Neutrinoless double beta decay with sterile neutrinos

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ArXiv: 2002.07182 accepted by JHEP

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Topical Collaboration Meeting

Outline :

1. Introduction

   - *Sterile neutrino*

2. Neutrinoless double beta decay

3. Application to Leptoquark

4. Summary

Introduction

Sterile neutrino

Hypothetical right-handed neutrino : ν_R

~ Gauge singlet

Yukawa *Mass*

$$\mathcal{L}_{\nu_R} = -Y_\nu \bar{L}\tilde{H}\nu_R - \frac{1}{2}\overline{\nu_R^c} M_R \nu_R + \text{H.C}$$

✦ *Neutrino (Majorana) mass*

$$\mathcal{L}_{\text{mass}} = -\frac{1}{2}\bar{\nu} m_\nu \nu$$

$$(\nu = \nu^c)$$

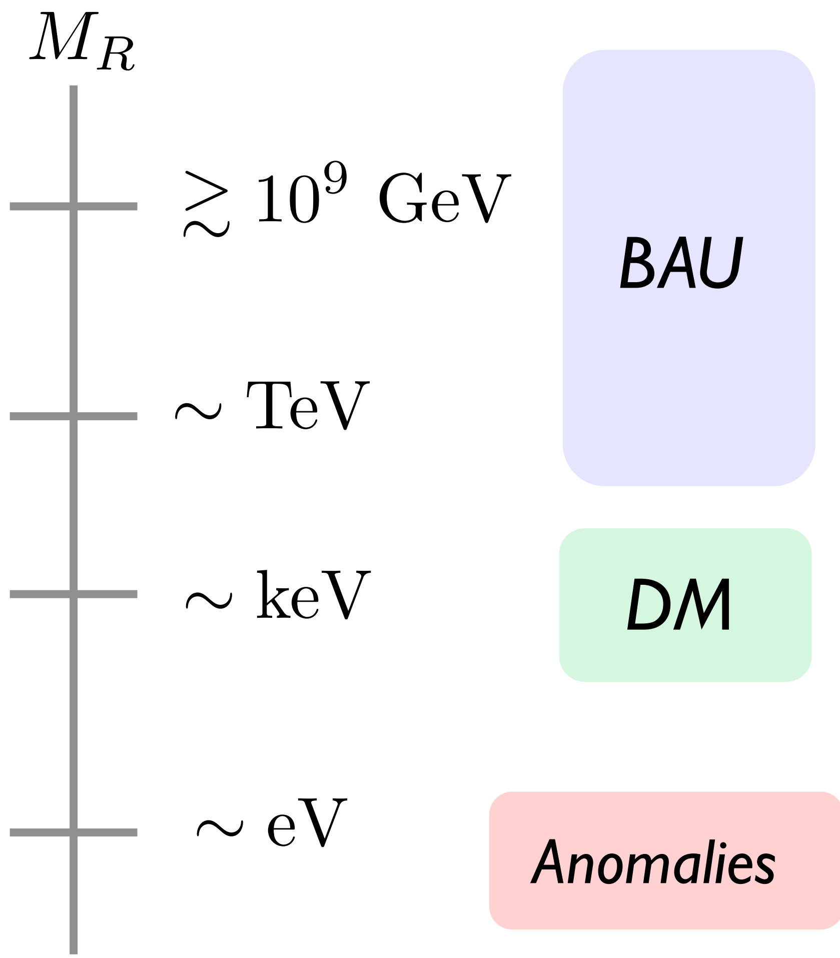
$$m_\nu \sim \frac{Y_\nu^2 v^2}{M_R}$$

$$v \simeq 246 \text{ GeV}$$

Sterile neutrino

For more details, see M. Drewes, 1303.6912

Other phenomenological aspects:



Wide mass range!

Thermal Leptogenesis

W. Buchmuller, et al , Ann.Rev.Nucl.Part.Sci. 55 (2005)311,

Resonant Leptogenesis

E. K. Akhmedov, et al, PRL81(1998)1359

DM candidate

S. Dodelson, L. M. Widrow, PRL72(1994)17

Short-baseline neutrino oscillation

LSND : PRD64(2001)112007
MiniBooNE : PRL110(2013)161801
Reactor anomaly : PRD83(2011)073006

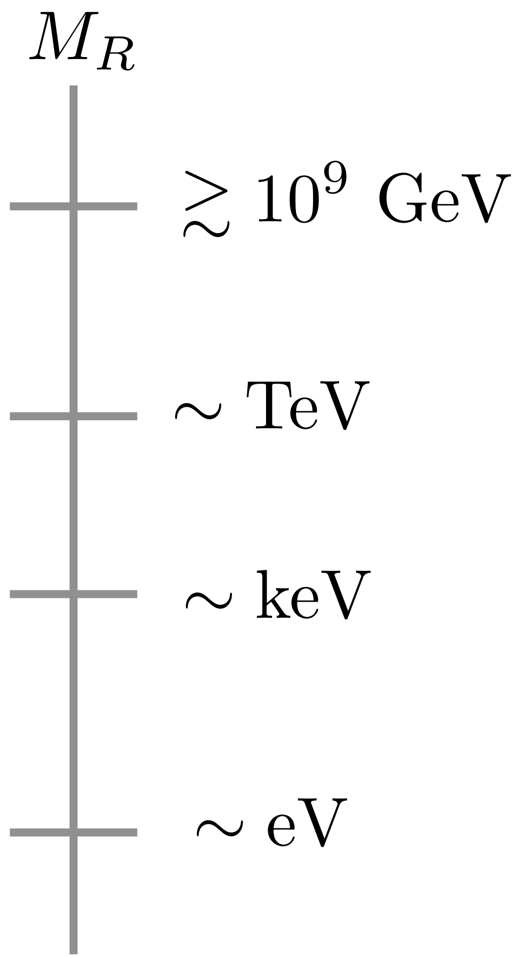
$\bar{\nu}_\mu \to \bar{\nu}_e$

MiniBooNE : PRL121(2018)221801
PRL102(2009)101802

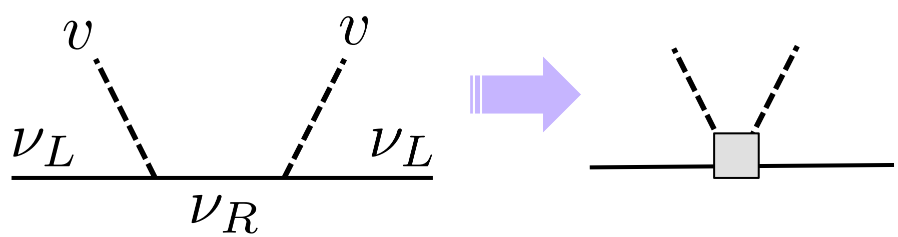
$\nu_\mu \to \nu_e$

Neutrinoless double beta decay

When $M_R \gg \mathcal{O}(100)\ \text{GeV}\,,$



Sterile neutrinos can be integrated out.



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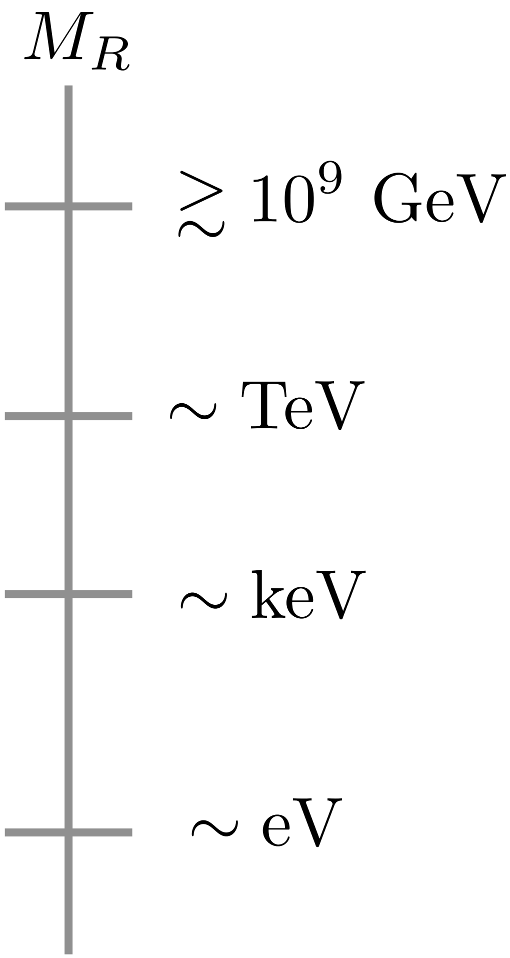

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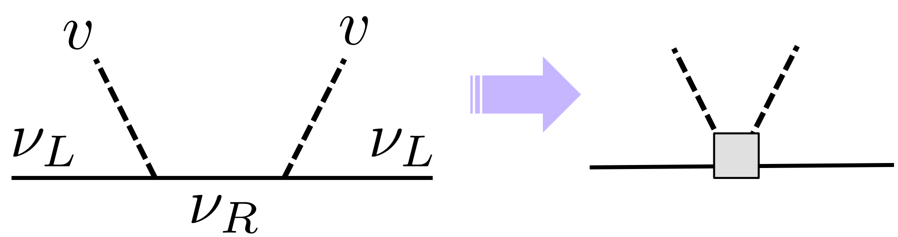
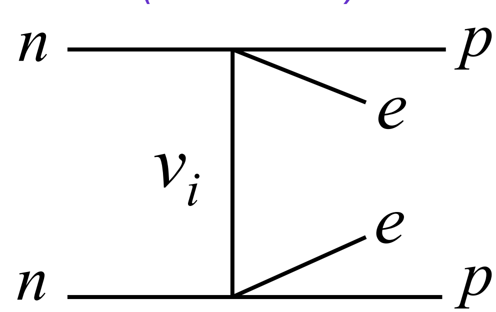


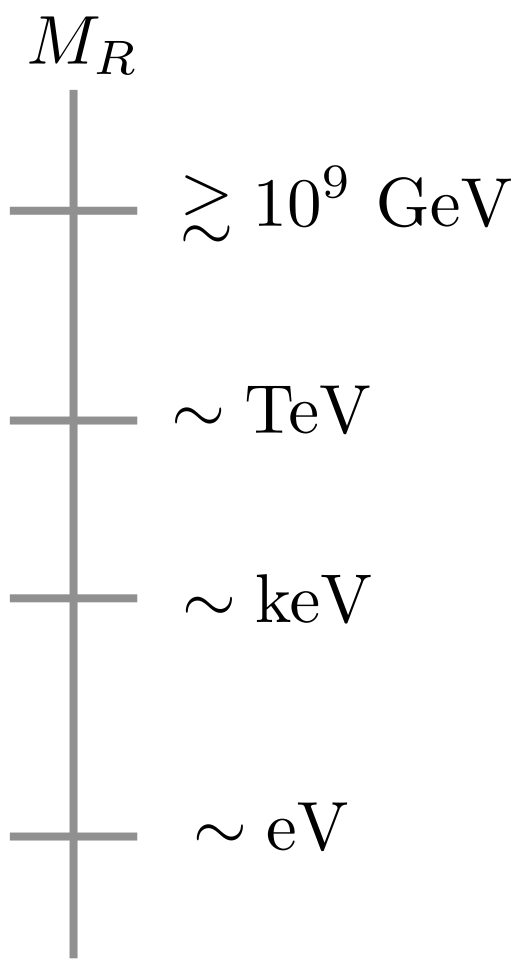
Standard Model Effective Field Theory (SM EFT)



V. Cirigliano, W. Dekens, J. de Vries, M. L. Graesser, and E. Mereghetti, JHEP 12, 082(2017)
V. Cirigliano, W. Dekens, J. de Vries, M. L. Graesser, and E. Mereghetti, JHEP 12, 097(2018)

Neutrinoless double beta decay

When $M_R \lesssim \mathcal{O}(100)\ \text{GeV}$,

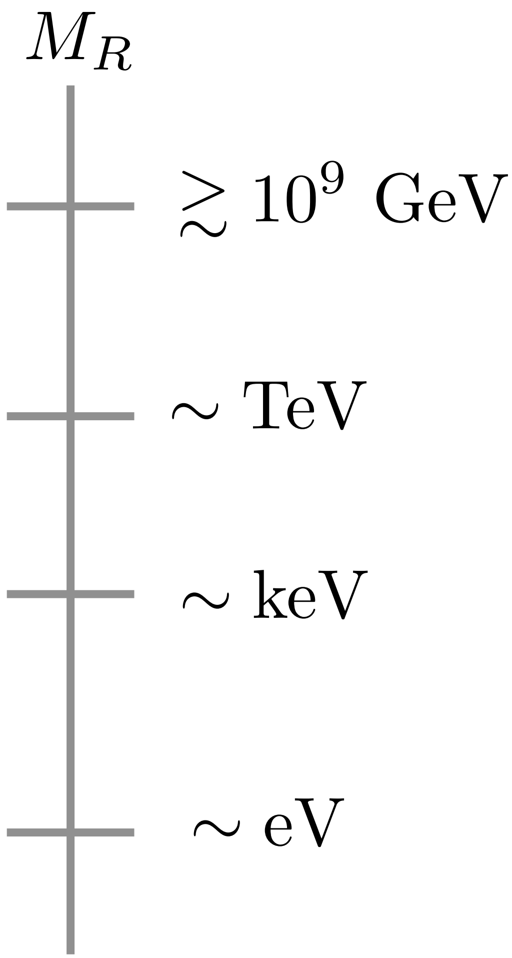


Need to extend SM EFT

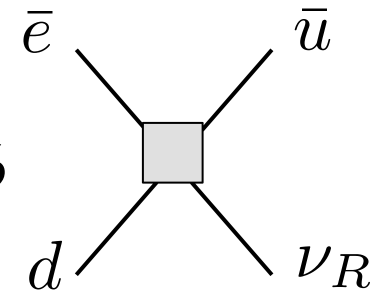
~ *SM* + *Sterile neutrinos*

Neutrinoless double beta decay

When $M_R \lesssim \mathcal{O}(100)\ \mathrm{GeV}$,



Today's talk : dim 6



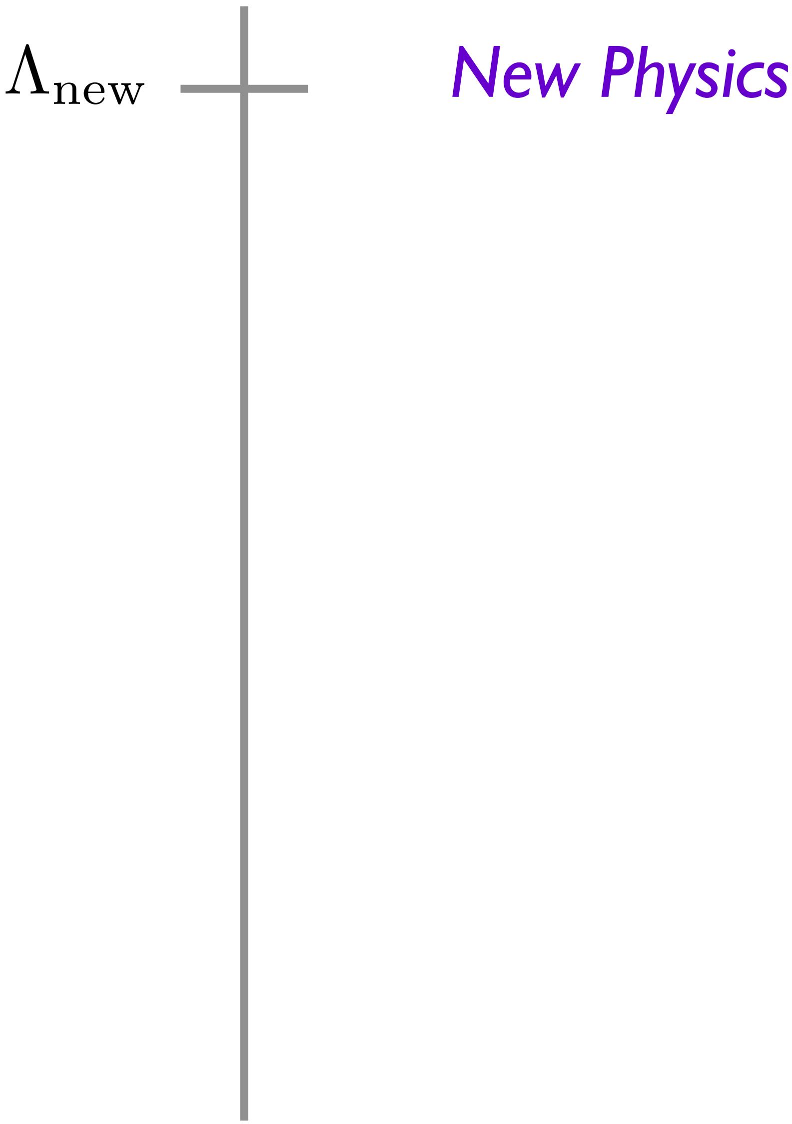
Need to extend SM EFT

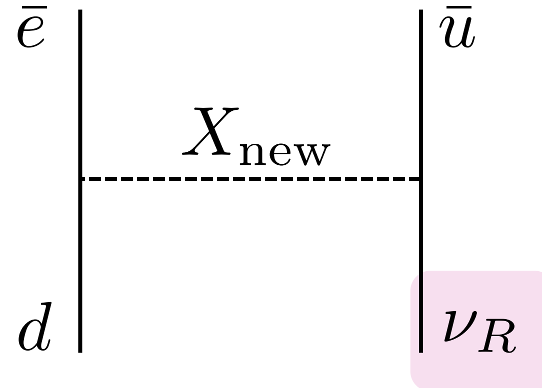
~ *SM* + *Sterile neutrinos*

Our Goal : Systematic analyses depending on ν_R mass

SM + Sterile neutrinos EFT

EFT approach



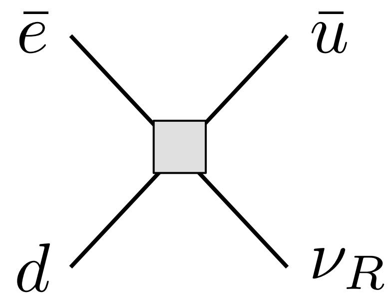


EFT approach

$\Lambda_{\rm new}$

New Physics

SM + sterile neutrino EFT



$$\sim \frac{1}{m_X^2}$$

EFT approach

Λ_{new}

New Physics

SM + sterile neutrino EFT

LNC dim 6 operators

$(\bar{L}\nu_R)\,\tilde{H}\,(H^\dagger H)$	$(\bar{d}\gamma^\mu u)\,(\bar{\nu}_R\gamma_\mu e)$
$(\bar{\nu}_R\gamma^\mu e)\left(\tilde{H}^\dagger iD_\mu H\right)$	$(\bar{Q}u)\,(\bar{\nu}_R L)$
$(\bar{L}\sigma_{\mu\mu}\nu_R)\,\tau^I\tilde{H}W^I$	$(\bar{L}\nu_R)\,\epsilon\,(\bar{Q}_R d)$
	$(\bar{L}d)\,\epsilon\,(\bar{Q}_R\nu_R)$

* *7 independent operators*

Y. Liao and X.-D. Ma, Phys. Rev. D96, 015012 (2017)

EFT approach

Λ_{new}

New Physics

SM + sterile neutrino EFT

$\sim 100\ \text{GeV}$

Mixing

$$\mathcal{L}_{\text{mass}} = -\frac{1}{2}\overline{N^c} M_\nu N + \text{h.c.}$$

$$N = \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix}, \qquad M_\nu = \begin{pmatrix} 0 & M_D^* \\ M_D^\dagger & M_R^\dagger \end{pmatrix}$$

- *Diagonalize M_ν with a unitary matrix U*
- *Integrate out heavy SM particles*

EFT approach

$\Lambda_{\rm new}$ — *New Physics*

SM + sterile neutrino EFT

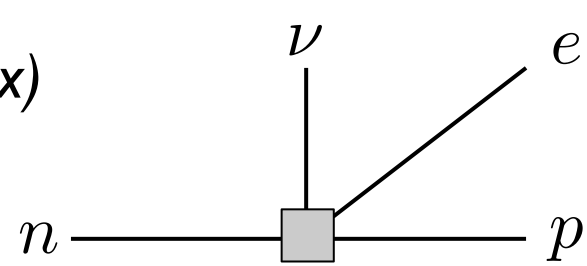
$\sim 100\ {\rm GeV}$ — *Mixing*

$\sim 1\ {\rm GeV}$ — *Nucleon and pion interactions*

~ *Chiral Perturbation Theory*

G. Prezeau, M. Ramsey-Musolf, and P. Vogel, PRD68, 034016 (2003)

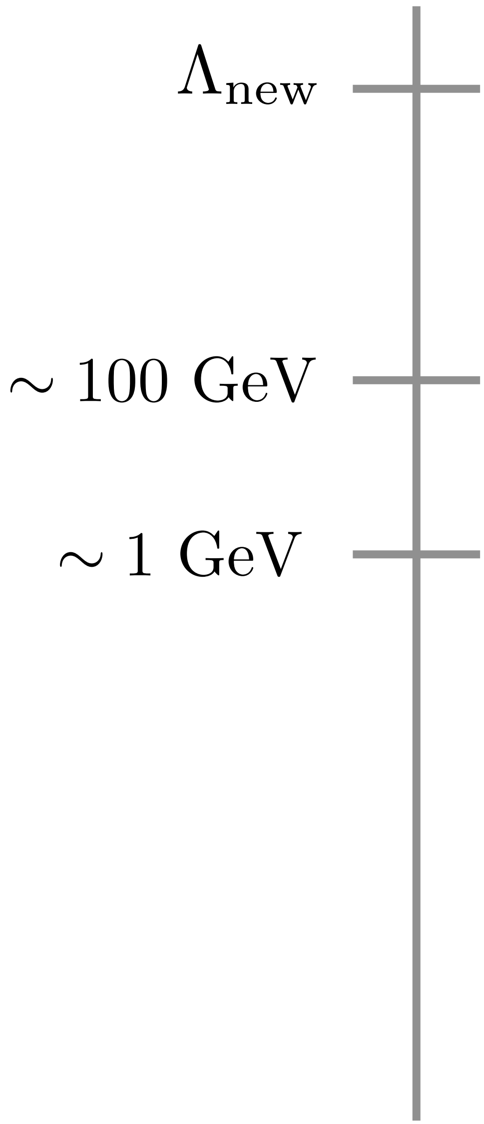
Ex)



$$\sim g_{\rm LEC}\ C^{(6)}_{\nu_R}$$

↑ Low Energy Constant

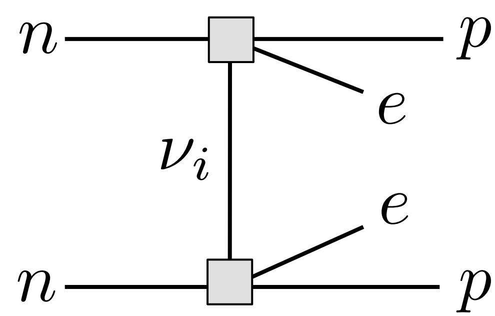
EFT approach



New Physics

SM + sterile neutrino EFT

Mixing

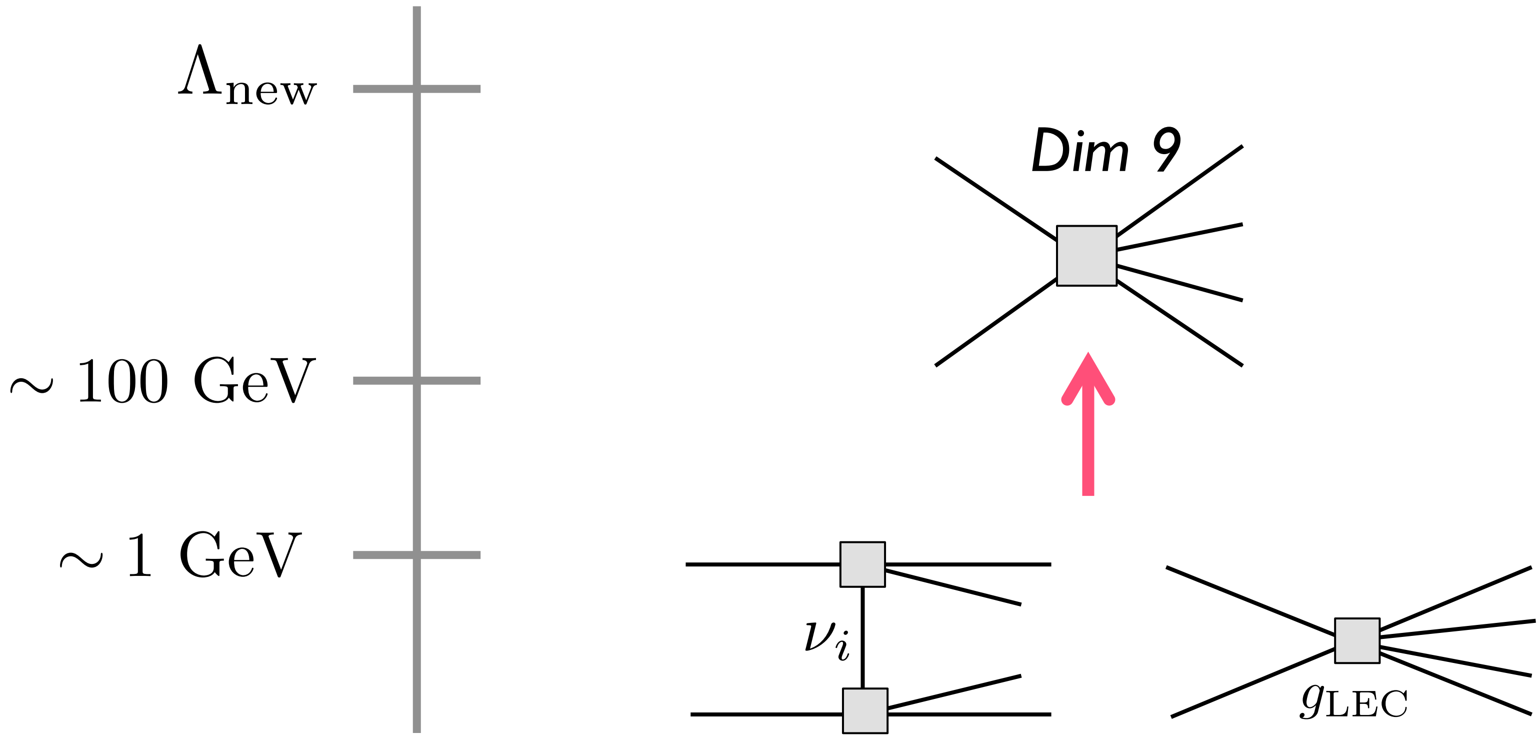


Transition amplitudes

$$\mathcal{A}_{0\nu2\beta}\left(g_{\rm LEC}\left(m_i\right), C^{(6)}_{\nu_R}, M_{\rm NME}\left(m_i\right)\right)$$

Interpolation formulae

EFT approach

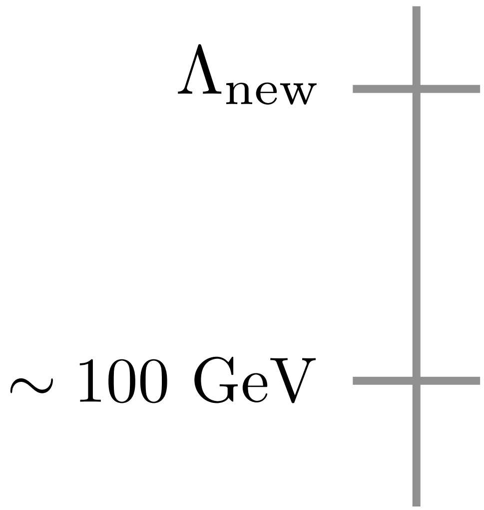


$M_{\rm NME}(m_i)$: Pade approximation

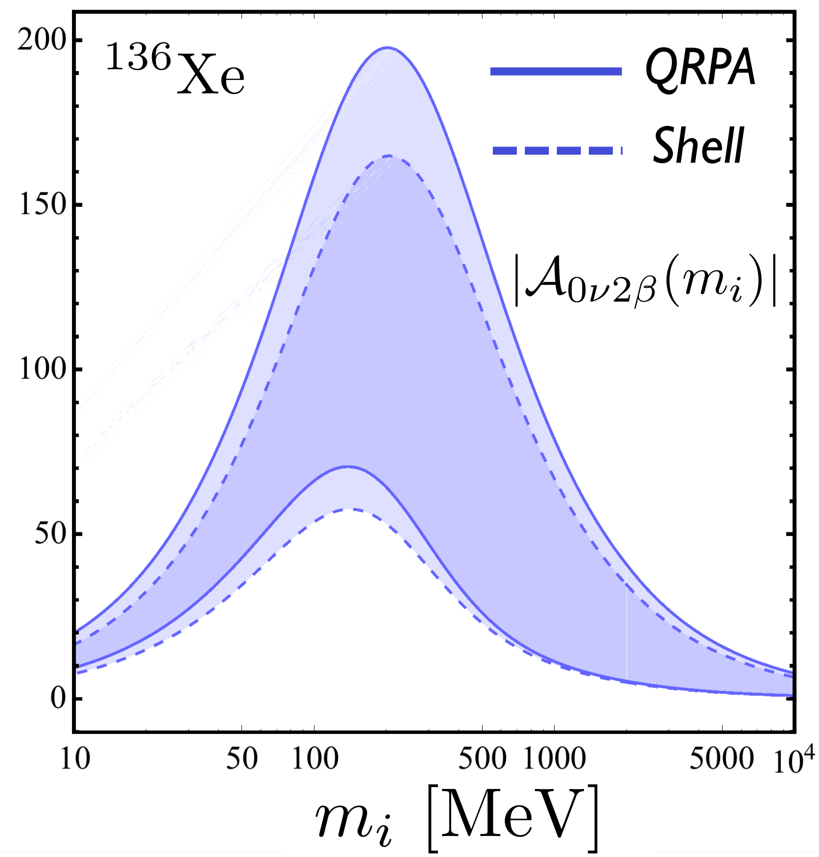
$g_{\rm LEC}(m_i)$: $\mathcal{A}_{0\nu2\beta}(m_i)|_{m_i \gg {\rm GeV}} = \mathcal{A}^{(9)}_{0\nu2\beta}(m_i)$

* Require to match dim 9 amplitude

EFT approach



$\text{Vector}: \bar{u}_L \gamma^\mu d_L \bar{e}_L \gamma_\mu \nu$



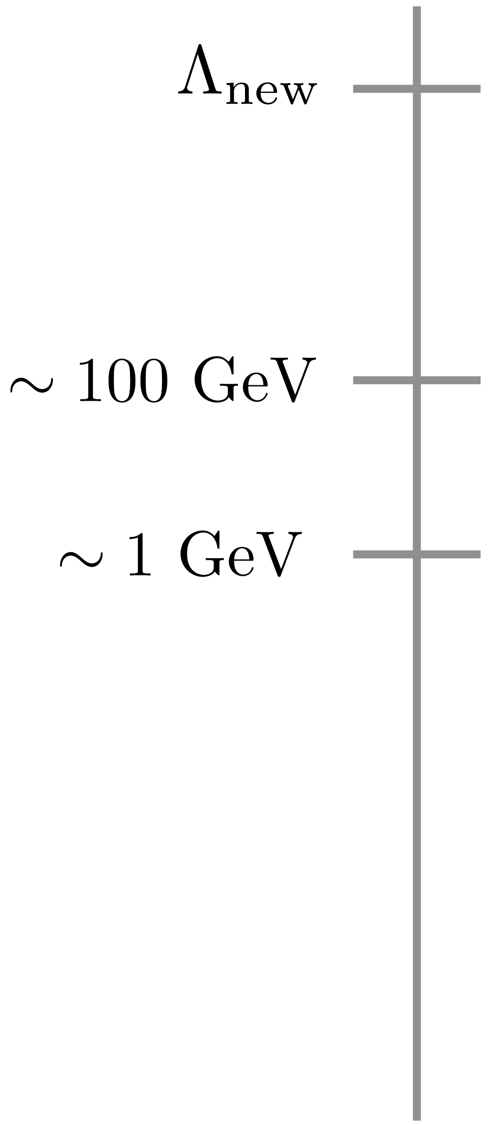
$$M_F(m_i) = \frac{m_\pi^2 M_{F,sd}}{m_i^2 + m_\pi^2 \frac{M_{F,sd}}{M_F}}$$

$$g_\nu^{\rm NN}(m_i) = \frac{g_\nu^{\rm NN}(0)}{1 - m_i^2 \frac{g_\nu^{\rm NN}(0)}{2}\left[\theta(m_0 - m_i)\hat{g}_1^{\rm NN}(m_0) + \theta(m_i - m_0)\hat{g}_1^{\rm NN}(m_i)\right]^{-1}}$$

$$m_0 \simeq 2 \text{ GeV} \quad \hat{g}_1^{\rm NN}(m_i) = g_1^{\rm NN}(m_i) - \frac{1}{4}(1 + 3g_A^2)$$

EFT approach

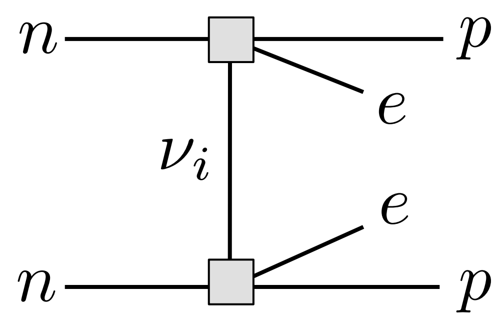
Let's see one example : Leptoquark



New Physics

SM + sterile neutrino EFT

Mixing



Inverse half-life :

$$\left(T_{1/2}^{0\nu}\right)^{-1} = g_A^4 G_{0\nu} \left|\mathcal{A}(m_i)\right|^2$$

$g_A = 1.27$ $\quad$ G : Phase space factor

Leptoquark

Leptoquark

J. M. Arnold, B. Fornal and M. B. Wise, Phys. Rev. D 88, 035009 (2013)
J. M. Arnold, B. Fornal and M. B. Wise, Phys. Rev. D 87, 075004 (2013)
I. Dorsner, S. Fajfer, A. Greljo, J. F. Kamenik and N. Kosnik, Phys. Rept. 641, 1 (2016)

Leptoquark (LQ) couples to the SM quark and lepton

+ sterile neutrinos (2 flavors)

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Scalar LQ : $\tilde{R}\,(\mathbf{3}, \mathbf{2}, 1/6)$ All possible scalar LQs: PRD43(1991)225

$$\mathcal{L}_{\rm LQ} = -y^{RL}\bar{d}_R\tilde{R}\epsilon L + y^{\overline{LR}}\bar{Q}\tilde{R}\nu_R$$

Leptoquark

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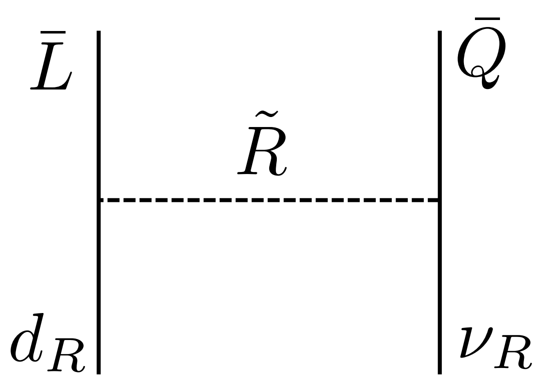

Gauge-invariant operator:

$$\mathcal{L}^{(6)}_{\nu_R} = C^{(6)}_{LdQ\nu}\left(\bar{L}d_R\right)\epsilon\left(\bar{Q}\nu_R\right)$$

$$C^{(6)}_{LdQ\nu} = \frac{1}{m^2_{LQ}}y^{\overline{LR}}y^{RL*}$$

Leptoquark

Scalar and tensor operators show up below EW scale:

$$\mathcal{L}^{(6)} = \frac{2G_F}{\sqrt{2}}\left[\bar{u}_L d_R \bar{e}_L C^{(6)}_{\mathrm{SRR}} \nu_i + \bar{u}_L \sigma^{\mu\nu} d_R \bar{e}_L \sigma_{\mu\nu} C^{(6)}_{\mathrm{TRR}} \nu_i\right]$$

$$C^{(6)}_{\mathrm{SRR}} = 4C^{(6)}_{\mathrm{TRR}} = \frac{v^2}{2} C^{(6)}_{LdQ\nu} \left(U^*_{4i} + U^*_{5i}\right) \quad (i = 1 \sim 5)$$

Leptoquark

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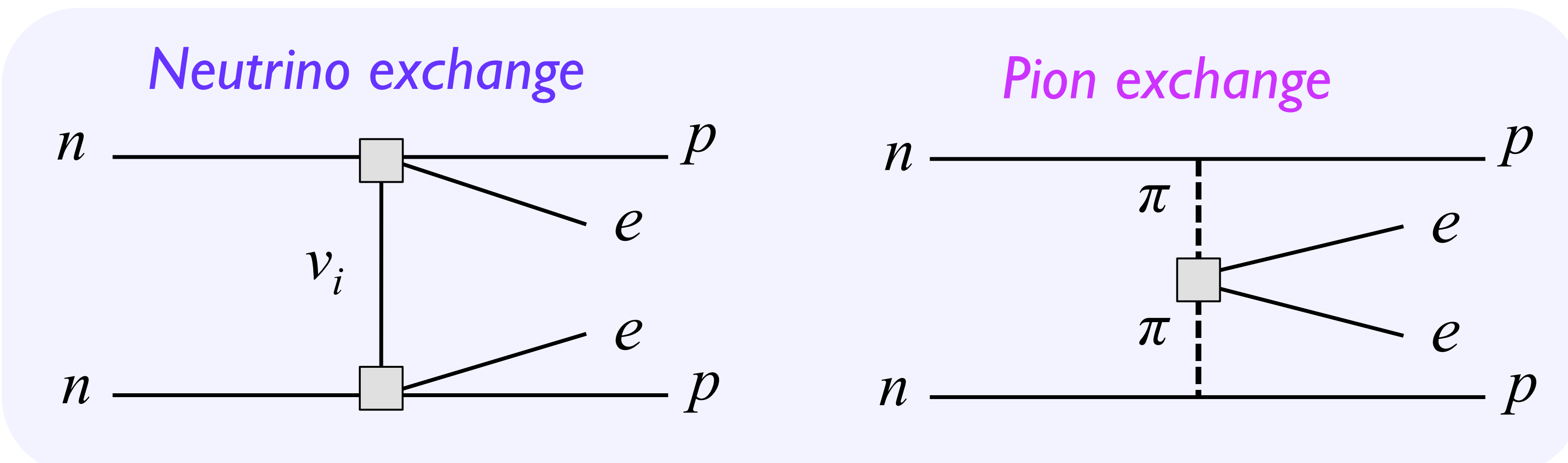


** πN and NN interactions are neglected in our analyses.*

Input parameters

LQ parameters : $m_{\mathrm{LQ}} = 10\ \mathrm{TeV} \quad y^{\overline{LR}} y^{RL*} = 1.0$

- Normal hierarchy is assumed.

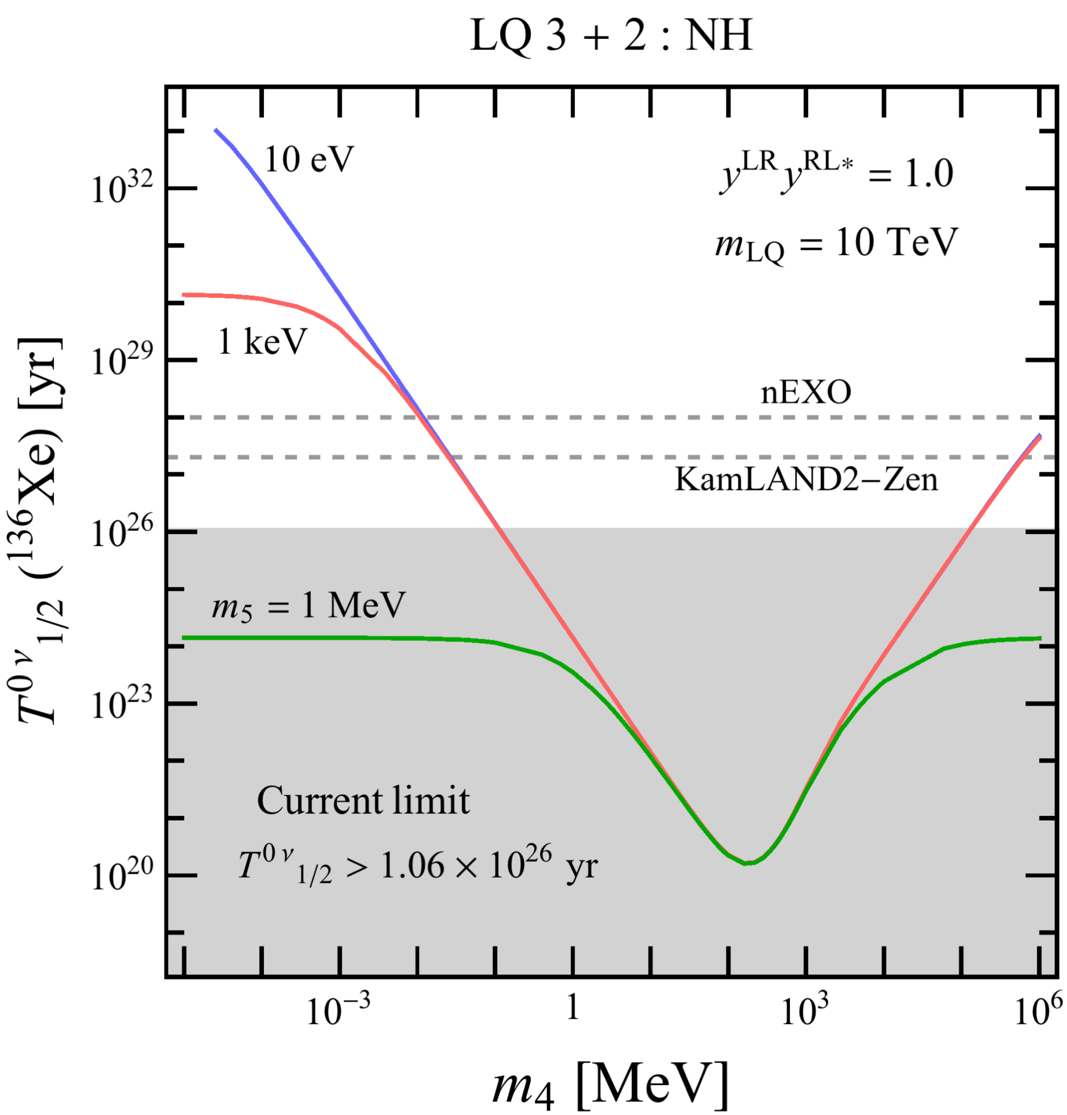
Oscillation parameters [PDG]PRD98, 030001(2018) and update (2019)

$\Delta m^2_{21} = 7.39 \cdot 10^{-5}\ [\mathrm{eV}^2]$	$\Delta m^2_{32} = 2.5 \cdot 10^{-3}\ [\mathrm{eV}^2]$
$\sin^2\theta_{12} = 3.10 \cdot 10^{-1}$	$\sin^2\theta_{23} = 5.58 \cdot 10^{-1}$
$\sin^2\theta_{13} = 2.241 \cdot 10^{-2}$	$\delta_{\mathrm{Dirac}} = 1.23\pi$

$[3+2] \quad \theta_{45} = \pi/8 \quad \gamma_{45} = 0.5 \quad \text{Majorana phases} = 0$

$m_{4,5}$: free parameters

m_4 vs Half-life



Three choices of m_5 :

Blue : $m_5 = 10$ eV

Red : $m_5 = 1$ keV

Green : $m_5 = 1$ MeV

Shaded region :

$$T^{0\nu}_{1/2} > 1.06 \times 10^{26} \text{ yr}$$

by KamLAND-Zen

Ruled out

0.1MeV < m_4 < 100GeV

Summary

Sterile neutrinos are motivated by several phenomena.

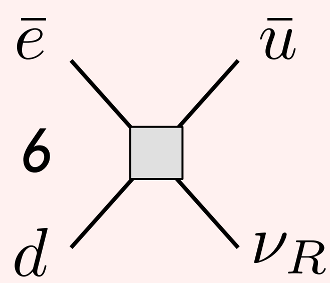
Mass Range

eV ⟷ $10^{15}\,\mathrm{GeV}$

✦ Systematic analyses are required depending on M_R.

Neutrinoless double beta decay

Dim 6



- ✔ *Establish master formulae in light ν_R case based on EFT*
- ✔ *Interpolation formulae for* $g_{\mathrm{LEC}}(m_i), M_{\mathrm{NME}}(m_i)$