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Neutrinos at colliders and lepton number violation

Martin Hirsch*
AHEP Group, Instituto de Física Corpuscular - CSIC/Universitat de València,
Calle Catedrático José Beltrán, 2 E-46980 Paterna, Spain
E-mail: mahirsch@ific.uv.es

The non-zero neutrino masses and angles, observed in neutrino oscillation experiments, are currently the only signal of physics beyond the standard model, that has been confirmed in controlled laboratory experiments. The origin of neutrino masses, however, is so far not understood. If neutrinos are Majorana particles, signals at colliders could appear, if the scale of lepton number violation is not to far from the electro-weak scale. In this talk, I will briefly review some recent work on displaced vertex signals, before discussing lepton number violation in beyond-minimal seesaw models of neutrino mass.

ALPS 2019 An Alpine LHC Physics Summit
April 22 - 27, 2019
Obergurgl, Austria

*Speaker.

PoS(ALPS2019)015

1. Introduction

More than 20 years have passed since Super-Kamiokande first observed neutrino oscillations in atmospheric neutrino measurements [1]. Nowadays we have very precise information on two mass squared splittings and all three standard leptonic mixing angles from a large variety of neutrino oscillation experiments [2]. However, we do not know so far, whether neutrinos are Majorana or Dirac particles, since no lepton number violating signal has been observed in any experiment. In particular, only lower limits on the half-live for neutrinoless double beta decay exist so far [3, 4], although there are several proposals, such as LEGEND [5] or nEXO [6], which could improve sensitivity by (1-2) orders of magnitude in the future.

Dirac neutrino masses are dimension-4 terms in the Lagrangian, which only require to enlarge the standard model particle content by (at least two) right-handed neutrinos. The corresponding Yukawa couplings have to be order $\mathscr{O}(10^{-12})$, to explain the experimental data. Theoreticians don't like such small numbers, so the literature is heavily biased towards Majorana neutrinos. [1] More important for the subject of this talk, however, is that Dirac neutrinos do not leave any interesting signals at accelerators. The situation is very different for Majorana neutrinos.

All Majorana neutrino mass models at low energy reduce to the Weinberg operator [10], $\mathscr{O}^W = \frac{c_{\alpha\beta}}{\Lambda} L_\alpha L_\beta HH$, or its higher-dimensional variants, $\mathscr{O}^W \times (H^\dagger H)^n$. Here, Λ is the scale at which new physics appears, while $c_{\alpha\beta}$ is a complex symmetric matrix of constants. If these constants take values order $\mathscr{O}(1)$, neutrino oscillation data would indicate $\Lambda \sim \mathscr{O}(10^{15})$ GeV, and neutrinoless double beta decay would be the only lepton number violating signal that one could realistically expect to see. This is the essence of the classical seesaw mechanism: Explain the smallness of neutrino masses via the existence of a new (and large) physics energy scale.

In this talk, however, I will assume a different approach. Consider the following expression for neutrino masses [11]:

$$m_\nu \propto \varepsilon \cdot \left(\frac{1}{16\pi^2}\right)^n \cdot \left(\frac{v}{\Lambda}\right)^{d-5} \cdot \frac{v^2}{\Lambda}. \tag{1.1}$$

Here, v is the SM Higgs vev, d stands for the dimension of the operator, n the number of loops needed to generate neutrino masses, while ε symbolically indicates additional suppression of lepton number violation that might be present in particular constructions, such as for example the inverse seesaw mechanism [12]. Finally, small couplings, not shown explicitly in Eq. (1.1), could lead to neutrino masses, smaller than expected from this equation.

Fig. (1) shows the resulting estimates for the energy scales of the different Majorana neutrino model variants, assuming average couplings $\langle y \rangle$ in the range of $[0.01, 1]$. For the standard tree-level type-I seesaw mechanism, i.e. adding right-handed Majorana neutrinos to the SM, one therefore expects $\langle y \rangle$ in the range of $\mathscr{O}(10^{-7} - 10^{-6})$, for Λ in the energy range testable by the LHC. For models with 2-loops (or more) or models with d larger than $d = 7$, on the other hand, larger couplings *and* an electro-weak scale Λ are expected from current data on neutrino masses.

[1] Recently, however, a number of papers on "naturally small" neutrino Dirac masses have appeared, see for example [7, 8, 9]. Common to all these attempts is the need to introduce a number of new particles, in addition to right-handed neutrinos. The mass scale at which these additional particles have to appear, unfortunately, can not be fixed for Dirac neutrinos, due to the $d = 4$ nature of Dirac masses.

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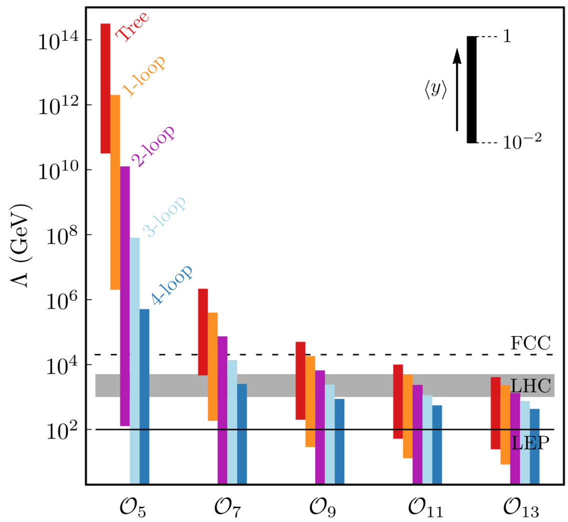

Figure 1: The typical energy scales (Λ) for which a neutrino mass model with a given dimension and number of loops (d,n) can explain correctly the observed sub-eV neutrino masses. Scale ranges are estimated using average couplings $\langle y \rangle$ in the range of $[0.01, 1]$.

In the next section, I will first discuss the expectations for the high-luminosity LHC for the case of a type-I seesaw, both classical and inverse seesaw. In section 3 I will discuss lepton number violation at the LHC in non-minimal neutrino mass models. I will then close with a short discussion and conclusion.

2. Expectations for simple seesaw models at the LHC

In this section, I will concentrate on the simplest SM extensions that can explain the neutrino oscillation data: Seesaw type-I and inverse seesaw. In the classical type-I seesaw, right-handed Majorana singlets are added to the SM. These states are either called sterile neutrinos, right-handed neutrinos or heavy neutral leptons (HNL) in the literature. Light neutrino masses are given by the famous seesaw formula, $m_\nu \simeq m_D^2/M_{HNL}$. The mixing between the active neutrinos and the HNLs is given by $U \propto m_D/M_{HNL}$.

In seesaw type-I both, production and decay, are proportional to $\sum_\alpha U_{\alpha i}^2$. Since this mixing is related to the light neutrino masses, one can calculate it as function of the HNL mass. This is shown in fig. (2). For HNLs with electro-weak scale mass, this mixing is tiny, due to the smallness of the active neutrino mass. This results in long decay lengths, as the plot on the right of this figure shows. While such large displaced vertices are an interesting signal (since it is practically background free), unfortunately small mixing implies small production cross section.

In the inverse seesaw model [12], in addition to the right-handed neutrinos one adds three singlets, S, which form quasi-Dirac pairs with the ordinary ν_R. The light neutrino masses are given by $m_\nu \propto (m_D/M_{HNL})^2\mu$, where μ is the Majorana mass term for S: μSS. Mixing between heavy and light neutrinos is still given by m_D/M_{HNL}, but due to the additional suppression of neutrino

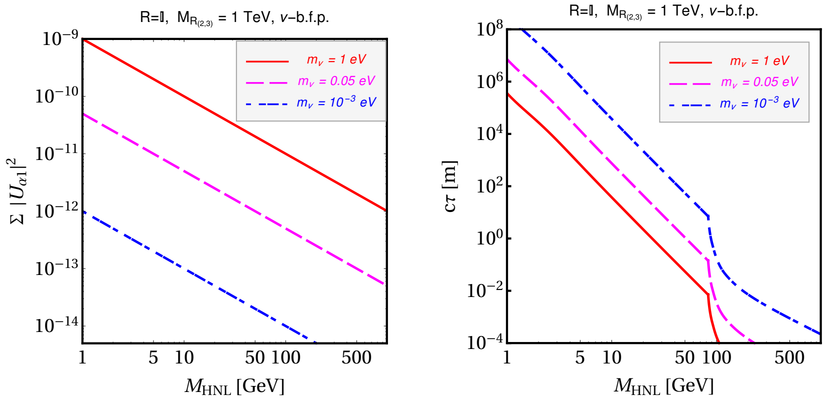

Figure 2: Typical values for the square of the heavy-light mixing and the decay length of the heavy neutral leptons (a.k.a. "sterile neutrinos" as function of the HNL mass. The plots assume a type-I seesaw and shows examples for three different choices of the active neutrino mass scale.

masses by μ, one expects larger mixing and thus larger production cross sections for the inverse seesaw than in the ordinary type-I seesaw.

Observation of displaced vertices and measurement of the HNL mass would then allow to determine whether neutrino masses are due to an ordinary or an inverse seesaw mechanism.

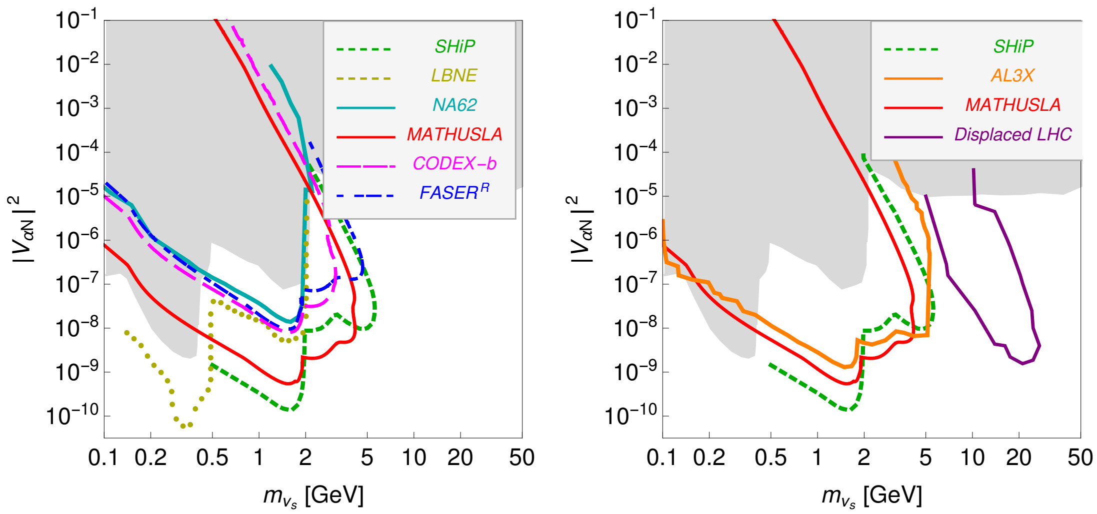

Figure 3: Comparison of the sensitvity of different experimental proposals to probe the parameter space of seesaw models, in the plane mixing squared versus mass. For a discussion see text.

In the past few years a number of different experimental proposals have appeared, aimed at searching for very long-lived light particles (LLLPs). Such LLLPs appear in dark photon and other exotic dark matter models and these models are often cited as the main motivation for the experimental proposals. However, as discussed above, if HNL with masses around the electroweak scale exist, the observed smallness of neutrino masses actually predicts that these HNLs are perfect LLLP candidates.

Figure (3) shows the forecast for the reach of the different proposals in the plane mixing squared versus mass. The plot shows expectations for SHiP [13], LBNE [14], the recalculated sensitivity of NA62 [15], MATHUSLA [16], CODEXb [17] and FASER [18], to the left. For comparison the plot to the right also shows AL3X [19] and an estimate for the reach of the ATLAS detector [20]. The sensitivity plot has been taken from [21], except for the estimate for AL3X, which is from [22] and the ATLAS estimate from [20]. Estimates are based on $3/ab$ (except CODEXb: $300/fb$ and AL3X: $250/fb$) of statistics. The grey area in the background is the region excluded by previous experiments.

It is noteworthy that ATLAS will test a different mass range than the other, dedicated LLLP experiments. Also, from the LLLP experiments shown, so far only NA62[2] is taking data, and only FASER has received funding for its phase-I. One should keep in mind that it is not likely that *all* the proposals will actually be funded. Nevertheless, let me stress that mixing squareds order $\mathscr{O}(10^{-9})$ or smaller can be tested at the high-luminosity LHC.

3. Non-minimal neutrino mass models and LNV at LHC

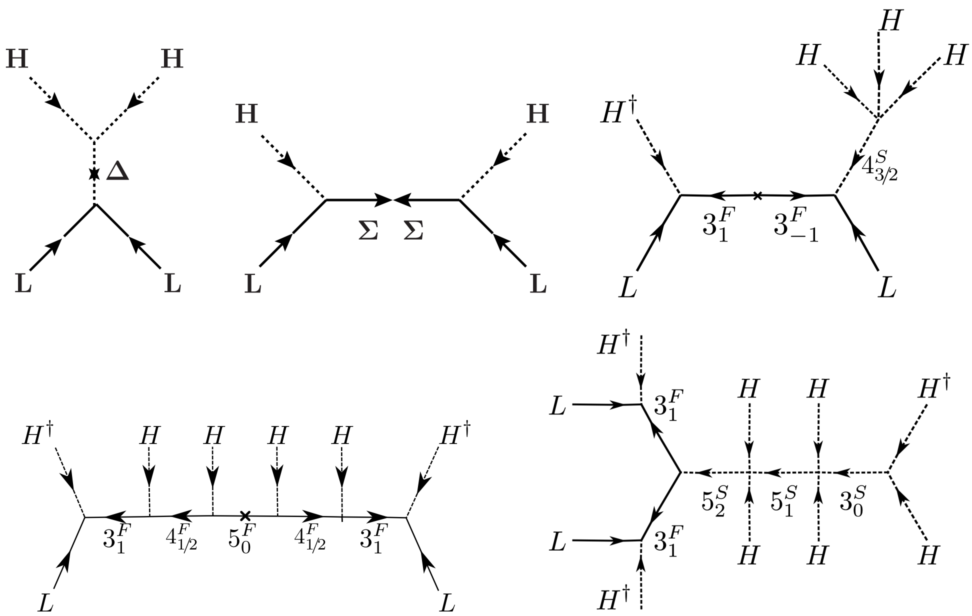

Figure 4: Top: Type-II seesaw (to the left), type-III seesaw (center) and the $d = 7$ “BNT” [24] neutrino mass model (to the right). Bottom: One example of a $d = 9$ (left) and one $d = 11$ model (right) [25].

There exist a plethora of models in the literature, impossible to even cite completely. At $d = 5$ there are also the type-II and type-III seesaw models, see fig. (4). One can classify all other models roughly as either (i) radiative or (ii) higher-dimensional neutrino mass models. The classical example of a radiative neutrino mass model is the Zee model [26]. There are now several papers systematically analyzing all 1-loop [11], 2-loop [27] and even 3-loop [28] neutrino mass models. Many references on radiative models can be found in the recent review [29].

[2]NA62's main motivation is to search for the very rare decay $K^+ \to \pi^+ \nu \bar{\nu}$ [23]. It is thus not a dedicated LLLP experiment, like the other proposals.

Here, I would like to discuss two recent papers [25, 30] on higher-dimensional neutrino mass models and their phenomenology. Higher-dimensional models need energy scales Λ of order $\mathcal{O}(1-10)$ TeV or so, see fig. (1) and thus the LHC can probe important parts of their parameter space. In fig. (4) I show a number of expample diagrams for tree-level neutrino mass models, starting with the well-known $d = 5$ seesaw type-II and type-III. Higher-d models that are genuine in the sense, that they automatically (without the use of extra symmetries beyond the SM ones) give the leading order contribution to the neutrino masses, need to introduce at least two BSM multiplets.

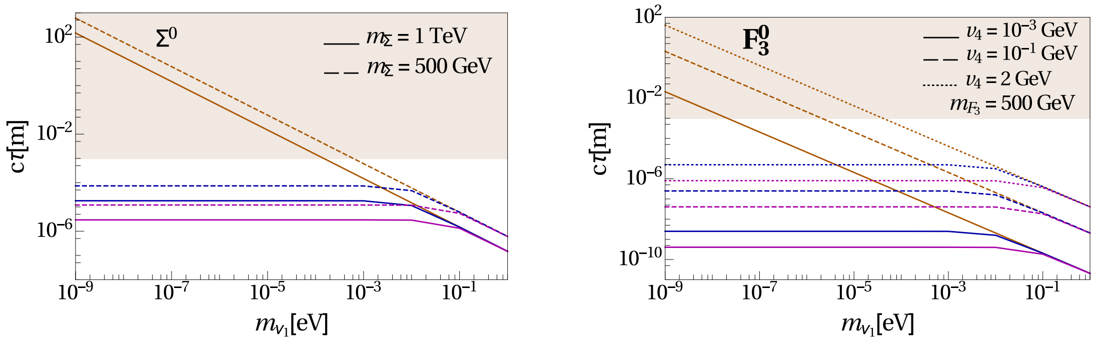

Figure 5: Decay lengths of the neutral fermions in seesaw type-III (left) and in the BNT model (right) as a function of the lightest neutrino mass.

Fig. (5) shows example decay lengths of the neutral fermions for the type-III seesaw (left) and the BNT model (right). The plot assumes three copies of the exotic fermions exist, each one generating one non-zero active neutrino mass. In magenta (blue) the state responsible for m_{ν_3} (m_{ν_2}), while the dark yellow lines are for the state that generates m_{ν_1}. Since there is currently no *lower* limit on the lightest neutrino mass, the latter state can have an arbitrarily long decay length. Measuring the decay length of this particle would allow to distinguish between different neutrino mass models, if the lightest neutrino mass were known, as can be seen by comparing the two plots. Figures for other fermions from high-d models can be found in [30] and are qualitatively similar.

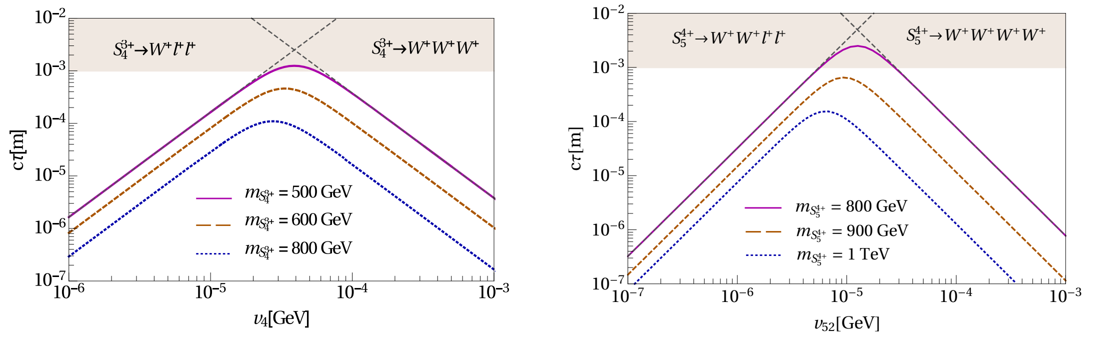

Figure 6: Decay lenghth ($c\tau$) versus exotic scalar vev. To the left, the decay of the S_4^{+3} from the BNT model. To the right S_5^{+4} from the scalar 5-plet with hypercharge $Y = 2$ from the $d = 11$ model, see fig. (4).

Many high-d models need exotic scalars. In the BNT model one introduces a scalar quadruplet with hypercharge $Y = 3/2$, for example. The neutral member of this multiplet will develop an induced vev, due to the coupling $(\mathbf{4}^S_{3/2})^\dagger HHH$, see fig. (4). Call this parameter v_4. The standard model ρ parameter puts an upper limit on v_4 of order $v_4 \leq 3.5$ GeV, while observed neutrino masses put only a very mild lower bound on v_4.

The charged members of $\mathbf{4}^S_{3/2}$ can either decay to leptons or to gauge bosons. Consider, for example S_4^{+3}. In the limit where the mass of S_4^{3+} is large, $m_4 \gg m_W$, one can find an approximate expression for its partial decay widths:

$$\Gamma(S^{3+} \to W^+W^+W^+) \sim \frac{3g^6}{2048\pi^3}\frac{v_4^2 m_4^5}{m_W^6}, \qquad \Gamma(S^{3+} \to W^+l^+l^+) \sim \frac{g^2}{3072\pi^3}\frac{m_4^3 \sum_i m_{\nu_i}^2}{v_4^2 m_W^2}. \quad (3.1)$$

Notably, the decays to gauge bosons are proportional to v_4^2, while the leptonic final states are proportional to $1/v_4^2$. This implies that there is an upper limit on the maximal decay length of this particle (which, however, also depends on its mass). This is shown in fig. (6) to the left. Several examples of m_4 masses are shown. For $m_4 = 500$ GeV, the decay length can be up to a mm or so. Finding longer displaced vertices with these exotic multi-particle final state would allow to *rule out* the BNT model as the correct explanation of neutrino masses.

Note that for all the scalars of the high-d models, a quantitatively similar behaviour is found. For example fig. (6) to the right, shows the decay lengths for S_5^{+4} from the scalar 5-plet with hypercharge $Y = 2$ from the $d = 11$ model. The decays of the S_5^{+4} are slower than those of the S_4^{3+}, essentially due to phase space suppression. Thus, (short) displaced vertices could appear in this model up to scalar masses of order roughly 800 GeV or so.

4. Discussion and conclusions

Majorana neutrino mass models can lead to a variety of exotic signals at the LHC. In this talk, I have concentrated on displaced vertex searches for neutral fermions and lepton number violating decays of exotic scalars.

Finally, let me mention some interesting conclusions that could be drawn, if LNV ever was to be discovered in an accelerator experiment [31]. One of the biggest question in physics nowadays is the origin of the baryon asymmetry in the universe. Especially popular as an explanation of the BAU is leptogenesis [32]. The mechanism relies on the production of a net lepton number, which is then transferred into a baryon number by standard model sphalerons at very early times. However, observing LNV events at the LHC can be converted into a lower limit of the washout factor of any pre-existing lepton asymmetry in the early universe [31], thus providing interesting constraints (or ruling out) any high-scale variant of leptogenesis. This is shown in fig. (4), which plots the washout factors for different values of the LHC cross section and the mass of the resonance, decaying to an LNV final state.

Acknowledgements

I would like to thank my co-authors for their valuable contributions, in particular: G. Anamiati, C. Arbeláez, R. Cepedello, G. Cottin, F. Deppisch, R. Fonseca, J. Harz and J.C. Helo. Funding by Spanish grants FPA2017-90566-REDC (Red Consolider MultiDark), FPA2017-85216-P and SEV-2014-0398 (AEI/FEDER, UE), as well as PROMETEO/2018/ 165 (Generalitat Valenciana) is acknowledged.

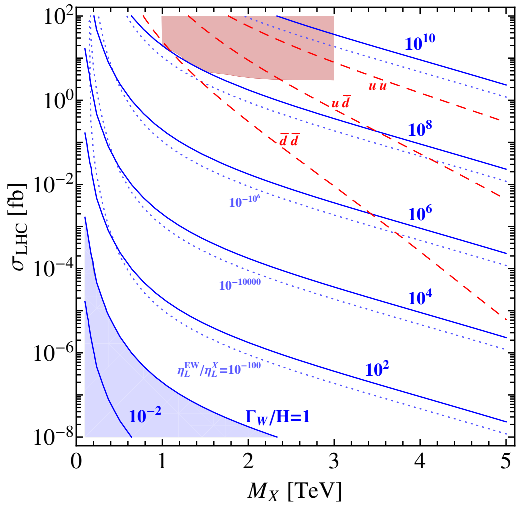

Figure 7: LHC cross section versus mass of a hypothetical particles X. Dashed lines are typical cross sections for X coupling to different quark combinations. The blue lines are the calculated washout factors for a lepton number asymmetry in the early universe, if the corresponding cross section were to be observed at the LHC [31].

References

[1] Y. Fukuda *et al.* [Super-Kamiokande Collaboration], Phys. Rev. Lett. **81**, 1562 (1998) doi:10.1103/PhysRevLett.81.1562 [hep-ex/9807003].

[2] P. F. de Salas, D. V. Forero, C. A. Ternes, M. Tortola and J. W. F. Valle, Phys. Lett. B **782**, 633 (2018) doi:10.1016/j.physletb.2018.06.019 [arXiv:1708.01186 [hep-ph]].

[3] M. Agostini *et al.* [GERDA Collaboration], Phys. Rev. Lett. **120**, no. 13, 132503 (2018) doi:10.1103/PhysRevLett.120.132503 [arXiv:1803.11100 [nucl-ex]].

[4] A. Gando *et al.* [KamLAND-Zen Collaboration], Phys. Rev. Lett. **117**, no. 8, 082503 (2016) Addendum: [Phys. Rev. Lett. **117**, no. 10, 109903 (2016)] doi:10.1103/PhysRevLett.117.109903, 10.1103/PhysRevLett.117.082503 [arXiv:1605.02889 [hep-ex]].

[5] J. Myslik [LEGEND Collaboration], arXiv:1810.00849 [physics.ins-det].

[6] S. A. Kharusi *et al.* [nEXO Collaboration], arXiv:1805.11142 [physics.ins-det].

[7] E. Ma and O. Popov, Phys. Lett. B **764**, 142 (2017) doi:10.1016/j.physletb.2016.11.027 [arXiv:1609.02538 [hep-ph]].

[8] S. Centelles Chuliá, R. Srivastava and J. W. F. Valle, Phys. Rev. D **98**, no. 3, 035009 (2018) doi:10.1103/PhysRevD.98.035009 [arXiv:1804.03181 [hep-ph]].

[9] S. Centelles Chuliá, R. Srivastava and J. W. F. Valle, Phys. Lett. B **781**, 122 (2018) doi:10.1016/j.physletb.2018.03.046 [arXiv:1802.05722 [hep-ph]].

[10] S. Weinberg, Phys. Rev. Lett. **43**, 1566 (1979). doi:10.1103/PhysRevLett.43.1566

[11] F. Bonnet, M. Hirsch, T. Ota and W. Winter, JHEP **1207**, 153 (2012) doi:10.1007/JHEP07(2012)153 [arXiv:1204.5862 [hep-ph]].

[12] R. N. Mohapatra and J. W. F. Valle, Phys. Rev. D **34**, 1642 (1986). doi:10.1103/PhysRevD.34.1642

[13] S. Alekhin *et al.*, Rept. Prog. Phys. **79**, no. 12, 124201 (2016) doi:10.1088/0034-4885/79/12/124201 [arXiv:1504.04855 [hep-ph]].

[14] C. Adams *et al.* [LBNE Collaboration], arXiv:1307.7335 [hep-ex].

[15] M. Drewes, J. Hajer, J. Klaric and G. Lanfranchi, JHEP **1807**, 105 (2018) doi:10.1007/JHEP07(2018)105 [arXiv:1801.04207 [hep-ph]].

[16] D. Curtin *et al.*, arXiv:1806.07396 [hep-ph].

[17] V. V. Gligorov, S. Knapen, M. Papucci and D. J. Robinson, Phys. Rev. D **97**, no. 1, 015023 (2018) doi:10.1103/PhysRevD.97.015023 [arXiv:1708.09395 [hep-ph]].

[18] J. L. Feng, I. Galon, F. Kling and S. Trojanowski, Phys. Rev. D **97**, no. 3, 035001 (2018) doi:10.1103/PhysRevD.97.035001 [arXiv:1708.09389 [hep-ph]].

[19] V. V. Gligorov, S. Knapen, B. Nachman, M. Papucci and D. J. Robinson, Phys. Rev. D **99**, no. 1, 015023 (2019) doi:10.1103/PhysRevD.99.015023 [arXiv:1810.03636 [hep-ph]].

[20] G. Cottin, J. C. Helo and M. Hirsch, Phys. Rev. D **98**, no. 3, 035012 (2018) doi:10.1103/PhysRevD.98.035012 [arXiv:1806.05191 [hep-ph]].

[21] J. C. Helo, M. Hirsch and Z. S. Wang, JHEP **1807**, 056 (2018) doi:10.1007/JHEP07(2018)056 [arXiv:1803.02212 [hep-ph]].

[22] D. Dercks, H. K. Dreiner, M. Hirsch and Z. S. Wang, Phys. Rev. D **99**, no. 5, 055020 (2019) doi:10.1103/PhysRevD.99.055020 [arXiv:1811.01995 [hep-ph]].

[23] C. Lazzeroni *et al.* [NA62 Collaboration], Phys. Lett. B **719**, 326 (2013) doi:10.1016/j.physletb.2013.01.037 [arXiv:1212.4012 [hep-ex]].

[24] K. S. Babu, S. Nandi and Z. Tavartkiladze, Phys. Rev. D **80**, 071702 (2009) doi:10.1103/PhysRevD.80.071702 [arXiv:0905.2710 [hep-ph]].

[25] G. Anamiati, O. Castillo-Felisola, R. M. Fonseca, J. C. Helo and M. Hirsch, JHEP **1812**, 066 (2018) doi:10.1007/JHEP12(2018)066 [arXiv:1806.07264 [hep-ph]].

[26] A. Zee, Phys. Lett. **93B**, 389 (1980) Erratum: [Phys. Lett. **95B**, 461 (1980)]. doi:10.1016/0370-2693(80)90349-4, 10.1016/0370-2693(80)90193-8

[27] D. Aristizabal Sierra, A. Degee, L. Dorame and M. Hirsch, JHEP **1503**, 040 (2015) doi:10.1007/JHEP03(2015)040 [arXiv:1411.7038 [hep-ph]].

[28] R. Cepedello, R. M. Fonseca and M. Hirsch, JHEP **1810**, 197 (2018) Erratum: [JHEP **1906**, 034 (2019)] doi:10.1007/JHEP10(2018)197, 10.1007/JHEP06(2019)034 [arXiv:1807.00629 [hep-ph]].

[29] Y. Cai, J. Herrero-Garcia, M. A. Schmidt, A. Vicente and R. R. Volkas, Front. in Phys. **5**, 63 (2017) doi:10.3389/fphy.2017.00063 [arXiv:1706.08524 [hep-ph]].

[30] C. Arbeláez, J. C. Helo and M. Hirsch, arXiv:1906.03030 [hep-ph].

[31] F. F. Deppisch, J. Harz and M. Hirsch, Phys. Rev. Lett. **112**, 221601 (2014) doi:10.1103/PhysRevLett.112.221601 [arXiv:1312.4447 [hep-ph]].

[32] M. Fukugita and T. Yanagida, Phys. Lett. B **174**, 45 (1986). doi:10.1016/0370-2693(86)91126-3