Using effective Lagrangians to model $0\nu\beta\beta$ and neutrino masses

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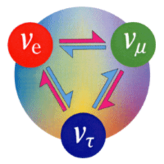
A TIME OF DISCOVERY

Neutrinos are massive, but their masses are extremely small, $m_\nu \lesssim 1$ eV. This is, maybe, the best indication that there should be more physics apart from that of the Standard Model.

We don't know yet the nature of this new physics (NP), but the sole fact that it creates masses for the neutrinos has many phenomenological consequences. For instance, there is mixing in the lepton sector, and the neutrino species oscillate.



Another consequence concerns lepton number violation (LNV): if the neutrino masses are Majorana, then LN is violated for good.

Dirac or Majorana?

The question is thus how we can distinguish between Dirac and Majorana masses. Oscillations offer no information on this.

Dirac masses can be generated with plain SM tools. Majorana masses, however, require NP:

$$\mathcal{L}_{\text{Maj}} = \frac{1}{2}\, m_{\alpha\beta}\, \overline{\nu^c_{\alpha L}}\nu_{\beta L} \quad \leftarrow \frac{c_{\alpha\beta}}{\Lambda}\left(\overline{\tilde{\ell}_\alpha}\phi\right)\left(\tilde{\phi}^\dagger \ell_\beta\right)$$

This NP, whatever it is, has to violate LN. We can thus look for it in LNV processes.

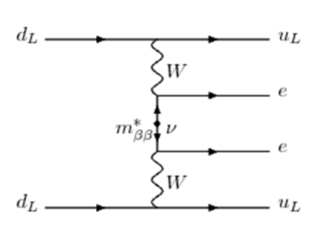
Of all such processes, neutrinoless double beta decay ($0\nu\beta\beta$) is the most sensitive and promising.

Enter $0\nu\beta\beta$

$0\nu\beta\beta$ is a nuclear decay apparently consisting in two simultaneous β decays with no outgoing neutrino:

$$ {}^{A}_{Z}X \longrightarrow {}^{\;\;A}_{Z+2}Y + 2e^{-} $$

This process violates lepton number in two units, $\Delta L = 2$, just like Majorana masses do. It is thus very natural to imagine $0\nu\beta\beta$ mediated by a LNV Majorana neutrino:



But then the NP is associated with neutrino mass generation, and will be in many cases rather heavy. Besides, planned $0\nu\beta\beta$ experiments will only see a signal if the ν hierarchy is degenerate.

Who's the mediator?

In the usual picture, $0\nu\beta\beta$ is mediated by ν masses:

$$\text{NP} \;\Rightarrow\; \nu\,\text{masses} \;\Rightarrow\; 0\nu\beta\beta \;\Rightarrow\; \Lambda \sim 10^6\ \text{TeV}\ (\text{seesaw},\ Y_\nu \simeq Y_\mu)$$

We can, however, imagine a scenario where the leading contribution to $0\nu\beta\beta$ is directly mediated by the new particles ; ν masses could then be generated radiatively from this same physics,

$$\text{NP} \;\Rightarrow\; 0\nu\beta\beta \;\Rightarrow \nu\,\text{masses} \;\Rightarrow\; \Lambda \sim 1\ \text{TeV}$$

and the light neutrino contribution to $0\nu\beta\beta$ would be subdominant, or even negligible.

In the end, our aim would be to provide models with signals at several experiments that allow us to correctly characterise the NP.

Enter effective theory

To realise these ideas we will use effective field theory (EFT).

EFT is constructed by eliminating from our description of physics the fields that are too heavy to be excited. We then build a theory which consists only of the low-energy fields, and nonrenormalisable operators that describe the low-energy action of the heavy fields,

$$\mathcal{L} = \mathcal{L}_{\text{low-en.}} + \sum_{n=5}^{\infty} \sum_{i} \left(\frac{C_i^{(n)}}{\Lambda^{n-4}} \mathcal{O}_i^{(n)} + \text{H.c.} \right) .$$

The scale Λ is related to the energy where the heavy fields make themselves visible. For energies above Λ, the EFT does not make sense anymore.

Enter effective theory

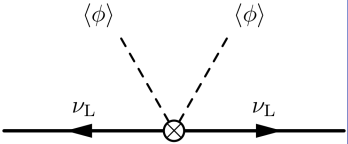
EFT is a way to inspect the effects of heavy fields in a completely model-independent way. In order to focus our efforts we will select only a handful of effective operators, thus restricting ourselves to theories having:

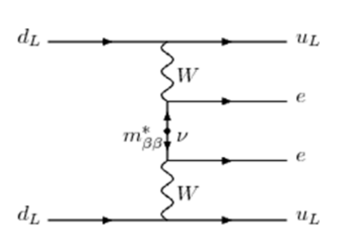
- The full SM as low-energy fields. This seems reasonable, as the new particles are expected to live above 100 GeV.
- Violation of LN, as is required to produce $0\nu\beta\beta$ and Majorana masses.
- No couplings of the NP to quarks. We will thus consider only operators that involve leptons and gauge bosons, which had been mostly ignored in previous works. This allows to avoid stringent bounds from, for example, proton decay.

A first example

The lowest-dimensional operator that fullfills this condition is the well-known Weinberg operator, of dimension 5:

$$\mathcal{O}^{(5)} = \frac{C^{(5)}_{\alpha\beta}}{\Lambda} \left(\overline{\tilde{\ell}_\alpha}\phi\right)\left(\tilde{\phi}^\dagger \ell_\beta\right) = -\frac{C^{(5)}_{\alpha\beta}\, v^2}{\Lambda}\, \overline{\nu^c_{\alpha L}}\nu_{\beta L} + \dots$$





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This operator provides:

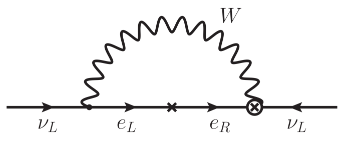
- Tree-level $0\nu\beta\beta$
- Tree-level ν masses
- The limits on $0\nu\beta\beta$ rate translate into

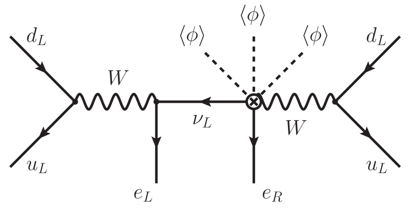
$$\frac{p_{\rm eff}}{G_F^2}\left|\mathcal{A}_{0\nu\beta\beta}\right| < 5\times 10^{-9} \quad\Longrightarrow\quad \Lambda > 10^{11}\,|C^{(5)}_{ee}|\ \mathrm{TeV}$$

A left-right operator

The lowest-dimension LNV operator involving a left- and a right-handed electron is of dimension 7,

$$\mathcal{O}^{(7)} = \frac{C^{(7)}_{\alpha\beta}}{\Lambda^3}\left(\phi^\dagger D_\mu \tilde{\phi}\right)\left(\phi^\dagger \overline{e_{\alpha R}} \gamma^\mu \tilde{\ell}_\beta\right) = i\,\frac{g v^3 C^{(7)}_{\alpha\beta}}{\sqrt{2}\,\Lambda^3} W^-_\mu \overline{e_{\alpha R}} \gamma^\mu \nu^c_{\beta L} + \ldots$$





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This operator provides:

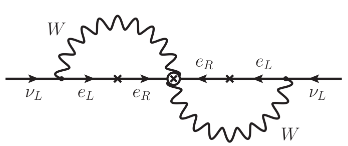
- Tree-level $0\nu\beta\beta$
- One-loop ν masses
- The limits on $0\nu\beta\beta$ rate translate into

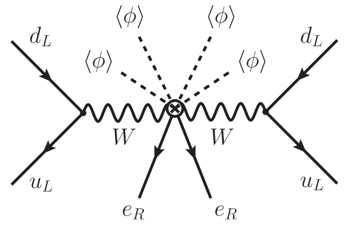
$$\frac{p_{\text{eff}}}{G_F^2}\left|\mathcal{A}_{0\nu\beta\beta}\right| < 5\times 10^{-9} \quad\Longrightarrow\quad \Lambda > 106\,|C^{(7)}_{ee}|^{1/3}\ \text{TeV}$$

A RIGHT-RIGHT OPERATOR

The lowest-dimension LNV operator involving two right-handed electrons has dimension 9,

$$\mathcal{O}^{(9)} = \frac{C^{(9)}_{\alpha\beta}}{\Lambda^5}\overline{e_{\alpha R}}e^c_{\beta R}\left(\phi^\dagger D\tilde{\phi}\right)^2 = -\frac{g^2 v^4 C^{(9)}_{\alpha\beta}}{2\Lambda^5}W^-_\mu W^{-\mu}\overline{e_{\alpha R}}e^c_{\beta R} + \ldots$$





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This operator provides:

- Tree-level $0\nu\beta\beta$
- Two-loop ν masses
- The limits on $0\nu\beta\beta$ rate translate into

$$\frac{p_{\rm eff}}{G_F^2}\left|\mathcal{A}_{0\nu\beta\beta}\right| < 5\times 10^{-9} \quad \Longrightarrow \quad \Lambda > 2.7\,|C^{(9)}_{ee}|^{1/5}\ \text{TeV}$$

Summary

As we have seen, the chirality of the outgoing electrons allows to classify the theories of this family, indicating the dimensionality of the leading operator and the potential suppression of ν masses:

Chirality	Lowest dim.	$0\nu\beta\beta$	ν mass	Bound on Λ ($C \sim 1$)
LL	5	Tree level	Tree level	10^{11} TeV
LR	7	Tree level	1 loop	100 TeV
RR	9	Tree level	2 loops	1 TeV

Note that this does not mean that all LR models will generate ν masses at one loop; nothing prevents a particular model from generating both $\mathcal{O}^{(5)}$ and $\mathcal{O}^{(7)}$ at the same order. To use this rule, we need to ensure that our model won't generate ν masses too soon!

An example of RR-type model

The operator $\mathcal{O}^{(9)}$ can be generated by a model with only scalar additions to the SM:

	$SU(2)_L$	$U(1)_Y$	Z_2
χ	1	+1	-
κ	0	+2	+
σ	0	0	-
SM			+

where σ is a real scalar field.

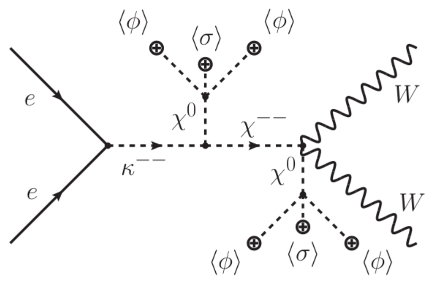
The relevant couplings for our discussion of this model are

$$g_{\alpha\beta}\,\overline{e_{\alpha R}}^{c} e_{\beta R}\,\kappa \qquad \mu_\kappa\,\kappa \mathrm{Tr}\left[\chi^\dagger\chi^\dagger\right] \qquad \lambda_6\,\sigma\,\phi^\dagger\chi\tilde{\phi}$$

Notice that the Yukawas $g_{\alpha\beta}$ assign LN to κ, while the λ_6 term breaks it explicitly.

$0\nu\beta\beta$ in the RR model

$0\nu\beta\beta$ appears at tree level, and as expected it requires nonvanishing g, μ_κ and λ_6. This last coupling can be expressed in terms of the VEV of χ.



If we demand that the $0\nu\beta\beta$ is below the present bound, but available to the next generation of experiments we obtain

$$8.75 \times 10^{-11} \overset{\text{Next}}{<} \frac{m_p \mu_\kappa v_\chi^2}{m_\kappa^2 m_\chi^2} |g_{ee}| < 1.75 \times 10^{-9} \quad (90\% \text{ C.L.})$$

LFV IN THE RR MODEL

The couplings of κ to a pair of charged leptons induce a variety of processes of the form $\ell_a^- \to \ell_b^+ \ell_c^- \ell_d^-$, which are well constrained.

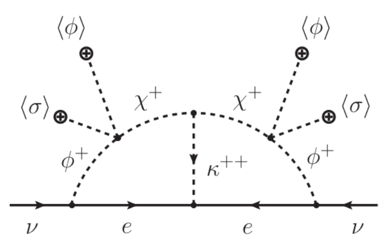
This allows to set direct bounds on the g's, which happen to be rather ubiquitous in the phenomenology of the model. The most relevant constraints are

$$\mathrm{BR}(\mu^- \to e^+ e^- e^-) < 1.0 \times 10^{-12} \Rightarrow |g_{\mu e} g_{ee}^*| < 2.3 \times 10^{-5} \left(m_\kappa / \mathrm{TeV} \right)^2$$
$$\mathrm{BR}(\tau^- \to e^+ \mu^- \mu^-) < 1.7 \times 10^{-8} \Rightarrow |g_{\tau e} g_{\mu\mu}^*| < 0.007 \left(m_\kappa / \mathrm{TeV} \right)^2$$

As we will see, the combination of these bounds with other phenomenological considerations will set strong constraints on the model.

ν MASS GENERATION

Neutrino masses are forbidden at tree level and one loop, but appear at two loops, as expected from the effective theory.



Each element of the neutrino mass matrix is proportional to the corresponding g coupling and to the masses of the charged leptons:

$$(m_\nu)_{\alpha\beta} = \frac{\mu_\kappa v_\chi^2}{2(2\pi)^4 v_\phi^4} m_\alpha g^*_{\alpha\beta} m_\beta I_\nu$$

Constraints on the ν mass matrix

This very particular structure of the ν mass matrix has two immediate consequences:

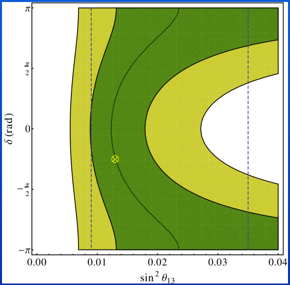
- The element m_{ee} is greatly suppressed by the factor m_e^2
- The element $m_{e\mu}$ is also suppressed, in this case due to the LFV bound on $g_{e\mu}$

The question is: is this situation compatible with our knowledge of neutrino masses? Remember that the ν mass matrix can be expressed in terms of the mass eigenvalues and the mixings and phases:

$$m_\nu = U_{\mathrm{PMNS}} \, \mathrm{diag}(m_1, m_2, m_3) \, U_{\mathrm{PMNS}}^T$$

Constraints on the ν mass matrix

And the answer is yes, provided m_1 is in the meV range and θ_{13} is nonzero. The values of θ_{13} predicted by the model are compatible with the latest measurements.

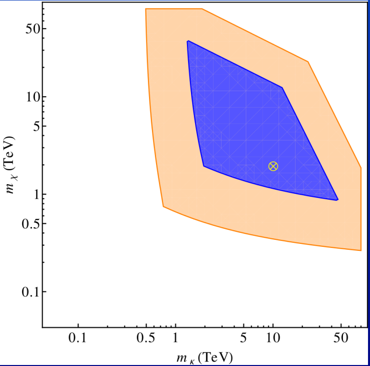


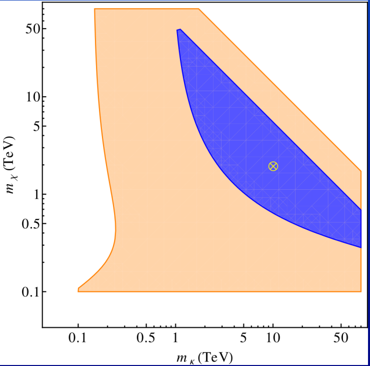
After these two strong constraints on m_{ee} and $m_{e\mu}$ there is no more freedom in the mixings and the rest of the mass matrix happens to be more or less fixed:

$$|m_\nu| = \begin{pmatrix} < 10^{-4} & < 10^{-4} & \sim 10^{-3} \\ < 10^{-4} & \sim 0.01 & \sim 0.01 \\ \sim 10^{-3} & \sim 0.01 & \sim 0.01 \end{pmatrix} \text{ eV}$$

Constraints on the doubly-charged scalars

All the competing constraints from $0\nu\beta\beta$, LFV, neutrino masses and mixings, and perturbativity of the theory can be translated into bounds on the masses of the doubly-charged particles, which provide the most distinctive signals in colliders:





Conclusions

- We have used effective field theory to study a family of models that provide $0\nu\beta\beta$. In this family, the new fields only couple to the lepton and gauge sectors of the SM.
- We have observed that the chirality of the electrons produced in $0\nu\beta\beta$ can be used to classify the models in the family.
- Left-left (LL) models are characterised by ν masses generated at tree level and $0\nu\beta\beta$ mediated in most cases by light neutrinos. These models tend to have very high NP scale, away from the reach of present or near future colliders. $0\nu\beta\beta$ will only be observable for the next generation of experiments if the ν mass hierarchy is degenerate (maybe inverse).

Conclusions

- LR models typically have NP scales above 100 TeV or maybe a bit lower. These models can potentially have ν masses suppressed by one loop respect to $0\nu\beta\beta$, and may provide $0\nu\beta\beta$ signals mediated by the heavy particles.
- RR models can have NP scales as low as 1 TeV, or even lower. ν masses can potentially be suppressed by two loops respect to $0\nu\beta\beta$. In such a case, signals in $0\nu\beta\beta$ experiments are likely to be mediated by the heavy fields.
- We have provided a model of the RR type realising the two-loop ν mass generation. The model provides a ν mass matrix that has necessarily nonzero θ_{13} and m_1. The model possesses doubly-charged scalars that could be observed at the LHC, but its parameter space is quite tightly constrained, especially if we want to see a signal in the next round of $0\nu\beta\beta$ experiments.

Thank you for your attention!

To see the original works: arXiv:1204.5986 [hep-ph]
arXiv:1111.6960 [hep-ph]