Letter

Low-scale leptogenesis with low-energy Dirac *CP*-violation

Alessandro Granelli ,[1,2,*] Silvia Pascoli,[1,2] and Serguey T. Petcov[3,4,†]

[1] *Dipartimento di Fisica e Astronomia, Università di Bologna, via Irnerio 46, 40126 Bologna, Italy*
[2] *INFN, Sezione di Bologna, viale Berti Pichat 6/2, 40127 Bologna, Italy*
[3] *INFN/SISSA, via Bonomea 265, 34136 Trieste, Italy*
[4] *Kavli IPMU (WPI), UTIAS, University of Tokyo, Kashiwa, Chiba 277-8583, Japan*

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We study the freeze-in scenario of leptogenesis via oscillations within the type-I seesaw model with two quasidegenerate heavy Majorana neutrinos $N_{1,2}$ having masses $M_2 > M_1 \sim (0.1\text{–}100)$ GeV, $(M_2 - M_1)/M_1 \ll 1$, focusing on the role of the CP-violation provided by the Dirac phase δ of the Pontecorvo-Maki-Nakagawa-Sakata lepton mixing matrix. We find that viable leptogenesis can be due solely to CP-violating values of δ and that the $N_{1,2}$ total mixing squared $\Theta^2 = \sum_\alpha \Theta_\alpha^2$ needed is within the reach of future experiments, Θ_α parametrizing the coupling to the charged lepton $\alpha = e, \mu, \tau$. Furthermore, the required parameter space differs from that associated with additional Casas-Ibarra sources of CP-violation. Future determination of δ, Θ^2 and/or the ratios $\Theta_\tau^2 : \Theta_\mu^2 : \Theta_e^2$ would provide a critical test of the considered scenario.

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Introduction. In the present observable Universe there is an overabundance of matter over antimatter. The asymmetry in baryons, or the baryon asymmetry of the Universe (BAU), can be parametrized by the baryon-to-photon ratio η_B. Observations of the cosmic microwave background anisotropies and the abundances of light primordial elements agree on the present value of $\eta_B \simeq 6.1 \times 10^{-10}$ [1,2]. An early mechanism to generate the BAU is referred to as baryogenesis (see Ref. [3] for a recent review), but it is unfeasible within the Standard Model (SM) of particle physics and new physics is required.

An alternative attractive mechanism is that of baryogenesis via leptogenesis (LG) [4], consisting of an early generation of a lepton asymmetry, which is then converted into the present BAU by the SM sphaleron processes [5]. The simplest scenario of LG is realized within the type-I seesaw extension of the SM [6–10], which also provides a mechanism for the generation of the light neutrino masses by augmenting the SM with right-handed sterile neutrinos. The type-I seesaw extension with two right-handed neutrinos and, correspondingly, with two heavy Majorana neutrinos $N_{1,2}$ with definite masses $M_{1,2} > 0$, is the minimal setup in which LG can be realized, while being also compatible with current data on light neutrino masses and mixing.

Many realizations of LG within the type-I seesaw extension are possible depending on the mass scale [4,5,11–15], through lepton number, C- and CP-violating, out-of-equilibrium processes involving the heavy Majorana neutrinos, the Higgs and left-handed lepton doublets, which satisfy the necessary Sakharov's conditions [16]. In this work, we are focused on the "freeze-in" mechanism proposed in [13,14] and extensively studied [17–33], in which the oscillations of the right-handed neutrinos during their out-of-equilibrium production are crucial for the generation of the BAU. This scenario of *LG via oscillations* can be successful for heavy Majorana neutrinos mass scales as low as 100 MeV, thus being accessible to low-energy searches of heavy neutral leptons [34,35].

Among the type-I seesaw model parameters, there are multiple CP-violating phases that could provide the CP-violation necessary for successful LG. Up to a change of basis, the CP-violating phases can be recast inside the matrix Y of the Yukawa coupling between $N_{1,2}$, the Higgs and the left-handed lepton doublets. Under the widely adopted Casas-Ibarra parametrization [36], the Yukawa matrix can be written as

$$Y = \pm i \frac{\sqrt{2}}{v} U \sqrt{\hat{m}_\nu} O^T \sqrt{\hat{M}_N}, \tag{1}$$

where U is the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) lepton mixing matrix, $\hat{m}_\nu \equiv \mathrm{diag}(m_1, m_2, m_3)$,

[*] alessandro.granelli@unibo.it
[†] Also at Institute of Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, 1784 Sofia, Bulgaria.

with $0 \leq m_{1,2,3} \ll M_{1,2}$, is the diagonal mass matrix for the light neutrinos, and $\hat{M}_N = \mathrm{diag}(M_1, M_2)$. The complex Casas-Ibarra matrix O, in the case of two heavy Majorana neutrinos, is 2×3 with orthonormal rows and it can be parametrized in terms of an arbitrary complex angle, thus containing CP-violating phases. With Y written as in Eq. (1), there is an explicit distinction between the CP-violating Dirac and Majorana phases of the PMNS matrix, which are associated to low-energy phenomenology, and those of the Casas-Ibarra matrix, which can manifest themselves in physical processes involving the heavy Majorana neutrinos.

A physically interesting possibility is when the requisite CP-violation in LG is only due to the phases of the PMNS lepton mixing matrix [37–48]. In this case, there would be a direct link between the BAU and CP-violating phenomena in low-energy neutrino physics, such as, e.g., in neutrino oscillations or in neutrinoless double beta decay (see e.g., [49]). At present, only indications of CP-violation in neutrino oscillations involving the Dirac phase δ exist. However, δ is determined in the global analyses with relatively large uncertainties [50–52] and CP-conserving values are not yet excluded. Current experiments such as T2K [53] and NOνA [54] will be able to provide additional information in the next future, potentially reaching $\sim 3\sigma$ for hints of CP-violation. The experiments DUNE [55], and T2Hyper-Kamiokande (T2HK) [56], currently under construction, will have much stronger sensitivity, aiming at a 5σ discovery of leptonic CP-violation for a large fraction of the possible values of δ.

Within the type-I seesaw extension, the phases of the PMNS matrix are the unique sources of CP-violation in the neutrino sector when the Casas-Ibarra matrix is CP conserving [37,38]. This condition corresponds to specific classes of seesaw models in which the elements of the matrix O are either real or purely imaginary and it can be realized, for instance, in flavor models based on sequential dominance [57] or with residual CP symmetries [58,59].

It is possible that the Dirac phase δ is the only source of CP-violation in the lepton sector. LG with Dirac CP-violation has been shown to work in the thermal high-scale scenarios [38,42–44,46–48], emerging as one of the motivations for the current and future neutrino oscillation experimental program. As great attention is being put to the searches of heavy neutral leptons at the GeV scale [34,35], the question on whether low-scale LG via oscillations can be successful with low-energy CP-violation solely from the Dirac phase should be answered also in this context. In this paper, we examine this physically interesting possibility with particular attention to the related low-energy phenomenology. This could serve as further motivations for neutrino oscillation experiments and suggest new directions for heavy neutral lepton searches.

The framework. We consider the minimal version of the type-I seesaw extension of the SM with two heavy Majorana neutrinos $N_{1,2}$ having masses $M_2 > M_1 \sim (0.1\text{–}100)$ GeV and a mass splitting $\Delta M \equiv M_2 - M_1 \ll M_1$ in the range $\Delta M/M_1 \sim (10^{-11}\text{–}10^{-4})$. In the type-I seesaw, after the neutral component of the Higgs doublet acquires a nonvanishing vacuum expectation value $v = 246$ GeV, one gets the well-known relation $(m_\nu)_{\alpha\beta} \simeq -(v^2/2)\sum_{j=1,2} Y_{\alpha j} Y_{\beta j} M_j^{-1}$, $\alpha, \beta = e, \mu, \tau$, for the entries of the tree-level light neutrino mass matrix m_ν, where $Y_{\alpha j}$ is the Yukawa coupling of N_j with the Higgs and left-handed lepton doublet of flavor α. The matrix m_ν can be diagonalized as $\hat{m}_\nu = U^\dagger m_\nu U^*$, where $\hat{m}_\nu \equiv \mathrm{diag}(m_1, m_2, m_3)$ and U represents the PMNS lepton mixing matrix. We adopt the standard parametrization for U [49] in terms of three neutrino mixing angles θ_{12}, θ_{23} and θ_{13}, the Dirac phase δ, and two Majorana phases α_{21} and α_{31} [60]. In the case of two heavy Majorana neutrinos, the lightest neutrino is massless at tree and one-loop levels and the light neutrino mass spectrum is hierarchical with either normal ordering (NO) $m_1 \simeq 0 \ll m_2 < m_3$, or inverted ordering (IO) $m_3 \simeq 0 \ll m_1 < m_2$. In the numerical analysis that follows, we consider the best-fit values of θ_{12}, θ_{23} and θ_{13}, and the two neutrino mass squared differences obtained in [51,52], but treat δ as a free parameter due to the relatively large uncertainty in its determination. The Majorana phases α_{21} and α_{31} cannot be constrained by the neutrino oscillation experiments [60] and are undetermined at present. In the studied case, only the combination $\alpha_{23} \equiv \alpha_{21} - \alpha_{31}$ (the phase α_{21}) is physical in the hierarchical NO (IO) case. We treat $\alpha_{23(21)}$ as free parameters. For reasons that will be clearer throughout the text, we concentrate the analysis mostly on the light-neutrino mass spectrum with NO and leave the IO case for a future longer work. Global analyses including data from atmospheric, reactor and long-baseline neutrino experiments give a mild preference for NO against the spectrum with IO [50,51].

We consider the Casas-Ibarra (CI) parametrization for the Yukawa matrix [36], which we rewrite explicitly as $Y_{\alpha j} = \pm i(\sqrt{2}/v)\sum_{a=1,2,3} U_{\alpha a}\sqrt{m_a} O_{ja}\sqrt{M_j}$. The arbitrary CI matrix O has entries $O_{11(13)} = O_{21(23)} = 0$, $O_{23(22)} = \varphi O_{12(11)} = \varphi\cos\theta$ and $O_{13(12)} = -\varphi O_{22(21)} = \varphi\sin\theta$ in the NO (IO) case, with $\theta \equiv \omega + i\xi$, ω and ξ being free real parameters and $\varphi = \pm 1$. We choose to work with $\varphi = +1$ but extend the range of the Majorana phases $\alpha_{23(21)}$ from $[0, 2\pi]$ to $[0, 4\pi]$. In this way, the same full sets of CI and Yukawa matrices are considered [61].

The SM flavor neutrinos also mix with the heavy Majorana neutrinos. The mixing $\Theta_{\alpha j} \simeq (v/\sqrt{2}) Y_{\alpha j}/M_j$ sets the coupling between N_j and the charged lepton α (ν_α) in the weak charged (neutral) current, thus being important for low-energy phenomenology. For instance, direct searches at colliders, beam-dump and kaon experiments are sensitive to $\Theta_\alpha^2 \equiv \sum_{j=1}^2 |\Theta_{\alpha j}|^2$ and $\Theta^2 \equiv \sum_{\alpha=e,\mu,\tau} \Theta_\alpha^2$. The same quantities are crucial in LG as they determine the strength of the *wash-out* processes.

Low-energy CP-violation. Within the considered CI parametrization, the CP-violating matrices can be either U, O or both. In the case of low-energy CP-violation (LECPV) we are interested in, the only CP-violating matrix is U, with the CI matrix being CP conserving. LECPV can be achieved [38] either by setting (i) $\xi = 0$ and $\omega \neq 0$, with real CI matrix; or (ii) $\omega = k\pi$, $k = 0, 1/2, 1, ...,$ and $\xi \neq 0$, so that $O_{12}O_{13}$ ($O_{11}O_{12}$) in the NO (IO) case is purely imaginary. Case (ii) is associated with relatively large values of the mixings Θ_α^2 and Θ^2, as the condition $|\xi| \gg 1$ leads to an overall exponential enhancement. Since we are interested in connecting with experimental searches of heavy Majorana neutrinos, we focus the analysis on the case with $\omega = k\pi$ and $\xi \neq 0$. We stress that the condition $\omega \neq k\pi$ when $\xi \neq 0$ would result in a CP-violating CI matrix (CICPV) [38].

To have LECPV, the phases in the PMNS matrix should be CP-violating, i.e., $\delta \neq 0, \pi$, and/or $\alpha_{21} \neq k_{21}\pi$ and/or $\alpha_{31} \neq k_{31}\pi$, $k_{21} = 0, 1, 2, \ldots$, $k_{31} = 0, 1, 2, \ldots$. It is also possible, however, that CP is violated even when U and O are CP conserving, but Y is not [38]. In this case, CP is broken due to an *interplay* between the PMNS and CI matrices in the CI parametrization of the Yukawa matrix. When $\xi \neq 0$ and $\omega = k\pi$, this can be realized for the CP-conserving values of the PMNS phases satisfying, additionally, $\alpha_{23} \neq \pm(2n+1)\pi$ ($\alpha_{21} \neq (2n+1)\pi$), $n = 0$, 1, in the NO (IO) case [38]. For the purpose of studying the case of LECPV uniquely from δ, we shall consider $\alpha_{23(21)} = \pi$ or 3π.

CP-violation in leptogenesis. All the CP-violating physical observables are expected to depend upon specific basis-independent quantities written in terms of the flavor parameters of the model, the so-called *CP-violating invariants*. For instance, the magnitude of CP-violation in $\nu_\alpha \to \nu_\beta$ and $\bar{\nu}_\alpha \to \bar{\nu}_\beta$ oscillations ($\alpha \neq \beta$) is determined by the rephasing invariant $J_{\rm CP} = \Im[U_{\mu 3}U_{e3}^*U_{e2}U_{\mu 2}^*]$ [62], analogous to the Jarlskog invariant in the quark sector [63–65]. Several CP invariants can be derived in the type-I seesaw extension of the SM starting from the Yukawa and heavy Majorana neutrino mass matrices [66–71], and those that are relevant to LG (at leading order and in the case of two quasidegenerate in mass heavy Majorana neutrinos) can be constructed out of the following two building blocks (see Ref. [31] for a recent derivation): $J_\alpha^{\rm LNC} = \Im[Y_{\alpha 1}^* Y_{\alpha 2}(Y^\dagger Y)_{21}]$ and $J_\alpha^{\rm LNV} = \Im[Y_{\alpha 1}^* Y_{\alpha 2}(Y^\dagger Y)_{12}]$. At leading order, the BAU arising in LG is proportional to a combination of $J_\alpha^{\rm LNC}$ and $J_\alpha^{\rm LNV}$ weighted over the lepton flavors [30,31,72–75]. For LECPV with $\omega = k\pi$ and $\xi \neq 0$, we have that $J_\alpha^{\rm LNC} = -J_\alpha^{\rm LNV} \propto \Re[U_{\alpha 3(2)}^* U_{\alpha 2(1)}]\sinh(2\xi)\cos(2k\pi)$ in the NO (IO) case.

For $M_1 \gtrsim 100$ GeV, outside the mass range of interest to this study, low-scale LG has been shown to reconnect with the resonant freeze-out mechanism [29,30]. In the resonant LG scenario and within the Boltzmann equations formalism, the lepton asymmetry of flavor α is proportional to the sum of the two invariants [30,72,73,76,77] $J_\alpha^{\rm LNC} + J_\alpha^{\rm LNV} \propto \sin(2\omega)$ up to corrections of the order of $\mathcal{O}(\Delta M/M_1)$, which vanishes when $\omega = k\pi$ contrarily to what happens in the low-scale LG scenario via oscillations. This highlights the importance of the oscillation mechanism in the considered framework.

We further note that, in the IO case, $\Re[U_{e2}^* U_{e1}] \propto \cos(\alpha_{21}/2)$, so that, when $\alpha_{21} = \pi, 3\pi$, $J_e^{\rm LNC} = J_e^{\rm LNV} = 0$, $J_\mu^{\rm LNC} = -J_\tau^{\rm LNC}$ and $J_\mu^{\rm LNV} = -J_\tau^{\rm LNV}$. In this case, higher order CP invariants can be relevant to LG, making the IO case more involved.

Results. We perform a numerical scan of the parameter space of viable LG. To calculate the BAU in the scenario of interest, we solve the momentum-averaged *density matrix equations* [13,14,18,23,26,28–30,75,78–80] for the evolution of the lepton asymmetries and heavy Majorana neutrino abundances. We consider the equations as in [28,31,33] and make use of the latest version of the ULYSSES PYTHON package [81,82]. We list in what follows the results of our numerical analysis.

(i) We show in Fig. 1 the region in the $\Theta^2 - M_1$ plane where LG with LECPV from δ is successful in reproducing the observed value of the BAU. For illustrative purposes, we choose $\delta = 3\pi/2$, $\alpha_{23} = \pi$ and $\omega = 0$, vary $\Delta M/M_1$ in the range $[10^{-11}, 10^{-4}]$ and focus on the NO case. A qualitatively similar figure for the same choice of parameters is obtained in the IO case, but not shown here.

The upper (lower) solid black line in the plot is the curve of maximal (minimal) mixing Θ^2 compatible with viable LG. The shaded blue area between the two black lines corresponds to successful LG for certain choices of $\Delta M/M_1$ and δ. We paint in darker (lighter) blue the regions of successful LG corresponding to larger (smaller) values of $\Delta M/M_1$. We find that the extreme values of Θ^2 can be obtained for $\Delta M/M_1 \lesssim 10^{-6}$, while, for larger splittings, the viable region reduces in size, with the maximal (minimal) allowed mixing taking smaller (larger) values.

The LG parameter space is bounded from below by the requirement of reproducing the light neutrino masses (lower gray region) and from above by the experimental limits on the couplings of the heavy Majorana neutrinos to the electron [83–93], the muon [83–90,92–96] and the tauon [83–85,97–99] flavor. Numerous planned and proposed experiments aim at improving the sensitivity to these couplings further [34,100–110]. The total mixing is also

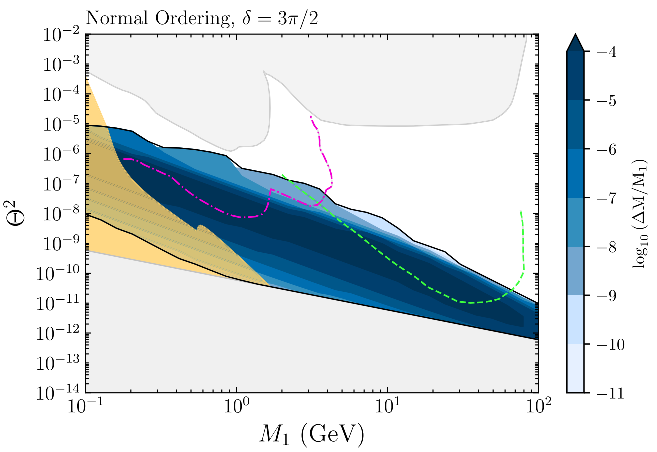

FIG. 1. The parameter space of viable LG with LECPV solely from δ, in the NO case, for $\omega = 0$, $\alpha_{23} = \pi$ and $\delta = 3\pi/2$. The lower gray area is forbidden in the type-I seesaw mechanism of light neutrino mass generation. The upper gray region is a combination of current constraints on Θ_τ^2 [83–85,97–99], the yellow one is excluded by BBN [111,112]. The dot-dashed purple line represents the expected sensitivities of several upcoming and proposed experiments [34,35,100–106], while the green dashed one is that of FCC-ee [113,114].

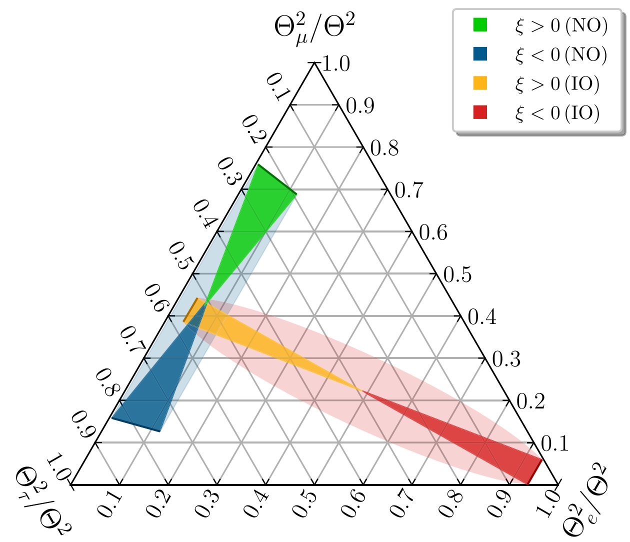

FIG. 2. A ternary plot illustrating the ratios Θ_e^2/Θ^2 (lower axis), Θ_μ^2/Θ^2 (right axis), and Θ_τ^2/Θ^2 (left axis). The triangular regions correspond to: $\xi > 0$ and NO (green), $\xi < 0$ and NO (blue), $\xi > 0$ and IO (orange), and $\xi < 0$ and IO (red). The other parameters are $\alpha_{23(21)} = \pi$ for the NO (IO) case, and δ varied in the range $[0, \pi]$ (or, equivalently, $[\pi, 2\pi]$). The fainter blue (red) region represents the results obtained by varying ξ, δ, $\alpha_{23(21)}$ over their entire ranges of allowed values (note that $\Theta_{e,\mu,\tau}^2/\Theta^2$ do not depend on ω nor $M_{1,2}$).

constrained by the big bang nucleosynthesis (BBN) [111,112]. The reported limits and projections on Θ^2, however, are currently based on the assumption that only the mixing in a particular flavor α is nonzero, i.e. $\Theta^2 = \Theta_\alpha^2$ for either $\alpha = e, \mu$ or τ. In Fig. 1, as long as large mixings are considered, i.e. $|\xi| \gg 1$, we find that LG is compatible with the condition $\Theta_\tau^2 > \Theta_\mu^2 > \Theta_e^2$ (see further). For this reason, we only consider the bounds on Θ_τ^2 when showing the region excluded from past and present searches [83–85,97–99] (upper gray region) and BBN [111,112] (yellow). Moreover, we project the expected sensitivities on Θ_τ^2 of upcoming and proposed experiments [34,35,100–106] (purple dot-dashed line). The prospective sensitivity on Θ^2 of the discussed FCC-ee [113,114] is also reported (green dashed line).

(ii) The maximal allowed values of Θ^2 compatible with viable LG with LECPV from δ depend on the value of the Dirac phase. For the case in Fig. 1 with $\delta = 3\pi/2$, these are $\Theta^2 \simeq 9 \times 10^{-6}, 5 \times 10^{-7}, 6 \times 10^{-9}, 9 \times 10^{-12}$ when $M_1 = 0.1, 1, 10, 100$ GeV, respectively. By fixing $\delta = 195°(345°)$, we find $\Theta^2 \simeq 2 \times 10^{-6} (1.5 \times 10^{-5})$, $9 \times 10^{-8} (1.5 \times 10^{-6})$, $2 \times 10^{-9} (1.2 \times 10^{-8})$, $6 \times 10^{-12} (4 \times 10^{-11})$ at $M_1 = 0.1, 1, 10, 100$ GeV. We compare these results with the case of CICPV fixing $\omega = \pi/4$ or $3\pi/4$, $\delta = 3\pi/2$ and $\alpha_{23} = \pi$, so to maximize the *CP* asymmetry and the maximal allowed mixing (see, e.g., [24,30,80]). We get $\Theta^2 \simeq 3 \times 10^{-5}$, 3×10^{-6}, 2.5×10^{-8}, 4×10^{-11} at $M_1 = 0.1$, 1, 10, 100 GeV (see also the results of [29,30] for comparison). We note, however, that the maximal allowed values of Θ^2 in the case of CICPV do not exhibit strong dependence on δ and α_{23}. The differences in the values obtained with LECPV from δ and from CICPV reveal a separation between the parameter spaces of successful LG in the two cases. The magnitude of this gap depends on δ and M_1.

(iii) We show in Fig. 2 the possible values of the mixing ratios Θ_α^2/Θ^2 in a ternary plot. The four triangular regions in the plot are obtained for $\alpha_{23(21)} = \pi$ and $\omega = 0$, and by marginalizing over δ in the range $[0, \pi]$, (or, equivalently, $[\pi, 2\pi]$), with the green and blue (yellow and red) triangles corresponding respectively to $\xi \geq 0$ and $\xi \leq 0$ in the NO (IO) case. In such triangular regions, we find viable LG with LECPV from δ. For $|\xi| \gg 1$, the triangles reduce to the shorter solid edges, while the intersection points correspond to $\xi = 0$. The larger and fainter blue (red) region, overlapping with the triangles associated to LECPV, is obtained by varying δ, $\alpha_{23(21)}$ and ξ within their entire allowed ranges of possible values, and here LG is viable with additional sources of *CP*-violation from the Casas-Ibarra matrix and/or the Majorana phases. In the NO case, one has $\Theta_{\mu,\tau}^2 > \Theta_e^2$, and, depending on whether $\xi \gg 1$, $\ll -1$ or ~ 0, either $\Theta_\mu^2 > \Theta_\tau^2$, $\Theta_\tau^2 > \Theta_\mu^2$ or $\Theta_\tau^2 \sim \Theta_\mu^2$.

(iv) Concentrating on the NO case, we scan the LG space over δ across the entire ranges of masses and splittings considered. We find the results to be symmetric under the simultaneous change $\delta \to \delta \pm \pi$ and $\xi \to -\xi$. Moreover, the present η_B can be reproduced with the correct sign only for (i) $\xi > 0$ and $0 < \delta < \pi$, or (ii) $\xi < 0$ and $\pi < \delta < 2\pi$. When large mixings are considered, i.e. $|\xi| \gg 1$, the above two cases correspond respectively to
   (i) $\Theta_\mu^2 > \Theta_\tau^2 > \Theta_e^2$ with $0.005 \lesssim \Theta_e^2/\Theta^2 \lesssim 0.12$, $0.69 \lesssim \Theta_\mu^2/\Theta^2 \lesssim 0.76$ and $0.19 \lesssim \Theta_\tau^2/\Theta^2 \lesssim 0.24$;
   (ii) $\Theta_\tau^2 > \Theta_\mu^2 > \Theta_e^2$ with $0.005 \lesssim \Theta_e^2/\Theta^2 \lesssim 0.12$, $0.13 \lesssim \Theta_\mu^2/\Theta^2 \lesssim 0.16$ and $0.75 \lesssim \Theta_\tau^2/\Theta^2 \lesssim 0.83$.

   The situation is more involved for the IO spectrum: a shift of sign in ξ changes prominently the mixings and the leading order CP invariant in the electron flavor vanishes for LECPV from δ. The IO case will be discussed in more details elsewhere.

The results were obtained for $\omega = 0$ and $\alpha_{23(21)} = \pi$. Everything would be the same for $\omega = \pi, 2\pi$, while setting $\alpha_{23(21)} = 3\pi$ would imply equivalent results provided that the overall sign of ξ is changed. An overall sign shift can be obtained by choosing $\omega = \pi/2, 3\pi/2$.

Conclusions. The results we have found indicate quite remarkably not only that LG with low-energy CP-violation solely from δ is viable in the mass range $0.1 \leq M_1/\mathrm{GeV} \leq 100$, but also that it is compatible with rather large values of Θ^2. As the sensitivity reaches of proposed experiments enter inside the region of viable LG in the entire considered mass range, they could potentially probe the parameter space of the LG scenario discussed in this work. Moreover, we find viable LG for broad ranges of δ values within $0 < \delta < \pi$ and $\pi < \delta < 2\pi$. Qualitatively similar results hold in the IO case as well.

We have found a correspondence between the sign of the BAU and that of $\sin\delta$ in the NO case, which is reflected in the differences in the flavor hierarchies. More specifically, LG with LECPV from δ is successful in reproducing the positive BAU for either $0 < \delta < \pi$ ($\pi < \delta < 2\pi$) and $\Theta_\mu^2 > \Theta_\tau^2 > \Theta_e^2$ or $\pi < \delta < 2\pi$ ($0 < \delta < \pi$) and $\Theta_\tau^2 > \Theta_\mu^2 > \Theta_e^2$ for $\omega = 0, \pi, 2\pi$ ($\pi/2, 3\pi/2$). As the physical observables at direct searches of heavy neutral leptons depend on the ratios $\Theta_\tau^2 : \Theta_\mu^2 : \Theta_e^2$, the above cases are phenomenologically different. Possible future signatures favoring a certain flavor hierarchy and a measurement of δ establishing whether $0 < \delta < \pi$ or $\pi < \delta < 2\pi$ could discriminate between the scenarios considered in this work. Additionally, if experiments suggest a flavor structure outside the green and blue (yellow and red) triangles of Fig. 2 in the NO (IO) case, but still inside the light-blue (light-red) regions, LG would necessitate additional sources of CP-violation, either from the Majorana phases and/or the Casas-Ibarra matrix.

Finally, we have shown that there is a gap between the parameter spaces of LG with LECPV and CICPV, with the separation depending on δ and M_1. A measurement of δ and Θ^2 at a certain mass scale in the associated gap would indicate the necessity of having additional sources of CP-violation other than δ.

Overall, our results show that high-precision measurements of δ, Θ^2 and/or the ratios $\Theta_\tau^2 : \Theta_\mu^2 : \Theta_e^2$ will be crucial for understanding whether, within the scenario of LG we are considering, the Dirac CP-violating phase of the PMNS matrix can be the unique source of CP-violation, or additional sources coming from the Casas-Ibarra matrix and/or the Majorana phases are required in order to explain the presently observed BAU.

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[1] N. Aghanim *et al.*, Astron. Astrophys. **641**, A6 (2020).
[2] R. J. Cooke, M. Pettini, and C. C. Steidel, Astrophys. J. **855**, 102 (2018).
[3] D. Bodeker and W. Buchmuller, Rev. Mod. Phys. **93**, 035004 (2021).
[4] M. Fukugita and T. Yanagida, Phys. Lett. B **174**, 45 (1986).
[5] V. A. Kuzmin, V. A. Rubakov, and M. E. Shaposhnikov, Phys. Lett. **155B**, 36 (1985).
[6] P. Minkowski, Phys. Lett. **67B**, 421 (1977).
[7] T. Yanagida, Conf. Proc. C **7902131**, 95 (1979).
[8] M. Gell-Mann, P. Ramond, and R. Slansky, Conf. Proc. C **790927**, 315 (1979).
[9] S. Glashow, NATO Adv. Stud. Inst. Ser. **61**, 687 (1980).

[10] R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. **44**, 912 (1980).
[11] A. Pilaftsis, Phys. Rev. D **56**, 5431 (1997).
[12] A. Pilaftsis and T. E. J. Underwood, Nucl. Phys. **B692**, 303 (2004).
[13] E. K. Akhmedov, V. A. Rubakov, and A. Y. Smirnov, Phys. Rev. Lett. **81**, 1359 (1998).
[14] T. Asaka and M. Shaposhnikov, Phys. Lett. B **620**, 17 (2005).
[15] J. Racker, M. Pena, and N. Rius, J. Cosmol. Astropart. Phys. 07 (2012) 030.
[16] A. D. Sakharov, Usp. Fiz. Nauk **161**, 61 (1991) [Sov. Phys. Usp. **5**, 32 (1991)].
[17] M. Shaposhnikov, Nucl. Phys. **B763**, 49 (2007).
[18] T. Asaka, S. Eijima, and H. Ishida, J. Cosmol. Astropart. Phys. 02 (2012) 021.
[19] L. Canetti, M. Drewes, T. Frossard, and M. Shaposhnikov, Phys. Rev. D **87**, 093006 (2013).
[20] B. Shuve and I. Yavin, Phys. Rev. D **89**, 075014 (2014).
[21] P. Hernández, M. Kekic, J. López-Pavón, J. Racker, and N. Rius, J. High Energy Phys. 10 (2015) 067.
[22] M. Drewes, B. Garbrecht, D. Gueter, and J. Klaric, J. High Energy Phys. 12 (2016) 150.
[23] P. Hernández, M. Kekic, J. López-Pavón, J. Racker, and J. Salvado, J. High Energy Phys. 08 (2016) 157.
[24] M. Drewes, B. Garbrecht, D. Gueter, and J. Klaric, J. High Energy Phys. 08 (2017) 018.
[25] T. Asaka, S. Eijima, H. Ishida, K. Minogawa, and T. Yoshii, Phys. Rev. D **96**, 083010 (2017).
[26] J. Ghiglieri and M. Laine, J. High Energy Phys. 05 (2017) 132.
[27] M. Drewes, B. Garbrecht, P. Hernández, M. Kekic, J. Lopez-Pavon, J. Racker, N. Rius, J. Salvado, and D. Teresi, Int. J. Mod. Phys. A **33**, 1842002 (2018).
[28] A. Abada, G. Arcadi, V. Domcke, M. Drewes, J. Klaric, and M. Lucente, J. High Energy Phys. 01 (2019) 164.
[29] J. Klarić, M. Shaposhnikov, and I. Timiryasov, Phys. Rev. Lett. **127**, 111802 (2021).
[30] J. Klarić, M. Shaposhnikov, and I. Timiryasov, Phys. Rev. D **104**, 055010 (2021).
[31] P. Hernandez, J. Lopez-Pavon, N. Rius, and S. Sandner, J. High Energy Phys. 12 (2022) 012.
[32] M. Drewes, J. Klarić, and J. López-Pavón, Eur. Phys. J. C **82**, 1176 (2022).
[33] S. Sandner, P. Hernandez, J. Lopez-Pavon, and N. Rius, arXiv:2305.14427.
[34] A. M. Abdullahi *et al.*, J. Phys. G **50**, 020501 (2023).
[35] C. Antel *et al.*, arXiv:2305.01715.
[36] J. A. Casas and A. Ibarra, Nucl. Phys. **B618**, 171 (2001).
[37] S. Pascoli, S. T. Petcov, and A. Riotto, Phys. Rev. D **75**, 083511 (2007).
[38] S. Pascoli, S. T. Petcov, and A. Riotto, Nucl. Phys. **B774**, 1 (2007).
[39] S. Blanchet and P. Di Bari, J. Cosmol. Astropart. Phys. 03 (2007) 018.
[40] G. C. Branco, R. Gonzalez Felipe, and F. R. Joaquim, Phys. Lett. B **645**, 432 (2007).
[41] S. Uhlig, J. High Energy Phys. 11 (2007) 066.
[42] A. Anisimov, S. Blanchet, and P. Di Bari, J. Cosmol. Astropart. Phys. 04 (2008) 033.
[43] E. Molinaro and S. T. Petcov, Eur. Phys. J. C **61**, 93 (2009).
[44] E. Molinaro and S. T. Petcov, Phys. Lett. B **671**, 60 (2009).
[45] G. Bambhaniya, P. S. Bhupal Dev, S. Goswami, S. Khan, and W. Rodejohann, Phys. Rev. D **95**, 095016 (2017).
[46] M. J. Dolan, T. P. Dutka, and R. R. Volkas, J. Cosmol. Astropart. Phys. 06 (2018) 012.
[47] K. Moffat, S. Pascoli, S. T. Petcov, and J. Turner, J. High Energy Phys. 03 (2019) 034.
[48] A. Granelli, K. Moffat, and S. T. Petcov, J. High Energy Phys. 11 (2021) 149.
[49] M. Tanabashi *et al.* (Particle Data Group Collaboration), Phys. Rev. D **98**, 030001 (2018).
[50] F. Capozzi, E. Di Valentino, E. Lisi, A. Marrone, A. Melchiorri, and A. Palazzo, Phys. Rev. D **101**, 116013 (2020).
[51] I. Esteban, M. C. Gonzalez-Garcia, M. Maltoni, T. Schwetz, and A. Zhou, J. High Energy Phys. 09 (2020) 178.
[52] Nufit v5.2, http://www.nu-fit.org.
[53] K. Abe *et al.* (T2K Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **659**, 106 (2011).
[54] M. A. Acero *et al.* (NOvA Collaboration), Phys. Rev. D **106**, 032004 (2022).
[55] V. Hewes *et al.* (DUNE Collaboration), Instruments **5**, 31 (2021).
[56] J. Bian *et al.* (Hyper-Kamiokande Collaboration), arXiv:2203.02029.
[57] S. F. King, Nucl. Phys. **B786**, 52 (2007).
[58] P. Chen, G.-J. Ding, and S. F. King, J. High Energy Phys. 03 (2016) 206.
[59] C. Hagedorn and E. Molinaro, Nucl. Phys. **B919**, 404 (2017).
[60] S. M. Bilenky, J. Hosek, and S. T. Petcov, Phys. Lett. **94B**, 495 (1980).
[61] E. Molinaro and S. T. Petcov, Eur. Phys. J. C **61**, 93 (2009).
[62] P. I. Krastev and S. T. Petcov, Phys. Lett. B **205**, 84 (1988).
[63] C. Jarlskog, Phys. Rev. Lett. **55**, 1039 (1985).
[64] C. Jarlskog, Z. Phys. C **29**, 491 (1985).
[65] J. Bernabeu, G. C. Branco, and M. Gronau, Phys. Lett. **169B**, 243 (1986).
[66] G. C. Branco, T. Morozumi, B. M. Nobre, and M. N. Rebelo, Nucl. Phys. **B617**, 475 (2001).
[67] G. C. Branco and M. N. Rebelo, New J. Phys. **7**, 86 (2005).
[68] E. E. Jenkins and A. V. Manohar, Nucl. Phys. **B792**, 187 (2008).
[69] E. E. Jenkins and A. V. Manohar, J. High Energy Phys. 10 (2009) 094.
[70] Y. Wang, B. Yu, and S. Zhou, J. High Energy Phys. 09 (2021) 053.
[71] B. Yu and S. Zhou, J. High Energy Phys. 10 (2021) 017.
[72] M. Flanz, E. A. Paschos, and U. Sarkar, Phys. Lett. B **345**, 248 (1995); **384**, 487(E) (1996); **382**, 447(E) (1996).
[73] L. Covi and E. Roulet, Phys. Lett. B **399**, 113 (1997).
[74] W. Buchmüller and M. Plümacher, Phys. Lett. B **431**, 354 (1998).
[75] T. Hambye and D. Teresi, Phys. Rev. D **96**, 015031 (2017).
[76] L. Covi, E. Roulet, and F. Vissani, Phys. Lett. B **384**, 169 (1996).

[77] A. Granelli, K. Moffat, and S. T. Petcov, Nucl. Phys. **B973**, 115597 (2021).
[78] L. Canetti, M. Drewes, T. Frossard, and M. Shaposhnikov, Phys. Rev. D **87**, 093006 (2013).
[79] J. Ghiglieri and M. Laine, J. High Energy Phys. 02 (2018) 078.
[80] S. Eijima, M. Shaposhnikov, and I. Timiryasov, J. High Energy Phys. 07 (2019) 077.
[81] A. Granelli, K. Moffat, Y. F. Perez-Gonzalez, H. Schulz, and J. Turner, Comput. Phys. Commun. **262**, 107813 (2021).
[82] A. Granelli, C. Leslie, Y. F. Perez-Gonzalez, H. Schulz, B. Shuve, J. Turner, and R. Walker, Comput. Phys. Commun. **291**, 108834 (2023).
[83] F. Bergsma *et al.* (CHARM Collaboration), Phys. Lett. **157B**, 458 (1985).
[84] P. Abreu *et al.* (DELPHI Collaboration), Z. Phys. C **74**, 57 (1997); **75**, 580(E) (1997).
[85] K. Abe *et al.* (T2K Collaboration), Phys. Rev. D **100**, 052006 (2019).
[86] G. Bernardi *et al.*, Phys. Lett. B **203**, 332 (1988).
[87] D. Liventsev *et al.* (Belle Collaboration), Phys. Rev. D **87**, 071102 (2013); **95**, 099903(E) (2017).
[88] A. Aguilar-Arevalo *et al.* (PIENU Collaboration), Phys. Rev. D **97**, 072012 (2018).
[89] A. M. Sirunyan *et al.* (CMS Collaboration), Phys. Rev. Lett. **120**, 221801 (2018).
[90] G. Aad *et al.* (ATLAS Collaboration), J. High Energy Phys. 10 (2019) 265.
[91] E. Cortina Gil *et al.* (NA62 Collaboration), J. High Energy Phys. 03 (2021) 058.
[92] A. Tumasyan *et al.* (CMS Collaboration), J. High Energy Phys. 07 (2022) 081.
[93] ATLAS Collaboration, Phys. Rev. Lett. **131**, 061803 (2023).
[94] P. Abratenko *et al.* (MicroBooNE Collaboration), Phys. Rev. D **101**, 052001 (2020).
[95] E. Cortina Gil *et al.* (NA62 Collaboration), Phys. Lett. B **816**, 136259 (2021).
[96] P. Abratenko *et al.* (MicroBooNE Collaboration), Phys. Rev. D **106**, 092006 (2022).
[97] R. Acciarri *et al.* (ArgoNeuT Collaboration), Phys. Rev. Lett. **127**, 121801 (2021).
[98] J. P. Lees *et al.* (*BABAR* Collaboration), Phys. Rev. D **107**, 052009 (2023).
[99] R. Barouki, G. Marocco, and S. Sarkar, SciPost Phys. **13**, 118 (2022).
[100] A. Ariga *et al.* (FASER Collaboration), Phys. Rev. D **99**, 095011 (2019).
[101] C. O. Dib, J. C. Helo, M. Nayak, N. A. Neill, A. Soffer, and J. Zamora-Saa, Phys. Rev. D **101**, 093003 (2020).
[102] G. Aielli *et al.*, Eur. Phys. J. C **80**, 1177 (2020).
[103] B. Batell, J. A. Evans, S. Gori, and M. Rai, J. High Energy Phys. 05 (2021) 049.
[104] E. Cortina Gil *et al.* (HIKE Collaboration), arXiv:2211.16586.
[105] O. Aberle *et al.* (SHiP Collaboration), BDF/SHiP at the ECN3 high-intensity beam facility, Technical Report No. CERN-SPSC-2022-032/SPSC-I-258, CERN, Geneva, 2022.
[106] C. Alpigiani *et al.* (MATHUSLA Collaboration), arXiv:2009.01693.
[107] J. Beacham *et al.*, J. Phys. G **47**, 010501 (2020).
[108] W. Altmannshofer *et al.* (PIONEER Collaboration), arXiv:2203.01981.
[109] N. Blinov, E. Kowalczyk, and M. Wynne, J. High Energy Phys. 02 (2022) 036.
[110] M. Alviggi *et al.* (SHADOWS Collaboration), SHADOWS Letter of Intent, Technical Report No. CERN-SPSC-2022-030/SPSC-I-256, CERN, Geneva, 2022.
[111] N. Sabti, A. Magalich, and A. Filimonova, J. Cosmol. Astropart. Phys. 11 (2020) 056.
[112] A. Boyarsky, M. Ovchynnikov, O. Ruchayskiy, and V. Syvolap, Phys. Rev. D **104**, 023517 (2021).
[113] A. Abada *et al.* (FCC Collaboration), Eur. Phys. J. C **79**, 474 (2019).
[114] A. Abada *et al.* (FCC Collaboration), Eur. Phys. J. Special Topics **228**, 261 (2019).
[115] https://site.unibo.it/openphysicshub/en.