Snowmass Letter of Interest:
Testable neutrino mass models

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The observation of nonzero neutrino masses provides a compelling evidence for physics beyond the Standard Model. In this letter, we explore the phenomenology of low-scale neutrino mass models and their implications for future experiments, as well as for other outstanding puzzles, such as dark matter and baryogenesis.

Thematic Areas: (NF08/TF11) Theory of neutrino physics, (NF03) BSM, (TF08) BSM model building
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I. MOTIVATION

The observation of neutrino oscillations has established that neutrinos have nonzero masses. This provides compelling experimental evidence for the existence of new physics beyond the Standard Model (SM), and therefore, a precise understanding of the neutrino mass mechanism is an important step in unveiling the fundamental theory of nature. To successfully generate neutrino masses new particles need to be added to the SM (for a review, see e.g. Ref. [1]). In many popular neutrino mass generation mechanisms, for example the type I seesaw [2–8] where right-handed Majorana neutrinos are introduced to the SM, the smallness of neutrino masses is explained via a suppression with respect to the electroweak scale by a large Majorana mass scale. In the canonical seesaw, due to the large mass of the sterile neutrinos they are not kinematically accessible at laboratory experiments. Even if the seesaw scale was naively lowered, the active-sterile mixing angle is typically suppressed by the same ratio which suppresses the light neutrino masses, and therefore, it does not leave any observable imprint in experiments. As nonvanishing neutrino mass is so far the only laboratory evidence for new physics beyond the SM, probing the neutrino mass mechanism and the new particles associated with it is of utmost importance making it crucial to develop experimentally testable neutrino mass models.

II. LOW-SCALE NEUTRINO MASS MODELS

One possibility to lower the mass scale of the additional seesaw messenger particles is to explain the smallness of the neutrino masses by a small lepton number breaking parameter instead of a suppression with respect to the electroweak scale. This is the idea behind the type II seesaw [7–12] and variants of the type I seesaw, like the inverse [13, 14], double [15, 16], linear [17, 18] or generalized inverse [19] seesaw. However in many model realizations the smallness of this parameter is arbitrary and not physically motivated (although counterexamples exist [20–27]). Finding a well-motivated explanation of such small dimensionful parameters is important to understand the origin of neutrino masses. In these models the small parameter leads to light neutrino masses such that a strong suppression of the electroweak scale is not necessary. Hence the sterile neutrinos can have a mass in the GeV–TeV range, and at the same time, the active-sterile neutrino mixing can be sizable allowing the sterile neutrinos to be probed at a variety of experiments [28–34] making a detailed study of their phenomenology of particular interest. Hybrid seesaw scenarios [35–38] can also accommodate a low new physics scale.

Another possibility to lower the mass scale of the new particle is explored in radiative neutrino mass models [39–43] (for a review, see e.g. Refs. [44, 45]). In these scenarios neutrinos are massless at tree level and their masses are generated radiatively at one or more loops. The suppression of the electroweak scale coming from the loop factors, together with new couplings, does not require the introduction of too heavy particles which allows them to be tested directly in various ways, including through collider searches for exotic fermions and scalars, and non-standard flavor effects in the charged-fermion, as well as neutrino oscillation sector.

Yet another possibility is to enlarge the SM gauge group, so that the sterile neutrinos are charged under the new gauge group. Typical examples include $U(1)_{B-L}$ [46–48] and left-right symmetric models [49–51]. In these scenarios, even if the sterile neutrinos have small mixing with the active sector, they can still have observable effects due to the new gauge interactions [52–56]. Models with secluded gauge symmetries [24, 57, 58] allow to link neutrino masses to dark sectors hence allowing for more testability in various ways.

III. PHENOMENOLOGY OF LOW SCALE NEUTRINO MASS MODELS

The introduction of new particles to generate neutrino masses, in particular the addition of sterile neutrinos also allows for the presence of a neutrino portal to a hidden new physics sector. This opens up the possibility that the additional particles involved in the neutrino mass mechanism could be connected to other open questions of the SM. For example, with additional CP-violating sources, they can be used to produce the observed baryon asymmetry of the Universe via the leptogenesis mechanism [59] which can be made consistent with low seesaw scale by virtue of either resonant [60–65] or ARS [66–73] mechanism (for reviews, see e.g. Refs. [74–76]). In addition, the sterile neutrinos can interact with Dark Matter, thereby serving as a portal to the dark sector [77–97].

Low scale neutrino mass models offer a rich phenomenology. For example, the additional particles can lead to neutrino non-standard interactions at an observable level [45] or lead to anomalous magnetic moments of leptons [98, 99]. The new particles can also be searched for directly in different near-future experiments. In the MeV-GeV mass range, SBN [100, 101] and the DUNE near detector [102] can probe heavy neutrinos in decay-in-flight searches. NA62 kaon factory operating in beam dump mode [103, 104] and dedicated long-lived particle search experiments like SHiP [105, 106], FASER [107] and MATHUSLA [108] can test sterile neutrinos from 400 MeV up to 5 GeV. Heavier neutrinos can be probed at current or proposed collider experiments [109–125]. Furthermore, sterile neutrinos can be searched for in lepton flavor violating processes [126, 127] and lepton-number violating processes (in the case of Majorana neutrinos) [30, 32, 128–134]. Most importantly, as these sterile neutrinos are related to neutrino mass generation, constraints from obtaining the observed light neutrino masses apply, which provides a defined parameter space that can be used as a target for the experiments.

Although sterile neutrinos are like the poster-child for seesaw mechanism, many of the low-scale neutrino mass models come with additional scalars, fermions or gauge bosons, each offering rich phenomenology in collider experiments, as well as in low-energy lepton flavor and lepton number violating searches [30, 32]. The complementarity of different search strategies puts these messengers of neutrino mass models at the crossroads of high and low energy experiments, making their detailed phenomenological study very appealing.

IV. SUMMARY

Nonvanishing neutrino masses provide the first conclusive experimental evidence of physics beyond the SM. Therefore, it is very important to explore the experimental signatures of neutrino mass models which might lead to some crucial insights into the underlying new physics. Going beyond the simple theoretical paradigm for neutrino masses, the high scale seesaw mechanism can be morphed into testable models which also provide attractive solutions to other open questions of the SM, like dark matter and the baryon asymmetry of the Universe.

Future prospects of the direct searches for messengers of neutrino mass mechanism at the energy frontier with colliders can offer an ideal testing ground for low-scale neutrino mass models, which is complementary to the low-energy probes and neutrino experiments at the intensity frontier.

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