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Flavour violation in charged leptons: Present and future

Violation de la saveur dans le secteur des leptons chargés : Présent et futur

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ABSTRACT

In the absence of a fundamental principle preventing charged lepton flavour violation, one expects that extensions of the Standard Model accommodating neutrino masses and mixings should also allow for charged lepton flavour violating processes such as $\ell_i \to \ell_j \gamma$, $\ell_i \to \ell_j \ell_k \ell_m$ and μ–e conversion in nuclei, for which the rates depend in general on the mechanism of neutrino mass generation. In addition to low-energy experiments, there are also searches for lepton flavour violation at colliders, where new physics can be directly probed through flavour violating production and/or decays of heavy states. In a model independent way, we briefly use effective operators responsible for these processes to derive information about the underlying framework of new physics. We then consider some specific classes of models (supersymmetry, extra dimensions, grand unified theories) that account for rich scenarios of charged lepton flavour violation. We also comment on the rôle of charged lepton flavour violation in disentangling between models of new physics.

RÉSUMÉ

En l'absence de tout principe fondamental qui interdirait la non-conservation de la saveur dans le secteur des leptons chargés, on s'attend que les extensions du Modèle Standard qui expliquent les masses et mélanges des neutrinos autorisent également la violation de la saveur à travers des processus tels que $\ell_i \to \ell_j \gamma$, $\ell_i \to \ell_j \ell_k \ell_m$ et la conversion μ–e dans les noyaux, dont les taux dépendent en général du mécanisme qui engendre des masses de neutrinos. On peut aussi rechercher des signes de cette violation directement aux collisionneurs, à travers des processus de production/désintégration de particules lourdes. D'une façon indépendante de tout modèle, nous montrons comment obtenir des informations sur la physique sous-jacente en utilisant des opérateurs effectifs. Enfin, nous considérons le rôle de la violation de la saveur leptonique dans des classes de modèles telles que la supersymétrie, les dimensions supplémentaires et les théories grand-unifiées.

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1. Introduction

Neutrino (ν) oscillation experiments provide indisputable evidence for flavour violation in the neutral lepton sector. One expects that extensions of the Standard Model (SM) accommodating neutrino masses (m_ν) and mixings should also allow for charged lepton flavour violation (cLFV) (for a review, see Ref. [1] and references therein). In the SM, as it was originally

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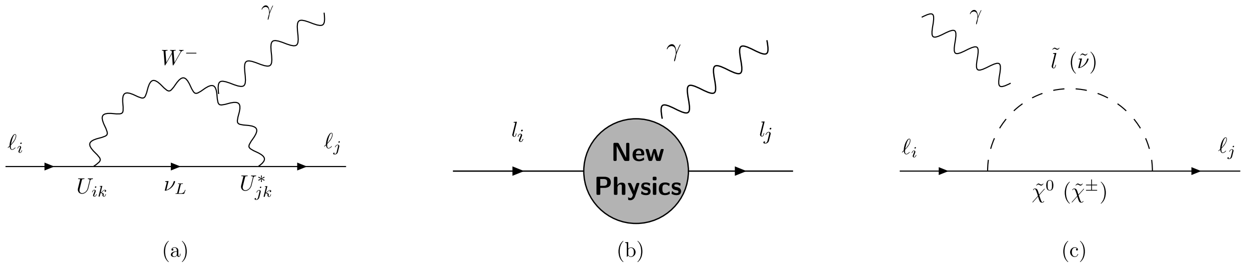

Fig. 1. Radiative decays $\ell_i \to \ell_j \gamma$: (a) in the SM ($m_\nu \neq 0$), in new physics models (b) and in SUSY models (c).

Fig. 1. Désintégrations radiatives $\ell_i \to \ell_j \gamma$ dans les cadres : (a) du Modèle Standard ($m_\nu \neq 0$), de nouvelle physique (b) et de la sypersymétrie (c).

formulated (massless ν), cLFV processes are forbidden. With massive νs (no assumption being made on the mechanism of ν mass generation), cLFV processes are suppressed by the tiny ν masses (GIM mechanism). For example, the branching ratio (BR) of the $\mu \to e\gamma$ decay, Fig. 1(a), is given by:

$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_i U^*_{\mu i} U_{ei} \frac{m^2_{\nu_i}}{M^2_W} \right|^2 \tag{1}$$

and using known oscillation parameters ($U = U_{\mathrm{MNS}}$ being the leptonic mixing matrix) [2], one finds $\mathrm{BR}(\mu \to e\gamma) \lesssim 10^{-54}$, thus clearly unaccessible to present and future experiments! In contrast with flavour violation in the hadronic sector, where phenomena such as neutral meson mixings and rare decays can be successfully explained by the SM, cLFV undisputably signals the presence of new physics (NP). Indeed, the additional particle content and new flavour dynamics present in many extensions of the SM may give contributions to cLFV processes such as radiative (e.g. $\mu \to e\gamma$) and three-body decays (e.g. $\mu \to eee$), so that the observation of such processes would provide an unambiguous signal of NP, see Fig. 1(b).

The quest for new physics is currently being pursued along different avenues: although high-energy colliders like the LHC are the ideal tools to directly search the particle content of the specific SM extension, low-energy experiments indirectly probe the NP model through its contributions to several observables (among which the muon anomalous magnetic moment, electric dipole moments, cLFV observables, B-physics, etc.). Thus, if observable, cLFV is expected to play a crucial rôle in successfully (or even partially) reconstructing the underlying framework of new physics.

In the SM, lepton number is an accidental symmetry due to the gauge group and particle content. The generation of ν masses exclusively using the SM field content requires adding to the SM Lagrangian non-renormalisable operators of dimension 5 (or higher), that break lepton number. The unique dimension 5 operator that can be built with the SM fields is the Weinberg operator, which is responsible for the Majorana mass of the neutrinos. In fact, any model of new physics that violates B–L will give rise to the Weinberg operator at low energies (when the heavy fields are integrated out). Among the dimension 6 operators (second order in an $1/M$ expansion, M being the scale of new physics), one finds a four-fermion operator responsible for cLFV processes. The breaking of lepton number, as required by Majorana ν masses, then provides a natural link between neutrino mass generation and cLFV.

2. Current experimental searches and future prospects

So far, no signal of cLFV has been observed. Although rare leptonic decay searches have been an important part of the experimental program for several decades, these searches gained a renewed momentum with the confirmation of neutral LFV (neutrino oscillations). Currently, the search for manifestations of charged LFV constitutes the goal of several experiments [3–15], exclusively dedicated to look for signals of rare lepton decay processes. Equally interesting LFV observables are μ–e conversions in heavy nuclei: although significant improvements are expected regarding the experimental sensitivity to $\mu \to e\gamma$ ($< 10^{-13}$ [12]), the most challenging experimental prospects arise for the CR(μ–e) in heavy nuclei such as titanium or gold [16,17]. The possibility of improving the sensitivities to values as low as $\sim 10^{-18}$ renders this observable an extremely powerful probe of LFV in the muon–electron sector. In the presence of CP violation, one can further have T- and P-odd asymmetries in cLFV decays and contributions to lepton electric dipole moments. In Table 1, we briefly survey some of the current bounds for the different cLFV processes, as well as the future experimental sensitivity.

In addition to low-energy experiments, there are also searches for cLFV at high energy: the presence of new flavour violating physics can be directly signalled via the LFV production and/or decays of heavy states (which must be nevertheless sufficiently light to be produced at present colliders (Tevatron, LHC)).

3. LFV within effective theories

In the absence of direct evidence for new physics, one can either consider well motivated models at high-energy scales and study their impact on low-energy observables (the top–down approach), or adopt an effective approach, which consists in studying in a model-independent way the impact of the potentially heavy new degrees of freedom. When integrated out,

Table 1
Present bounds and future sensitivities for several LFV observables.

Tableau 1
Limites actuelles et sensibilités futures pour diverses observables violant la saveur leptonique.

LFV process	Present bound		Future sensitivity	
BR($\mu \to e\gamma$)	1.2×10^{-11}	[2]	10^{-13}	[12]
BR($\tau \to e\gamma$)	1.1×10^{-7}	[4]	10^{-9}	[11]
BR($\tau \to \mu\gamma$)	4.5×10^{-8}	[15]	10^{-9}	[11]
BR($\mu \to 3e$)	1.0×10^{-12}	[2]		
BR($\tau \to 3e$)	3.6×10^{-8}	[2]	2×10^{-10}	[11]
BR($\tau \to 3\mu$)	3.2×10^{-8}	[2]	2×10^{-10}	[11]
CR(μ–e, Ti)	4.3×10^{-12}	[2]	$\mathcal{O}(10^{-16(-18)})$	[16] ([17])
CR(μ–e, Au)	7×10^{-13}	[2]		
CR(μ–e, Al)			$\mathcal{O}(10^{-16})$	[17]

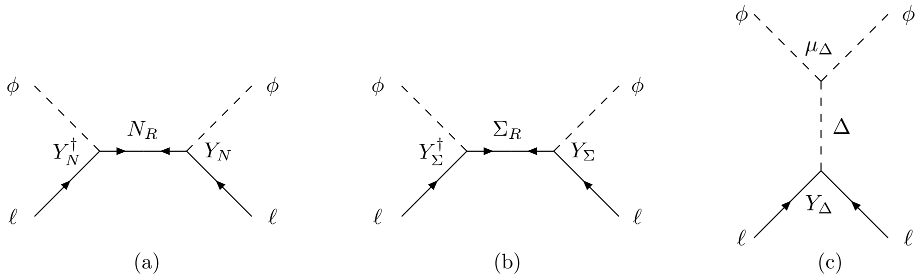

Fig. 2. Seesaw mechanisms: (a) singlet fermion, (b) triplet fermion and (c) triplet scalar exchange.

Fig. 2. Les mécanismes de la balançoire : échange de (a) singlet fermionique, (b) triplet fermionique et (c) triplet scalaire.

these heavy fields give rise to non-renormalisable effective operators that may induce contributions to several observables (among which cLFV).

3.1. Neutrino mass generation

There are typically three possible ways to generate non-vanishing m_ν. Firstly, ν masses can be generated radiatively through higher order loop corrections (as in the case of R-parity violating supersymmetric (SUSY) models [18], variations of the Zee model, etc.). The second option consists in invoking a geometrical suppression mechanism: the SM fields can be localised on a four-dimensional brane, while the extra heavy fields responsible for $m_\nu \neq 0$ live in the bulk. Their couplings to the SM fields are small due to geometrical suppression factors of large extradimensions (extraD), thus inducing small m_ν. Finally, the most elegant mechanism is perhaps the so-called seesaw mechanism, which generates small m_ν at tree level via the exchange of extra heavy fields. Here we will focus on the different realisations of this mechanism [19].

It can be shown that one can only have three types of basic seesaw mechanism, depending on the nature of the new heavy fields: right-handed neutrinos (type I) [20], heavy scalars (type II) [21] or fermionic triplets (type III) [22], as depicted in Fig. 2. It is important to notice that all these mechanisms can be embedded into larger frameworks such as grand unified theories (GUTs), SUSY and extraD. Moreover, one can have simultaneous combinations of different seesaw types (e.g. I and III), or an inverse seesaw. Hereafter, we will focus on the effective operators characteristic to each realisation.

3.2. Effective approach

In the effective approach, the higher dimensional operators are obtained when expanding the heavy field propagators in $1/M$, M being their mass, i.e. the scale of physics beyond the SM. In the case of a type I or III seesaw, the heavy fermionic propagator is expanded as

$$\frac{1}{\not{D} - M} \sim -\frac{1}{M} - \frac{1}{M}\not{D}\frac{1}{M} + \cdots$$

The first term scales as $1/M$, thus inducing a $d = 5$ scalar operator, which flips chirality and generates a ν mass term. The second term ($\sim 1/M^2$) preserves chirality and induces a correction to the kinetic terms of the light fields, since it is proportional to the covariant derivative. The coefficients that weigh the $d = 6$ operator, $c^{d=6} \propto \frac{1}{M^2}$, are suppressed compared

Table 2
Dimension 6 operators (and their coefficients) responsible for cLFV, also displaying the corresponding $d = 5$ coefficient.

Tableau 2
Opérateurs de dimension 6 des processus cLFV (et leurs coefficients) ainsi que les coefficients $d = 5$ correspondants.

Model	Effective Lagrangian $\mathcal{L}_{eff} = c_i \mathcal{O}_i$		
	$c^{d=5}$	$c^{d=6}$	$\mathcal{O}^{d=6}$
Fermionic singlet (type I)	$Y_N^T \frac{1}{M_N} Y_N$	$\left(Y_N^\dagger \frac{1}{M_N^\dagger} \frac{1}{M_N} Y_N\right)_{\alpha\beta}$	$(\overline{\ell_{L\alpha}} \tilde{\phi}) i \not\partial (\tilde{\phi}^\dagger \ell_{L\beta})$
Scalar triplet (type II)	$4 Y_\Delta \frac{\mu_\Delta}{M_\Delta^2}$	$\frac{1}{M_\Delta^2} Y_{\Delta\alpha\beta} Y^\dagger_{\Delta\gamma\delta}$	$(\overline{\widetilde{\ell_{L\alpha}}} \vec{\tau} \ell_{L\beta})(\overline{\ell_{L\gamma}} \vec{\tau} \widetilde{\ell_{L\delta}})$
Fermionic triplet (type III)	$Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma$	$\left(Y_\Sigma^\dagger \frac{1}{M_\Sigma^\dagger} \frac{1}{M_\Sigma} Y_\Sigma\right)_{\alpha\beta}$	$(\overline{\ell_{L\alpha}} \vec{\tau} \tilde{\phi}) i \not{D} (\tilde{\phi}^\dagger \vec{\tau} \ell_{L\beta})$

to those associated to the $d = 5$ operator, $c^{d=5} \propto \frac{1}{M}$. The situation is different in the case of heavy scalar triplets, since the scalar propagator expands as

$$\frac{1}{D^2 - M^2} \sim -\frac{1}{M^2} - \frac{D^2}{M^4} + \cdots$$

implying that the $d = 5$ operator already scales as $1/M^2$.

Independently of the model, the only possible $d = 5$ operator is the Weinberg operator [23],

$$\delta\mathcal{L}^{d=5} = \frac{1}{2} c_{\alpha\beta}^{d=5} \left(\overline{\ell^c_{L\alpha}} \tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger \ell_{L\beta}\right) + \text{h.c.}$$

where ℓ_L stands for the lepton doublets and $\tilde{\phi}$ is related to the SM Higgs doublet. The coefficient $c^{d=5}$ is a matrix of inverse mass dimension, which is not invariant under $B - L$, and is thus a source of Majorana ν masses. In the case of the type I and III seesaws, $c^{d=5} = Y_N^T \frac{1}{M_N} Y_N$, Y_N being the Yukawa couplings to the Higgs field and M_N the heavy fermion masses. Accommodating ν data with natural coefficients ($c^{d=5} \sim \mathcal{O}(1)$), implies $M_N \sim 10^{15}$ GeV, intriguingly close to the GUT scale. However, the scale of NP can be lowered to ~ 1 TeV if one allows for couplings as small as the charged lepton ones. In the case of a scalar triplet, $c^{d=5} \propto Y_\Delta \mu_\Delta / M_\Delta^2$, the scale μ_Δ can be directly related to the smallness of m_ν thus allowing to have $M_\Delta \sim$ TeV with natural Yukawa couplings.

More importantly, and since such a $d = 5$ operator is characteristic to all models with Majorana ν, the coefficient $c^{d=5}$ does not allow to discriminate among the different models. In order to do so, one must either produce the heavy mediators or call upon the low-energy effects of the different $d = 6$ operators. There is a large number of such operators [24] but here we will only focus on those inducing cLFV processes.[1] In Table 2 we list the $d = 6$ cLFV operators as well as the corresponding coefficient for each type of seesaw and, for comparison, the $d = 5$ coefficient. From a symmetry point of view, it is natural to have large $c^{d=6}$ coefficients, since the $d = 6$ operators preserve $B - L$, in contrast with the $d = 5$ operator. For example, in the type II seesaw, the dimensionful μ_Δ coefficient, which is directly related to the smallness of m_ν, does not affect the dimension 6 operator. However, decoupling the $d = 5$ and $d = 6$ coefficients is not possible in the fermionic seesaw, see Table 2.

3.3. Charged lepton flavour violation

In the effective approach, the observables can be written in terms of effective parameters, encoding the flavour mixing generated by the model, which remains valid up to a scale Λ. For example, in models onto which a type II seesaw is embedded ($\Lambda = M_\Delta$), the BRs for radiative and three body decays read

$$\frac{\text{BR}(l_i \to l_j \gamma)}{\text{BR}(l_i \to l_j \nu_i \bar{\nu}_j)} = \frac{\alpha}{48\pi} \frac{25}{16} \frac{|\Sigma_k Y^\dagger_{\Delta_{l_k l_i}} Y_{\Delta l_j l_k}|^2}{G_F^2 \Lambda^4}; \qquad \text{BR}\left(\ell_l^- \to l_i^+ l_j^- l_j^-\right) = \frac{1}{G_F^2 \Lambda^4} |Y_{\Delta_{li}}|^2 |Y_{\Delta_{jj}}|^2 \tag{2}$$

A signal from MEG [12] (Table 1), i.e. $10^{-13} \lesssim \text{BR}(\mu \to e\gamma) \lesssim 10^{-11}$, will put constraints on Λ, depending on the size of the couplings: assuming natural values of $Y_\Delta \sim \mathcal{O}(1)$ implies that 15 TeV $< \Lambda <$ 50 TeV, while for $Y_\Delta \sim \mathcal{O}(10^{-2})$, a $\text{BR}(\mu \to e\gamma)$ within MEG reach would lead to 0.15 TeV $< \Lambda <$ 0.5 TeV.

4. cLFV and new physics

Depending on the mechanism of ν mass generation, and especially on the scales of the mediators and size of the couplings, one can have very different scenarios of LFV at low energies. Whichever NP is called upon to explain the origin of (Majorana) ν masses and mixings, the effective theory will contain at least $d = 5$ and $d = 6$ operators. Whether or not

[1] We will not address here issues such as electroweak precision observables and unitarity violation.

the $d = 6$ coefficient is sufficiently large to generate observable cLFV strongly depends on two main ingredients: the typical scale of NP (not necessarily the scale of the seesaw mediator) and the amount of mixing present in the lepton sector, parametrised by an effective mixing θ_{ij} (U_{MNS} and additional mixings). For $\mu \to e\gamma$, one approximately has

$$\text{BR}(\mu \to e\gamma) = 10^{-11} \times (2\ \text{TeV}/\Lambda)^4 \times (\theta_{\mu e}/0.01)^2. \tag{3}$$

There are several classes of well-motivated extensions of the SM, aiming at overcoming both its theoretical and experimental shortcomings. These models can either offer new explanations for the smallness of m_ν (e.g. through a geometrical suppression mechanism, as is the case of large extraD, or via R-parity violation in the case of SUSY models), or onto them one can embed a seesaw mechanism. In addition, these extensions can provide new sources of LFV.[2] In all cases, once the new fields are integrated out, one finds the $d = 5, 6$ operators of Table 2. Notice however that in order to firmly establish that a given mechanism is at work, one needs to observe several cLFV processes that share a common source of LFV.

In many of these extensions, the low-energy cLFV observables can be significantly enhanced when compared to the minimal seesaw [1]. As an example, let us consider here the case of a type I SUSY seesaw, where cLFV decays are mediated by sleptons and gauginos, as illustrated in Fig. 1(c). Flavour violation in the ν sector is transmitted to the charged lepton sector via radiative effects involving ν Yukawa couplings Y^ν. Even under the assumption that the SUSY breaking mechanism is flavour conserving, renormalisation effects (RGE) can induce a sufficiently large amount of FV as to account for sizable cLFV rates [25]. Using the leading log approximation, the dominant contribution to the ℓ_i–ℓ_j transitions are given by

$$\frac{\text{BR}(\ell_i \to \ell_j\gamma)}{\text{BR}(\ell_i \to \ell_j\nu_i\bar{\nu}_j)} = \frac{\alpha^3 \tan^2\beta}{G_F^2\, m_{\text{SUSY}}^8}\left|\frac{(3m_0^2 + A_0^2)}{8\pi^2}\left(Y^{\nu\dagger} L Y^\nu\right)_{ij}\right|^2, \qquad \frac{\text{BR}(\ell_i \to 3\ell_j)}{\text{BR}(\ell_i \to \ell_j\gamma)} = \frac{\alpha}{3\pi}\left(\log\frac{m_{l_i}^2}{m_{l_j}^2} - \frac{11}{4}\right) \tag{4}$$

In the above, m_0 and A_0 denote universal soft-SUSY breaking terms, m_{SUSY} corresponds to an average scale of the SUSY particles, $\tan\beta$ is the ratio of the Higgs vacuum expectation values and one has assumed that the dominant contribution to the three body decays originates from γ-penguin diagrams.

In addition to these low-energy observables, interesting phenomena are expected to be observed at colliders. In the SUSY seesaw case, one can have sizable widths for processes like $\chi_2^0 \to \chi_1^0 \ell_i^\pm \ell_j^\mp$, flavoured slepton mass splittings (especially between the first and second generation of left-handed sleptons) and finally the appearance of new edges in same-flavour dilepton mass distributions. This clearly illustrates that in addition to directly probing the model of NP by searching for the new fields at colliders, one may also address cLFV at high energies. Furthermore, having a unique source of LFV (neutrino mass generation), the interplay of low- and high-energy LFV observables can lead to strenghten or disfavour the underlying model of NP. An illustrative example of the potential of this interplay can be found for instance in [26].

In order to reduce the arbitrariness of the seesaw parameters, one can embed the seesaw in GUT frameworks, considering larger gauge groups such as SU(5) and SO(10). In ordinary non-SUSY SU(5), the addition of a 24_F fermionic multiplet leads to interesting FV scenarios (especially when compared to the inclusion of a 15_H Higgs multiplet). A mixing of type I and III seesaws, accompanied by the prediction of an SU(2) fermionic triplet below the TeV scale, would lead to a testable seesaw at the LHC [27].

cLFV has also been extensively addressed in SUSY GUTs. For example, cLFV observables were analysed for SO(10)-motivated Y^ν ansätze [28] (where at least one neutrino Yukawa coupling is as large as the top Yukawa coupling), considering two limits: CKM-like and MNS-like mixings. The interplay of the different observations (or lack thereof) at upcoming facilities would allow to derive hints on the structure of the unknown neutrino Yukawa couplings, or even falsify some of the SUSY GUT scenarios.

Another class of models for generating non-trivial lepton flavour structures is associated to the displacement of SM fermions along extra dimensions (scenarios with either large flat [29] or small warped [30] extraDs). In the lepton sector, the experimental upper limit on BR($\mu \to 3e$) imposes that the mass of the Kaluza–Klein (KK) excitations be $M_{KK} \gtrsim 30$ TeV [31], thus beyond the reach of the LHC.

Finally, cLFV is a feature common to non-SUSY multi-Higgs doublet extensions of the SM, and can occur both through charged and neutral currents. In these models it has been pointed out that, even for massless νs, lepton flavour can be violated [32]. However, in the context of the minimal extension with a type I seesaw, LFV effects are extremely small.

5. Conclusions

Up to now, the non-observation of cLFV signals at low energies has only allowed to derive bounds on models of new physics. Impressive experimental efforts are currently being put in the search for cLFV: observation of processes such as $\ell_i \to \ell_j\gamma$, $\ell_i \to \ell_j\ell_k\ell_m$ and μ–e conversion would necessarily point towards the existence of heavy states with a typical scale around the TeV, and hence within reach of present colliders (LHC, Tevatron). In addition, one can also expect cLFV in the decay and/or production of these heavy states. Different new physics scenarios imply very distinct phenomenology; if cLFV is observed, one needs to study the correlations between several observables (LFV charged lepton decays and LFV at

[2] It is important to stress that if strictly seesaw-related, the new sources of flavour violation will not provide additional contributions to hadronic low-energy observables, nor to proton decay.

colliders), and to take into account the complementary information from new particle searches, in order to be able to pin down the origin of LFV. Under the assumption of a common source for ν mass generation and cLFV, the interplay of direct searches for new physics at colliders and indirect signals (such as lepton flavour violating transitions) can hint towards the mechanism of ν-mass generation, probing physics at very high scales (for instance close to the GUT scale). In particular, from the combination of different observables one might be able to discriminate between models of Majorana neutrinos.

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