# Determining the leading-order contact term induced by sterile neutrinos in neutrinoless double $\beta$ decay

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Based on: *V. Cirigliano, W. Dekens,* ***SUQ****, JHEP 04 (2025) 181*

# Neutrino Mass and New Physics

- $M_\nu \neq 0$ requires introducing new degrees of freedom

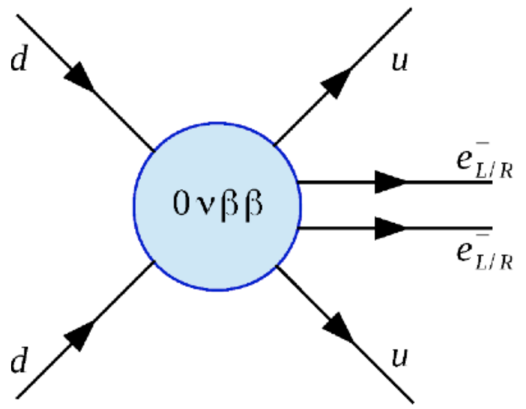
$$\mathscr{L}_{\nu\mathrm{SM}} = \mathscr{L}_{\mathrm{SM}} + \mathscr{L}_{\nu-\mathrm{mass}} + \ldots$$

- **Key questions:**
  - ➡ *Is Lepton Number a good symmetry of the new dynamics?*
  - ➡ *What are the sources and mediators of Lepton Flavor Violation?*

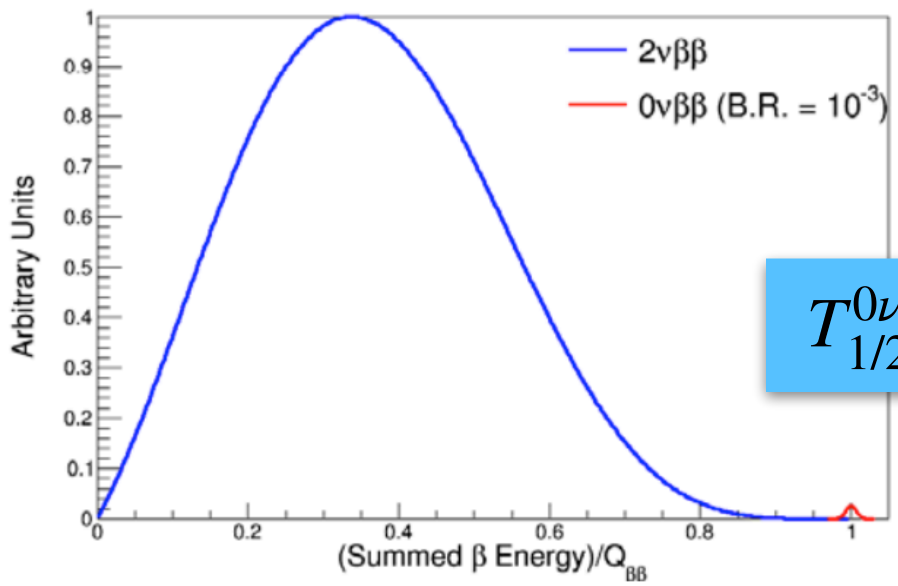
- Nuclear probes can address these questions:
  - ➡ Neutrinoless double beta decay $(0\nu\beta\beta)$ is the strongest probe of LNV
  - ➡ $\mu \to e$ in nuclei and $ep \to \tau X$ @ EIC are powerful probes of LFV

# $0\nu\beta\beta$ and Lepton Number Violation

$$(N, Z) \to (N-2, Z+2) + 2e^-$$



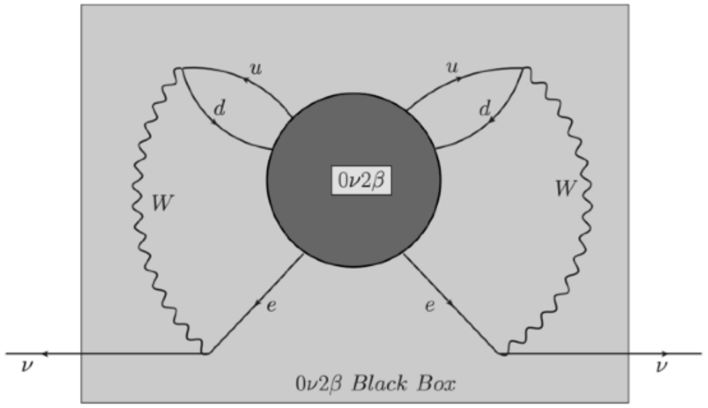

$$\Delta L = 2$$




$T^{0\nu}_{1/2} \gtrsim 10^{26}$ yr

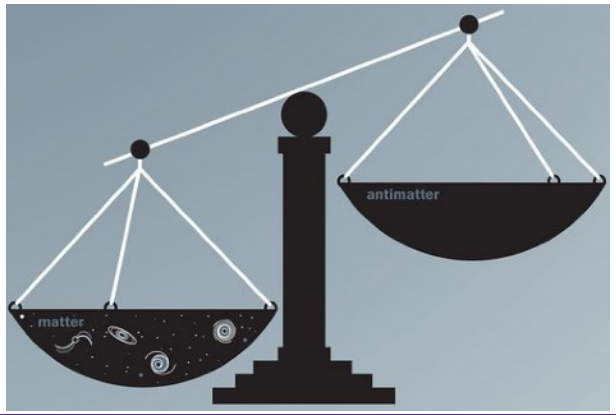
- $(B-L)$ conserved in SM $\to$ $0\nu\beta\beta$ observation would signal new physics

✔ Demonstrate that neutrinos are Majorana fermions




Schechter-Valle 1982

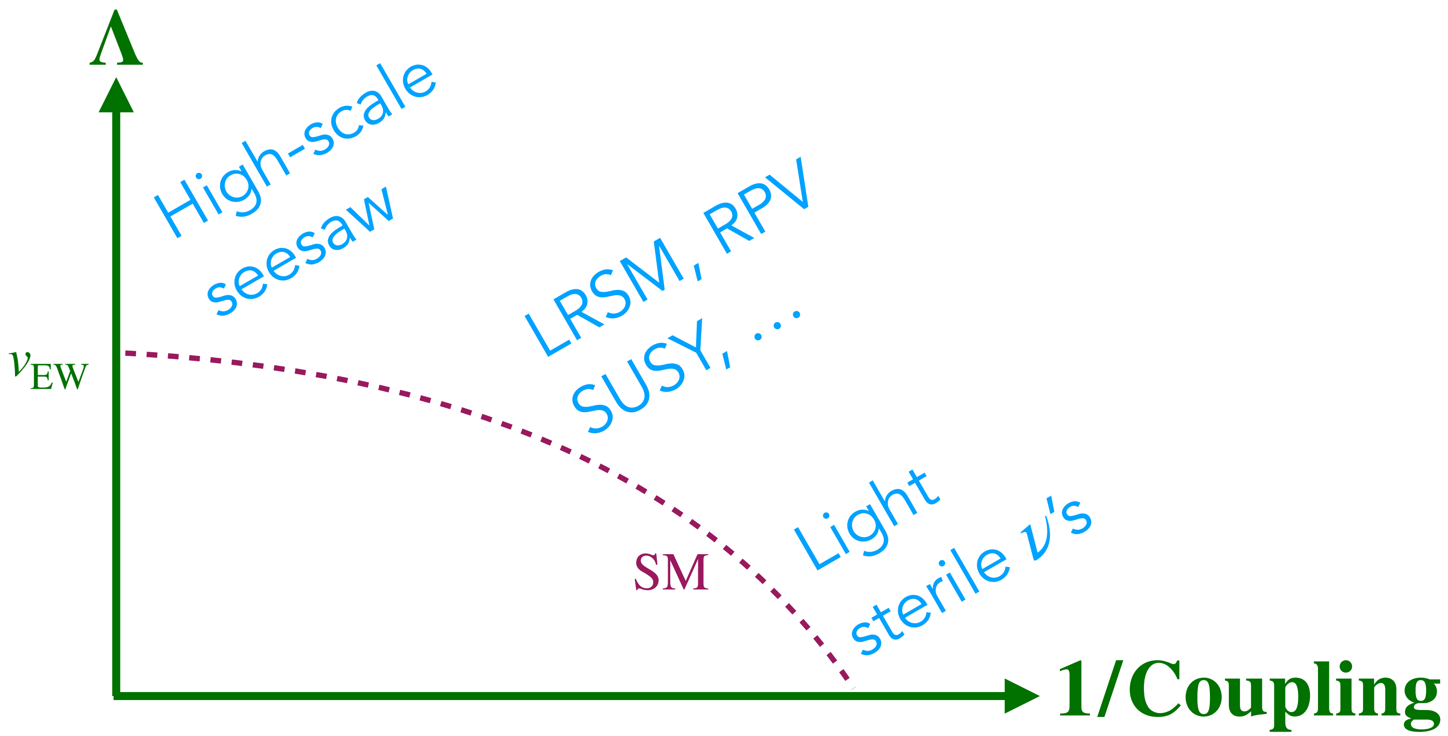
✔ Establish a key ingredient to generate the baryon asymmetry via leptogenesis




Fukugita-Yanagida 1987

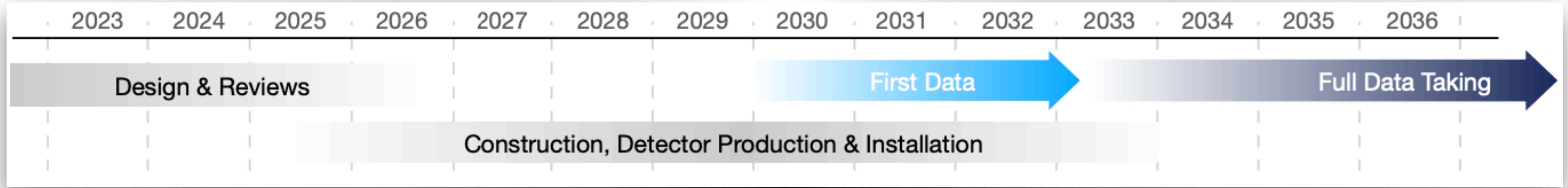
# $0\nu\beta\beta$ — Physics Reach

- Ton-scale $0\nu\beta\beta$ searches $(T_{1/2}^{0\nu} > 10^{27-28}\,\text{yr})$ will probe LNV at unprecedented levels from a broad range of mechanisms



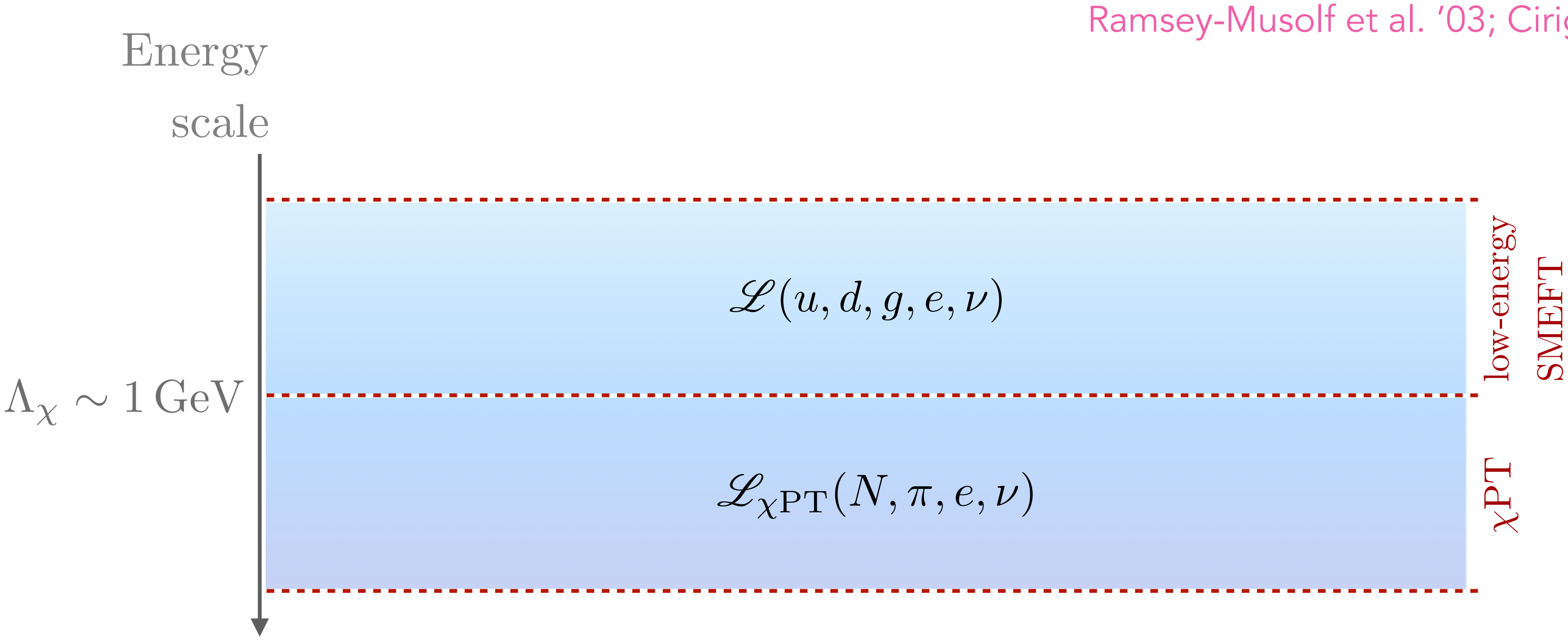

Impact of $0\nu\beta\beta$ searches most efficiently analyzed within an "end-to-end" EFT framework: connecting new physics at the scale $\Lambda$ to nuclear scales, with controllable uncertainties!

Notional schedule of the LEGEND-1000 experiment



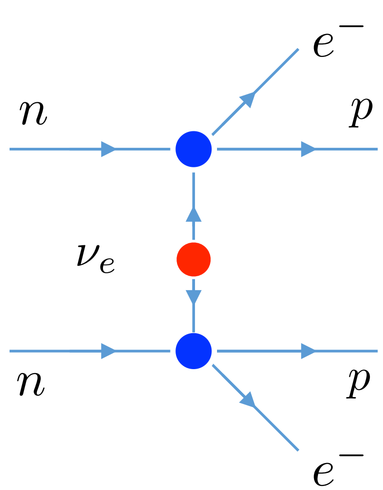
# $0\nu\beta\beta$: from quarks to nuclei using EFT

Ramsey-Musolf et al. '03; Cirigliano et al. '17; Detmold et al. 22'; Nicholson et al. 18'




- ➡ The operators' structure is determined by chiral symmetry
- ➡ Each of them is accompanied by unknown constants (LECs)
- ➡ They are organized according to power-counting in $Q/\Lambda_\chi$

## Leading order $0\nu\beta\beta$ operators

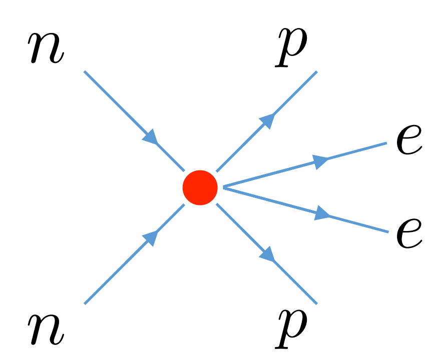



Hadronic input:
$g_A$

Tree-level exchange of Majorana neutrinos

LEC:
$g_\nu^{NN} \sim 1/(4\pi F_\pi)^2$ in NDA/Weinberg

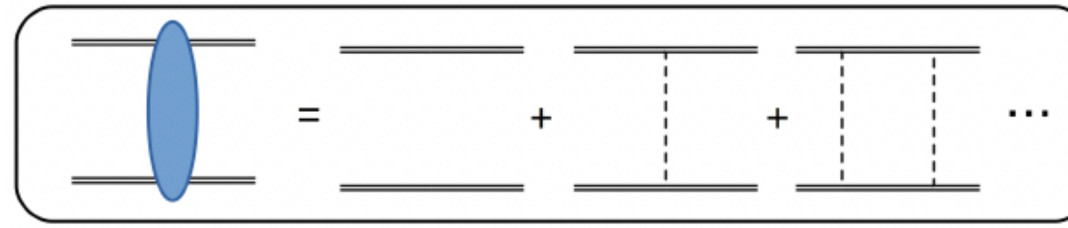
*Sub-dominant?*

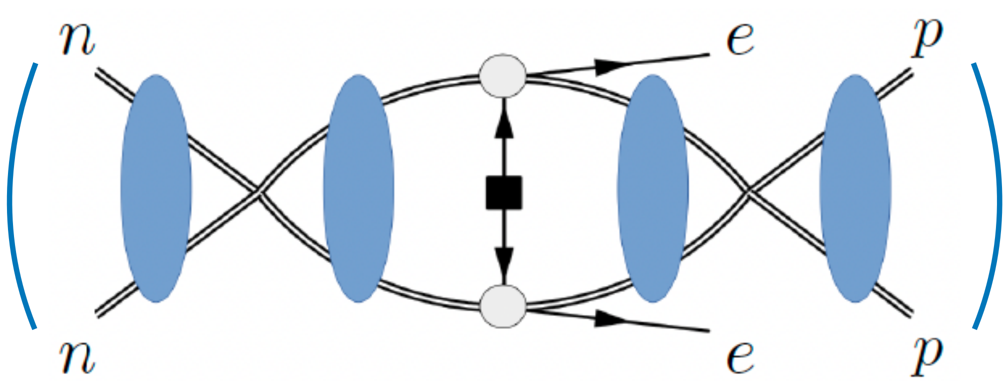



Chiral symmetry also allows a contact term

# Checking $nn \to ppe^- e^-$

**$nn \to pp$ amplitude: LNV + strong interactions**




$$\mathrm{Re}\left( \cdots \right) = -\left(\frac{m_N^2}{4\pi}\right)^2 \frac{(1+2g_A^2)}{2}\left[\log\left(\frac{\mu_\chi^2}{|\mathbf{p}|_{\mathrm{ext}}^2}\right)+1\right] + \text{ finite}$$

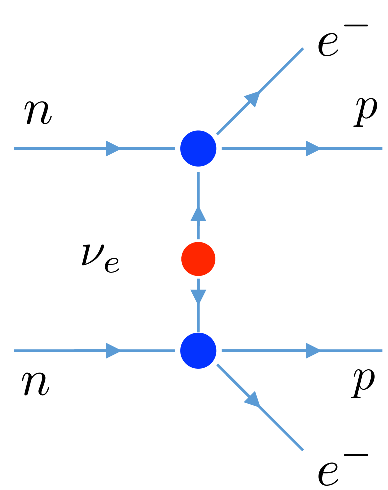
$V_S(\mathbf{p},\mathbf{p}') = C + (C_2/2)(\mathbf{p}^2 + \mathbf{p}'^2)$

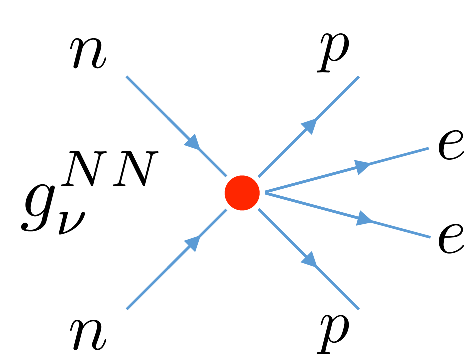
$|\mathbf{p}|_{\mathrm{ext}} \equiv |\mathbf{p}| + |\mathbf{p}'|$

- Some diagrams are divergent! Here $\mu_\chi$ is the renormalization scale in $\overline{\mathrm{MS}}$
- New interaction is needed at **LO** to get physical amplitudes:

$$\mathcal{L}_{CT} = 2G_F^2 V_{ud}^2 m_{\beta\beta}\, g_\nu^{NN}\, \bar{p}n\, \bar{p}n\, \bar{e}_L C \bar{e}_L^T$$

$$V_{\Delta L=2} = V_\nu + V_{\nu,CT} =$$




$g_\nu^{NN}$ TBD from Lattice QCD; active area of research!

- Davoudi & Kadam '20, '21
- Feng et al. '20

Cirigliano et al. '18, '19

# Challenge: determining $g_\nu^{NN}$

Analytical Approach — Cirigliano et al. '20, '21; Cirigliano, Dekens, SUQ, '24

- Analogy to the Cottingham approach for pion/nucleon mass differences — W. Cottingham '63; H. Harari '66

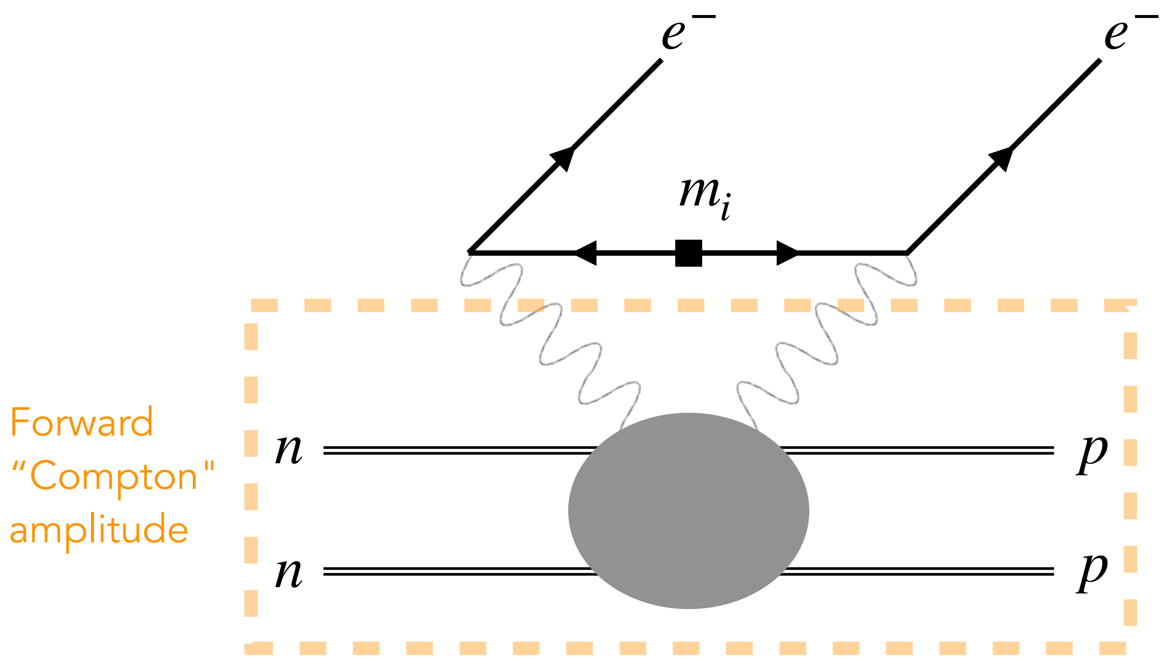
- $\Delta L = 2$ amplitudes controlled by neutrinoless effective action:

$$\langle e_1^- e_2^- pp \,|\, S_{\rm eff}^{\Delta L=2} \,|\, nn\rangle = (2\pi)^4\, \delta^{(4)}(p_f - p_i)\Big(4G_F^2 V_{ud}^2\ \bar{u}_L(p_1) u_L^c(p_2)\Big) \times \sum_{i=1}^{3+n} U_{ei}^2\, m_i\, \mathcal{A}_\nu(m_i)$$

$$\mathcal{A}_\nu(m_i) \propto \int \frac{d^4k}{(2\pi)^4} \frac{g_{\mu\nu}}{k^2 - m_i^2 + i\epsilon} \int d^4x\ e^{ik\cdot x} \langle pp \,|\, T\{J_W^\mu(x)\, J_W^\nu(0)\} \,|\, nn\rangle$$

✓ For a generic Majorana neutrino (active or sterile) with mass $m_i \lesssim \Lambda_\chi$

✓ Results valid for limit $m_i \to 0$



# Challenge: determining $g_\nu^{NN}$

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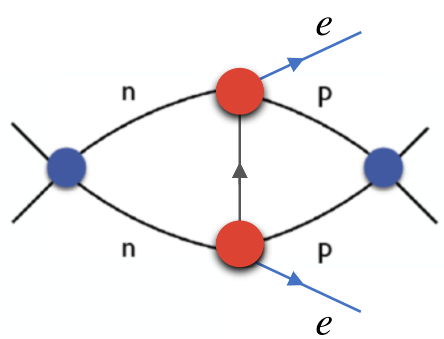
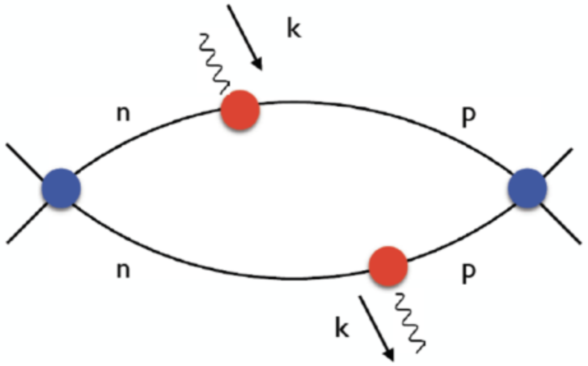
- Matching at the amplitude level:

$$\mathcal{A}_\nu^{\chi\mathrm{EFT}}(m_i) = \mathcal{A}_\nu^{\mathrm{full}}(m_i) \qquad \overline{\mathcal{A}}_X \equiv \left(\frac{4\pi}{m_N}\right)^2 \mathcal{A}_X$$

$\mathcal{A}_\nu^{\mathrm{full}}(m_i) =$ 

$\propto \int d|\mathbf{k}|\, a(|\mathbf{k}|, m_i) = \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2 - m_i^2 + i\epsilon} \times$ 

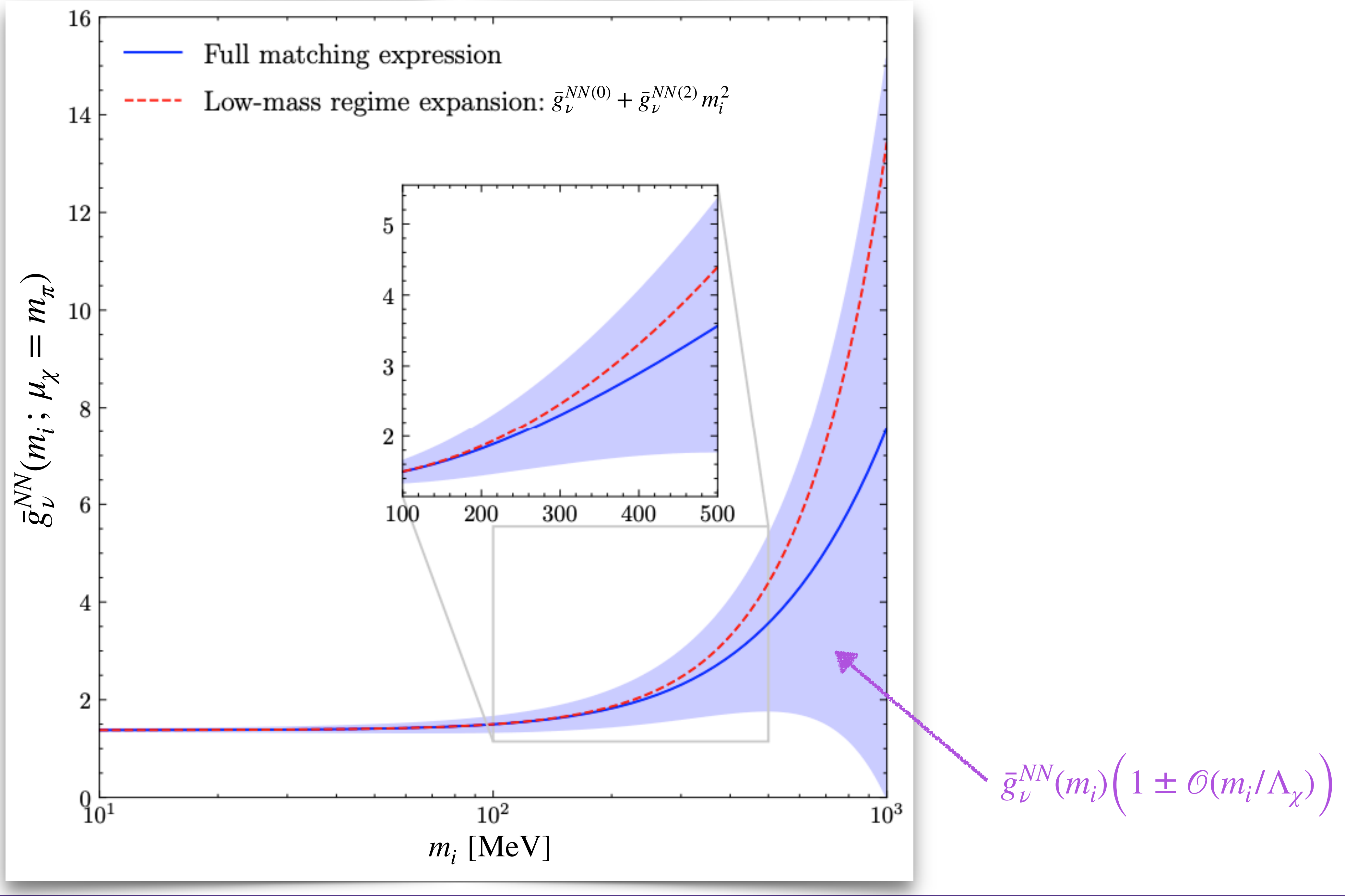

- Estimation of $\mathcal{A}_\nu^{\mathrm{full}}$ by modeling integrand:
  - The region $|\mathbf{k}| \ll \Lambda_\chi$ is determined by $\chi$EFT
  - The region $|\mathbf{k}| \gg \mathcal{O}(\mathrm{GeV})$ matches the OPE
  - The intermediate region is modeled using
    - Form factors
    - Off-shell effects from $NN$ intermediate states

- Challenges of the $\mathcal{A}_\nu^{\chi\mathrm{EFT}}$ calculation:
  - The behavior of $g_\nu^{NN}(m_i)$ is expected to be corrected by terms of $\mathcal{O}(m_i/\Lambda_\chi)$ that we do not control

# Determining $g_\nu^{NN}$ — Results

Since the small-$m_i$ behavior is phenomenologically interesting, we provide the explicit first few terms for the expansion in the IR limit of $m_i \ll \lambda < \Lambda$:

$$\bar{g}_\nu^{NN}(m_i\,;\,\mu_\chi = m_\pi) = 1.377 + \left(\frac{12.062}{\text{GeV}^2}\right) m_i^2 + \left(\frac{-16.735}{\text{GeV}^4}\right) m_i^4$$



# Example: A minimal $\nu_R$ scenario

- Add $n$ singlets, $\nu_R$, to the SM:

$$\mathcal{L}_{\nu_R} = \mathrm{i}\bar{\nu}_R \partial\!\!\!/ \nu_R - \frac{1}{2}\bar{\nu}_R^c M_R \nu_R - Y_D \bar{L}\tilde{H}\nu_R + \cancel{\mathcal{L}^{(6)}_{\nu_R} + \mathcal{L}^{(7)}_{\nu_R}}$$

- After EWSB,

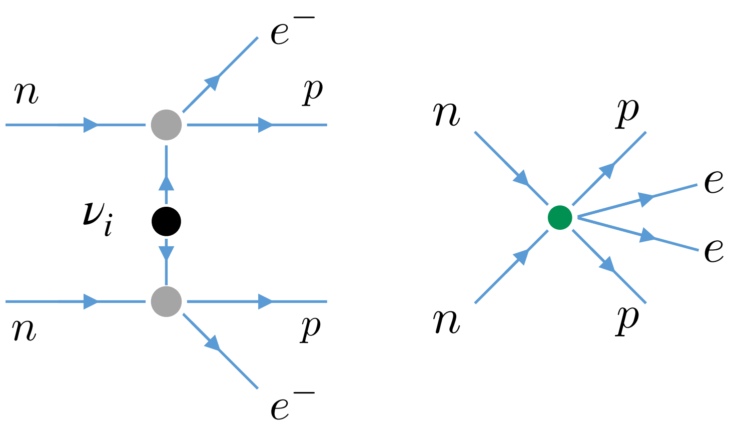
$$\mathcal{L}_{\text{mass}} = \frac{1}{2}\bar{N}^c M_\nu N \qquad N = \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} \qquad M_\nu = \begin{pmatrix} 0 & \frac{v}{\sqrt{2}} Y_D \\ \frac{v}{\sqrt{2}} Y_D & M_R^\dagger \end{pmatrix} \qquad \nu_{\text{mass}} = U N_{\text{flavor}}$$

- $0\nu\beta\beta$ contributions:

**`Usual' contributions:**

- Similar to $m_{\beta\beta}$ case

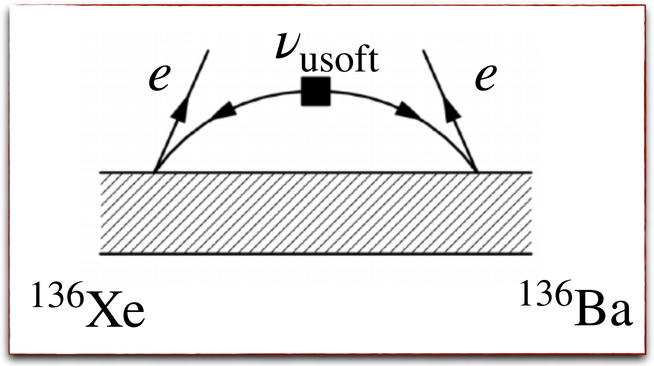
  ➡ NMEs and LECs are now $m_i$ dependent




**New: `Ultrasoft' neutrinos:**

- See the nucleus as a whole, have momenta $q^0 \sim |\vec{q}\,| \sim k_F^2/m_N \sim Q$

  Cirigliano et al., '17; Castillo et al.,'23, '24



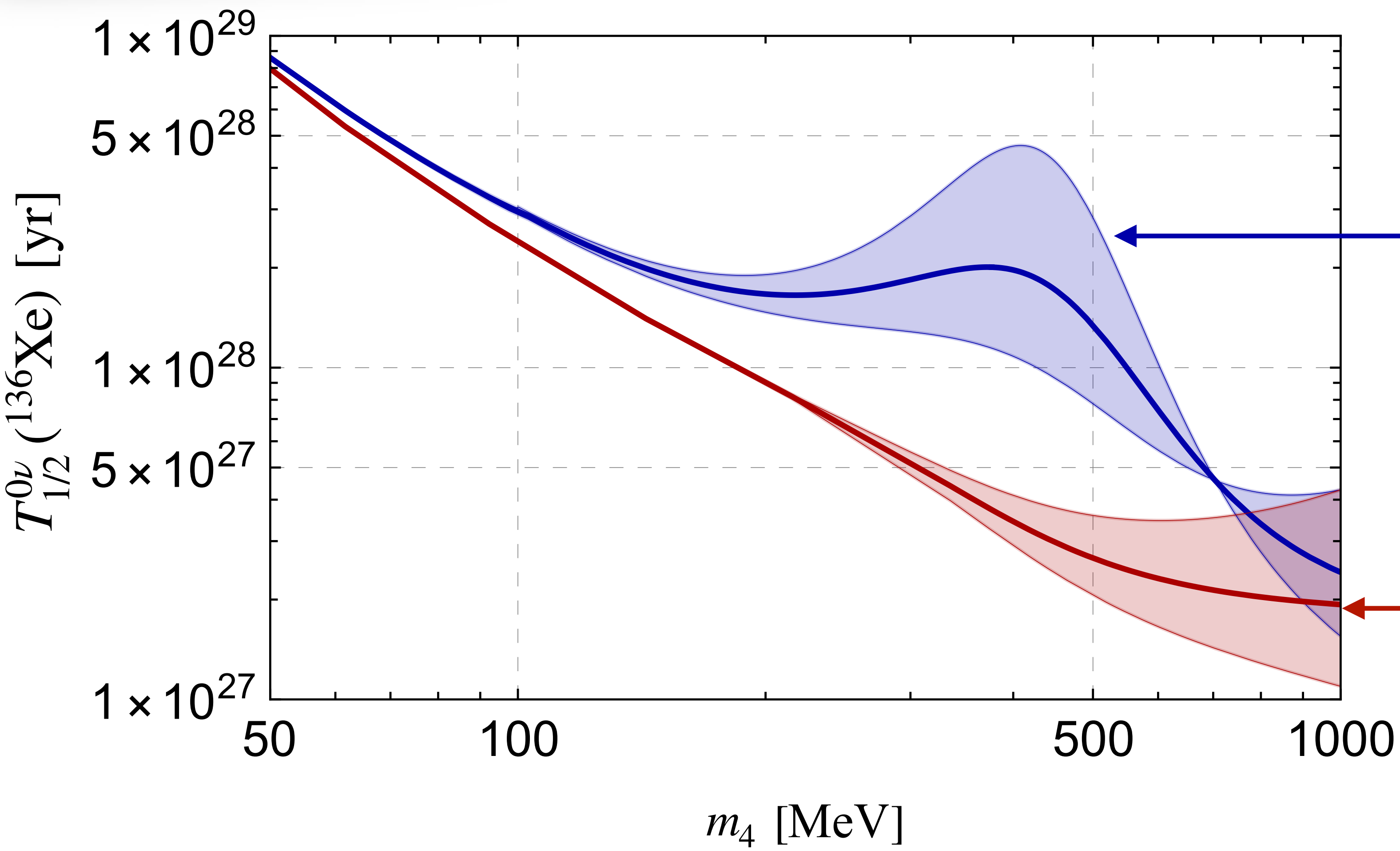
# Example: Minimalistic minimal scenario (3 + 1)

- Add just **one** sterile neutrino to the SM
  - ➡ Assume a simple mass matrix

$$M_\nu = \begin{pmatrix} 0 & 0 & 0 & M_D \\ 0 & 0 & 0 & M_D \\ 0 & 0 & 0 & M_D \\ M_D & M_D & M_D & M_R \end{pmatrix}$$

❎ Not realistic:
- It does not reproduce all neutrino masses/mixings

✅ Simple scenario to test the impact:
- Similar features to more realistic cases




Adding $g_\nu^{NN}(m_4)$ to the interpolation formula

Interpolation formula between $g_\nu^{NN}(0)$ and $\sim m_i^{-2}$ scaling region

Dekens et al. [2402.07993]

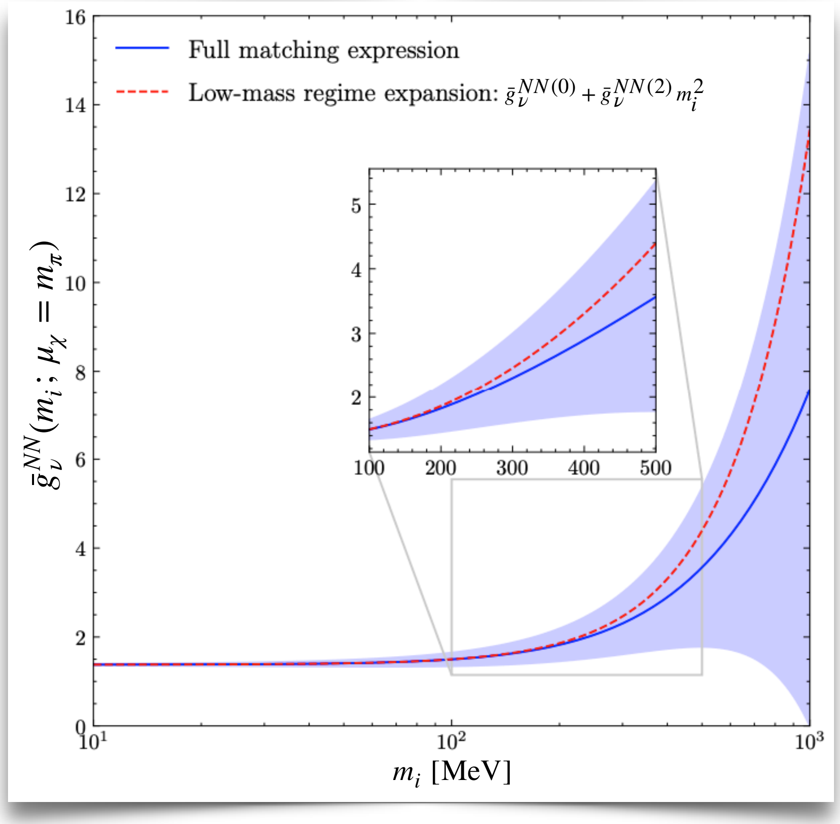
# Summary

- Combining EFTs and the Cottingham-like matching strategy successfully determined the mass dependence of the short-range $nn \to pp$ effective couplings

  ✓ Generalizing the previous massless results

  ✓ Subtleties in the matching analysis from the IR

  ✓ Explicit expansion in powers of $m_i$




- Impact in $0\nu\beta\beta$ predictions from sterile neutrino models: $\nu$SM

  ✓ Significant modifications by including $g_\nu^{NN}(m_i)$