Snowmass2021 - Letter of Interest

Testing quasi-Dirac leptogenesis through neutrino oscillations

NF Topical Groups:

■ (NF1) Neutrino oscillations
■ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
☐ (NF4) Neutrinos from natural sources
☐ (NF5) Neutrino properties
☐ (NF6) Neutrino cross sections
☐ (NF7) Applications
■ (TF11) Theory of neutrino physics
☐ (NF9) Artificial neutrino sources
☐ (NF10) Neutrino detectors
☐ (Other)

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Abstract: The lightness of the Standard Model (SM) neutrinos could be understood if their masses were to be generated by new physics at a high scale, through the so-called seesaw mechanism involving heavy fermion singlets. If new physics violates baryon minus lepton number by only a small amount, the heavy fermion singlets as well as the SM neutrinos split into pairs of quasi-Dirac states. At the scale of the fermion singlets, this quasi-Diracness allows to enhance CP violation in their decays and the cosmic matter-antimatter asymmetry can be successfully generated through resonant leptogenesis. At lower scale, this quasi-Diracness results in small SM neutrino mass splitting which can be probed in oscillation experiments. Remarkably, the parameter space for viable leptogenesis spans over the regime relevant for solar and atmospheric neutrino oscillations.

Main: The nature of the Standard Model (SM) neutrinos ν_L, whether Dirac or Majorana is still an open question. In the former case, baryon number minus lepton number $B-L$ remains an exact global symmetry while in the latter case, it has to be broken.

If neutrinos are Majorana particles with mass term $m_\nu \bar{\nu}_L \nu_L^c$, no new light degrees of freedom beyond the SM are required, and their lightness can be elegantly explained by the seesaw mechanism through the unique dimension-5 Weinberg operator[1]. Once the SM Higgs doublet acquires a vacuum expectation value (vev) $v = 174$ GeV, one obtains $m_\nu = cv^2/\Lambda$, where c is some dimensionless coefficient and $\Lambda \gg v$ is the $B-L$-violating scale.

If neutrinos are Dirac particles, one will need to introduce new light degrees of freedom ν_R's (right-handed neutrinos) to couple to ν_L through $m_\nu \bar{\nu}_L \nu_R$. This Dirac mass term (protected by a $B-L$ symmetry) can arise at renormalizable level with $m_\nu = y_\nu v$ and the neutrinos' lightness is accommodated through a very tiny Yukawa coupling $y_\nu \sim 10^{-12}$. Another interesting possibility is to have the neutrino Dirac mass suppressed by heavy $B-L$-conserving new physics scale Λ through the Dirac seesaw mechanism. To realize this scenario some additional symmetry is needed to forbid the renormalizable mass term. For instance, in mirror world models[2–4] and Twin Higgs models[5], where the SM field content as well as gauge symmetry are duplicated, the new gauge symmetry forbids the renormalizable Dirac mass and the Dirac seesaw mechanism can be implemented. In this case, one has $m_\nu = cvf/\Lambda$ where ν_R's reside in the mirror lepton doublets and f is the vev of the mirror scalar doublet.

The existence of new physics at a scale Λ has important implications for the generation of a baryon asymmetry through leptogenesis[6;7]. In ref.[8], it is shown that successful leptogenesis can be achieved in the mirror Dirac seesaw model[8;9] down to 10^7 GeV, a scale still too high for experimental verification. In this proposal we want to explore the *quasi-Dirac* scenario[10] by introducing small $B-L$-violating terms to the model of[8;9], as shown in [11]. As a consequence, light neutrinos split into quasi-Dirac (active-sterile) pairs[1] where the mass squared splitting in the range $10^{-12} - 10^{-5}\,\mathrm{eV}^2$ can be constrained by neutrino oscillation experiments[17–20]. At the same time, the heavy singlet fermions also split into quasi-Dirac pairs and CP violation in their decays can *naturally* be enhanced to realize *resonant* leptogenesis[21–23] around the weak scale as long as sufficient asymmetry is generated before electroweak (EW) sphaleron interactions become ineffective at $T \sim 132$ GeV as in the SM[24].[2] The main result of [11]is summarized by the following equation

$$|\epsilon^{\max}| \simeq \frac{\delta m}{2m_\nu}, \tag{1}$$

where $|\epsilon^{\max}|$ quantifies the maximal CP violation for leptogenesis while δm is the small mass splitting of light neutrinos of mass scale m_ν. Since successful leptogenesis put a lower bound on $|\epsilon^{\max}|$ while neutrino oscillation experiments can put an upper bound on δm, this represents a rare testable leptogenesis model which is directly linked to low energy observable in neutrino oscillation phenomena. If this small splitting is observed experimentally, we can infer that neutrinos are indeed Majorana particles and identify the parameter space which leads to successful leptogenesis.

As a benchmark scenario, we consider the neutrino Yukawa couplings to be the same for the SM and the mirror sector (Z_2 symmetric) and also equal decay branching ratios for the quasi-Dirac singlets to leptons of different flavors. Figure 1 shows the regime where sufficient baryon asymmetry is generated in the plane of m_ν and $\delta m/(2m_\nu)$. As references, the two dotted vertical black lines indicate the solar $m_{\rm sol} = 8.6$ meV and atmospheric $m_{\rm atm} = 50$ meV mass scales. The gray, blue and light blue solid lines represent

[1] In [12;13] instead the authors consider active-active pairs of quasi-Dirac neutrinos, which have been ruled out by neutrino oscillation experiments[14–16].

[2] Leptogenesis where light neutrinos are also quasi-Dirac has been considered in ref.[25]. However, in this work, $B-L$ is broken by a large Majorana mass term and the connection with low energy phenomena is lost.

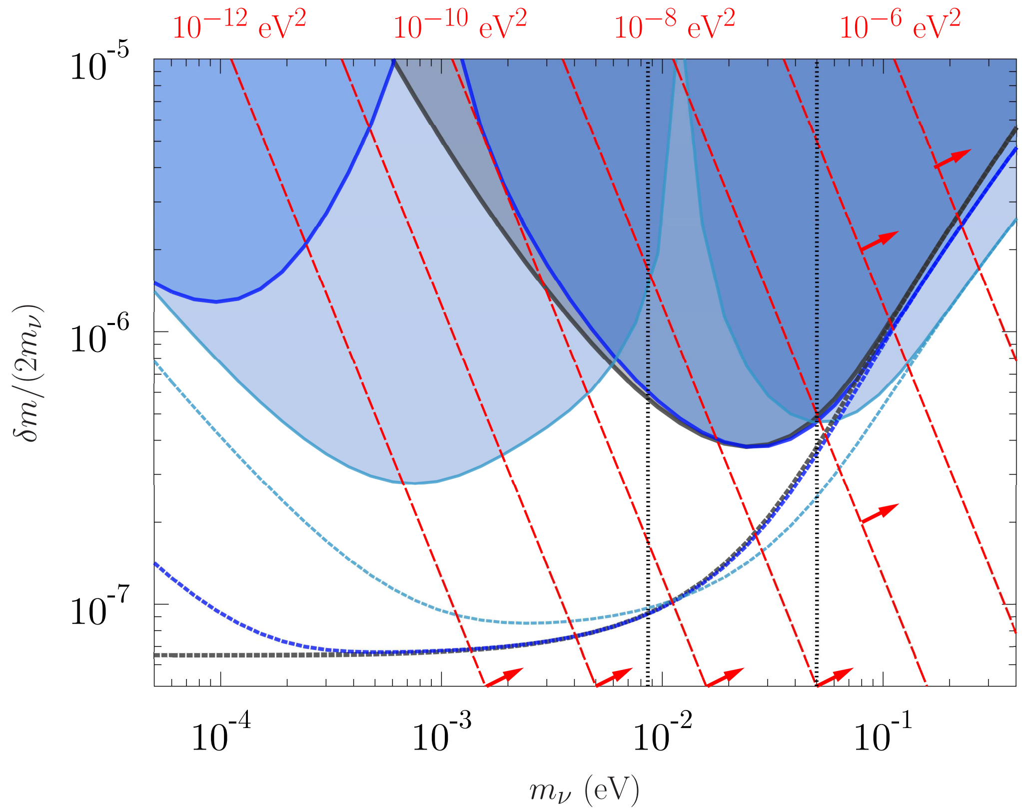

Figure 1: Regions in the m_ν vs $\delta m/(2m_\nu)$ plane where sufficient baryon asymmetry is generated for $M \gg 1\,\text{TeV}$ (gray), $M = 1\,\text{TeV}$ (blue) and $M = 1\,\text{TeV}$ (light blue) for zero (solid) and thermal (short dashed) initial N_i abundance. Long dashed red lines indicate parameter space which can be constrained in neutrino oscillation experiments (see text for details).

the parameter space where the observed baryon asymmetry is obtained for different mass of quasi-Dirac singlets: $M \gg 1$ TeV, $M = 1$ TeV and $M = 500$ GeV respectively, with zero initial N_i abundance. Within the shaded areas, the baryon asymmetry is above the observed value. For the case of $M = 1$ TeV and $M = 500$ GeV, the parameter space is separated into two islands due to sign change in the final baryon symmetry towards small m_ν as not all N_i can decay before the EW sphaleron processes freeze out. The short dashed lines with the same color coding are for thermal initial N_i abundance where above the lines, the baryon asymmetry is above the observed value. The red dashed lines indicate the mass squared difference of quasi-Dirac light neutrinos $\varepsilon^2 \equiv 4m_\nu\delta m$ which can be probed by neutrino oscillation experiments ranging from $10^{-12}\,\text{eV}^2$ to $10^{-6}\,\text{eV}^2$. The arrows represent the parameter space which can potentially be excluded in neutrino oscillation experiments. Solar neutrino experiment are not sensitive to values of $\varepsilon^2 \lesssim 10^{-12}\,\text{eV}^2$, but this could by probed by measuring the flavor content of high-energy astrophysical neutrinos[26–29]. The neutrino oscillation constraints on ε depend on which light neutrino mass eigenstate m_k ($k = 1, 2, 3$) is split (denoting the splitting by ε_k^2). In ref.[19], a two-parameter fit was performed (turning on one ε_k^2 and another new mixing angle at a time), leading to constraints in the range $\varepsilon_k^2 \lesssim 10^{-12} - 10^{-5}\,\text{eV}^2$ for $k = 1, 2$. Larger values of ε_k^2 are also allowed for fine-tuned values of the mixing angle. For $k = 3$, the bound is in general much weaker: $\varepsilon_3^2 \lesssim 10^{-5}\,\text{eV}^2$. As we can see in Figure 1, the parameter space that is being probed by solar and atmospheric neutrino oscillation overlaps with the one where leptogenesis is viable.

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