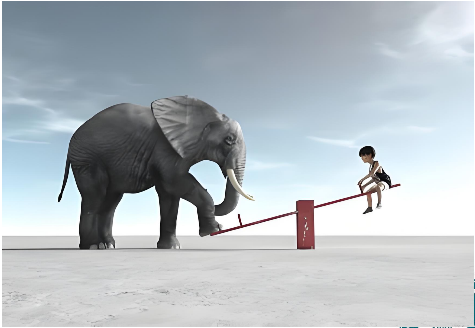


Neutrino oscillation between three generations

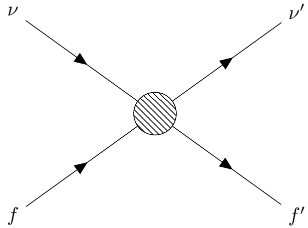
Seesaw Mechanisms

- 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
- $\cdots$





Probing NP via low-energy effective interactions



$$C_i(\bar{\nu}\Gamma_i\nu)(\bar{f}\Gamma^i f'), \quad \Gamma_i = S, P, V, A, T$$

Example: impact of neutrino-light-quark ($f = u, d, s$) effective scalar interactions:

- Coherent elastic neutrino-nucleus scattering (CEνNS)
- Meson (π^0, η, η') invisible decays
- Neutrino mass

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.

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

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

$$\rm LEFT + N_R \longrightarrow LNEFT$$

Neutrinos and light quarks scalar interactions

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

$$
\begin{aligned}
\mathcal{L}_{\rm LNEFT}^{\rm LNC} \supset & L_{\substack{\nu N u \\ prst}}^{S,RR}(\bar{\nu}_{Lp} N_{Rr})(\bar{u}_{Ls} u_{Rt}) + L_{\substack{\nu N u \\ prst}}^{S,RL}(\bar{\nu}_{Lp} N_{Rr})(\bar{u}_{Rs} u_{Lt}) \\
& + L_{\substack{\nu N d \\ prst}}^{S,RR}(\bar{\nu}_{Lp} N_{Rr})(\bar{d}_{Ls} d_{Rt}) + L_{\substack{\nu N d \\ prst}}^{S,RL}(\bar{\nu}_{Lp} N_{Rr})(\bar{d}_{Rs} d_{Lt}) + \mathrm{h.c.}\,, \qquad (3)
\end{aligned}
$$

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

$$
\begin{aligned}
\mathcal{L}_{\rm LNEFT}^{\rm LNV} \supset & L_{\substack{\nu u \\ prst}}^{S,LR}(\bar{\nu}_{Lp}^{c} \nu_{Lr})(\bar{u}_{Ls} u_{Rt}) + L_{\substack{\nu u \\ prst}}^{S,LL}(\bar{\nu}_{Lp}^{c} \nu_{Lr})(\bar{u}_{Rs} u_{Lt}) \\
& + L_{\substack{\nu d \\ prst}}^{S,LR}(\bar{\nu}_{Lp}^{c} \nu_{Lr})(\bar{d}_{Ls} d_{Rt}) + L_{\substack{\nu d \\ prst}}^{S,LL}(\bar{\nu}_{Lp}^{c} \nu_{Lr})(\bar{d}_{Rs} d_{Lt}) \\
& + L_{\substack{N u \\ prst}}^{S,RR}(\bar{N}_{Rp}^{c} N_{Rr})(\bar{u}_{Ls} u_{Rt}) + L_{\substack{N u \\ prst}}^{S,RL}(\bar{N}_{Rp}^{c} N_{Rr})(\bar{u}_{Rs} u_{Lt}) \\
& + L_{\substack{N d \\ prst}}^{S,RR}(\bar{N}_{Rp}^{c} N_{Rr})(\bar{d}_{Ls} d_{Rt}) + L_{\substack{N d \\ prst}}^{S,RL}(\bar{N}_{Rp}^{c} N_{Rr})(\bar{d}_{Rs} d_{Lt}) + \mathrm{h.c.}\,, \qquad (4)
\end{aligned}
$$

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]

Neutrino mass from loop corrections

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

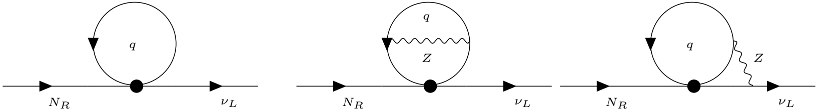
$$m_{\rm eff}^{(1)} \approx \frac{1}{2} L_\nu N_C \frac{m_q^3}{(4\pi)^2} \ln \frac{\mu^2}{m_q^2}, \tag{5}$$

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

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

  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

- Since the neutrino masses are well below chiral scale $\mu_\chi \sim 4\pi F_\pi$, the observed degrees of freedom are no longer the light quarks but the pseudoscalars (π, K, η), the effective interactions shall be described by the χPT
- The external field method

$$\begin{aligned}\mathcal{L} =&\mathcal{L}^0_{\rm QCD} + \mathcal{L}_{\rm ext} \\ =&\mathcal{L}^0_{\rm QCD} + \bar{q}_L\gamma^\mu l_\mu q_L + \bar{q}_R\gamma^\mu r_\mu q_R + \bar{q}_L S q_R + \bar{q}_R S^\dagger q_L + \bar{q}_L\sigma^{\mu\nu} t_{\mu\nu} q_R + \bar{q}_R\sigma^{\mu\nu} t^\dagger_{\mu\nu} q_L\,,\end{aligned} \tag{7}$$

- The χPT counterparts of $\bar{q}_L\tilde{S}q_R$ at the lowest chiral power order $[\mathcal{O}(p^4)]$

$$\begin{aligned}\bar{q}_L\tilde{S}q_R \to -2B_0\Big[&\frac{1}{4}F_0^2\langle\tilde{S}U\rangle + L_4\langle D_\mu U^\dagger D^\mu U\rangle\langle\tilde{S}U\rangle + L_5\langle\tilde{S}UD_\mu U^\dagger D^\mu U\rangle \\ &+ 2L_6\langle U^\dagger\chi + \chi^\dagger U\rangle\langle\tilde{S}U\rangle - 2L_7\langle U^\dagger\chi - \chi^\dagger U\rangle\langle\tilde{S}U\rangle + 2L_8\langle\tilde{S}U\chi^\dagger U\rangle \\ &+ H_2\langle\tilde{S}\chi\rangle\Big] + \mathcal{O}(p^6),\end{aligned} \tag{8}$$

$$U = \exp\left(i\frac{\Phi}{F_0}\right)\,, \qquad \Phi = \lambda^a\phi^a = \begin{pmatrix} \pi^0 + \frac{1}{\sqrt{3}}\eta & \sqrt{2}\pi^+ & \sqrt{2}K^+ \\ \sqrt{2}\pi^- & -\pi^0 + \frac{1}{\sqrt{3}}\eta & \sqrt{2}K^0 \\ \sqrt{2}K^- & \sqrt{2}\bar{K}^0 & -\frac{2}{\sqrt{3}}\eta \end{pmatrix} \tag{9}$$

where $\langle\cdots\rangle$ represents the trace in flavor space, $\chi = -2B_0 S^\dagger$ with $B_0 = -\langle 0|\bar{q}q|0\rangle/F_0^2$

- Matching LNEFT to χPT (here I only show the LNC operators)

$$\tilde{S}_{uu} = L^{S,RR}_{\substack{\nu Nu \\ pruu}} (\bar{\nu}_{Lp} N_{Rr}) + L^{S,RL*}_{\substack{\nu Nu \\ pruu}} (\bar{N}_{Rr} \nu_{Lp}) \,, \tag{10}$$

$$\tilde{S}_{dd} = L^{S,RR}_{\substack{\nu Nd \\ prdd}} (\bar{\nu}_{Lp} N_{Rr}) + L^{S,RL*}_{\substack{\nu Nd \\ prdd}} (\bar{N}_{Rr} \nu_{Lp}) \,, \tag{11}$$

$$\tilde{S}_{ss} = L^{S,RR}_{\substack{\nu Nd \\ prss}} (\bar{\nu}_{Lp} N_{Rr}) + L^{S,RL*}_{\substack{\nu Nd \\ prss}} (\bar{N}_{Rr} \nu_{Lp}) \,. \tag{12}$$

- Take only the vacuum state of the theory, i.e., the 3×3 identity matrix of the U matrix ($U = 1 + i\Phi/F_0 + \cdots$), to obtain the following effective mass term:

$$\delta m^{qc}_{\nu_{\mathrm{eff}}} = -\frac{1}{2} B_0 F_0^2 \sum_q \tilde{S}_{qq} = \frac{1}{2} \langle 0|\bar{q}q|0\rangle \sum_q L^{S,AB}_{\substack{iq' \\ prqq}} \,. \tag{13}$$

The numerical value of $\langle 0|\bar{q}q|0\rangle$ will be quoted from the results of lattice QCD

$$\langle 0|\bar{u}u|0\rangle^{\overline{\mathrm{MS}}}(2\ \mathrm{GeV}) = -(283(2)\ \mathrm{MeV})^3, \tag{14}$$

$$\langle 0|\bar{d}d|0\rangle^{\overline{\mathrm{MS}}}(2\ \mathrm{GeV}) = -(283(2)\ \mathrm{MeV})^3, \tag{15}$$

$$\langle 0|\bar{s}s|0\rangle^{\overline{\mathrm{MS}}}(2\ \mathrm{GeV}) = -(296(11)\ \mathrm{MeV})^3 \tag{16}$$

Numerical estimate

- The total effective neutrino mass for a single nonzero Wilson coefficient

$$\delta m_\nu^{\rm eff} = \begin{cases} (0.022_{\rm loop} - 0.011_{qc}) L^{S,AB}_{\substack{iq' \\ prqq}} \cdot {\rm GeV}^3\,, & \text{for } q = u \\ (0.047_{\rm loop} - 0.011_{qc}) L^{S,AB}_{\substack{iq' \\ prqq}} \cdot {\rm GeV}^3\,, & \text{for } q = d \\ (0.944_{\rm loop} - 0.013_{qc}) L^{S,AB}_{\substack{iq' \\ prqq}} \cdot {\rm GeV}^3\,, & \text{for } q = s \end{cases}, \tag{17}$$

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

$$m_{\nu_e}^{\rm eff} < 0.45 \text{ eV} \quad \text{KATRIN, Science 388 (2025) 6743, adq9592} \tag{18}$$

$$m_{ee}^{\rm eff} < 36 - 156 \text{ meV} \quad \text{KamLAND-Zen, Phys. Rev. Lett.130, 5, 051801 (2023)} \tag{19}$$

- Constraint

$$\delta m_\nu^{\rm eff} < m_{\nu_e, ee}^{\rm eff} \tag{20}$$

CEνNS and light pseudoscalar meson invisible decays

- CEνNS

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{4\pi}\left[\xi_S^2 \frac{E_r}{E_r^{\max}} + \xi_V^2\left(1 - \frac{E_r}{E_r^{\max}}\right)\right], \tag{21}$$

$$\xi_{V,\mathrm{SM}}^2 = [\mathbb{N} - (1-4\sin^2\theta_W)\mathbb{Z}]^2 F^2(q^2) \tag{22}$$

$$\xi_S^2 = \begin{cases} \sum\limits_{j;pr}\left|\frac{1}{\sqrt{2}G_F}\sum\limits_q (L^{S,RR}_{\substack{iq\\prqq}} + L^{S,RL}_{\substack{iq\\prqq}})\left(\mathbb{Z}_j \frac{m_p}{m_q} f^p_{T_q} + \mathbb{N}_j \frac{m_n}{m_q} f^n_{T_q}\right)\right|^2 F^2(q^2), & \text{for } i = \nu N \\ \sum\limits_{j;pr}\left|\frac{\sqrt{2}}{G_F}\sum\limits_q (L^{S,LR}_{\substack{iq\\prqq}} + L^{S,LL}_{\substack{iq\\prqq}})\left(\mathbb{Z}_j \frac{m_p}{m_q} f^p_{T_q} + \mathbb{N}_j \frac{m_n}{m_q} f^n_{T_q}\right)\right|^2 F^2(q^2), & \text{for } i = \nu \end{cases}, \tag{23}$$

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

$$\begin{aligned} \mathcal{B}(P \to \text{invible}) = \frac{\tau_P m_P}{16\pi}\sum_{q;pr}\Bigg[& 2\left|\frac{h_P^q}{4m_q}\left(L^{S,RR}_{\substack{\nu Nq\\prqq}} - L^{S,RL}_{\substack{\nu Nq\\prqq}}\right)\right|^2\left(1-\frac{m_{N_R}^2}{m_P^2}\right)^2 \\ & + \left|\frac{h_P^q}{2m_q}\left(L^{S,RL}_{\substack{Nq\\prqq}} - L^{S,RR}_{\substack{Nq\\prqq}}\right)\right|^2\left(1-2\frac{m_{N_R}^2}{m_P^2}\right)\left(1-4\frac{m_{N_R}^2}{m_P^2}\right)^{\frac{1}{2}} \\ & + \left|\frac{h_P^q}{2m_q}\left(L^{S,LL}_{\substack{\nu q\\prqq}} - L^{S,LR}_{\substack{\nu q\\prqq}}\right)\right|^2, \end{aligned} \tag{24}$$

Results

L_i [GeV^{-2}]	$m^{\rm eff}_{\nu_e}$	CEνNS	$\pi^0\to$inv	$\eta\to$inv	$\eta'\to$inv
$L^{S,RR(RL)}_{\substack{\nu Nu \\ eeuu}}$	4.3×10^{-8}	7.6×10^{-7}	4.8×10^{-7}	8.5×10^{-4}	1.5×10^{-2}
$L^{S,RR(RL)}_{\substack{\nu Nd \\ eedd}}$	1.2×10^{-8}	8.8×10^{-7}	1.1×10^{-6}	1.8×10^{-3}	3.2×10^{-2}
$L^{S,RR(RL)}_{\substack{\nu Nd \\ eess}}$	4.8×10^{-10}	9.4×10^{-6}	$\cdots$	5.5×10^{-4}	5.6×10^{-3}

表: Constraints on the upper limits of LNC scalar LNEFT Wilson coefficients.

L_i [GeV^{-2}]	$m^{\rm eff}_{ee}$	CEνNS	$\pi^0\to$inv	$\eta\to$inv	$\eta'\to$inv
$L^{S,LL(LR)}_{\substack{\nu u \\ eeuu}}$	$(1.3\text{–}5.8)\times10^{-9}$	3.8×10^{-7}	3.0×10^{-7}	6.0×10^{-4}	1.1×10^{-2}
$L^{S,LL(LR)}_{\substack{\nu d \\ eedd}}$	$(3.9\text{–}16.9)\times10^{-10}$	4.4×10^{-7}	6.7×10^{-7}	1.3×10^{-3}	2.3×10^{-2}
$L^{S,LL(LR)}_{\substack{\nu d \\ eess}}$	$(1.5\text{–}6.6)\times10^{-11}$	4.7×10^{-6}	$\cdots$	3.9×10^{-4}	4.0×10^{-3}
$L^{S,RR(RL)}_{\substack{Nu \\ eeuu}}$	$\cdots$	$\cdots$	3.0×10^{-7}	6.0×10^{-4}	9.2×10^{-3}
$L^{S,RR(RL)}_{\substack{Nd \\ eedd}}$	$\cdots$	$\cdots$	6.7×10^{-7}	1.3×10^{-3}	2.0×10^{-2}
$L^{S,RR(RL)}_{\substack{Nd \\ eess}}$	$\cdots$	$\cdots$	$\cdots$	3.9×10^{-4}	4.0×10^{-3}

表: Constraints on the upper limits of LNV scalar LNEFT Wilson coefficients

Conclusions

1. We investigate the neutrino mass that being generated by light-quark-neutrino scalar effective interactions;
2. We use LNEFT to describe the neutrino-quark scalar interactions;
3. The neutrino effective mass can be generated from two different ways: 1) loop corrections, which are perturbative contributions, 2) quark condensate, which are nonperturbative contributions;
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 !!