Snowmass2021 - Letter of Interest
Neutrinos Across Frontiers

Topical Group(s):

☑ **(NF1) Neutrino oscillations**

☑ **(NF2) Sterile neutrinos**

☑ **(NF3) Beyond the Standard Model**

☑ **(NF4) Neutrinos from natural sources**

☑ **(NF5) Neutrino properties**

☑ **(NF6) Neutrino cross sections**

☑ **(TF11) Theory of neutrino physics**

☑ **(NF9) Artificial neutrino sources**

☑ **(NF10) Neutrino detectors**

☑ **(Other) Cosmic Frontier (CF4, CF7); Theory Frontier (TF9, TF11)**

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Abstract

The current scientific epoch, more than ever before in the past, provides new opportunities to learn more science using input from multiple research frontiers. This is certainly the case with the physics of neutrinos. In particular, explaining the origin of neutrino masses is currently one of the major open issues in fundamental physics. Moreover, the properties of neutrinos that may explain the abundance of matter over antimatter in the universe make the quest for the absolute value of the neutrino mass among the most urgent questions of nuclear and particle physics. Here we advocate for a coherent effort to explore possible synergies, including cosmology (sum of neutrino masses), neutrinoless double beta decay $0\nu\beta\beta$ search (Majorana mass), beta decay (effective neutrino mass) searches, long-baseline oscillation measurements (squared mass differences), and to look for alternative methods to search for Majorana and sterile neutrinos. This combination of redundant and complementary experimental avenues in the neutrino sector increases the confidence that advances in our understanding of neutrino physics can be made in the near future. Results in one area could inform the development of observational strategies in another area. Possible incompatible results from different research areas may point to the possibility that non-standard and yet-to-be-explored theories are hiding behind these tensions, as well as reveal subtle systematic errors. The Snowmass process presents an opportunity to form multidisciplinary science teams, and also to encourage the agencies to find ways to join forces in order to optimize the science efforts.

Introduction

Cornering unknowns in neutrino physics is one of the top goals in particle physics in the next decade. Experimental and theoretical advances are expected from multiple areas, including laboratory searches (oscillation experiments, kinematic probes, neutrino interactions, $0\nu\beta\beta$ searches), astroparticle searches (the wide variety of neutrino telescopes), and cosmology (observations of anisotropies in the CMB and studies of the large-scale distribution of matter). Each probe is sensitive to different combinations of neutrino properties, and comes with a set of independent analysis techniques. This combination of independent search avenues in the neutrino sector provides a powerful approach to advance our understanding of BSM physics in the near future. Results in one area are expected to inform the development of observational strategies in another area. Possible incompatible results will guide us to explore new theoretical ideas and can at the same time help us to uncover subtle systematic errors that were previously missed. The key requirement to fully exploit the complementarity of the aforementioned probes is the availability of results obtained by different experimental platforms, and the ability to perform cross-field tests of individual results. This major goal of testing experimental and theoretical results across different physics frameworks requires a full understanding of how the results are obtained and how different communities will facilitate the full exploitation of the rich datasets expected in the near future. The exploration of the BSM physics territory, of which the neutrino sector is one of the smoking guns, is a major challenge in fundamental physics and one that would enormously benefit from a collaborative approach -- bridging the gap across frontiers may be an essential element in making fundamental advances.

Science Opportunities

Measurements of the absolute mass scale, determination of the mass hierarchy, and understanding of the nature of neutrinos: These are the major targets for ongoing and upcoming experiments across the frontiers. Each of them have their own strengths and weaknesses and it will be important to view them in an overarching way, rather than in isolation. In particular:

- Cosmological observations are highly sensitive to neutrino physics [1,2] and will deliver improved limits in the next few years with, e.g., DESI, Vera Rubin Observatory, Simons Observatory and CMB-S4. Given the current results from oscillation experiments, they have a "guaranteed" signal. However, the interpretations of cosmological tests [3-7] assume the validity of the LCDM model, and as a consequence these constraints will depend on the underlying assumptions of the cosmological model used in the analysis, a potential source of systematic bias.
- Neutrinoless double-beta decay is a powerful tool to investigate lepton number violation, and perhaps the only known practical way to assess the Majorana nature of neutrinos. Experimental sensitivities are constantly improving; the experiments are expected to start probing the boundary (in $m_{\beta\beta}$) between an inverted and normal hierarchy within the next 10 years [8,9,33]. The outcomes of $0\nu\beta\beta$ searches will have model dependencies (nuclear, mass mechanism, Majorana nature); there is no guaranteed signal (neutrinos might be Dirac particles; even if it is a Majorana particle and the hierarchy is normal, Majorana phases could make the $0\nu\beta\beta$ amplitude vanish).
- Kinematic searches will continue to probe the effective neutrino mass, m_β [10,11]. These searches are model independent; the sensitivity of the Project8 experiment is expected to get down to ~40 meV within 10 years (an equivalent to $\Sigma m_\nu \sim 0.12$ meV, the current limit from the combined Planck+BAO data set [32]).
- Neutrino oscillation probes are insensitive to the absolute mass scale, but long baseline experiments (DUNE, HyperK) will pin down the hierarchy at 5σ within 5-10 years, after their start [12]. Oscillation parameters (mass splittings, mixing angles, phases)[13-15] are needed to compare different quantities (Σm_ν, m_β, $m_{\beta\beta}$) to be probed by the searches mentioned above.

Beyond active neutrino mass measurements, sterile neutrinos and new interactions provide another exciting area for cross-frontier collaborations:

- Sterile neutrinos: mass measurements can also provide information about the existence of eV-scale sterile neutrinos. For example, "incompatible" differences (in, e.g., Σm_ν - $m_{\beta\beta}$) might hint at the existence of a sterile neutrino [16-21].
- Secret interactions could be searched for through different probes (cosmology, $0\nu\beta\beta$, oscillations, neutrino telescopes, supernovae) but also in this case a robust detection from a single probe is very unlikely. Again, if hints emerge in the near future, the strategy might be to look deeper into other available datasets, or to design a new experiment (e.g. beam dump) to search for signatures of new interactions [22-27].

Summary Discussion

The combination of redundant and complementary experimental avenues in the neutrino sector increases the confidence that advances in our understanding of neutrinos can be made in the near future. Results in one area could inform the development of observational strategies in another area. In the following we discuss some plausible scenarios, not in any particular order:

- There is no consensus on what the "best probe" to access the absolute value of m_ν would be. Different approaches all bring both strengths and weaknesses, with different systematics. They provide measurements of different quantities, related to each other based on assumptions about the underlying particle physics. We assume the complementarity of all these approaches will be a key to constrain the absolute value of the ν mass. A synergetic approach is required as none of these probes alone is currently guaranteed to provide a definite measurement of the mass scale [17,19].
- If the LCDM model is correct, the next-generation cosmological experiments will measure the neutrino mass with 3-4 sigma significance [28]. If not, cosmological assumptions will need to be revised. To tighten constraints of LCDM, laboratory measurements of the neutrino mass will be beneficial.
- If $0\nu\beta\beta$ searches observe a signal (ideally with multiple isotopes), and if the results come out to be incompatible with measurements from cosmology, we would have a hint regarding BSM physics. Again, that would be a very interesting situation possibly indicating the mass mechanism is not the dominant contribution to the $0\nu\beta\beta$ decay width.
- In any case, combination of forthcoming cosmo+$0\nu\beta\beta$+oscillation data will sensibly reduce the available neutrino mass parameter space (also possibly hinting to physics beyond LCDM and/or beyond the SM of particle physics) [20,28-31]. The complementarity would come with some degree of model dependence, and the task would be to quantify the degree of the dependence.
- Kinematic measurements are model-independent, and any positive signal would be convincing, informing other searches on where to look. But, given their sensitivity, such a scenario is unlikely within the next 10 years unless our cosmology/particle physics assumptions are incorrect. Again, if the signal detection is achieved at the current sensitivity level, we would need to revisit our assumptions. Otherwise, results from forthcoming cosmology and $0\nu\beta\beta$ searches will inform us about the best strategy for future steps. If the sensitivity needed cannot be reached with existing techniques, we need to push forward on R&D aimed at devising new experimental strategies.

As argued above we insist on the complementarity of different experimental and theoretical approaches, assuming that any probe in the physics of neutrino mass will inform complementary searches. Together these pieces will point to directions that are more promising, and eventually lead to discoveries in the neutrino sector.

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