

Right-handed leptonic mixing and enhancement band in left-right symmetry

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Left-right (LR) symmetric theories predict right-handed charged currents whose flavor structure encodes the realization of parity. While the right-handed quark mixing matrix closely tracks its left-handed counterpart, the leptonic sector with purely Dirac neutrinos has remained structurally unclear. We show that, in contrast to the quark case, parity in the Dirac leptonic sector admits a localized, branch-dependent enhancement band in which right-handed–left-handed (RH-LH) misalignment becomes parametrically large despite small parity breaking. We derive analytic solutions of the LR consistency equation and demonstrate that the interplay between spontaneous parity violation and spectral near degeneracies leads to a qualitatively new pattern of right-handed mixing. This establishes the Dirac leptonic sector of the minimal LR model as a predictive and structurally distinct regime.

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I. INTRODUCTION

Left-right (LR) symmetric theories provide a well-motivated extension of the Standard Model, restoring parity at high energies and relating left-handed (LH) and right-handed (RH) charged currents [1–4]. In this framework, the flavor structure of RH interactions is in principle constrained by the underlying symmetry.

In the quark sector, this relation has been understood in detail: despite sizable parity breaking, the RH mixing matrix closely tracks its left-handed counterpart, a consequence of the strong hierarchy of quark masses [5,6]. A natural open question is whether an analogous behavior holds in the leptonic sector.

The answer depends crucially on the nature of neutrino masses. While LR symmetry naturally accommodates Majorana neutrinos through seesaw realizations [7–11], Dirac neutrinos are equally consistent from the viewpoint of the symmetry, in particular in the minimal doublet-breaking realization [12]. In this case, however, the leptonic sector has received comparatively less attention as a predictive and self-contained framework.

In this work we adopt a minimal viewpoint and take the Dirac LR model at face value, without addressing the origin of the small neutrino masses. Instead, we investigate the structural consequences implied by parity symmetry.

We show that, in contrast to the quark case, the leptonic sector exhibits a qualitatively different behavior. The LR

consistency conditions reduce to a nonlinear relation whose solutions organize into discrete branches. In mixed-sign branches, the interplay between small parity breaking and small neutrino mass splittings leads to a parametric enhancement of RH-LH mixing differences. As a result, sizable misalignment can arise despite the smallness of the symmetry-breaking parameter ϵ , while outside this localized band the mixing remains perturbatively aligned.

In this framework, the RH leptonic mixing matrix is fixed in terms of the left-handed one, the neutrino spectrum, and a single spontaneous parity-breaking parameter ϵ , up to discrete sign assignments.

We analyze this structure analytically in complementary regimes and solve the exact matrix equation numerically in the $(m_{\nu, \text{lightest}}, \epsilon)$ plane, providing a unified description of the enhancement mechanism across parameter space.

It is useful to clarify the relation of the present analysis to earlier work. The parity-based reconstruction of RH mixing, including the quark-sector treatment and the small- ϵ expansion, was developed in Refs. [5,6]; this provides the direct methodological starting point for the present analysis. Related LR-symmetry constraints on leptonic Dirac mass matrices were studied in the Majorana LR realization, in which the Dirac matrix enters the seesaw relation rather than describing light Dirac neutrinos directly [13–15]. The present work extends the parity-based RH-mixing reconstruction to the minimal doublet model with purely Dirac neutrinos, where the solution space is qualitatively different: the lightest neutrino mass becomes a control parameter and the discrete sign branches determine whether RH leptonic mixing remains aligned or becomes enhanced.

The resulting framework therefore defines a predictive Dirac benchmark within LR symmetry, characterized by a calculable pattern of RH leptonic mixing that differs

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qualitatively from both the quark sector and the Majorana realization.

II. MINIMAL DIRAC LEFT-RIGHT SETUP

We consider the minimal left-right symmetric model with generalized parity $\mathcal{P}$ and doublet-driven LR breaking, in which neutrinos are purely Dirac. The gauge group is $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ with $g_L = g_R \equiv g$. The scalar sector contains a bidoublet $\Phi(2, 2, 0)$ generating fermion Dirac masses and LR-breaking doublets $\phi_{L,R}$; parity acts as $\Phi \leftrightarrow \Phi^\dagger$ and $\phi_L \leftrightarrow \phi_R$, implying Hermitian Yukawa couplings $Y_{1,2}^{(f)} = Y_{1,2}^{(f)\dagger}$ for $f = q, \ell$. We take the bidoublet vacuum expectation value (vev) $\langle \Phi \rangle = v \text{diag}(\cos \beta, \sin \beta e^{i\alpha})$. In the lepton sector, the Dirac mass matrices are

$$\begin{aligned} M_\nu &= v(Y_1^{(\ell)} \cos \beta + Y_2^{(\ell)} \sin \beta e^{-i\alpha}), \\ M_e &= v(Y_1^{(\ell)} \sin \beta e^{i\alpha} + Y_2^{(\ell)} \cos \beta), \end{aligned} \quad (1)$$

with $Y_{1,2}^{(\ell)}$ Hermitian by $\mathcal{P}$. The departure of these matrices from Hermiticity is governed by the single parity-breaking parameter

$$\epsilon \equiv \sin \alpha \tan 2\beta. \quad (2)$$

Equivalently, parity implies the coupled constraints

$$M_\nu - M_\nu^\dagger = i\epsilon(e^{i\alpha} \tan \beta M_\nu - M_e), \quad (3)$$

$$M_e - M_e^\dagger = i\epsilon(M_\nu - e^{-i\alpha} \tan \beta M_e), \quad (4)$$

which make explicit that flavor non-Hermiticity is controlled by the single parameter ϵ .

In the minimal bidoublet Dirac realization, achieving $m_\nu \ll m_e$ requires a nongeneric Yukawa and vev structure. Independently of how this hierarchy is arranged, we show that parity alone already implies predictive and previously unrecognized structure in the right-handed leptonic mixing matrix.

The Dirac mass matrices are diagonalized as $M_{\nu,e} = U_L^{(\nu,e)} m_{\nu,e} U_R^{(\nu,e)\dagger}$, with $m_{\nu,e}$ diagonal and positive. Parity then correlates the unitary rotations through the mismatch matrices $U_\nu \equiv U_L^{(\nu)\dagger} U_R^{(\nu)}$ and $U_e \equiv U_L^{(e)\dagger} U_R^{(e)}$, so that

$$V_L^{(\ell)} U_\nu = U_e V_R^{(\ell)}, \quad (5)$$

with observable leptonic mixings

$$V_L^{(\ell)} = U_L^{(e)\dagger} U_L^{(\nu)}, \quad V_R^{(\ell)} = U_R^{(e)\dagger} U_R^{(\nu)}, \quad (6)$$

where $V_L^{(\ell)}$ corresponds to the Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix. In the parity limit

$\epsilon = 0$, both mismatch matrices reduce to diagonal sign matrices, $U_e = S_e$ and $U_\nu = S_\nu$, yielding the aligned solution

$$V_R^{(\ell)} = S_e V_L^{(\ell)} S_\nu. \quad (7)$$

Here $S_e = \text{diag}(s_{e_i})$ and $S_\nu = \text{diag}(s_{\nu_i})$, with $s_{e_i} = \pm 1$ and $s_{\nu_i} = \pm 1$.

Away from the parity limit, for small but nonvanishing ϵ and in the leptonic hierarchy limit $m_\nu \ll m_e$, the charged-lepton rotation remains well approximated by its parity-limit form, $U_e = S_e$, while the neutrino rotation, U_ν , receives nontrivial ϵ -dependent corrections. In this regime, the LR consistency conditions reduce to a single nonlinear equation governing the neutrino sector. Defining $X \equiv U_\nu m_\nu$, one finds

$$X^2 = m_\nu^2 + i\epsilon H X, \quad (8)$$

where

$$H \equiv V_L^{(\ell)\dagger} \hat{m}_e V_L^{(\ell)}, \quad (9)$$

and $\hat{m}_e \equiv S_e m_e$ denotes the diagonal matrix of signed charged-lepton masses, $\hat{m}_{e_i} = s_{e_i} m_{e_i}$. A derivation of Eq. (8) from the full coupled system is given in the Appendix, following the parity-reconstruction strategy developed for the quark sector in Refs. [5,6].

Once Eq. (8) is solved, the neutrino rotation follows as $U_\nu = X m_\nu^{-1}$, and therefore

$$V_R^{(\ell)} = S_e V_L^{(\ell)} U_\nu, \quad (10)$$

so the RH leptonic mixing matrix is fully determined by $(m_\nu, m_e, V_L^{(\ell)}, \epsilon)$ up to discrete signs.

Unitarity of U_ν further implies $U_\nu m_\nu - m_\nu U_\nu^\dagger = i\epsilon H$, from which one obtains the analytic unitarity bound

$$|\epsilon| \leq \min_{i,j} \frac{m_{\nu_i} + m_{\nu_j}}{|H_{ij}|}. \quad (11)$$

This bound provides a conservative estimate of the physical domain; the exact boundary is determined numerically below. For the input used below, the minimum is controlled approximately by the (1,1) entry in the normal hierarchy (NH), with the (3,3) entry becoming relevant as the spectrum becomes compressed, and by the (3,3) entry in the inverted hierarchy (IH), giving the representative scalings

$$|\epsilon|_{\text{max}}^{\text{NH}} \sim (5-10) \frac{m_{\nu, \text{lightest}}}{m_\tau}, \quad |\epsilon|_{\text{max}}^{\text{IH}} \sim 5 \frac{m_{\nu, \text{lightest}}}{m_\tau}. \quad (12)$$

To understand the structure of the solutions within this domain, we now derive analytic approximations of Eq. (8).

III. ANALYTIC STRUCTURE

Small- ϵ regime. For $|\epsilon| \ll 1$ the master equation (8) admits a perturbative expansion (see also Ref. [5]). The series can be constructed recursively order by order; the explicit recursion relations are given in Appendix A. To first order the RH mixing matrix takes the form

$$(V_R^{(\ell)})_{ij} = s_{e_i} (V_L^{(\ell)})_{ik} \left[\delta_{kj} + i\epsilon \frac{H_{kj}}{\hat{m}_{\nu_k} + \hat{m}_{\nu_j}} \right] s_{\nu_j} + \mathcal{O}(\epsilon^2), \quad (13)$$

with $\hat{m}_{\nu_i} = s_{\nu_i} m_{\nu_i}$ and $s_{\nu_i} = \pm 1$.

The denominators $(\hat{m}_{\nu_i} + \hat{m}_{\nu_j})^{-1}$ can become enhanced for specific sign configurations. In particular, in mixed-sign branches the sum can effectively turn into a difference, and the (12) channel becomes the most sensitive one in practice. For $s_{\nu_1} = -s_{\nu_2}$ the leading solar-angle deviation, $\delta\theta_{12} \equiv \theta_{12}^R - \theta_{12}^L$ (with angles defined in the standard PDG parametrization), scales as

$$\delta\theta_{12} \simeq -\epsilon \frac{\Im H_{12}}{\hat{m}_{\nu_1} + \hat{m}_{\nu_2}}, \quad (14)$$

revealing the enhancement associated with small neutrino mass splittings.

The mixed-sign choice identifies the branches that can be enhanced, but it is the spectral compression of the corresponding neutrino pair that controls whether the enhancement becomes parametrically large.

Thus the solar angle is the most sensitive to parity breaking, while the remaining angles receive only sub-leading corrections.

Quasidegenerate regime. The small- ϵ expansion can cease to be reliable in the presence of near-degenerate neutrino masses, where mixed-sign denominators become small, even though the exact solution of Eq. (8) remains well defined. This motivates a complementary expansion tailored to the quasidegenerate regime. Expanding around a common neutrino mass scale $m_0 \simeq m_{\nu, \text{lightest}}$,

$$m_{\nu_i}^2 = m_0^2 + \Delta m_{\nu_i}^2, \quad \left| \frac{\Delta m_{\nu_i}^2}{m_0^2} \right| \ll 1, \quad (15)$$

the master equation can be solved perturbatively in $\Delta m_{\nu_i}^2/m_0^2$. The corresponding recursive construction is summarized in Appendix A. To leading order the RH mixing matrix reads

$$(V_R^{(\ell)})_{ij} = s_{e_i} \left[e^{i\phi_i} \delta_{ik} + \frac{(V_L^{(\ell)} \frac{\Delta m_{\nu_i}^2}{m_0^2} V_L^{(\ell)\dagger})_{ik}}{e^{-i\phi_i} + e^{i\phi_k}} \right] (V_L^{(\ell)})_{kj} - \frac{1}{2} s_{e_i} e^{i\phi_i} \left(V_L^{(\ell)} \frac{\Delta m_{\nu_i}^2}{m_0^2} \right)_{ij} + \mathcal{O}\left(\frac{\Delta m_{\nu_i}^4}{m_0^4}\right). \quad (16)$$

The phases are

$$e^{i\phi_i} = s_{\nu_i} \sqrt{1 - \epsilon^2 \frac{\hat{m}_{e_i}^2}{4m_0^2}} + i\epsilon \frac{\hat{m}_{e_i}}{2m_0}, \quad s_{\nu_i} = \pm 1. \quad (17)$$

This expression makes the quasidegenerate physical domain transparent: the phases remain on the unit circle only for

$$|\epsilon| \leq \min_i \frac{2m_0}{|\hat{m}_{e_i}|} = \frac{2m_0}{m_\tau}. \quad (18)$$

In the quasidegenerate regime, the analytic upper range of ϵ is therefore set simply by the common neutrino mass scale and the largest charged-lepton mass, giving the same estimate for NH and IH.

In contrast with the small- ϵ regime, the dependence on ϵ is now effectively resummed into the phases ϕ_i . In the limit $\Delta m_{\nu_i}^2 \rightarrow 0$, $V_R^{(\ell)}$ differs from $V_L^{(\ell)}$ only by diagonal phases, while the first RH-LH mixing deviations arise from the off-diagonal correction proportional to $V_L^{(\ell)} \Delta m_{\nu_i}^2 V_L^{(\ell)\dagger}$. For mixed-sign configurations the denominator $e^{-i\phi_i} + e^{i\phi_k}$ can become small due to phase antialignment, leading to enhanced RH-LH misalignment.

Focusing on the enhanced branch $s_{\nu_1} = -s_{\nu_2}$, the leading solar-angle deviation extracted from Eq. (16) behaves as

$$\delta\theta_{12} \simeq 2s_{\nu_1} \frac{c_{23}^L}{c_{13}^L} \frac{\Im[(V_L^{(\ell)} \Delta m_{\nu_i}^2 V_L^{(\ell)\dagger})_{12}]}{\epsilon m_0 (\hat{m}_\mu - \hat{m}_e)}. \quad (19)$$

The hatted charged-lepton masses keep the S_e -branch dependence explicit.

Equation (19) gives the corresponding quasi-degenerate expression for the enhanced mixed-sign neutrino branch. The apparent $1/\epsilon$ behavior should not be interpreted as a physical singularity: as $\epsilon \rightarrow 0$ the quasidegenerate expansion leaves its domain of validity and the perturbative small- ϵ expansion must be used instead.

Together the small- ϵ and quasidegenerate limits describe complementary asymptotic regions of the enhanced branch structure, while the intermediate nonlinear regime is determined numerically.

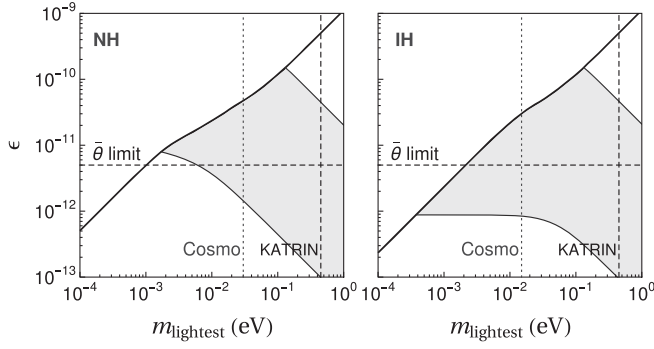


FIG. 1. Structure of the $(m_{\nu, \text{lightest}}, \epsilon)$ plane in the minimal Dirac LR model for normal (NH, left) and inverted (IH, right) hierarchies. The solid black curve shows the maximal $|\epsilon|$ for which Eq. (8) admits physical solutions. The curves mark the loci where mixed-sign neutrino branches reach $|\theta_{12}^R - \theta_{12}^L| = 8^\circ$. The shaded band shows the corresponding enhancement region obtained by taking the union over these mixed-sign branches, where localized RH-LH leptonic mixing misalignment can become sizable. Vertical lines indicate the KATRIN and cosmological bounds on the lightest neutrino mass, while the horizontal line shows the value of ϵ implied by the neutron-EDM constraint $|\bar{\theta}| \lesssim 10^{-10}$. Only $\epsilon > 0$ is shown, since the full branch set is symmetric under $\epsilon \rightarrow -\epsilon$ once all charged-lepton sign choices are included.

IV. PARAMETER SPACE AND BRANCH STRUCTURE

We map the physical domain of the model in the $(m_{\nu, \text{lightest}}, \epsilon)$ plane by determining numerically the maximal value of ϵ for which Eq. (8) admits physical solutions. In constructing the physical domain and the branch scans, we retain only solutions for which $U_\nu = X m_\nu^{-1}$ is unitary and satisfies the original parity constraints. The resulting boundary closely follows the conservative estimate of Eq. (11) and is shown in Fig. 1. For the numerical analysis we use the current global-fit values of the neutrino oscillation parameters from Ref. [16].

Within the allowed domain, the phenomenologically relevant structure is set by the onset of sizable RH-LH misalignment in the leptonic mixing angles. As a direct and basis-independent diagnostic, we identify the locus where

$$|\theta_{12}^R - \theta_{12}^L| = 8^\circ. \quad (20)$$

The numerical value is not a sharp physical threshold, but a representative choice: it corresponds to a visibly non-aligned RH leptonic mixing pattern, well separated from the typical quarklike near alignment outside the enhancement region, while still low enough to trace the onset of the mixed-sign band in both hierarchies.

For three generations the sign matrices S_e and S_ν formally give $2^3 \times 2^3 = 64$ assignments. The simultaneous overall sign flip of both matrices is redundant, leaving 32

distinct $V_R^{(\epsilon)}$ branches. The sign of ϵ is likewise redundant once the full charged-lepton sign set is included, so we show only $\epsilon > 0$ in Fig. 1.

The 8° onset curves are obtained from the analytic solutions described above. In the small- ϵ regime we use the perturbative solution of Eq. (13), while in the quasidegenerate regime we employ Eq. (16). The two analytic expansions reproduce the numerical solution in their respective domains of validity and provide a useful description of the boundaries of the enhancement region.

The resulting band, shown in Fig. 1, originates from mixed-sign configurations in which the analytic denominators become small. In the small- ϵ regime the enhancement is governed by the neutrino combination $(\hat{m}_{\nu_i} + \hat{m}_{\nu_j})^{-1}$, whereas in the quasidegenerate regime the same branch sensitivity is encoded in the possible phase antialignment of $e^{-i\phi_i} + e^{i\phi_j}$.

The band is obtained by taking the union over mixed-sign neutrino branches associated with the relevant enhanced pair. The all-equal S_ν branches remain smooth and perturbatively aligned and therefore do not contribute to this enhancement region. The selected branches correspond to genuine continuations of the parity-limit sign choices.

Outside this band the RH and LH leptonic mixings remain closely aligned across all branches. Inside it, however, the mixed-sign neutrino branches can develop localized but sizable deviations.

The hierarchy of RH-LH angle deviations is strongly nonuniform, with the dominant effect appearing in the solar angle. This behavior can be understood analytically in the two complementary regimes. In the small- ϵ regime, the enhanced correction is confined to the (12) sector and feeds $\delta\theta_{12}$ already at first order, while the remaining angles are only reached at higher order. In the quasidegenerate regime, all three angles receive leading corrections, but $\delta\theta_{12}$ still dominates because its numerator receives a contribution from the atmospheric mass splitting, whereas the corrections to θ_{13} and θ_{23} are mainly controlled by the solar scale. Thus the dominance of the solar angle reflects a robust structural property of the mixed-sign (12) branches rather than an accidental feature of a particular approximation.

An estimate shows that an enhancement in channel (i, j) becomes visible only when $|\epsilon|$ exceeds a characteristic scale of order $|m_i - m_j|/|H_{ij}|$. The appearance of the effect depends not only on the mass splittings but also on the mixing structure encoded in H_{ij} . In particular, strongly hierarchical spectra or small off-diagonal mixings can push the onset scale beyond the physically allowed ϵ range.

The global structure of the parameter space can then be understood from the competition between the onset scale and the maximal allowed value of ϵ . At low $m_{\nu, \text{lightest}}$, the physical ϵ range is small and the relevant neutrino pair may not be sufficiently compressed, so the onset can lie outside the allowed domain. As the spectrum becomes more

compressed, the onset scale decreases and the enhancement can enter the physical region. This explains why compressed spectra can display sizable RH-LH misalignment, and why in IH the effect persists farther into the low-lightest-mass region, since the relevant (1, 2) pair is already compressed. For larger $m_{\nu, \text{lightest}}$, the quasidegenerate expression (19) describes the large-mass side of the band. The fixed-angle contour continues toward smaller ϵ , while in the exact degenerate limit the off-diagonal misalignment vanishes.

This demonstrates that RH leptonic mixing in the minimal Dirac LR model exhibits a highly structured pattern: significant misalignment arises only in localized regions controlled by the interplay of parity breaking and spectral near degeneracies, whereas the bulk of parameter space remains perturbatively stable.

To visualize this structure along a fixed slice of the parameter space, we examine the behavior of the RH mixing angles as functions of ϵ . We extract the angles using the same global-fit values of the neutrino oscillation parameters. Since the diagonal external phases are fixed by the master equation, the resulting angles are unambiguously defined.

Figure 2 shows the branch structure of the solar-angle deviation for both NH and IH at $m_{\nu, \text{lightest}} = 0.01$ eV. The gray curves correspond to the discrete sign branches, while the black envelope indicates the extremal RH-LH deviation at fixed ϵ . The localized peak reflects the mixed-sign enhancement already identified in the analytic treatment and in the parameter-space map of Fig. 1.

The behavior differs qualitatively between the two hierarchies. In the IH case, the enhancement lies entirely within the physically allowed range of ϵ . In contrast, for NH it occurs at larger values of ϵ , so that the $\bar{\theta}$ constraint intersects the enhancement region before it fully develops. As a result, both hierarchies reach comparable maximal deviations, but the NH profile is effectively truncated by the $\bar{\theta}$ bound, while the IH case exhibits the full enhancement structure.

For the benchmark shown in Fig. 2, fixing the charged-lepton sign choice leaves four distinct mixed-sign branches in the (12)-enhanced sector. Their spread opens up only after the peak, illustrating that the RH-LH misalignment is not only localized in ϵ but also branch dependent.

V. PHENOMENOLOGICAL CONSTRAINTS

Direct neutrino-mass limits. Direct kinematic measurements of tritium β decay constrain the effective neutrino mass. The current KATRIN bound $m_\beta < 0.45$ eV (90% C.L.) [17] implies $m_{\nu, \text{lightest}} < 0.45$ eV, shown in Fig. 1.

Cosmological limits. Cosmological analyses constrain the neutrino mass sum at the $\mathcal{O}(0.1$ eV) level, e.g., $\Sigma \lesssim 0.12$ eV from CMB+baryon acoustic oscillation (BAO) data [18]. This translates into a corresponding bound on

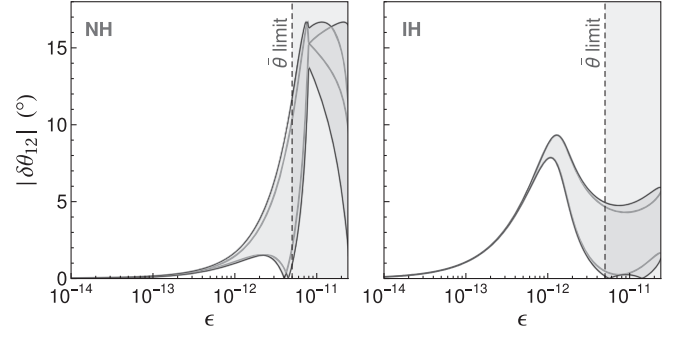


FIG. 2. Representative branch behavior of the solar-angle deviation $|\theta_{12}^R - \theta_{12}^L|$ as a function of positive $\epsilon = \sin \alpha \tan 2\beta$ for normal (NH, left) and inverted (IH, right) hierarchies at fixed $m_{\nu, \text{lightest}} = 0.01$ eV. Gray curves show the four mixed-sign branches in the (12)-enhanced sector ($s_{\nu_1} = -s_{\nu_2}$), with fixed charged-lepton signs $S_e = \text{diag}(+, +, -)$, while the black envelope indicates the extremal RH-LH deviation at fixed ϵ within this set of branches. The vertical dashed line marks the value of ϵ implied by the neutron-EDM constraint $|\bar{\theta}| \lesssim 10^{-10}$, and the shaded region lies beyond the corresponding bound.

$m_{\nu, \text{lightest}}$, shown in Fig. 1. As it depends on cosmological assumptions, we show it for reference.

Implications for strong CP. In left-right theories with generalized parity, the strong CP phase $\bar{\theta}$ vanishes in the parity-symmetric limit and becomes calculable after spontaneous parity breaking [19–22]. At leading order one finds

$$\bar{\theta} \simeq \epsilon \frac{m_t}{2m_b}, \quad (21)$$

up to subleading corrections [20,21]. The neutron electric dipole moment constrains $|\bar{\theta}| \lesssim 10^{-10}$ [23,24]. The resulting bound on ϵ is indicated in Fig. 1 and in Fig. 2.

In the present Dirac-neutrino framework ϵ is not free but is bounded by the requirement that Eq. (8) admit physical solutions

$$|\epsilon| \lesssim \epsilon_{\text{max}}(m_{\nu, \text{lightest}}) \sim \mathcal{O}\left(\frac{m_\nu}{m_\ell}\right). \quad (22)$$

Thus the leptonic consistency conditions directly translate into a strong suppression of the induced strong- CP phase $\bar{\theta}$, whose maximal size is controlled by the lightest neutrino mass.

This does not constitute a dynamical solution of the strong CP problem, since the smallness of ϵ is not symmetry protected. Nevertheless, the Dirac doublet framework exhibits a structural correlation absent in the triplet (Majorana) realization: the parameter controlling RH leptonic mixing simultaneously suppresses $\bar{\theta}$, allowing sizable leptonic misalignment within the enhancement region while keeping the strong CP phase small.

The situation differs in the triplet (Majorana) realization, where the strong- CP phase can receive additional radiative contributions, leading to further constraints on the leptonic Yukawa sector and on the heavy-neutrino scale [25–27].

Collider implications. The leptonic mixing effects discussed above are challenging to probe directly. If W_R and the light RH neutrinos were produced, the charged-current decay $W_R \rightarrow \ell_R \nu_R$ would contain the matrix elements $(V_R^{(\ell)})_{\ell i}$. However, in the purely Dirac realization the RH neutrinos are effectively massless at collider scales and appear only as missing energy. For an inclusive measurement at fixed charged-lepton flavor one therefore sums over the unobserved neutrino species,

$$\sum_i |(V_R^{(\ell)})_{\ell i}|^2 = 1, \quad (23)$$

so the mixing angles themselves are not resolved. The enhancement band found above should therefore be viewed primarily as a structural prediction of the parity-constrained Dirac leptonic Yukawa sector, rather than as an immediately accessible collider observable.

Nevertheless, the gauge sector offers a clean collider discriminator of the left-right symmetry-breaking pattern. In left-right theories the ratio of heavy neutral and charged gauge-boson masses depends on the scalar representation responsible for breaking $SU(2)_R \times U(1)_{B-L}$. The quoted numerical ratios assume the parity-symmetric LR limit $g_R = g_L$, with g_{B-L} fixed by the standard hypercharge matching, $g_Y^2 = g_R^2 + g_{B-L}^2$. With this convention, the minimal triplet realization gives $M_{Z_R}/M_{W_R} \simeq 1.7$, while doublet breaking gives the smaller ratio $M_{Z_R}/M_{W_R} \simeq 1.2$. This standard representation dependence of the heavy gauge-boson spectrum is used, for example, in Ref. [28].

A measurement of the heavy gauge-boson spectrum would therefore directly probe the nature of left-right symmetry breaking: a ratio near the triplet prediction would favor the Majorana realization, while a value close to the doublet prediction would point toward the Dirac scenario studied here.

Current LHC searches constrain heavy RH gauge bosons to the multi-TeV range through charged-lepton plus missing-energy and dilepton resonance searches [29,30]. Representative bounds are $M_{W_R} \gtrsim 5\text{TeV}$ and $M_{Z_R} \gtrsim 4\text{TeV}$. Dijet searches provide complementary constraints on W_R at the few-TeV level [31]. Collider implications and constraints on the gauge and scalar sectors in the doublet left-right framework have been studied in Refs. [28,32,33].

The situation is different in the conventional triplet (Majorana) realization, where heavy RH neutrinos can make the flavor structure of RH currents accessible through lepton-number- and lepton-flavor-violating channels, including the Keung-Senjanović (KS) same-sign dilepton process [34] and its use in probing RH lepton mixing at the LHC [35,36].

The collider phenomenology of the KS channel across the heavy-neutrino mass range, including prompt, displaced, and invisible regimes, has been studied in Ref. [37]. Recent full-Run-2 ATLAS and CMS searches constrain the corresponding heavy-neutrino realization at the multi-TeV scale, with limits on m_{W_R} reaching about 5–6.4 TeV depending on the heavy-neutrino mass and decay channel [38,39]. Scalar-mediated variants involving the triplet sector provide additional lepton-number-violating (LNV) probes [40], while related collider probes of the neutrino Dirac mass matrix have been discussed in trilepton channels [41].

VI. CONCLUSIONS

Right-handed leptonic mixing in the minimal Dirac left-right model exhibits a branch-dependent enhancement band arising from the near-singular structure of the LR consistency equation.

Two complementary perturbative regimes control the behavior of the solutions. For generic spectra and small parity breaking, an expansion in ϵ applies and the leading effects arise from denominators $(\hat{m}_{\nu_i} + \hat{m}_{\nu_j})^{-1}$, producing localized enhancements driven by neutrino mass splittings. In the quasidegenerate regime the appropriate expansion is instead organized around a common neutrino mass scale, where the dependence on ϵ is effectively resummed into phase factors and the enhancement is controlled by phase antialignment. Together these regimes provide a unified analytic understanding of the enhancement band across the $(m_{\text{lightest}}, \epsilon)$ plane.

A characteristic nonlinear pattern emerges: specific sign branches develop localized RH-LH mixing enhancements while the bulk of parameter space remains perturbatively aligned. This behavior reflects the spectral instability of nearly degenerate systems: small perturbations can induce large rotations when eigenvalues approach each other.

The resulting hierarchy of RH-LH angle deviations is strongly nonuniform, with the dominant effect appearing in the solar-angle deviation, making θ_{12} the most sensitive probe of this scenario, whereas θ_{13} and θ_{23} receive only subleading corrections.

An important structural feature of the Dirac realization is that the same parameter ϵ controlling leptonic misalignment also induces the strong CP phase. The leptonic consistency bound on ϵ therefore suppresses $\bar{\theta}$, bringing it close to the current experimental limit. At the same time, the gauge sector provides a collider discriminator: doublet breaking predicts a characteristic heavy gauge boson mass ratio $M_{Z_R}/M_{W_R} \approx 1.2$, distinct from the triplet (Majorana) expectation.

The minimal doublet left-right model thus exhibits a tightly correlated structure linking parity breaking, neutrino spectra, leptonic mixing, and strong CP . It therefore provides a predictive Dirac benchmark against which more

elaborate left-right constructions can be systematically compared.

Future experimental probes of right-handed currents and neutrino properties may therefore provide a direct window into this structure.

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DATA AVAILABILITY

The numerical inputs used in this work for the neutrino oscillation parameters and the direct and cosmological neutrino-mass bounds are taken from Refs. [16–18]. No additional research data or software are publicly available.

APPENDIX: DERIVATION OF THE LEPTONIC MASTER EQUATION AND ANALYTIC RECURSIONS

In this appendix we derive the leptonic master equation and summarize the recursive constructions underlying the two analytic expansions. For completeness, we briefly repeat the relevant definitions and notation.

The starting point and perturbative strategy follow the parity-reconstruction method developed previously for the quark sector [5,6], while the reduction to the Dirac leptonic hierarchy, the resulting equation for $X \equiv U_\nu m_\nu$, and the quasidegenerate expansion are specific to the present analysis.

1. From parity constraints to the coupled system

Starting from the parity constraints in the lepton sector,

$$M_\nu - M_\nu^\dagger = i\epsilon(e^{i\alpha} \tan \beta M_\nu - M_e), \quad (\text{A1})$$

$$M_e - M_e^\dagger = i\epsilon(M_\nu - e^{-i\alpha} \tan \beta M_e), \quad (\text{A2})$$

we diagonalize the Dirac mass matrices as

$$M_\nu = U_L^{(\nu)} m_\nu U_R^{(\nu)\dagger}, \quad M_e = U_L^{(e)} m_e U_R^{(e)\dagger}, \quad (\text{A3})$$

with m_ν and m_e diagonal and positive. As in the main text, we define the mismatch matrices

$$U_\nu \equiv U_L^{(\nu)\dagger} U_R^{(\nu)}, \quad U_e \equiv U_L^{(e)\dagger} U_R^{(e)}, \quad (\text{A4})$$

and the observable leptonic mixings

$$V_L^{(\ell)} = U_L^{(e)\dagger} U_L^{(\nu)}, \quad V_R^{(\ell)} = U_R^{(e)\dagger} U_R^{(\nu)}. \quad (\text{A5})$$

These satisfy

$$V_L^{(\ell)} U_\nu = U_e V_R^{(\ell)}. \quad (\text{A6})$$

It is convenient to introduce

$$X_\nu \equiv U_\nu m_\nu, \quad X_e \equiv U_e m_e. \quad (\text{A7})$$

Using Eq. (A6) to eliminate $V_R^{(\ell)}$ from Eqs. (A1)–(A2), we obtain the coupled system

$$X_\nu^2 = m_\nu^2 - i\epsilon(\tan \beta e^{i\alpha} m_\nu^2 - V_L^{(\ell)\dagger} X_e^\dagger V_L^{(\ell)} X_\nu), \quad (\text{A8})$$

$$X_e^2 = m_e^2 + i\epsilon(\tan \beta e^{-i\alpha} m_e^2 - V_L^{(\ell)} X_\nu^\dagger V_L^{(\ell)\dagger} X_e). \quad (\text{A9})$$

This form is exact and encodes the full leptonic parity constraints.

2. Leptonic hierarchy limit and master equation

In the leptonic hierarchy regime $m_\nu \ll m_e$, the coupled system simplifies substantially. Keeping the nontrivial nonlinear structure intact, one may consistently neglect the purely diagonal $\mathcal{O}(\epsilon)$ terms proportional to $\tan \beta e^{\pm i\alpha}$ in the rhs of Eqs. (A8) and (A9), as well as the $\mathcal{O}(\epsilon m_\nu/m_e)$ off-diagonal correction to X_e . For the latter, even using the electron mass gives

$$\frac{m_\nu}{m_e} \lesssim \frac{0.1 \text{ eV}}{0.511 \text{ MeV}} \simeq 2 \times 10^{-7}. \quad (\text{A10})$$

Since this correction is also proportional to ϵ , it is safely subpercent throughout the ϵ range of interest. These terms only induce tiny diagonal rephasings and doubly suppressed off-diagonal corrections, and do not affect the determination of $V_R^{(\ell)}$ at the level of interest, and neither can they spoil the enhancement band discussed in the main text.

To this accuracy one finds

$$X_e = S_e m_e \equiv \hat{m}_e, \quad (\text{A11})$$

where S_e is a diagonal sign matrix and $\hat{m}_e$ the corresponding signed charged-lepton mass matrix.

Substituting into Eq. (A8), one obtains

$$X_\nu^2 = m_\nu^2 + i\epsilon V_L^{(\ell)\dagger} \hat{m}_e V_L^{(\ell)} X_\nu. \quad (\text{A12})$$

Defining

$$H \equiv V_L^{(\ell)\dagger} \hat{m}_e V_L^{(\ell)}, \quad (\text{A13})$$

and identifying $X_\nu \equiv X$, this yields the master equation quoted in the main text,

$$X^2 = m_\nu^2 + i\epsilon H X. \quad (\text{A14})$$

Once Eq. (A14) is solved, the neutrino mismatch matrix follows from

$$U_\nu = X m_\nu^{-1}, \quad (\text{A15})$$

and the RH leptonic mixing matrix is then

$$V_R^{(\ell)} = S_e V_L^{(\ell)} U_\nu. \quad (\text{A16})$$

3. Recursive expansion for small ϵ

For $|\epsilon| \ll 1$, the master equation (A14) can be solved perturbatively by expanding

$$X = \sum_{n=0}^{\infty} (i\epsilon)^n X^{(n)}, \quad X^{(0)} = S_\nu m_\nu \equiv \hat{m}_\nu, \quad (\text{A17})$$

with S_ν a diagonal sign matrix and $\hat{m}_\nu$ the corresponding signed neutrino mass matrix. Substituting into Eq. (A14) gives the recursion relation

$$X_{ij}^{(n)} = \frac{(HX^{(n-1)})_{ij} - \sum_{k=1}^{n-1} (X^{(k)} X^{(n-k)})_{ij}}{\hat{m}_{\nu_i} + \hat{m}_{\nu_j}}, \quad n \geq 1. \quad (\text{A18})$$

The RH leptonic mixing matrix then follows from Eq. (A15) and Eq. (A16).

At first order one recovers Eq. (13), used in the main text. The recursion relation (A18) makes explicit that denominators of the form $(\hat{m}_{\nu_i} + \hat{m}_{\nu_j})^{-1}$ appear at each order, providing the origin of the branch-dependent enhancement discussed in the main text.

4. Recursive expansion in the quasidegenerate regime

In the quasidegenerate regime we write

$$m_{\nu_i}^2 = m_0^2 + \Delta m_{\nu_i}^2, \quad \Delta_i \equiv \frac{\Delta m_{\nu_i}^2}{m_0^2}, \quad |\Delta_i| \ll 1, \quad (\text{A19})$$

so that

$$m_\nu^2 = m_0^2(\mathbf{1} + \Delta), \quad \Delta = \text{diag}(\Delta_1, \Delta_2, \Delta_3). \quad (\text{A20})$$

It is convenient to parametrize

$$X = m_0 V_L^{(\ell)\dagger} (Y^{(0)} + Y^{(1)} + \dots) V_L^{(\ell)}, \quad Y^{(n)} = \mathcal{O}(\Delta^n). \quad (\text{A21})$$

Substituting into Eq. (A14) and solving order by order in Δ gives, at zeroth order,

$$Y_{ij}^{(0)} = e^{i\phi_i} \delta_{ij}, \quad e^{i\phi_i} = s_{\nu_i} \sqrt{1 - \epsilon^2 \frac{\hat{m}_{e_i}^2}{4m_0^2}} + i\epsilon \frac{\hat{m}_{e_i}}{2m_0}, \quad (\text{A22})$$

where the discrete signs $s_{\nu_i} = \pm 1$ label the solution branches.

At first order one finds

$$Y_{ij}^{(1)} = \frac{(V_L^{(\ell)} \Delta V_L^{(\ell)\dagger})_{ij}}{e^{-i\phi_i} + e^{i\phi_j}}, \quad (\text{A23})$$

while higher orders satisfy, for $n \geq 2$,

$$Y_{ij}^{(n)} = - \frac{\sum_{k=1}^{n-1} (Y^{(k)} Y^{(n-k)})_{ij}}{e^{-i\phi_i} + e^{i\phi_j}}. \quad (\text{A24})$$

Using Eqs. (A21), (A15), and (A16) one then obtains the quasidegenerate expansion for the RH leptonic mixing matrix quoted in the main text. To first order in $\Delta m_\nu^2/m_0^2$ this gives Eq. (16).

The two expansions are complementary: the small- ϵ series provides analytic control at weak parity breaking for generic spectra, while the quasi-degenerate expansion captures the regime where neutrino mass splittings are the perturbative quantities and the ϵ dependence is effectively resummed into the phases (A22).

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