Neutrinoless Double-Beta Decay in the Standard Model Effective Field Theory

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Advertizement: virtual ACFI workshop
“Prospects for Baryon Number Violation by Two Units”
August 3 - August 6

Josh Barrow, Leah Broussard, JdV, Mike Wagman
Non-standard mechanisms for 0vbb

- Appropriate for e.g. high-scale see-saw mechanism
- This talk focuses on LNV at lower scales
Part I: Non-standard mechanisms for 0vbb and the SM-EFT

Part II: Low-scale seesaw and 0vbb
Non-Standard interpretation

- $0\nu\beta\beta$ does not have to be induced by light-neutrino exchange
- Many models induce lepton-number violation in different ways
- Example: in LR symmetric models (but also RPV SUSY, LQs, …)

- No direct link to neutrino mass apart that nothing forbids Majorana masses
Applications of effective field theory

- $0\nu\beta\beta$ is a low-energy nuclear process. Scale $\sim m_\pi$
- It cannot resolve UV `details’
- Suggest an **EFT** description of LNV.

  See e.g.: Pas et al `99 `01, de Gouvea-Jenkins ‘07, Deppisch et al `12, de Gouvea-Vogel ’13

- **At what scale do we start the EFT description ?**
- Could start around 1 GeV: build Lagrangian of $\Delta L=2$ operators
- Symmetries: Lorentz, $U_{em}(1) \times SU_c(3)$, d.o.f light quarks, leptons, gluons

\[
\mathcal{L} = \frac{G_F^2}{2} m_p^{-1} \{ \epsilon_1 J J j + \epsilon_2 J^{\mu\nu} J_{\mu\nu} j + \epsilon_3 J^\mu J_{\mu} j + \epsilon_4 J^\mu J_{\mu\nu} j^\nu + \epsilon_5 J^\mu J j^\mu \\
+ \epsilon_6 J^{\mu\nu} j_{\mu\nu} + \epsilon_7 J J^{\mu\nu} j_{\mu\nu} + \epsilon_8 J_{\mu\alpha} j^{\mu\nu} j_{\nu} \},
\]

  Pas et al `01

- Dimension-9 operators from products of hadronic currents, e.g.
  \[ J^\mu = \bar{u} \gamma^\mu d \quad \text{and} \quad \Delta L=2 \text{ currents, e.g.} \quad j^\mu = \bar{e} \gamma^\mu e^c \]
It might be advantageous to start above the electroweak scale

1. Matching to explicit UV-complete model is done at the scale where heavy particles are integrated out.
2. Incorporate constraints from $SU_L(2)$ gauge symmetry
3. Operators involve heavy SM fields ($W, Z, h, t$). $0v_{bb}$ can be directly connected to other probes (LHC, flavor, etc)

See talk by R. Ruiz
**Typical Energy Scale**

- $\Lambda$  \(\sim\) TeV
- $M_{EW} \sim \nu \sim M_{Z,W,H,t}$  \(\sim\) 100 GeV
- $\Lambda_\chi \sim 2\pi F_\pi \sim M_N$  \(\sim\) 1 GeV
- $100$ MeV

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**Beyond-the-SM**

- $L_{EFF}$  RG flow
- $L''_{EFF}$  RG flow
- $L'''_{EFF}$  Lattice QCD + chiral effective field theory

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**SM-EFT**

**LHC observables**

**Integrate out heavy SM fields**

**Nonperturbative QCD regimes**

**Nuclear $0\nu\beta\beta$ operators**

**Many-body methods**
Effective lepton number violation

- Lepton number = **accidental** symmetry in Standard Model (at zero $T$)
- But no longer once we allow for operators of dim > 4

- SM as an EFT
  \[ L_{\text{new}} = L_{\text{SM}} + \frac{1}{\Lambda} L_5 + \frac{1}{\Lambda^2} L_6 + \cdots \]

- Contain SM fields and obey SM gauge and Lorentz symmetry
- At energy $E$, operators of dim $(4+n) \sim (E/\Lambda)^n$
Effective lepton number violation

- Lepton number = **accidental** symmetry in Standard Model (at zero T)
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- SM as an EFT
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- Contain SM fields and obey SM gauge and Lorentz symmetry
- At energy E, operators of dim \((4+n) \sim (E/\Lambda)^n\)
- **Gauge symmetry is restrictive:** only 1 dim-5 operator
  \[ L_5 = \frac{c_5}{\Lambda} (L^T C \tilde{H})(\tilde{H}^T L) \quad L^T = (\nu_L e_L) \]

  \(^{\text{Weinberg '79}}\)

- Contains **two** lepton fields and **no** anti-lepton fields \(\rightarrow\)
  \[ L_5 \rightarrow c_5 \frac{\nu^2}{\Lambda} \nu_L^T C \nu_L \quad \rightarrow \text{Majorana neutrino mass term} \]

\[ m_{\nu} \sim 0.1 \text{ eV} \quad \Lambda \sim c_5 \cdot 10^{15} \text{ GeV} \]
Higher-order in the SM-EFT

- $\Delta L = 2$ operators only appear at odd dimensions 5, 7, ....  
  Kobach '16

### Dimension-five

- $L_5 = \frac{c_5}{\Lambda} (L^T C \tilde{H})(\tilde{H}^T L)$
  - Weinberg '79

- One operator
- Induces Majorana mass

### Dimension-seven

- $\Delta L = 2$ operators

#### Lehman '14

1. $\bar{\psi} \psi H^4 + \text{h.c.}$
   - $O_{LH} \left( c_{j,\mu} (L'C \gamma_5 L') \bar{H}^H H^H (H' H) \right)$

2. $\bar{\psi} D^4 \psi + \text{h.c.}$
   - $O_{LDD} \left( c_{j,\mu} (L'C \gamma_5 L') \bar{H}^D D^D (D' D) \right)$

3. $\bar{\psi} \theta^4 \psi + \text{h.c.}$
   - $O_{LDE} \left( c_{j,\mu} (L'C \gamma_5 L') \bar{H}^D E^E (E' E) \right)$

4. $\bar{\psi} \frac{1}{2} [D_L D_R, H^H H] + \text{h.c.}$
   - $O_{LDD} \left( c_{j,\mu} (L'C \gamma_5 L') \bar{H}^D D^D (D' D) \right)$

#### Full basis not known

- 4-quark 2-lepton operators + 2 quark/2 lepton + Higgs currents

### Dimension-nine

- $\phi^+ D_\mu \phi$
Higher-order in the SM-EFT

- $\Delta L = 2$ operators only appear at odd dimensions 5, 7, .... Kobach '16

### Dimension-five

- Formula: $\mathcal{L}_5 = \frac{c_5}{\Lambda} (L^T C \tilde{H})(\tilde{H}^T L)$
- One operator
- Induces Majorana mass

### Dimension-seven

<table>
<thead>
<tr>
<th>Operator</th>
<th>Description</th>
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<tbody>
<tr>
<td>$\mathcal{O}_{LR}$</td>
<td>$\psi H^4 + h.c.$</td>
</tr>
<tr>
<td>$\mathcal{O}_{LR,De}$</td>
<td>$c_2 \psi H^4 D + h.c.$</td>
</tr>
<tr>
<td>$\mathcal{O}_{LR,De}^{(1)}$</td>
<td>$c_2 \tilde{c}_L \psi (L'C \tilde{N}) H H^m D^e H^n$</td>
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<tr>
<td>$\mathcal{O}_{LR,De}^{(2)}$</td>
<td>$c_2 \tilde{c}_L \psi (L'C \tilde{N}) H H^m D^e H^n$</td>
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<tr>
<td>$\mathcal{O}_{LR,De}^{(3)}$</td>
<td>$c_2 \tilde{c}_L \psi (L'C \tilde{N}) H H^m D^e H^n$</td>
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Lehman '14

### Dimension-nine

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<td>$\mathcal{O}_{LR,De}^{(4)}$</td>
<td>$c_2 \tilde{c}_L \psi (L'C \tilde{N}) H H^m D^e H^n$</td>
</tr>
<tr>
<td>$\mathcal{O}_{LR,De}^{(5)}$</td>
<td>$c_2 \tilde{c}_L \psi (L'C \tilde{N}) H H^m D^e H^n$</td>
</tr>
<tr>
<td>$\mathcal{O}_{LR,De}^{(6)}$</td>
<td>$c_2 \tilde{c}_L \psi (L'C \tilde{N}) H H^m D^e H^n$</td>
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</table>

Graesser '16 '18

- Full basis not known

- 4-quark 2-lepton operators + 2 quark/2 lepton + Higgs currents

- $\tilde{\varphi} D_\mu \varphi$

- Seems crazy to go to dim-7 if expansion parameter is $\left( \frac{\nu}{\Lambda} \right)^2 \sim 10^{-24}$
- Unless $c_5 \ll 1$ for whatever reason....
- Small Yukawa couplings, symmetries, radiative mass models, ..... 
- Example: in LR symmetry $c_5 \sim y_e^2 \sim 10^{-10}$, $c_7 \sim y_e \sim 10^{-5}$, $c_9 \sim y_e^0 \sim 1$
- Then if scale is low $\Lambda \sim (10 - 100) \text{TeV}$, dim5 $\sim$ dim7 $\sim$ dim 9
Lowering the energy scale

\[ M_{EW} = 100 \text{ GeV} \]

\[ \Lambda \chi \sim 2\pi F_\pi = 1 \text{ GeV} \]

*Higgs takes vev + integrate out W bosons*

\[ \sim c_7 \frac{v}{\Lambda^3} \]

- Beta-decay a la Fermi \( \sim \text{dim-6} \)
- But ‘wrong’ neutrino
- Hard to probe in single beta decay
- Scalar, Vector, Tensor \( C_{6}^{S,V,T} \)

- Neutron and pion ‘beta’ decay operators + ....

** One-loop QCD RGE included for all operators
Lowering the energy scale

\[ \Lambda \sim 2\pi F_\pi \quad 1 \text{ GeV} \]

\[ M_{EW} \quad 100 \text{ GeV} \]

- Hadrons-electron-electron-electron couplings

- Hadronization

- \( \sim c_7 \frac{1}{v^2 \Lambda^3} \)

- \( \sim c_9 \frac{1}{\Lambda^5} \)

- 0νββ operators \( \sim \text{‘dim 9’} \)

- Scalar and Vector operators
Summary of the perturbative part

Hadronization

Now it gets more problematic....
Chiral effective field theory

• Make use of the great progress in ab initio nuclear calculations
  See e.g. single-beta decay spectra  Gysberg et al, Nature ‘19

• Use chiral EFT to match quark-gluon operators to hadronic operators
• Incorporates symmetries of QCD (Lorentz/chiral/isospin/gauge)
• Systematic power counting in

\[ \frac{Q}{\Lambda_\chi} \sim \frac{m_\pi}{\Lambda_\chi} \quad \Lambda_\chi \equiv 1 \text{GeV} \]

• Close and fruitful connection to lattice QCD
• Systematic inclusion of ultrasoft, potential, hard virtual neutrinos
• Treat NN forces and 0vbb currents on the same footing

Prezeau et al’ 03, Cirigliano, JdV et al ‘17 ‘18 ’19

Recent 0vbb EFT without chiral EFT: Graf et al ‘18 Horoi/Neacsu ‘17
The ‘dim 6’ pieces

\[ \Lambda_{\chi} \sim 2\pi F_\pi \]
\[ > 1 \text{ GeV} \]

- LNV operators handled same way
- Scalar, Vector, Tensor
- Change the ‘standard’ chiral sources \((l, r, s, p, t)\) accordingly

\[
\begin{align*}
    l_\mu &= c_7^l \frac{v}{\Lambda^3} \bar{e}_R \gamma^\mu \nu_L^c \tau^+ \\
    r_\mu &= c_7^r \frac{v}{\Lambda^3} \bar{e}_R \gamma^\mu \nu_L^c \tau^+ \\
    s + ip &= c_7^s \frac{v}{\Lambda^3} \bar{e}_L \nu_L^c \tau^+ \\
    t_{\mu\nu} &= c_7^t \frac{v}{\Lambda^3} \bar{e}_L \sigma^{\mu\nu} \nu_L^c \tau^+
\end{align*}
\]

- Need nucleon charges: \(g_A, g_S, g_T, g_M\) (known pretty well)
- One unknown low-energy constant (LEC) at NLO

Cirigliano et al '17
The ‘dim 9’ pieces

\[ \Lambda_\chi \sim 2\pi F_\pi > 1 \text{ GeV} \]

- No standard sources for these terms
- In LR models e.g:

\[
O_4 = \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\alpha + \bar{q}_R^\beta \gamma_\mu \tau^+ q_R^\beta \bar{e}_L C \bar{e}_T^T
\]

\[
O_5 = \bar{q}_L^\alpha \gamma_\mu \tau^+ q_L^\beta \bar{q}_R^\beta \gamma_\mu \tau^+ q_R^\alpha \bar{e}_L C \bar{e}_T^T
\]

- 2 LECs \( g_{4,5} \) ... In principle unknown
- But related by SU(3) to \( K \rightarrow \pi\pi \)
- Lattice for Kaon processes (FLAG ‘16)

\[
g_4 = -(2.5 \pm 1.2) \text{GeV}^2 \quad g_5 = -(11 \pm 4) \text{GeV}^2
\]

- Agrees with direct lattice QCD computation

\[
g_4 = -(1.9 \pm 0.2) \text{GeV}^2 \quad g_5 = -(8 \pm 0.6) \text{GeV}^2
\]

- Color octet operators large.

Prezeau et al ’03
Cirigliano et al ‘16 ‘17
Nicholson et al ‘18
The chiral Lagrangian

\[ L = L_{QCD} + L_{Fermi} - m_{\beta\beta} \nu_L^T C \nu_L + C_\Gamma \bar{\nu} \Gamma \nu^T O_{2q}^\Gamma + C_\Gamma' \bar{e} \Gamma' e^c O_{4q}^\Gamma \]

\[ \sim \text{GeV} \]

\[ \sim 100 \, \text{MeV} \quad \text{Neutrinos are still degrees of freedom in the low-energy EFT} \]

\[ \Delta L=2 \quad \text{Majorana mass} \quad \nu_L \leftrightarrow \nu_L \sim m_{\beta\beta} \]

\[ \Delta L=2 \quad \text{beta decay} \]

\[ \Delta L=2 \quad \text{‘neutrinoless’} \]
The ‘neutrino potential’

• Derive the $nn \to pp + ee$ transition operator order-by-order (LO shown)

• Long-range LECs are known well. Short-distance not at all. **LO problem!**

<table>
<thead>
<tr>
<th>$n \to p\nu\nu, \pi \to e\nu$</th>
<th>$\pi\pi \to ee$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g_A$ 1.271 ± 0.002 [58]</td>
<td>$g_1^{\pi\pi}$ 0.36 ± 0.02 [44]</td>
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<tr>
<td>$g_S$ 0.97 ± 0.13 [59]</td>
<td>$g_2^{\pi\pi}$ 2.0 ± 0.2 GeV$^2$ [44]</td>
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<tr>
<td>$g_M$ 4.7 [58]</td>
<td>$g_3^{\pi\pi}$ -(0.62 ± 0.06) GeV$^2$ [44]</td>
</tr>
<tr>
<td>$g_T$ 0.99 ± 0.06 [59]</td>
<td>$g_4^{\pi\pi}$ -(1.9 ± 0.2) GeV$^2$ [44]</td>
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<td>$</td>
<td>g_T^{\nu}</td>
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<tr>
<td>$g_T^{\nu}$ 2.7 GeV</td>
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<td>$</td>
<td>g_T^{NN}</td>
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<td>$</td>
<td>g_S^{NN},s,0</td>
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<td>$</td>
<td>g_{VL}^{NN}</td>
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<td>g_{TN}^{NN}</td>
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<td>$</td>
<td>g_{FR}^{NN}</td>
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<td>$</td>
<td>g_{V_{LR}}^{NN}</td>
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<td>g_{3,3,3,3}</td>
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Active lattice QCD efforts to determine LECs

Nicholson et al ’18
Tuo et al ‘19
Detmold, Murphy ‘20
The neutrinoless decay rate

Decay rate \( \Gamma \sim \int d^3k_1 d^3k_2 |A|^2 F(Z,E_1) F(Z,E_2) \delta(E_1 + E_2 + E_f - M_i) \)

- **Amplitude** \( A = \sum_i \langle 0^+ | V^i_v | 0^+ \rangle \otimes \bar{e}(k_1) \Gamma^i_e e^c(k_2) \)

- Electron phase space integrals are known Kotila/Iachello ‘12, Stefanik et al ‘14

- **Nuclear Mattix Elements (NMEs)** \( M_i = \langle 0^+ | V^i_v | 0^+ \rangle \)

- **All NMEs for non-standard LNV contained in ‘standard’ mechanism**

- **Can use existing calculations:**  
  - **QPRA** (Hyvarinen/Suhonen ‘15)  
  - **Shell model** (Horoi/Neacsu ‘17 & Menendez ’17)  
  - **IBM** (Barea et al ’15)

- Going towards first-principle ChEFT calculations Yao et al, PRL ‘20
Many-body uncertainties for SM-EFT

- Leading-order requires 9 combinations of NMEs
- Uncertainties similar to standard scenario
- Short-distance matrix elements more ‘spread’ in the applied method
Chiral symmetry matters

- Chiral properties important to include! Example:

\[ L = \left[ C_2 \bar{u}_L d_R \bar{u}_L d_R + C_3 \bar{u}_L^\alpha d_R^\beta \bar{u}_L^\alpha d_R^\beta \right] \]

- Large contributions from pi-pi effects

\[ M = \frac{-1}{2m_N^2} (C_2 g_2^{\pi\pi} + C_3 g_3^{\pi\pi}) \left( \frac{1}{2} M_{GT, sd}^{AP} + M_{GT, sd}^{PP} \right) \approx 0.3 C_2 - 0.1 C_3 \]

- Non-chiral approach based on factorization

\[ \langle pp|L|nn\rangle = C_2 \langle p|\bar{u}_L d_R|n\rangle \langle p|\bar{u}_L d_R|n\rangle = \frac{g_s^2}{4} \bar{p}n\bar{p}n \]

- Insert short-distance NME

\[ M_{fac} = \frac{-g_s^2}{2g_A^2 m_N^2} C_2 \; M_{F,sd} \approx 10^{-3} \; C_2 \]

- Misses contributions by factor 100 and ignores the color octet operators
‘The neutrinoless double-beta metro map’

Energy

1. \(\bar{\text{dim}} - 5\)
2. \(\bar{\text{dim}} - 7\)
3. \(\bar{\text{dim}} - 9\)

\(\Lambda\)

SM-EFT

\(m_{\beta\beta}: \nu \rightarrow \nu^c\)

\(d \rightarrow ue\nu\)

\(d \rightarrow ue\nu \otimes \partial_\mu\)

\(dd \rightarrow uuee\)

\(\sim 100\,\text{GeV}\)

\(\sim 1\,\text{GeV}\)

\(\sim 100\,\text{MeV}\)

\(\sim 1\,\text{MeV}\)

ChiPT

\(\nu \rightarrow \nu^c\)

\(n \rightarrow p e\nu\)

\(\pi \rightarrow e\nu\)

\(nn \rightarrow p p e e\)

\(n \rightarrow p e\pi e\)

\(\pi\pi \rightarrow e e\)

\(\text{Match to ChiPT (LECs in Table 1)}\)

\(\text{Construct } 0\nu\beta\beta\text{ operators (Eq. 24)}\)

\(\text{NMEs (Table 2)}\)

\(\text{Phase space integrals (Table 4)}\)

\(\text{Master formula (Eq. 38)}\)

\(\mathcal{M}_F, \mathcal{M}_{AA,AP,PP,MM}\)

\(\mathcal{M}_{F,\text{sd}}, \mathcal{M}_{GT,\text{sd}}, \mathcal{M}_{AP,PP,MM}\)

Many body Methods

Mathematica notebook walks through steps automatically
Limits on LNV sources

- **KAMLAND limit** $T_{1/2}^{0\nu}(^{136}Xe \rightarrow ^{136}Ba) > 1.07 \times 10^{26}$ yr

- **Dim-7 operators** $C_7 \sim (\nu/\Lambda)^3$ are probed at 10-100 TeV

- **Dim-9 operators** $C_9 \sim (\nu/\Lambda)^5$ are probed at few TeV

- Difference between operators due to chiral/phase space suppression factors

![Graph showing limits on LNV sources with different operators](image-url)
Phenomenology

• Particular dimension-7 operator (e.g. appearing in eptoquark models)

\[ C_7 \sim (\nu / \Lambda)^3 \]
\[ \Lambda > 400 \text{ TeV} \]
\[ \Lambda_{LHC} > 5 \text{ TeV} \]

• Operator has same ‘leptonic’ structure as standard mechanism

• Interference with Majorana mass: interpretation needs care
Phenomenology

• Particular dimension-7 operator (e.g. appearing in eptoquark models)

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\[ \Lambda_{LHC} > 5 \text{ TeV} \]

• Operator has \textit{same} ‘\textit{leptonic}’ structure as standard mechanism

• Interference with Majorana mass: \textit{interpretation needs care}

• Signal in next-generation does not mean inverse hierarchy per se
Disentangling LNV sources

- A single measurement can be from any LNV operator
- Isotope ratios not too discriminating (NME uncertainties)
- Instead: **angular & energy** distributions of the outgoing electrons
- This might be science fiction for now

\[ C_7 \sim (v / \Lambda)^3 e^{i \alpha} \]

\[ \nu_L \leftrightarrow \nu_L \]

\[ d \leftarrow \nu_L \rightarrow u \]

\[ \nu_L \rightarrow e_R \]

- Of course if scale is low, we can use other probes of LNV (e.g. LHC)

References:
- Fogli et al '09
- Lisi et al '15
- Cirigliano et al '17
An example: LR model

See Juan’s talk next!

\[ y_e \sim \frac{m_e}{v} \]

\[ \Delta L = 2 \]

Mohapatra, Pati, Salam, Senjanovic ’75
Prezeau et al ‘03
Nemevsek et al ’11
Cirigliano et al ‘18

SU(3)xSU(2)xU(1) invariant EFT

Naively of similar size for \( \Lambda = 1-10 \text{ TeV} \)
- **Part I:** Non-standard mechanisms for 0vbb and the SM-EFT

![Diagram showing non-standard mechanisms](image1)

- **Part II:** Low-scale seesaw and 0vbb

![Diagram showing low-scale seesaw](image2)
The role of light (almost) sterile neutrinos

- If Yukawa couplings are small (and why not?) \( v_R \) could appear at any scale

- Sterile neutrinos could interact with decoupled BSM sector (e.g. mLRSM)
- Can be described in the neutrino-extended SMEFT

\[
L = L_{SMEFT} - \frac{1}{2} v_R^c M_R v_R - \bar{\nu}_D \nu_R \bar{H} + L_{6, v_R} + L_{7, v_R}
\]

- Repeat all EFT steps but include sterile neutrinos explicitly
- Main complication: \textit{neutrino mass dependence of matrix elements}

Akhmedov et al ‘98
Canetti et al ‘12
Drewes/Garbrecht ‘15

del Aguil et al ’08, Aparici et al ’09, Bhattacharya/Wudka ‘15, Liao/Ma ‘16 Cai et al ‘17, Chala et al ‘21
In the small and large regimes, we have clear QCD guidance

Interpolate middle region: non-trivial $m_{\nu_R}$-dependence
Mass dependence of the NMEs

- The nuclear matrix elements seem to have a simple $m_i$ dependence

\[
h_K^{ab}(r, m_i) = \frac{2}{\pi} R_A \int_0^\infty d|q| \frac{q^2}{q^2 + m_i^2} h_K^{ab}(q^2) j_\lambda(|q|r) .
\]

Blennow, Fernandez-Martinez, Lopez-Pavon, Menendez ’14

See also: Faessler et al ‘09 , Kovalenko et al ’09, Barea et al ‘15
Consider for simplicity a 3+1 model with sterile mass $m_i$

Say $m_i$ small compared to nuclear scale $k_F \sim p \sim 100$ MeV

\[
\frac{1}{p^2 - m_i^2} = \frac{1}{p^2} + \frac{m_i^2}{p^4} + \mathcal{O}\left(\frac{m_i^4}{p^8}\right)
\]

\[
M_{\nu\beta\beta}(m_i) = M_{\nu\beta\beta}(0) \left[1 + \frac{m_i^2}{p^2} + \mathcal{O}\left(\frac{m_i^4}{p^4}\right)\right]
\]

Then in minimal see-saw the leading contributions vanish (unitarity)

Corrections scale as

\[
\sum_{i=1}^{4} m_i U_{ei}^2 = 0,
\]

\[
\sum_{i=1}^{4} U_{ei}^2 m_i^3/k_F^2 \neq 0
\]

e.g. Bolton et al ‘19

Seem to scale as $m_i^3$ in small $m_i$ regime (used in phenomenological studies)
Minimal-see-saw corrections

- Consider for simplicity a 3+1 model with sterile mass $m_i$
- Say $m_i$ small compared to nuclear scale $k_F \sim p \sim 100$ MeV

\[ \frac{1}{p^2 - m_i^2} = \frac{1}{p^2} + \frac{m_i^2}{p^4} + O\left(\frac{m_i^4}{p^8}\right) \]

\[ M^{\nu\beta\beta}(m_i) = M^{\nu\beta\beta}(0)\left[1 + \frac{m_i^2}{p^2} + O\left(\frac{m_i^4}{p^4}\right)\right] \]

- Then in minimal see-saw the leading contributions vanish (unitarity)

\[ \sum_{i=1}^{4} m_i U_{ei}^2 = 0, \quad \sum_{i=1}^{4} U_{ei}^2 m_i^3 / k_F^2 \neq 0 \]

- Seem to scale as $m_i^3$ in small $m_i$ regime (used in phenomenological studies)
- **This might be too simple**! Careful when LO pieces vanish!
- EFT analysis shows contributions from ultrasoft neutrinos ($p_i \sim m_i \sim k_F^2 / m_N$)

\[ \sum_n \int \frac{d^{d-1}k}{(2\pi)^{d-1}} \frac{1}{E_\nu} \left[ \frac{\langle f|J_\mu|n\rangle\langle n|J^\mu|i\rangle}{E_\nu + E_2 + E_n - E_i - i\varepsilon} + \frac{\langle f|J_\mu|n\rangle\langle n|J^\mu|i\rangle}{E_\nu + E_1 + E_n - E_i - i\varepsilon} \right] \]

- **Work in progress**, but we find $m_i^2 / (k_F^2)$ and $m_i \log (m_i^2)$ corrections
- Enhanced sensitivity to $O($KeV-MeV$)$ neutrinos in minimal see-saw?
Mass dependence of LECs

- Example mLRSM: mass eigenstates with LH + RH interactions
- If $m_i \gg \text{GeV}$, integrate it out and obtain dim-9 operators. E.g.:

  \[
  L = \frac{1}{m_i} [C_4 \bar{u}_L \gamma^\mu d_L \bar{u}_R \gamma_\mu d_R] \bar{e}_L C \bar{e}_L^T
  \]

  - Lead to the ‘pionic’ operator with known LEC: $g_4^{\pi\pi}$
- If $m_{vR} \ll \text{MeV}$, then long-distance and ‘hard’ neutrino contributions
- ‘Hard’ neutrino exchange directly related to EM pion mass splitting

\[
g^{\pi\pi}_{LR}(m_i = 0) = \frac{m_{\pi^\pm}^2 - m_{\pi^0}^2}{2e^2} \approx 0.8F_\pi^2
\]

- If we increase $m_i$ the amplitudes must match

\[
g_4^{\pi\pi} = -4 \frac{m_i^2 g^{\pi\pi}_{LR}(m_i)}{F_\pi^2} \bigg|_{m_i \geq \Lambda_X}
\]

- This requires a non-trivial mass dependence of LECs.
- Dispersive (Knecht et al ‘98, Braaten et al ‘92) + matching to obtain the implicit $m_i$ dependence of hadronic low-energy constants
Combine NMEs + LECs

- Uncertainties from LECs and NMEs (similar sized)
- Non-trivial behaviour due to $m_\nu$ dependence of QCD matrix elements
- ‘Standard mechanism’ similar to previous interpolations
- Non-standard mechanisms can show enhanced sensitivity to GeV neutrinos

Dekens et al ‘20

Barea et al ‘15
Illustration of the framework

- Consider a simple toy-model 3+1 sterile (not realistic: 2 massless neutrinos)
- Too small 0vbb rates in minimal scenario
- Disclaimer: small neutrino regime $m_{\nu R} \ll \text{MeV}$ not too reliable perhaps
Illustration of the framework

- Consider a simple toy-model 3+1 sterile (not realistic: 2 massless neutrinos)
- Too small $0vbb$ rates in minimal scenario
- Disclaimer: small neutrino regime $m_{\nu_R} <<$ MeV not too reliable perhaps
- Sensitivity to non-standard interactions? Example: leptoquarks

\[ \mathcal{L}^{(6)}_{\Delta L=0} = \frac{2G_F}{\sqrt{2}} \left[ c_{SR}^{(6)} \bar{d}_R \sigma_{\mu\nu} \bar{e}_{L\mu} \nu_{Ra} + c_{Ta}^{(6)} \bar{u}_L \sigma_{\mu\nu} d_{R\mu} \sigma_{\nu\nu} \nu_{Ra} \right] \]

\[ \mathcal{L}_{LQ} = -y_{ab}^{RL} \bar{d}_R \tilde{R}^i \epsilon_{ij} L^j_{Lb} + y_{ab}^{LR} \bar{Q}_{La} \tilde{R}^i \nu_{Rb} \]

- Just an illustration: can be matched to any non-standard interaction

![Graph](image1)

![Graph](image2)
3+2 models

- More realistic 3+2 model fitted to mass splitting and oscillation data
- Other angles/phases chosen as O(1) (no scan)

In general, nEXO cannot probe minimal 3+2 models in NH
3+2 models + non-standard interaction

- Non-standard interactions at 10-100 TeV depending on sterile masses
- Framework is setup to study any model with light or heavy sterile neutrinos
- **Plan: make code public and provide ready-to-use tool**
- Useable in global analysis of vSMEFT with LHC/Cosmology/Flavor
Conclusion/Summary

**Neutrinoless Double Beta Decay**

- Powerful search for BSM physics (probe high scales)
- Well motivated in order to probe nature of neutrino masses
- However, complicated low-energy observable

**Standard Model EFT and chiral EFT frameworks**

- Keep track of **symmetries** (gauge/lepton# / chiral) from Tev to nuclear scales
- Chiral EFT to organize neutrino potential in systematic fashion
- Light sterile neutrinos included but complicate matters!

**Phenomenology**

- Current experiments set very strong limits (>500 TeV in some cases)
- Differential measurements can disentangle certain sources
- Sterile neutrinos at MeV-GeV scale lead to interesting pheno
Derive the ‘neutrino potential’

• Similar derivation for ‘non-standard’ LNV terms. More topologies:

\[ \begin{align*}
\text{A} &:& n \rightarrow p \rightarrow e \rightarrow n \\
\text{B} &:& n \rightarrow p \rightarrow e \rightarrow n \\
\text{C} &:& n \rightarrow e \rightarrow p \rightarrow n \\
\end{align*} \]

• The long-range LECs are known pretty well. Short-distance not at all.
• Unfortunately, long-distance processes (A & B) are not physical by themselves.

\[ \sim m_N^2 \int \frac{d^3q d^3k}{m_N E - q^2} \frac{1}{(q - k)^2} \frac{1}{m_N E' - k'^2} \]

• Integrals are divergent and topology ‘C’ is always leading order!
• See Vincenzo’s slides from Monday for more details
• Higher-order corrections from: pion loops, N^2LO LECs, closure corrections