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# Tests of low-scale leptogenesis in charged lepton flavour violation experiments

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## ABSTRACT

We consider low-energy tests of low-scale leptogenesis based on the type I seesaw scenario with three right-handed singlet neutrinos  $\nu_{iR}$ . In this scenario, successful leptogenesis is possible for quasi-degenerate in mass heavy Majorana neutrinos  $N_{1,2,3}$ ,  $M_{1,2,3} \cong M$ ,  $|M_j - M_i| \ll M$ ,  $i \neq j = 1, 2, 3$ , heavy Majorana neutrino masses  $M \sim (0.05 - 5 \times 10^5)$  GeV, and  $N_j$  charged current and neutral current weak interaction couplings as large as  $\mathcal{O}(10^{-2})$ . We derive the constraints on the corresponding leptogenesis parameter space from the existing data from low-energy experiments, including the limits from the experiments on  $\mu \rightarrow e\gamma$  decay and on the rate of  $\mu - e$  conversion in gold. We show also that the planned and upcoming experiments on charged lepton flavour violation with  $\mu^\pm$ , MEG II on the  $\mu \rightarrow e\gamma$  decay, Mu3e on  $\mu \rightarrow eee$  decay, Mu2e and COMET on  $\mu - e$  conversion in aluminium and PRISM/PRIME on  $\mu - e$  conversion in titanium, can probe significant region of the viable leptogenesis parameter space, and thus have a potential for a discovery. Experiments on  $\tau \rightarrow eee(\mu\mu\mu)$  and  $\tau \rightarrow e(\mu)\gamma$  decays (e.g., BELLE II) also can probe a part of the leptogenesis parameter space, although a relatively small one.

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## 1. Introduction

In the present article, we investigate the possibility to test the low-scale leptogenesis scenarios of generation of the Baryon Asymmetry of the Universe (BAU) [1–6] based on the type I seesaw mechanism [7–11] in experiments sensitive to beyond the Standard Model physics at sub-TeV scales. As is well known, an integral part of the type I seesaw mechanism and the related leptogenesis scenarios are the right-handed (RH) neutrinos  $\nu_{aR}$  (RH neutrino fields  $\nu_{aR}(x)$ ), which can be added as  $SU(2)_L$  singlets to the Standard Model (SM) without modifying its basic properties. Such a SM extension with two seesaw RH neutrinos and, correspondingly, with two heavy Majorana neutrinos  $N_j$  with definite masses  $M_j > 0$ ,  $j = 1, 2$ , is the minimal set-up in which leptogenesis can be realised, satisfying the three Sakharov's conditions [12] for a dynamical generation of the matter-antimatter asymmetry.

In classical thermal leptogenesis with  $N_j$  having hierarchical mass spectrum, the generation of the BAU, due to the out-of-equilibrium L-, C- and CP-violating decays of  $N_j$ , takes place at scales which are typically by a few to several orders of magnitude smaller than the scale of unification of the electroweak and strong interactions,  $M_{\text{GUT}} \cong 2 \times 10^{16}$  GeV (see, e.g., [13] and the recent review article [14], which include also extended lists of references). The scale of leptogenesis is determined, in general, by the values and the spectrum of masses of the heavy Majorana neutrinos  $N_j$ . A rather detailed analysis of the high scale thermal (non-resonant) leptogenesis scenario with three RH neutrinos performed in [15,16] showed that, with flavour effects taken into account and mildly hierarchical heavy Majorana neutrino masses,  $M_2 \sim 3M_1$ ,  $M_3 \sim 3M_2$ , the leptogenesis scale can be as low as  $M_1 \sim 10^6$  GeV. Testing experimentally even this high scale leptogenesis scenario seems impossible at present.

A unique possibility to test experimentally the leptogenesis idea is provided by the low-scale scenarios based on the type I seesaw mechanism proposed in [3,4,17] and in [5,6]. In these scenarios, the heavy Majorana neutrinos can have masses at the sub-TeV scales, which makes the scenarios testable, in principle, at collid-

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ers (LHC and/or future planned) and/or at low-energy experiments (see further).

In resonant leptogenesis [3,4,17–23], the baryon asymmetry is produced exclusively by the CP-violating  $N_j$  and Higgs decays mediated by the neutrino Yukawa couplings with  $N_j$  having masses  $M_j < (\ll) 1$  TeV. In the simplest case with two RH neutrinos, the resonant regime is realised if the associated two heavy Majorana neutrinos  $N_{1,2}$  form a pseudo-Dirac pair<sup>2</sup> [26,27] such that the splitting between their masses,  $M_2 - M_1 \equiv \Delta M > 0$ , is of the order of the  $N_{1,2}$  decay widths  $\Gamma_{1,2}$ :  $\Delta M/\Gamma_{1,2} \sim 1$ , which typically implies also that  $\Delta M \ll M_{1,2}$ . This scenario was re-visited using the formalism of Boltzmann equations most recently in [28], where the authors concentrated on the case of  $M_{1,2} \lesssim 100$  GeV,  $\Delta M \ll M_{1,2}$  (for earlier discussions see, e.g., [29,30]). Both the relevant  $1 \leftrightarrow 2$  decays and inverse decays and  $2 \leftrightarrow 2$  scattering processes (involving quarks and gauge fields), including flavour effects and thermal effects (thermal masses and soft collinear processes involving gauge fields in the thermal plasma), were taken into account. Results were presented in [28] for the two possible  $N_{1,2}$  initial abundances at temperature  $T_0 \gg T_{\text{sph}}$ ,  $T_{\text{sph}}$  being the sphaleron decoupling temperature  $T_{\text{sph}} = 131.7$  GeV<sup>3</sup>: i)  $N_{1,2}$  Thermal Initial Abundance (TIA), and ii)  $N_{1,2}$  Vanishing (zero) Initial Abundance (VIA). The light neutrino mass spectrum with normal ordering (NO) (see, e.g., [31]) was considered. It was found that successful resonant leptogenesis is possible in the VIA (TIA) case for masses of the heavy Majorana neutrinos across the whole of the experimentally accessible region of  $M_{1,2} \cong 0.3$  (5.0) – 100 GeV, and for values of the charged and neutral current couplings of  $N_{1,2}$  in the weak interaction Lagrangian, denoted in [28] as  $(RV)_{\ell j}$ ,  $\ell = e, \mu, \tau$ ,  $j = 1, 2$ , in the range of  $(10^{-6} - 5 \times 10^{-5})$ .

In [5,6], the so-called “freeze-in” leptogenesis mechanism by which the BAU is generated via RH neutrino oscillations during the epoch when the RH neutrinos, or equivalently, the heavy Majorana neutrinos  $N_j$ , are being produced and are out of equilibrium, was put forward. This mechanism was extensively studied (see, e.g., [32–42] and references quoted therein).

Resonant leptogenesis and leptogenesis via neutrino oscillations were usually treated as separate in baryogenesis mechanisms. Only recently, the parameter space of the two scenarios was studied in a unified framework in [43] (see also [44]) based on density matrix-like equations (see, e.g., [45,46] for a review of the formal treatments of resonant leptogenesis).<sup>4</sup> Considering the case of two heavy Majorana neutrinos  $N_{1,2}$  forming a pseudo-Dirac pair, in [43] it was shown that i) the observed baryon asymmetry can be generated for all experimentally allowed values of the Majorana neutrino masses  $M_{1,2} \cong M \gtrsim 100$  MeV and up to the TeV scale, and that ii) leptogenesis is effective in a broad range of the relevant parameters, including mass splitting between the two Majorana neutrinos as large as  $\Delta M/M \sim 0.1$ , as well as couplings of  $N_{1,2}$  in the weak charged lepton current which depend on the value of  $M$ : for, e.g.,  $M = 1$  and 50 GeV, they are in the range of  $(10^{-5} - 10^{-3})$

<sup>2</sup> It was shown in [24,25] that, in this case, the radiative corrections to the light neutrino masses are negligible. We verify that this condition is satisfied, and reject all points for which the radiative corrections are comparable to the tree level contribution.

<sup>3</sup> The baryon asymmetry  $\eta_B$  during the generation process “freezes” at  $T_{\text{sph}}$  as the temperature of the Universe decreases and the value of  $\eta_B$  at  $T_{\text{sph}}$  should be compared with the observed one.

<sup>4</sup> The density matrix equations used in this work were derived independently in the density matrix formalism for mixing neutrinos [40,47,48] and in the Closed-Time-Path (CTP) formalism using the gradient expansion [37,49,50]. The resulting asymmetries were shown to agree with the full CTP approach in a static Universe, for  $\Delta M/M \ll 1$  [45]. On the other hand, following similar considerations, the authors of [51,52] claim to have found an additional source of CP violation related to the phenomenon of resonant flavour mixing, distinct from that of heavy Majorana neutrino oscillation, which can lead to additional contribution to the baryon asymmetry, and thus further theoretical uncertainty.

and  $(10^{-6} - 3 \times 10^{-5})$ , respectively. The results derived in [43] and in [28] are largely compatible in the leptogenesis parameter space regions where they can be compared, such as, e.g., in the regions corresponding to the case of TIA and light neutrino mass spectrum with NO. The region of viable leptogenesis parameter space for  $M \gtrsim 0.2$  GeV found in [28,43], leads to an upper bound on the weak lepton charged current (CC) interactions  $M \cdot U^2 \lesssim 5 \cdot 10^{-6}$  GeV, where  $U^2 \equiv \sum_{\ell i} |(RV)_{\ell i}|^2$ . This is too small to be probed in low-energy experiments,<sup>5</sup> but could be probed in fixed target experiments [54,55], future colliders [55–58], or potentially already at the HL-LHC [59,60] (see, e.g., Fig. 1 in [43]).

The unified treatment of low-scale leptogenesis was extended in [61] to the case of three quasi-degenerate heavy Majorana neutrinos  $N_{1,2,3}$ , with  $M_{1,2,3} \cong M$ . The authors of [61] presented results for  $M$  between 50 MeV and 70 TeV, focusing on the case of light neutrino mass spectrum with NO, either hierarchical (NH) or quasi-degenerate (QD), and considered both vanishing and thermal initial conditions. The major finding in [42,61] is that the range of heavy Majorana neutrino CC and neutral current (NC) couplings for which one can have successful leptogenesis is by several orders of magnitude larger than the range in the scenario with two heavy Majorana neutrinos, reaching at, e.g.,  $M = 100$  GeV values  $\sim 5 \times 10^{-2}$  in the case of TIA and even somewhat larger values in the case of VIA.<sup>6</sup> For heavy Majorana neutrinos with masses below the TeV scale, a large range of couplings can already be probed in direct searches at the LHC [54,55,64–66], as well as in fixed target experiments [54,55] and future colliders [55–58]. In the present article, we investigate the possibility to test directly the low-scale leptogenesis scenarios discussed in [61] (see also [42]) in upcoming high precision experiments on charged lepton flavour violation (cLFV) searching for  $\mu^\pm \rightarrow e^\pm + \gamma$  and  $\mu^\pm \rightarrow e^\pm + e^+ + e^-$  decays and for  $\mu - e$  conversion in nuclei.

## 2. Aspects of the seesaw formalism and the analysis

In the set-up with three singlet RH neutrinos  $\nu_{aR}$  and in the leptogenesis framework based on type I seesaw mechanism, in general, the required non-conservation of the total lepton charge  $L$  is provided, as is well known, by the Majorana mass term of the singlet neutrinos  $\nu_{aR}$  and the neutrino Yukawa coupling  $\mathcal{L}_Y(x)$  involving  $\nu_{aR}$  and the SM lepton and Higgs doublets,  $\psi_{\ell L}(x)$  and  $\Phi(x)$ . The requisite breaking of C- and CP-symmetries is ensured by the  $\nu_{aR}$  Majorana mass term and/or the Yukawa coupling  $\mathcal{L}_Y(x)$ .

In the diagonal mass basis of the RH neutrinos  $\nu_{aR}$  and the charged leptons  $\ell^\pm$ ,  $\ell = e, \mu, \tau$ , which proves convenient for the leptogenesis analysis and was used in [28,43,61], the neutrino Yukawa coupling  $\mathcal{L}_Y(x)$  and the seesaw Majorana mass term are given by:

$$\begin{aligned} \mathcal{L}_{Y,M}(x) = & - (Y_{\ell i} \overline{\psi}_{\ell L}(x) i\tau_2 \Phi^*(x) N_{iR}(x) + \text{h.c.}) \\ & - \frac{1}{2} M_i \overline{N}_i(x) N_i(x), \end{aligned} \quad (1)$$

where  $Y_{\ell i}$  is the matrix of neutrino Yukawa couplings (in the chosen basis),  $(\psi_{\ell L}(x))^T = (v_{\ell L}^T(x) \ \ell_L^T(x))$ ,  $\ell = e, \mu, \tau$ ,  $v_{\ell L}(x)$  and  $\ell_L(x)$

<sup>5</sup> The only exception could be the neutrinoless double beta decay experiments, which can have a contribution from the heavy Majorana neutrinos with large mass splittings  $\Delta M/M \gtrsim 10^{-3}$ , and masses below 2 GeV, as was shown in [38,53].

<sup>6</sup> Note that the possibility of large couplings was found in [62,63] in the special regime of resonant  $\tau$ -leptogenesis in which the coupling of the heavy Majorana neutrinos to the  $\tau$  charged lepton is negligible, while the couplings to  $e$  and  $\mu$ , although relatively large, do not play a role in leptogenesis. Although the results of [42,61] allow for such a BAU production mechanism, this was not found to be the dominant mechanism which is associated with large Majorana neutrino couplings to  $e, \mu$  and  $\tau$  charged leptons.

being the left-handed (LH) flavour neutrino and charged lepton fields,  $(\Phi(x))^T = (\Phi^{(+)}(x) \Phi^{(0)}(x))$  and  $N_i$  ( $N_i(x)$ ) is the heavy Majorana neutrino (field) possessing a mass  $M_i > 0$ . In the same basis, the flavour neutrino fields  $\nu_{\ell L}(x)$ ,  $\ell = e, \mu, \tau$ , which enter into the expressions of the charged and neutral currents in the weak interaction Lagrangian, are given by:

$$\nu_{\ell L}(x) = \sum_i (1 + \eta) U_{\ell i} \nu_{iL}(x) + \sum_j (RV)_{\ell j} N_{jL}(x), \quad (2)$$

where  $N_{jL}(x)$  are the LH components of the fields of the heavy neutrinos  $N_j$ ,  $\nu_{iL}(x)$ ,  $i = 1, 2, 3$ , are the LH components of the fields of three light Majorana neutrinos  $\nu_i$  having masses  $m_i$ ,  $m_i \lesssim 0.5 \text{ eV} \ll M_j$ ,  $U$  is a  $3 \times 3$  unitary matrix and  $\eta = -(1/2)(RV)(RV)^\dagger$ . The matrix  $R$  is determined by  $R \cong M_D M_N^{-1}$ ,  $M_D$  and  $M_N$  being the seesaw neutrino Dirac and the RH neutrino Majorana mass matrices, respectively,  $|M_D| \ll |M_N|$ , and  $V$  is the unitary matrix which (to leading approximation in  $M_D/M_N$ ) diagonalises the Majorana mass matrix of the heavy RH neutrinos  $M_N$  (see, e.g., [67]). The matrix  $M_D$  is related to the matrix of neutrino Yukawa couplings  $Y$  in Eq. (1) as follows:  $M_D = (v/\sqrt{2})Y V^T$ ,  $v = 246 \text{ GeV}$ . The Majorana mass matrix of the LH flavour neutrinos is given by the well known seesaw expression:

$$\begin{aligned} (m_\nu)_{\ell\ell'} &\cong - \left[ M_D M_N^{-1} (M_D)^T \right]_{\ell\ell'} = - \frac{v^2}{2} Y_{\ell j} M_j^{-1} Y_{j\ell'}^T \\ &= (U \hat{m}_\nu U^T)_{\ell\ell'}, \end{aligned} \quad (3)$$

where  $\hat{m}_\nu = \text{diag}(m_1, m_2, m_3)$ .

It follows from Eq. (2) that, in the seesaw scenario we are considering, the PMNS matrix has the form:

$$U_{\text{PMNS}} = (1 + \eta) U. \quad (4)$$

The matrix  $\eta$  describes the deviations from unitarity of the PMNS matrix. The elements of  $\eta$  are constrained by electroweak data and data on flavour observables [68,69]. For  $M_j \gtrsim 500 \text{ MeV}$  and depending on the element of  $\eta$ , these constraints are in the range  $(10^{-4} - 10^{-3})$  at  $2\sigma$  C.L. For  $M_j$  larger than the electroweak scale, the constraint on  $\eta_{e\mu} = \eta_{\mu e}$  is even stronger:  $|\eta_{e\mu}| < 1.2 \times 10^{-5}$ . Given the stringent upper bounds on the elements of  $\eta$ , to a very good approximation one has:  $U_{\text{PMNS}} \cong U$ . Following [28,43,61] we use in our analysis the standard parametrisation of the PMNS matrix  $U_{\text{PMNS}}$  [31]:

$$\begin{aligned} U_{\text{PMNS}} = & \begin{pmatrix} c_{12}c_{13} & & s_{12}c_{13} & & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & & c_{23}c_{13} \end{pmatrix} \\ & \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{\frac{i\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{\frac{i\alpha_{31}}{2}} \end{pmatrix}, \end{aligned} \quad (5)$$

where  $c_{ij} \equiv \cos\theta_{ij}$ ,  $s_{ij} \equiv \sin\theta_{ij}$ ,  $\delta$  is the Dirac CP violation (CPV) phase, while  $\alpha_{21}$  and  $\alpha_{31}$  are the two Majorana CPV phases [70]. In the numerical analysis that follows, we will use the values of the three neutrino mixing angles  $\theta_{12}$ ,  $\theta_{23}$  and  $\theta_{13}$ , and the two neutrino mass squared differences obtained in the global neutrino oscillation data analysis performed in [71] and quoted in Table 1. It follows from [71], in particular, that the  $3\sigma$  allowed interval of values of the Dirac CPV phase  $\delta$  is rather large. Furthermore, the Majorana phases  $\alpha_{21}$  and  $\alpha_{31}$  cannot be constrained by the neutrino oscillation experiments. Thus, we will treat the Dirac and Majorana CPV phases as free parameters.

**Table 1**

The best fit values of the three neutrino mixing angles  $\theta_{12}$ ,  $\theta_{13}$ ,  $\theta_{23}$  and the two neutrino mass squared differences in the case of light neutrino mass spectrum with NO [71]. The best fit value for the Dirac phase  $\delta$  is also reported for completeness, even though in our analysis we treat it as a free parameter.

Best Fit Values of the Neutrino Parameters

$\theta_{12}$ ( $^\circ$ )	$\theta_{13}$ ( $^\circ$ )	$\theta_{23}$ ( $^\circ$ )	$\delta$ ( $^\circ$ )	$\Delta m_{21}^2$ ( $10^{-3} \text{ eV}^2$ )	$\Delta m_{31(32)}^2$ ( $10^{-3} \text{ eV}^2$ )
33.44	8.57	49.2	197	7.42	2.517

The quantities  $(RV)_{\ell j}$  in Eq. (2) determine the strength of the CC and NC weak interaction couplings of the heavy Majorana neutrinos  $N_j$  to the  $W^\pm$  bosons and the charged lepton  $\ell$ , and to the  $Z^0$  boson and the LH flavour neutrino  $\nu_{\ell L}$ ,  $\ell = e, \mu, \tau$  in the weak interaction Lagrangian:

$$\mathcal{L}_{\text{CC}}^N = - \frac{g}{2\sqrt{2}} \bar{\ell} \gamma_\alpha (RV)_{\ell j} (1 - \gamma_5) N_j W^\alpha + \text{h.c.}, \quad (6)$$

$$\mathcal{L}_{\text{NC}}^N = - \frac{g}{4c_w} \bar{\nu}_{\ell L} \gamma_\alpha (RV)_{\ell j} (1 - \gamma_5) N_j Z^\alpha + \text{h.c.}, \quad (7)$$

where  $c_w \equiv \cos\theta_w$ ,  $\theta_w$  being the weak mixing angle.

The magnitude of the couplings  $(RV)_{\ell j}$  in the region of the parameter space of successful leptogenesis is crucial for the possibility to test the low-scale leptogenesis scenarios.

Equation (3) allows to relate the matrix of the neutrino Yukawa couplings  $Y$  and the matrix  $U$  [72]. In the diagonal mass basis we are using, this relation has the form (Casas-Ibarra parametrisation):

$$Y = i \frac{\sqrt{2}}{v} U \sqrt{\hat{m}_\nu} O^T \sqrt{\hat{M}}, \quad (8)$$

where  $O$  is a complex orthogonal matrix,  $O^T O = O O^T = I$  and  $\hat{M} = \text{diag}(M_1, M_2, M_3)$ . The usual parametrisation for the matrix  $O$ , e.g. adopted in [28,43,44], is that given in terms of three Euler complex angles  $\theta_j = \omega_j + i\xi_j$ , with  $j = 1, 2, 3$  and  $\omega_j, \xi_j \in \mathbb{R}$  for any  $j$ , and reads:

$$O = \begin{pmatrix} c_2c_3 & & c_2s_3 & & s_2 \\ -s_1s_2c_3 - c_1s_3 & & -s_1s_2s_3 + c_1c_3 & & s_1c_2 \\ -c_1s_2c_3 + s_1s_3 & & -c_1s_2s_3 - s_1c_3 & & c_1c_2 \end{pmatrix}, \quad (9)$$

where  $s_j \equiv \sin(\theta_j)$  and  $c_j \equiv \cos(\theta_j)$ . An equivalent alternative parametrisation was utilised in [61]. It has the form:

$$O = (O_\nu R_C O_N)^T, \quad (10)$$

where  $O_\nu = O_\nu^{(13)} O_\nu^{(23)}$  and  $O_N = O_N^{(23)} O_N^{(13)}$  represent products of real rotations in the 1-3 and 2-3 planes, while  $R_C = R_C^{(12)}$  describes a rotation by a complex angle in the 1-2 plane. This parametrisation proves convenient in the three RH (heavy Majorana) neutrino case since it involves just one complex angle (in  $R_C$ ), denoted as  $\theta_C$  in what follows.

The  $O$ -matrix defined above has  $\det(O) = 1$ . Often, in the literature on the subject, the factor  $\varphi = \pm 1$  is included in the definition of certain elements of  $O$  to allow for the both cases  $\det(O) = \pm 1$ . We will work with the matrix in Eq. (10), but extend the range of the Majorana phases  $\alpha_{21(31)}$  from  $[0, 2\pi]$  to  $[0, 4\pi]$ , which effectively accounts for both cases of  $\det(O) = \pm 1$  [73]. In this way, the same full set of  $O$  and Yukawa matrices is considered.

From the results obtained in [61] in the three RH neutrino case with quasi-degenerate heavy Majorana neutrinos for  $M_{1,2,3} \cong M \leq 70 \text{ TeV}$ , it follows, as we have already briefly discussed, that one can have successful leptogenesis for either NH or QD light neutrino mass spectrum, and for  $M$  in the ranges  $1.7 \text{ GeV} - 70 \text{ TeV}$  and  $50 \text{ MeV} - 70 \text{ TeV}$  in the cases of TIA and VIA, respectively. In the

region of viable leptogenesis, the observable quantity related to the heavy Majorana neutrino couplings,  $\sum_{\ell j} |(RV)_{\ell j}|^2$ , varies in a wide range, having relatively large values accessible to low-energy experiments other than, for example, SHiP and those at the discussed FCC-ee collider. For  $m_1 = 0$  (NH spectrum) and  $M = 100$  GeV (70 TeV), for example, as was reported in [61],  $\max(\sum_{\ell j} |(RV)_{\ell j}|^2) \cong 0.1$  ( $10^{-5}$ ). The value of the observable  $\sum_{\ell, i} |(RV)_{\ell i}|^2$  of interest exhibits a relatively weak dependence on the Dirac and Majorana phases, mild dependence on the Casas-Ibarra real angles of the parametrisation in Eq. (10) and strong dependence on the imaginary part of  $\theta_C$ .

### 3. Low-energy phenomenology: limits and prospective tests by cLFV experiments

The low-energy phenomenology of the considered type I seesaw scenario has been investigated, e.g., in [67,74–76]. The CC and NC couplings in Eqs. (6) and (7) can induce (via one-loop diagrams with exchange of virtual  $N_{1,2,3}$  charged lepton flavour violating (cLFV) processes  $\mu^\pm \rightarrow e^\pm + \gamma$ ,  $\mu^\pm \rightarrow e^\pm + e^+ + e^-$ ,  $\mu - e$  conversion in nuclei, etc. [77,78].

The most stringent upper limits on the rates of these processes have been obtained in experiments with muons. The best experimental limits on  $\mu \rightarrow e\gamma$  and  $\mu \rightarrow eee$  decay branching ratios,  $\text{BR}(\mu \rightarrow e\gamma)$  and  $\text{BR}(\mu \rightarrow eee)$ , and on the relative  $\mu - e$  conversion cross section in a nucleus  ${}^A_Z X$ ,  $\text{CR}(\mu {}^A_Z X \rightarrow e {}^A_Z X)$  ( $Z$  and  $A$  are the atomic and mass numbers, respectively), have been reported by the MEG [79], SINDRUM [80] and SINDRUM II [81,82] Collaborations:

$$\text{BR}(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13} \text{ (90\% C.L.)}, \quad (11)$$

$$\text{BR}(\mu \rightarrow eee) < 1.0 \times 10^{-12} \text{ (90\% C.L.)}, \quad (12)$$

$$\text{CR}(\mu {}^{48}_{22}\text{Ti} \rightarrow e {}^{48}_{22}\text{Ti}) < 4.3 \times 10^{-12} \text{ (90\% C.L.)}, \quad (13)$$

$$\text{CR}(\mu {}^{197}_{79}\text{Au} \rightarrow e {}^{197}_{79}\text{Au}) < 7.0 \times 10^{-13} \text{ (90\% C.L.)}. \quad (14)$$

The planned MEG II update of the MEG experiment [83] aims at reaching sensitivity to  $\text{BR}(\mu \rightarrow e\gamma) \simeq 6 \times 10^{-14}$ . The sensitivity to  $\text{BR}(\mu \rightarrow eee)$  is planned to be increased by up to three (four) orders of magnitude to  $\text{BR}(\mu \rightarrow eee) \sim 10^{-15}$  ( $10^{-16}$ ) with the realisation of Phase I (Phase II) of the Mu3e Project [84]. The Mu2e [85] and COMET [86] collaborations studying  $\mu - e$  conversion in aluminium plan to reach sensitivity to  $\text{CR}(\mu {}^{27}_{13}\text{Al} \rightarrow e {}^{27}_{13}\text{Al}) \sim 6 \times 10^{-17}$ . The planned PRISM/PRIME experiment [87] aims at a dramatic increase of sensitivity to the  $\mu - e$  conversion rate in titanium, allowing to probe values as small as  $\text{CR}(\mu {}^{48}_{22}\text{Ti} \rightarrow e {}^{48}_{22}\text{Ti}) \sim 10^{-18}$ , an improvement by six orders of magnitude of the current bound given in Eq. (13).

The predictions of the seesaw model under discussion, e.g., for the rates of the  $\mu \rightarrow e\gamma$  and  $\mu \rightarrow eee$  decays and  $\mu - e$  conversion in nuclei, as can be shown, depend on the quantity  $|\sum_{i=1,2,3} (RV)_{\mu i}^* (RV)_{ei}|^2$ , and, for  $|M_i - M_j| \ll M_k$ ,  $i \neq j = 1, 2, 3$ ,  $k = 1, 2, 3$ , on the mass  $M_{1,2,3} \simeq M$  of the heavy Majorana neutrinos  $N_{1,2,3}$ . The expressions for  $\text{BR}(\mu \rightarrow e\gamma)$ ,  $\text{BR}(\mu \rightarrow eee)$  and  $\text{CR}(\mu {}^A_Z X \rightarrow e {}^A_Z X)$  in the case of interest can be easily obtained from those given in Refs. [74,75,88] and we are not going to reproduce them here. Let us add that the rates of the cLFV decays of the  $\tau$  lepton are proportional to the product of couplings  $|\sum_{j=1,2,3} (RV)_{\tau j}^* (RV)_{e' j}|^2$ ,  $e' = e, \mu$ . However, the current constraints and the prospective improvements of the sensitivity of the experiments on cLFV decays of  $\tau^\pm$  are respectively less stringent and not so significant as in the case of experiments on cLFV processes with  $\mu^\pm$  and we are not going to consider them here.

In the region of viable leptogenesis, the quantity of interest  $|\sum_{i=1,2,3} (RV)_{\mu i}^* (RV)_{ei}|$  can be as large as  $10^{-1}$  (see Fig. 1), which

opens up the possibility to test the low-scale leptogenesis scenario with three quasi-degenerate heavy Majorana neutrinos in experiments on cLFV with  $\mu^\pm$ . Indeed, consider as an example the experiments on  $\mu \rightarrow e\gamma$  decay. The  $\mu \rightarrow e\gamma$  decay branching ratio is given by [74] (see also [77,78,89]):

$$\text{BR}(\mu \rightarrow e\gamma) = \frac{\Gamma(\mu \rightarrow e + \gamma)}{\Gamma(\mu \rightarrow e + \nu_\mu + \bar{\nu}_e)} = \frac{3\alpha_{\text{em}}}{32\pi} |T|^2, \quad (15)$$

where  $\alpha_{\text{em}}$  is the fine structure constant and

$$T \cong [G(X) - G(0)] \sum_{i=1,2,3} (RV)_{\mu i}^* (RV)_{ei}. \quad (16)$$

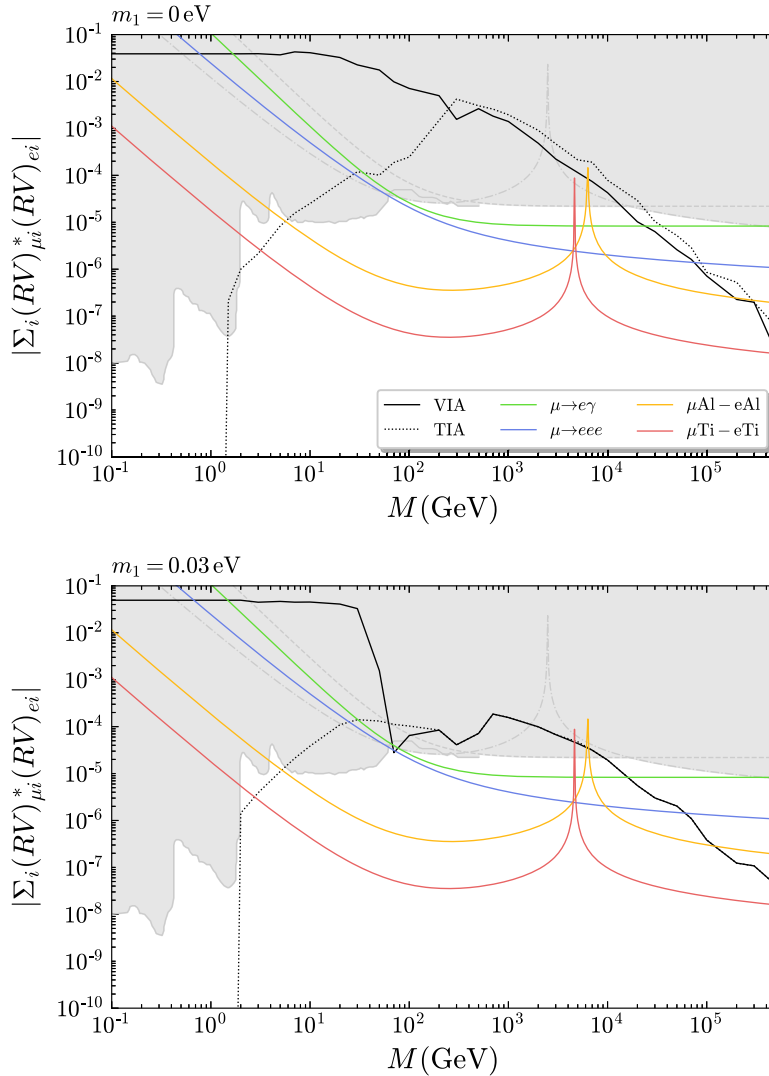
Here,  $G(X)$  is a loop integration function,  $X \equiv (M/M_W)^2$  and we have taken into account that the differences between  $M_1$ ,  $M_2$  and  $M_3$  are negligibly small, with  $M_{1,2,3} \cong M$ . The function  $G(X)$  is monotonic<sup>7</sup> and takes values in the interval  $[4/3, 10/3]$ , with  $G(X) \cong 10/3 - X$  for  $X \ll 1$ . At, e.g.,  $M = M_W$  ( $M = 1000$  GeV) we have  $G(X) - G(0) = -0.5$  ( $\simeq -1.9$ ). It is not difficult to show, using these values of  $G(X) - G(0)$  and Eqs. (15) and (16), that the MEG II experiment aiming to probe  $\text{BR}(\mu \rightarrow e\gamma)$  down to  $6 \times 10^{-14}$ , will be sensitive for  $M = M_W$  ( $M = 1000$  GeV) to values of  $|\sum_{i=1,2,3} (RV)_{\mu i}^* (RV)_{ei}| \gtrsim 3.3 \times 10^{-5}$  ( $8.9 \times 10^{-6}$ ). This is approximately by 1 to 3 orders of magnitude smaller than the maximal value of  $|\sum_{i=1,2,3} (RV)_{\mu i}^* (RV)_{ei}|$  at  $M = M_W$  ( $M = 1000$  GeV) for which we can have successful low-scale leptogenesis in the scenario with three quasi-degenerate in mass heavy Majorana neutrinos in the TIA and VIA cases.

Even smaller values of  $|\sum_{i=1,2,3} (RV)_{\mu i}^* (RV)_{ei}|$  can be probed in the Mu3e experiment [84], planning to reach sensitivity to  $\text{BR}(\mu \rightarrow eee) \sim 10^{-15}$  ( $10^{-16}$ ) and especially in the upcoming Mu2e [85], and COMET [86] experiments on  $\mu - e$  conversion in aluminium, aiming ultimately to be sensitive to  $\text{CR}(\mu {}^{27}_{13}\text{Al} \rightarrow e {}^{27}_{13}\text{Al}) \sim 6 \times 10^{-17}$ . Values as small as  $|\sum_{i=1,2,3} (RV)_{\mu i}^* (RV)_{ei}| \sim 10^{-7}$  at  $M \sim 100$  GeV can be probed in planned PRISM/PRIME experiment [87], aiming at an impressive increase of sensitivity to the  $\mu - e$  conversion rate in titanium to  $\text{CR}(\mu {}^{48}_{22}\text{Ti} \rightarrow e {}^{48}_{22}\text{Ti}) \sim 10^{-18}$ .

In order to obtain the region of viable leptogenesis in terms of the cLFV observable quantities, we solve the density matrix equations from [43,61], and scan the parameter space for the largest allowed values of  $|\sum_{i=1,2,3} (RV)_{\mu i}^* (RV)_{ei}|$ . In Fig. 1 we show the regions of viable low-scale leptogenesis in the considered scenario in the  $|\sum_{i=1,2,3} (RV)_{\mu i}^* (RV)_{ei}| - M$  plane for  $|\sum_{i=1,2,3} (RV)_{\mu i}^* (RV)_{ei}| \geq 10^{-11}$  and  $M$  in the interval  $M = (0.1 - 5 \times 10^5)$  GeV in the TIA and VIA cases (regions below the dotted and solid black lines, respectively). The light neutrino mass spectrum is assumed to be with NO. The lightest neutrino mass is set to  $m_1 = 0$  (top panel) and  $m_1 = 0.03$  eV (bottom panel). The subregion which is excluded by the current low-energy data [90], including the current upper limitations on  $\text{BR}(\mu \rightarrow e\gamma)$  and on  $\text{CR}(\mu {}^{197}_{79}\text{Au} \rightarrow e {}^{197}_{79}\text{Au})$  given in Eqs. (11) and (14), is shown in grey. The green, blue, yellow and red lines represent, from top to bottom, the prospective sensitivities of the planned experiments on  $\mu \rightarrow e\gamma$  and  $\mu \rightarrow eee$  decays, as well as on  $\mu - e$  conversion in aluminium and titanium.<sup>8</sup> As the two figures clearly indicate, the planned experiments on cLFV with  $\mu^\pm$  (i.e., on  $\mu$ LFV) can probe directly significant region of the leptogenesis parameter space,

<sup>7</sup> The explicit analytic expression for the function  $G(X)$  can be found in [74].

<sup>8</sup> The spikes in the curves related to  $\mu - e$  conversions, appearing for different RH neutrino masses in relation to the considered nucleus, are present because the relative rates of the processes, calculated at leading (one-loop) order and neglecting the differences between the masses of  $N_{1,2,3}$ , go through zero [75,88,91].



**Fig. 1.** The region in the  $|\sum_{i=1,2,3}(RV)_{\mu i}^*(RV)_{ei}| - M$  plane of successful low-scale leptogenesis in the case of NH light neutrino mass spectrum with  $m_1 = 0$  (top panel) and for NO spectrum with  $m_1 = 0.03$  eV (bottom panel). The solid and dotted black curves are the constraints from successful leptogenesis in the VIA and TIA cases, respectively. The grey region with solid contour that extends to  $M \sim 500$  GeV is excluded by low-energy experiments as shown in [90], that with dashed and dot-dashed contours are excluded by the current upper limits  $BR(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$  [79] and  $CR(\mu_{13}^{27}\text{Au} \rightarrow e_{13}^{27}\text{Au}) < 7 \times 10^{-13}$  [82], respectively. The green, blue, yellow and red lines correspond, from top to bottom, to the sensitivities of the upcoming experiments on  $\mu^\pm \rightarrow e^\pm + \gamma$ ,  $\mu^\pm \rightarrow e^\pm + e^+ + e^-$  decays and on  $\mu - e$  conversion in aluminium and titanium. See the text for further details.

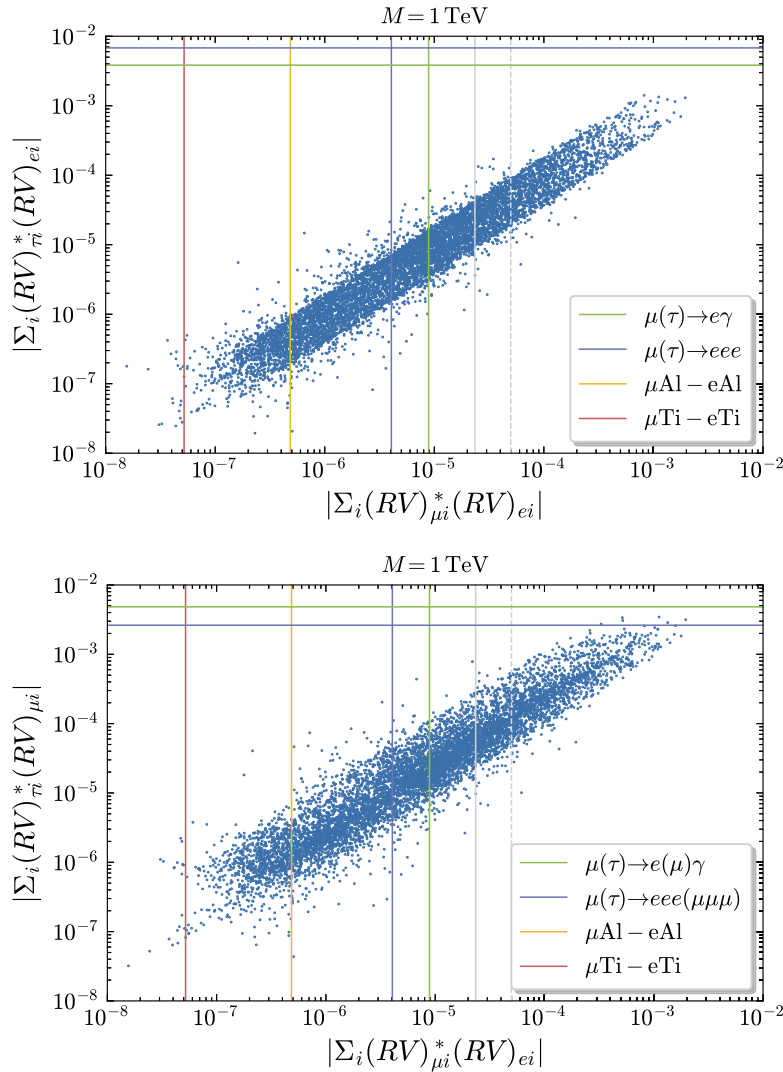
which cannot be explored by any other experiments. More specifically, the future MEG II and Mu3e experiments on  $\mu \rightarrow e\gamma$  and  $\mu \rightarrow eee$  decays will probe the currently allowed leptogenesis regions, which extend respectively from  $M \cong 90$  GeV to  $M \cong 2 \times 10^4$  GeV and from  $M \cong 60$  GeV to  $M \cong 7 \times 10^4$  GeV in the VIA case and to slightly larger values in the TIA case; they will probe values of the parameter  $|\sum_{i=1,2,3}(RV)_{\mu i}^*(RV)_{ei}|$  down to  $8 \times 10^{-6}$  and  $1.5 \times 10^{-6}$ . Except for a narrow region in the vicinity of the spike at 6.0 TeV, in the VIA (TIA) case the upcoming experiments on  $\mu - e$  conversion in aluminium Mu2e [85] and COMET [86] will probe the allowed leptogenesis region within the interval  $M \cong (4 (6) - 3 \times 10^5)$  GeV and values of  $|\sum_{i=1,2,3}(RV)_{\mu i}^*(RV)_{ei}|$  down to  $2 \times 10^{-7}$ , while the planned experiment with higher sensitivity on  $\mu - e$  conversion in titanium PRISM/PRIME [87] will test (apart from a narrow interval around the spike at 4.5 TeV) the leptogenesis region in the range of  $M \cong 2 (3) - 5 \times 10^5$  GeV and values of  $|\sum_{i=1,2,3}(RV)_{\mu i}^*(RV)_{ei}|$  as small as  $1.6 \times 10^{-8}$ . If any of the considered  $\mu$ LFV experiments finds a positive result, that will serve also as an indication in favour of the considered low-scale leptogenesis scenario with three (RH) quasi-degenerate

in mass heavy Majorana neutrinos. From the data on the rate of the observed process one would determine the values of  $M$  and  $|\sum_{i=1,2,3}(RV)_{\mu i}^*(RV)_{ei}|$  (with certain uncertainties). That will allow to make specific predictions for the rates for the other two processes, which, if confirmed experimentally, would constitute further evidence for the discussed low-scale leptogenesis scenario with three RH neutrinos based on the type I seesaw mechanism of neutrino mass generation.

We note that in the region of parameter space of successful leptogenesis, the heavy Majorana neutrinos can have sizeable CC couplings not only to the electron and muon, but to the electron, muon and tauon simultaneously. This is illustrated in Fig. 2 in which we show a generic example of points in the leptogenesis parameter space for  $M = 1$  TeV where both  $\mu$ -LFV and  $\tau$ -LFV processes are possible simultaneously and can proceed with rates that can be probed in future planned experiments.

#### 4. Summary

To summarise, we have shown that the upcoming and planned experiments on charged lepton flavour violation with  $\mu^\pm$ , MEG



**Fig. 2.** We show in the top (bottom) panel of the figure the points in the  $|\sum_i (RV)_{\mu i}^* (RV)_{ei}| - |\sum_i (RV)_{\tau i}^* (RV)_{e(\mu)i}|$  plane for which we find viable leptogenesis for  $M = 1 \text{ TeV}$  and  $m_1 = 0$  (NH light neutrino mass spectrum). The vertical grey lines are the upper limits on  $|\sum_i (RV)_{\mu i}^* (RV)_{ei}|$  implied by the current limits  $\text{BR}(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$  (solid) and  $\text{CR}(\mu\text{Au} \rightarrow e\text{Au}) < 7 \times 10^{-13}$  (dashed). The green, blue, yellow and red vertical lines, from right to left, correspond to the sensitivities on  $|\sum_i (RV)_{\mu i}^* (RV)_{ei}|$  of the upcoming  $\mu\text{LFV}$  experiments on  $\mu \rightarrow e\gamma$ ,  $\mu \rightarrow eee$ ,  $\mu - e$  in aluminium and  $\mu - e$  in titanium, planning to reach, respectively,  $\text{BR}(\mu \rightarrow e\gamma) \sim 6 \times 10^{-14}$ ,  $\text{BR}(\mu \rightarrow eee) \sim 10^{-15}$ ,  $\text{BR}(\mu\text{Al} \rightarrow e\text{Al}) \sim 6 \times 10^{-17}$  and  $\text{BR}(\mu\text{Ti} \rightarrow e\text{Ti}) \sim 10^{-18}$ . The horizontal blue and green lines in the top (bottom) panels are, from top (bottom) to bottom (top), the sensitivities on  $|\sum_i (RV)_{\tau i}^* (RV)_{e(\mu)i}|$  of upcoming experiments on  $\tau \rightarrow eee(\mu\mu\mu)$  and  $\tau \rightarrow e(\mu)\gamma$ , planning to reach sensitivity to  $\text{BR}(\tau \rightarrow eee(\mu\mu\mu)) \sim 5 \times 10^{-10}$  ( $7 \times 10^{-11}$ ) and  $\text{BR}(\tau \rightarrow e(\mu)\gamma) \sim 2(3) \times 10^{-9}$  [92–94].

II on the  $\mu \rightarrow e\gamma$  decay, Mu3e on  $\mu \rightarrow eee$  decay, Mu2e and COMET on  $\mu - e$  conversion in aluminium and PRISM/PRIME on  $\mu - e$  conversion in titanium, can probe directly significant regions of the viable parameter space of low-scale leptogenesis based on the type I seesaw mechanism with three quasi-degenerate in mass heavy Majorana neutrinos  $N_{1,2,3}$ , and thus test this attractive leptogenesis scenario with a potential for a discovery. The BELLE II experiments on  $\tau \rightarrow eee(\mu\mu\mu)$  and  $\tau \rightarrow e(\mu)\gamma$  also can probe a part of the leptogenesis parameter space, although a relatively small one. We are looking forward to the results of these very important experiments on beyond the Standard Model physics.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Data availability

No data was used for the research described in the article.

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