The next revolution in neutrino physics

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Abstract: The present research proposal focuses on further enriching the physics scope of the US neutrino experimental program. The PI aims to systematically study standard and beyond standard physics scenarios that can be probed in neutrino oscillation experiments, as well as to propose new searches and strategies to be performed specifically in liquid argon time projection chambers. The outcomes of this project will be implemented in event generators and other automated tools, and will be made available publicly.

A remarkable era is foreseen in the field of neutrino physics, particularly due to the advent of large liquid Argon Time Projection Chamber (LArTPC) experiments. LArTPCs can be envisaged as modern bubble chambers: charged particles traversing it deposit a characteristic amount of energy, leaving well defined tracks that can be used for exceptional particle identification and event reconstruction. Such capabilities will allow for percent/sub-percent measurements of mass splittings and mixing angles, the determination of the neutrino mass ordering, and an unprecedented measurement of CP violation in the lepton sector.

Accompanying an extraordinary experimental effort there is a fertile theory program. For many years, there has been considerable effort in developing strategies to probe standard and beyond standard physics in the context of neutrino oscillation experiments. With the advent of LArTPCs, there has been renewed interest in developing new ideas that can enrich the physics case of the neutrino program and define new searches that exploit the strengths of such experiments to their fullest; as well as improving and broadening our understanding of what neutrino physics can teach us in addition to high energy colliders, flavor and precision physics observables. The goal of this proposal is to further enlarge the physics case of future neutrino experiments, particularly the Short-Baseline Neutrino Program (SBN) and the Deep Underground Neutrino Experiment (DUNE). The proposed work consists of the following three cornerstones.

Systematic study of standard and beyond standard scenarios that can be probed using LArTPCs. The PI proposes to study in depth scenarios which are uniquely enabled by the LArTPC technology or which have not been scrutinized so far. Among these topics, three will be highlighted:

- The unique opportunity to perform measurements of atmospheric neutrinos below the GeV by DUNE, enabled by its multi-kton size and ability to reconstruct low energy recoiled charged particles. Since the oscillations of this atmospheric neutrinos below the GeV are considerably affected by the leptonic CP phase, this study will lead to the only determination of this phase independent of accelerator neutrinos;
- The use of DUNE-PRISM and the high pressure gas TPC as DUNE near detectors to probe new physics such as light dark matter scenarios;
- The rich phenomenology of ultra-light bosonic dark matter coupling to neutrinos which induces temporal periodicity in neutrino masses and mixing angles and may lead to time variation signatures in oscillation experiments and distortions of neutrino oscillation probabilities. The large expected number of events and unique broad band neutrino beam place DUNE in an excellent position to probe such models, particularly via the temporal signature.

These studies will be conducted in depth and particular attention will be given to the impact of neutrino interaction (relevant to all aforementioned topics) uncertainties and intra-nuclear cascade modeling (specially relevant to the first topic) on the projected experimental sensitivity.

Development of novel ideas and identification of new experimental signatures in LArTPCs. The purpose of the second cornerstone is to propose novel ideas, connecting major open questions of nature to neutrino experiments and conceivably leading to new experimental signatures which in turn may be exploited by current and future neutrino experiments. Which other possible connections are there between low energy neutrino experiments and the neutrino masses or dark matter? Can the flavor puzzle have associated dynamics at low scales?

To be more concrete, the PI will exemplify this cornerstone with an example based on previous work. In [1] an ultra-violet complete framework was proposed for dynamical generation of neutrino masses at low scales. The mechanism involves MeV$\sim$GeV sterile neutrinos and a new gauge symmetry in the sterile sector which is responsible for the lightness of neutrino masses. This setup can lead to trident signatures such as $\nu\,\mathrm{Ar} \to \nu\,\ell^+\ell^-\mathrm{Ar}$, and even possibly explain the low energy excess of events observed by the MiniBooNE experiment. Due to superb event reconstruction, LArTPCs are expected to be particularly sensitive to the energy and angular distributions of the lepton pair. This framework connects a deep question of the standard model, the mechanism of neutrino masses, to a new signature in oscillation experiments that can be uniquely probed at LArTPCs.

Implementation of these models and searches in automated tools. To reap maximum benefits from this proposal, the last step is to implement models and searches in automated tools, such as Feynman rule calculators, event generators, and neutrino experiment simulators, such as `FeynRules`, `GENIE`, and `GLoBES`. These implementations, particularly in event generators, will be performed in collaboration with experimentalists and event generator experts based at Fermilab, and with nuclear theorists at Fermilab and Argonne. These codes will be made public.

I believe I am fit to carry out this endeavor due to my expertise in neutrino physics, my ability to communicate with my experimental colleagues and the breadth of my research. Besides, Fermilab is ideally suited for this proposal due to the close contact between theorists and experimenters. If funded, this research grant will support the effort of the PI and 2 postdocs to collaborate closely with neutrino experimentalists at Fermilab in order to expand the physics case of SBN and DUNE in new directions. This grant will also support the establishment of a new code base available to neutrino experiments and fellow theorists, contributing to the training of the next generation of neutrino theorists in a data rich environment, as well as a biennial set of joint experimental-theory workshops. Moreover, this proposal will benefit from and enhance the periodic *SBN-Theory meeting*, led by myself in close coordination with the Short-Baseline Neutrino Detector spokespeople in which experimenters and theorists discuss and work together on new ideas and searches for the Short-Baseline Neutrino Program. Working groups on specific models/searches will be organized and two reviews on the extended physics case of SBN and DUNE will be produced by the end of the funding period.

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[1] E. Bertuzzo *et. al.*, Phys. Rev. Lett. 121 (2018) no.24 241801; arXiv:1808.02500

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