Testing a lepton quarticity flavor theory of neutrino oscillations with the DUNE experiment

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Oscillation studies play a central role in elucidating at least some aspects of the flavor problem. Here we examine the status of the predictions of a lepton quarticity flavor theory of neutrino oscillations against the existing global sample of oscillation data. By performing quantitative simulations we also determine the potential of the upcoming DUNE experiment in narrowing down the currently ill-measured oscillation parameters θ_{23} and δ_{CP} . We present the expected improved sensitivity on these parameters for different assumptions.

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I. INTRODUCTION

Despite the overwhelming success of the standard model of particle physics, it does not shed any light on the understanding of the masses and mixings of quarks and leptons - the so-called flavor problem. The experimental discovery of neutrino oscillations [1, 2] not only constitutes the first window into particle physics beyond the Standard Model, but also exacerbates the challenge posed by the flavor problem. Indeed, the observed pattern of neutrino oscillation parameters [3] indicates that leptons are very different from quarks insofar as the pattern of their charged current mixing is concerned.

There have been several recent theoretical models proposed in order to address the flavor problem by incorporating various flavor symmetries [4–12] to account for the valuable information that comes from oscillation studies. An alternative approach focusing upon the possible residual CP symmetries characterizing the neutrino mass matrices, irrespective of the details of the underlying theory, has also been considered in [13, 14].

Some of these theoretical constructions [7, 8] have prompted dedicated studies confronting their predictions with global neutrino oscillation data [15–17]. Here we consider a previously proposed neutrino oscillation theory. The flavor model construction implements an A_4 flavor symmetry as well as lepton quarticity symmetry [18]. The latter correlates dark matter stability with the predicted Dirac nature of neutrinos [19].

While this is an interesting connection in itself, leading to a viable dark matter scenario, it leads to novel neutrino predictions, for example the presence of neutrinoless quadruple beta decay $(0\nu4\beta)$ signal in the absence of neutrinoless double beta decay $(0\nu2\beta)$ [20]. Considering that Majorana neutrinos have so far remained elusive [21–23] the possibility that the quadruple beta decay might exist on its own [24] is especially intriguing and has already been subject to a dedicated experimental search by the NEMO collaboration [25].

Apart from these interesting features of the model, which arise from the quarticity symmetry, the model has other novel features owing to the presence of A_4 flavor symmetry. Thanks to the latter, the tree level dimension-4 Dirac mass terms for the neutrinos are forbidden. However, the A_4 symmetry allows us to generate seesaw-induced small neutrino masses. In addition, the model predicts a successful generalized "golden" Bottom-Tau unification formula [26–29], as well as definite predictions for neutrino oscillations. For example, the scheme leads to normal neutrino mass ordering. It also leads to a strong correlation between the two currently ill-measured oscillation parameters, namely the leptonic CP phase $\delta_{\rm CP}$ and the mixing angle θ_{23} . This correlation in turn implies that CP must be significantly violated in neutrino oscillations, with the atmospheric angle θ_{23} lying in the second octant.

Owing to the precise predictions made by the model, it constitutes an ideal candidate to be probed at the forthcoming long baseline oscillation experiments aimed at measuring δ_{CP} and θ_{23} , such as DUNE. Here we scrutinize the neutrino oscillation predictions obtained in the model against the latest available global neutrino oscillation study [3] as well as the future discriminating power of the DUNE experiment. Our strategy here is then, given the

current measurements of the four "well determined" oscillation parameters, i.e. the mass splittings characterizing solar and atmospheric oscillations plus the two mixing angles θ_{12} and θ_{13} , to determine the potential of the upcoming DUNE experiment in narrowing down the still poorly measured parameters θ_{23} - δ_{CP} . We do this for the general "unconstrained" three-neutrino oscillation paradigm, as well for our "constrained" scenario in which the model predictions are taken into account. From our results we conclude that substantial improvements are to be expected.

II. CURRENT STATUS OF THE MODEL

In order to define our goal we first determine the current status of the neutrino oscillation parameters within the model, by taking into account the latest global analysis. We provide an improved update of the model neutrino oscillation predictions [18], originally tested against our previous oscillation global fit presented in [30] assuming only the one-dimensional 3σ intervals. Here we confront the model with the new results [3] and use the more complete χ^2 -distributions. In order to do so, we generated many points consistent with the model predictions. The latter are obtained by first randomly varying all the free parameters such as Yukawa couplings and new scalar field vevs over their allowed theoretical ranges. The points thus obtained are then tested for their compatibility with the currently well measured observables, such as quark and charged lepton masses ¹. For more details on the model predictions see [18]. Only points within the 3σ range of these parameters are retained as genuine points. Next, using the results from the global fit to neutrino oscillations in Ref. [3], we assign to each of those points a χ^2 -value that quantifies their agreement with most recent data. Given the negligible effect of solar parameters in DUNE we have simply selected those oscillation parameter sets with solar parameters within their allowed 3σ region, as derived in [3]. The resulting 4-dimensional χ^2 -maps are minimized over Δm_{31}^2 and $\sin^2\theta_{13}$, leading to the final distribution as a function of the parameters of interest, θ_{23} and $\delta_{\rm CP}$.

The results for the current status of the model are presented in Fig. 1. One finds that, thanks to the new oscillation data, the predicted regions have shrunk significantly with respect to those in Ref. [18], so that CP phase values $\delta_{\text{CP}} \leq \pi$ are allowed only at 3σ . Indeed, one sees that, at 3σ confidence level, one of the two allowed branches has nearly disappeared. We find that the new 4σ regions are roughly similar to the old 3σ regions, and there are no points surviving at the 1σ confidence level. Note that neither the current best fit point nor the local minimum from the global neutrino oscillation fit in [3] lies within the parameter region predicted by the model. As a result, if new data confirm the current best fit point, the local minimum or nearby values, the model would be strongly disfavored.

¹ The constraints coming from neutrino oscillation parameters are not imposed at this point. However, we do impose the cosmological limit on sum of neutrino masses [31].

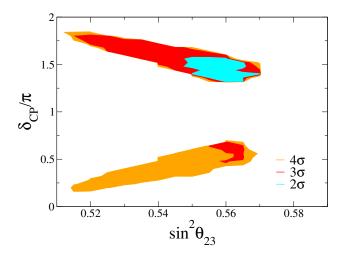


Figure 1: Allowed regions at 2, 3 and 4σ in the plane θ_{23} - δ_{CP} within the model, given the current global neutrino oscillation analysis.

III. SIMULATION OF THE DUNE EXPERIMENT

We simulate the DUNE experiment using the GLoBES package [32, 33] and the auxiliary file [34] used to produce the plots in Ref. [35]. In our simulation DUNE is running 3.5 years in the neutrino mode and another 3.5 years in the anti-neutrino mode. Using its 80 GeV beam with 1.07 MW beam power and the 40 kt far detector, this gives an exposure of 300 kton-MW-years, which corresponds to 1.47×10^{21} protons on target (POTs) each year.

We consider the disappearance channels for neutrinos and anti-neutrinos, as well as the appearance channels. We also simulate the backgrounds, taking into account several sources of errors in our simulation, where we assign a 2% error on the signals in the appearance channels and 5% in the disappearance channels, as indicated in the studies performed by the DUNE Collaboration [35]. Likewise, we have implemented backgrounds ranging between 5% and 20%. These include misinterpretation of neutrinos as antineutrinos and vice-versa, contamination of electron neutrinos and antineutrinos in the beam, misinterpretation of muon as electron neutrinos, as well as the appearance and misinterpretation of tau neutrinos and neutral current interactions.

Here we are mainly interested in the currently poorly determined oscillation parameters $\sin^2\theta_{23}$ and $\delta_{\rm CP}$. Therefore, in order to simulate the future event rate in DUNE we fix the rest of the parameters to their best fit values reported in [3]. Then, in the statistical analysis performed to determine the DUNE sensitivity, we marginalize over θ_{13} , θ_{12} , Δm_{31}^2 and Δm_{21}^2 within their 1σ -ranges, see Table I. Concerning the parameters of interest, we generate future DUNE data by assuming several pairs of $(\theta_{23}^{\rm true}, \delta_{\rm CP}^{\rm true})$. For each set of reconstructed parameters $(\theta_{23}, \delta_{\rm CP})$ we calculate the χ^2 -function, given as

$$\chi^{2}(\theta_{23}, \delta_{\text{CP}}) = \min_{\theta_{1j}, \Delta m_{j1}^{2}, \vec{\alpha}} \sum_{\text{channels}} 2 \sum_{n} \left[N_{n}^{\text{test}} - N_{n}^{\text{dat}} + N_{n}^{\text{dat}} \log \left(\frac{N_{n}^{\text{dat}}}{N_{n}^{\text{test}}} \right) \right] + \sum_{i} \left(\frac{\alpha_{i}}{\sigma_{i}} \right), \quad (1)$$

parameter	best fit value	relative error
Δm_{21}^2	$7.56 \times 10^{-5} \text{eV}^2$	2.5%
Δm_{31}^2	$2.55 \times 10^{-3} \text{eV}^2$	1.6%
$\sin^2 \theta_{13}$	0.02155	3.9%
$\sin^2 \theta_{12}$	0.321	5.5%

Table I: Best fit values and 1σ relative uncertainties for the better determined neutrino oscillation parameters from [3].

where θ_{1j} , Δm_{j1}^2 (j=2,3) denote the four well-measured oscillation parameters. Here $N_n^{\rm dat}$ corresponds to the simulated event number in the *n*-th bin obtained with $\theta_{23}^{\rm true}$ and $\delta_{\rm CP}^{\rm true}$. $N_n^{\rm test}$ is the event number in the *n*-th bin associated to the parameters (θ_{23} , $\delta_{\rm CP}$) and α_i and σ_i are the nuisance parameters and their corresponding standard deviations, respectively. Although not explicitly shown, note that $N_n^{\rm test}$ also depends on $\vec{\alpha}$.

IV. RESULTS

In this section we present the main results of the analyses which we have performed in order to test the neutrino oscillation model in question. We start in Sec. IV A by performing an unconstrained DUNE sensitivity analysis for seven years of run time, assuming 3.5 years runs in both neutrino and anti-neutrino mode. In this analysis we have assumed that $\theta_{23}^{\text{true}}$ and $\delta_{\text{CP}}^{\text{true}}$ lie within the 1σ region obtained in the recent neutrino oscillation global fit [3]. This analysis is performed in order to quantify the projected sensitivity of the DUNE experiment given the current status of these parameters, and is completely model-independent.

In Sec. IV B, we present the expected sensitivity on the currently ill-measured parameters after seven years running of DUNE, assuming that $\theta_{23}^{\text{true}}$ and $\delta_{\text{CP}}^{\text{true}}$ lie in the range predicted by the model. In this analysis we have taken into account only the model prediction for these parameters and have not taken into account the current global oscillation fit. Finally, in Sec. IV C we perform a combined analysis of the expected DUNE sensitivity taking into account, as input, both the range predicted by the model as well as the current oscillation global fit. The different analyses are performed in order to highlight the discriminating power of DUNE in various scenarios of interest, both from the model point of view as well from that of the current global fit.

A. Model-independent DUNE sensitivity

As explained above, in this section we study the sensitivity of DUNE to θ_{23} and δ_{CP} , taking into account the current status of neutrino oscillations as reported in [3]. Assuming the true oscillation parameters to be the current best fit values would be too strong an

assumption. We have therefore decided to vary $\theta_{23}^{\text{true}}$ and $\delta_{\text{CP}}^{\text{true}}$ within their 1σ ranges for two degrees of freedom (d.o.f.), indicated by the dashed black lines in Fig. 2. We have performed this analysis separately for the values in the lower and the upper octant of the atmospheric angle. For this we have defined

$$\chi_{1\sigma}^2(\theta_{23}, \delta_{\text{CP}}) = \min_{\theta_{23}^{\text{true}}, \delta_{\text{CP}}^{\text{true}}} \chi^2(\theta_{23}, \delta_{\text{CP}}), \tag{2}$$

where $(\theta_{23}^{\text{true}}, \delta_{\text{CP}}^{\text{true}})$ run first over all the values allowed in the lower octant, and later over all those allowed in the upper octant. Here $\chi^2(\theta_{23}, \delta_{\text{CP}})$ is the function given in Eq. 1.

The results of this minimization can be seen in Fig. 2, where we plot the 1σ , 2σ , 3σ and 4σ allowed regions for 2 d.o.f in the $\sin^2\theta_{23}$ – $\delta_{\rm CP}$ plane. The left (right) panel corresponds to the analysis assuming $\theta_{23}^{\rm true}$ to lie in the lower (upper) octant. At the moment, the lower octant is preferred by the global oscillation data, and therefore there are much more points in this region, resulting in a bigger region in our plot.

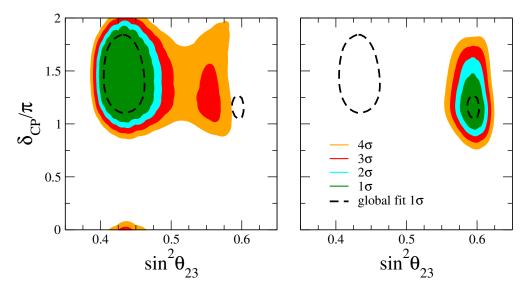


Figure 2: Potential of DUNE running 7 years in narrowing down the currently ill-measured parameters θ_{23} - δ_{CP} . The left (right) panel only assumes that θ_{23}^{true} lies in the lower (upper) octant. Both θ_{23}^{true} and δ_{CP}^{true} are allowed to vary in their allowed 1σ -regions. The dashed black line is the 1σ region from the global fit performed in [3]. See text for more details.

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Notice that in the left panel, the degenerate solution in the second octant appears only at the 3σ confidence level. Conversely, if the true value of the atmospheric mixing angle lies in the small region in the upper octant (see right panel of Fig. 2), the degenerate first-octant solution would be ruled out at more than 4σ . Maximal mixing is disfavored at more than 3σ (5σ) for $\theta_{23}^{\rm true}$ in the lower (upper) octant. In both cases, values of $\delta_{\rm CP} \approx 0.5\pi$ would be excluded with very high significance.

B. Testing the model with DUNE

In order to quantify the sensitivity of DUNE to test the model predictions, we now perform a simulation of DUNE suited to the model of interest. Our procedure will not depend on any input from global neutrino oscillation fits. This means we assume the model prediction for θ_{23} and δ_{CP} to be the true values used to generate DUNE data. As in the last section, we define the χ^2 function as

$$\chi^2_{\text{DUNE+model}}(\theta_{23}, \delta_{\text{CP}}) = \min_{\substack{\theta_{23}^{\text{true}}, \delta_{\text{CP}}^{\text{true}}}} \chi^2(\theta_{23}, \delta_{\text{CP}}).$$
 (3)

In this case, $(\theta_{23}^{\text{true}}, \delta_{\text{CP}}^{\text{true}})$ are not the values from the 1σ regions of [3], but include, instead, all the points predicted by the model and consistent at 3σ with the current global fit, see Fig. 1. The resulting regions corresponding to 1σ to 4σ confidence level for 2 d.o.f. are presented in Fig. 3. These results correspond to the case where only the model predictions are taken into account. In this case one finds that, by themselves, model predictions plus DUNE data would not suffice to determine the octant of the atmospheric angle or a unique preferred range for the CP phase, at least not for all parameter choices 2 .

By including valuable information on the current status of global fits to neutrino oscillations one can sharpen the expected DUNE sensitivity to the oscillation parameters, beyond the results of Fig. 3. This is done in the next section.

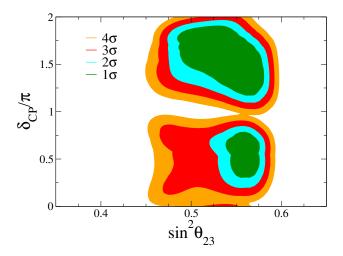


Figure 3: DUNE sensitivity to the $(\sin^2 \theta_{23}, \delta_{CP})$ parameter region predicted by the model consistent with the current global fit at 3σ .

² Notice that, ideally, only one set of $(\theta_{23}, \delta_{CP})$ would be realized in nature as the true value while, to be conservative, here we marginalize over all neutrino oscillation parameters possible in the model.

C. Testing the model with DUNE: the global picture

In order to better quantify the sensitivity of DUNE to test the model predictions we now perform a "constrained global neutrino oscillation fit" suited to the model of interest. We do this by combining the DUNE simulation with the global fit to neutrino oscillations in Ref. [3] in the context of the lepton quarticity flavor model under study. In order to combine the results of the DUNE simulations performed here with the global analysis of neutrino oscillation data we simply sum the χ^2 function defined in Sec. IV B with the χ^2 grid obtained in the global fit to neutrino oscillations in Ref. [3],

$$\chi_{\text{tot}}^2(\theta_{23}, \delta_{\text{CP}}) = \chi_{\text{DUNE+model}}^2(\theta_{23}, \delta_{\text{CP}}) + \chi_{\text{fit}}^2(\theta_{23}, \delta_{\text{CP}}). \tag{4}$$

The results are presented in Fig. 4, where we plot the regions allowed at 1σ to 4σ confidence level for 2 d.o.f. One sees that by combing all the relevant information the regions shrink with respect to those of Fig. 3, since the global fit to current neutrino data disfavors δ_{CP} in the range $[0, \pi]$. This result is shown in the corresponding panel of Fig. 8 in [3]. One sees that, by properly taking into account the current knowledge of neutrino oscillation parameters and the model under consideration, one concludes that DUNE will determine rather well the CP phase at the 1σ level, excluding CP-conserving scenarios at more than 3σ . One sees also that, at the 1σ level, the second octant would be singled out. Besides that,

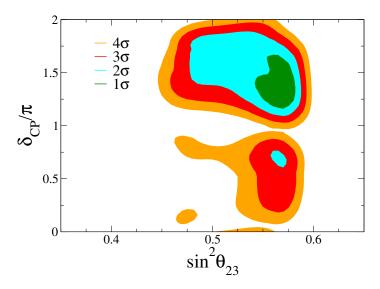


Figure 4: DUNE sensitivity to the $(\sin^2 \theta_{23}, \delta_{CP})$ parameter region predicted by the model, taking into account the constraints from the current global neutrino oscillation fit in [3].

the status of maximal mixing would worsen in comparison to Fig. 3, as a consequence of the recent global fit results, although it would still remain allowed at the 2σ level for certain consistent model parameter choices. As commented before, here we are marginalizing over a large set of true oscillation parameters and therefore, the real sensitivity given in Fig. 4 would still be too conservative.

V. SUMMARY AND DISCUSSION

Neutrino oscillation studies may play a key role in elucidating major aspects of the flavor problem. Here we have provided a quantitative study of the status of the predictions of a lepton quarticity flavor theory of neutrino oscillations. Thanks to the assumed flavor symmetry, the model explains the small neutrino masses as a result of a variant of the seesaw mechanism leading to Dirac neutrinos. Due to quarticity, the model has a viable dark matter candidate stabilized by the Diracness of neutrinos. In addition, it leads to a successful "golden" Bottom-Tau unification formula, as well as definite predictions for neutrino oscillations, first studied in [18]. Here we have reexamined the consistency of neutrino oscillation model predictions in view of the latest global sample of neutrino oscillation data [3]. One finds that the model predicts normal neutrino mass ordering, and significant violation of CP in neutrino oscillations, with the atmospheric angle θ_{23} lying in the second octant. Our results are given in Fig. 1. By performing dedicated simulations we have also determined the potential of future DUNE data in further restricting the currently ill-measured oscillation parameters, θ_{23} and δ_{CP} . Fig. 2 illustrates the resulting sensitivity for the "unconstrained" model-independent case, assuming the true θ_{23} and $\delta_{\rm CP}$ parameters to lie within the 1σ region obtained from the recent global fit to neutrino oscillations as given in [3]. By taking into account not only the information from the current neutrino oscillation global fit results but also the specific model predictions, we have shown that DUNE data should unambiguously single out the second octant of θ_{23} and exclude values of δ_{CP} below π at the 1σ level, as seen in Fig. 4. Finally we stress that, as already mentioned, by marginalizing over a large set of potential true oscillation parameter values, we are being conservative in our estimate of the improved sensitivity of DUNE to test the model under consideration.

ACKNOWLEDGMENTS

Work supported by the Spanish grants FPA2014-58183-P, FPA2017-85216-P and SEV-2014-0398 (MINECO), PROMETEOII/2014/084 and GV2016-142 grants from Generalitat Valenciana. MT is also supported by a Ramón y Cajal contract (MINECO).

^[1] T. Kajita, Nobel Lecture: Discovery of atmospheric neutrino oscillations, Rev. Mod. Phys. 88 (2016) 3 030501.

^[2] A. B. McDonald, Nobel Lecture: The Sudbury Neutrino Observatory: Observation of flavor change for solar neutrinos, Rev. Mod. Phys. 88 (2016) 3 030502.

^[3] P. F. de Salas et al., Status of neutrino oscillations 2017 (2017), arXiv:1708.01186 [hep-ph].

^[4] K. S. Babu, E. Ma and J. W. F. Valle, Underlying A(4) symmetry for the neutrino mass matrix and the quark mixing matrix, Phys. Lett. **B552** (2003) 207–213, arXiv:hep-ph/0206292

- [hep-ph].
- [5] G. Altarelli and F. Feruglio, *Models of neutrino masses and mixings*, New J.Phys. **6** (2004) 106, edited by F. Halzen, M. Lindner and A. Suzuki, arXiv:hep-ph/0405048 [hep-ph].
- [6] S. Morisi and J. W. F. Valle, Neutrino masses and mixing: a flavour symmetry roadmap, Fortsch.Phys. 61 (2013) 466-492, arXiv:1206.6678 [hep-ph].
- [7] S. Morisi, D. Forero, J. C. Romao and J. W. F. Valle, Neutrino mixing with revamped A4 flavour symmetry, Phys.Rev. **D88** (2013) 016003, arXiv:1305.6774 [hep-ph].
- [8] P. Chen et al., Warped flavor symmetry predictions for neutrino physics, JHEP 01 (2016) 007, arXiv:1509.06683 [hep-ph].
- [9] E. Ma, Soft $A_4 \rightarrow Z_3$ symmetry breaking and cobimaximal neutrino mixing, Phys. Lett. **B755** (2016) 348–350, arXiv:1601.00138 [hep-ph].
- [10] A. E. Carcamo Hernandez et al., *Predictive Pati-Salam theory of fermion masses and mixing*, JHEP **07** (2017) 118, arXiv:1705.06320 [hep-ph].
- [11] E. Ma, Cobimaximal Neutrino Mixing from $S_3 \times Z_2$ (2017), arXiv:1707.03352 [hep-ph].
- [12] S. F. King, Unified Models of Neutrinos, Flavour and CP Violation, Prog. Part. Nucl. Phys. 94 (2017) 217–256, arXiv:1701.04413 [hep-ph].
- [13] P. Chen et al., Generalized $\mu \tau$ reflection symmetry and leptonic CP violation, Phys. Lett. **B753** (2016) 644–652, arXiv:1512.01551 [hep-ph].
- [14] P. Chen et al., Classifying CP transformations according to their texture zeros: theory and implications, Phys. Rev. D94 (2016) 3 033002, arXiv:1604.03510 [hep-ph].
- [15] P. Pasquini, S. C. Chuliá and J. W. F. Valle, Neutrino oscillations from warped flavor symmetry: predictions for long baseline experiments T2K, NOvA and DUNE, Phys. Rev. D95 (2017) 9 095030, arXiv:1610.05962 [hep-ph].
- [16] S. S. Chatterjee, P. Pasquini and J. W. F. Valle, Probing atmospheric mixing and leptonic CP violation in current and future long baseline oscillation experiments, Phys. Lett. B771 (2017) 524–531, arXiv:1702.03160 [hep-ph].
- [17] S. S. Chatterjee et al., Cornering the revamped BMV model with neutrino oscillation data, Phys. Lett. **B774** (2017) 179–182, arXiv:1708.03290 [hep-ph].
- [18] S. Centelles Chuliá, R. Srivastava and J. W. F. Valle, Generalized Bottom-Tau unification, neutrino oscillations and dark matter: predictions from a lepton quarticity flavor approach, Phys. Lett. B773 (2017) 26–33, arXiv:1706.00210 [hep-ph].
- [19] S. Centelles Chuliá et al., Dirac Neutrinos and Dark Matter Stability from Lepton Quarticity, Phys. Lett. B767 (2017) 209–213, arXiv:1606.04543 [hep-ph].
- [20] M. Hirsch, R. Srivastava and J. W. F. Valle, Can one ever prove that neutrinos are Dirac particles? (2017), arXiv:1711.06181 [hep-ph].
- [21] M. Agostini et al., Background free search for neutrinoless double beta decay with GERDA Phase II (2017), [Nature544,47(2017)], arXiv:1703.00570 [nucl-ex].

- [22] J. Albert et al. (EXO-200 Collaboration), Search for Majorana neutrinos with the first two years of EXO-200 data, Nature 510 (2014) 229-234, arXiv:1402.6956 [nucl-ex].
- [23] C. Alduino et al. (CUORE), First Results from CUORE: A Search for Lepton Number Violation via $0\nu\beta\beta$ Decay of ¹³⁰ Te (2017), arXiv:1710.07988 [nucl-ex].
- [24] J. Heeck and W. Rodejohann, Neutrinoless Quadruple Beta Decay, EPL 103 (2013) 3 32001, arXiv:1306.0580 [hep-ph].
- [25] R. Arnold et al. (NEMO-3), Search for neutrinoless quadruple-β decay of ¹⁵⁰Nd with the NEMO-3 detector, Phys. Rev. Lett. **119** (2017) 4 041801, arXiv:1705.08847 [hep-ex].
- [26] S. Morisi et al., Relating quarks and leptons without grand-unification, Phys.Rev. **D84** (2011) 036003, arXiv:1104.1633 [hep-ph].
- [27] S. King et al., Quark-Lepton Mass Relation in a Realistic A4 Extension of the Standard Model, Phys. Lett. B **724** (2013) 68–72, arXiv:1301.7065 [hep-ph].
- [28] S. Morisi et al., Quark-Lepton Mass Relation and CKM mixing in an A4 Extension of the Minimal Supersymmetric Standard Model, Phys.Rev. D88 (2013) 036001, arXiv:1303.4394 [hep-ph].
- [29] C. Bonilla et al., Relating quarks and leptons with the T₇ flavour group, Phys. Lett. **B742** (2015) 99–106, arXiv:1411.4883 [hep-ph].
- [30] D. Forero, M. Tortola and J. W. F. Valle, Neutrino oscillations refitted, Phys.Rev. D90 (2014) 9 093006, arXiv:1405.7540 [hep-ph].
- [31] M. Lattanzi (Planck), Planck 2015 constraints on neutrino physics, J. Phys. Conf. Ser. 718 (2016) 3 032008.
- [32] P. Huber, M. Lindner and W. Winter, Simulation of long-baseline neutrino oscillation experiments with GLoBES (General Long Baseline Experiment Simulator), Comput. Phys. Commun. 167 (2005) 195, arXiv:hep-ph/0407333 [hep-ph].
- [33] P. Huber et al., New features in the simulation of neutrino oscillation experiments with GLoBES 3.0: General Long Baseline Experiment Simulator, Comput.Phys.Commun. 177 (2007) 432–438, arXiv:hep-ph/0701187 [hep-ph].
- [34] T. Alion et al. (DUNE), Experiment Simulation Configurations Used in DUNE CDR (2016), arXiv:1606.09550 [physics.ins-det].
- [35] R. Acciarri et al. (DUNE), Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) (2015), arXiv:1512.06148 [physics.ins-det].