October 21, 2014

Experimental program at the Long Baseline Neutrino Facility (ELBNF)

Letter of Intent

Executive Summary

This Letter of Intent (LOI) brings together an international community to pursue an accelerator based long-baseline neutrino experiment, as well as neutrino astrophysics and nucleon decay, with a 40 kton liquid argon TPC(LAr-TPC) detector located deep underground. Several independent worldwide efforts, developed through many years of detailed studies, have now converged around the opportunity provided by the megawatt neutrino beam facility planned at Fermilab and by the new significant expansion with improved access foreseen at the Sanford Underground Research Facility (SURF) in South Dakota. The new international team has the necessary expertise, technical knowledge, and critical mass to design and implement this exciting discovery experiment in a relatively short timeframe. The goal is the deployment of the first 10-kton detector on the timescale of 2021. The PIP-II accelerator upgrade at Fermilab will provide 1.2 MW of power by 2025 to drive a new neutrino beam line at Fermilab. With the availability of space for expansion and improved access at SURF, this international collaboration will develop the necessary framework to design, build and operate a world-class deep-underground neutrino observatory. Fermilab will act as the host laboratory and CERN will support the long baseline neutrino program. This plan is aligned with the CERN European Strategy and the HEPAP P5 report.

Introduction

Over the past two decades or so, the study of the properties of the neutrino have provided many surprises, representing the first evidence of physics beyond the Standard Model of particles and interactions. The phenomenon of neutrino oscillations, whereby they change flavor as they propagate through space and time, is now well established. Neutrino oscillations imply that neutrinos have mass and that the different flavors mix.

With the exception of the possible hints for the existence of sterile neutrinos, the current data can be described in terms of so-called 3-neutrino-paradigm, in which the quantum-mechanical mixing of three mass eigenstates produces the three known neutrino-flavor states. The mixing is described by the so-called Pontecorvo-Maki-Nakagawa-Sakata matrix (PMNS). Attempts to explain, rather than describe, neutrino oscillations require either that the neutrino is its own antiparticle (an entirely new state of matter) or that a global lepton number is conserved (an entirely new law of Nature). Hence, new experiments are needed to complete our understanding of neutrino oscillations and to elucidate the underlying physics.

Speculations on the origin of neutrino masses are wide-ranging. An attractive possibility is that neutrino masses are related to a new ultra-high-energy scale that may be associated with the unification of matter and forces. Such theories are able to describe the absence of antimatter in the Universe in terms of the properties of ultra-heavy particles as well as offering a description of cosmological inflation in terms of the phase transitions associated with the breaking of symmetries that pertain at the ultra-high-energy scale. Piecing together the neutrino-mass puzzle will require more precise and detailed experimental information. Long-baseline neutrino-oscillation experiments are essential if the requisite neutrino transitions are to be measured with the necessary precision.

One of the primary questions that the experimental program outlined in this LOI seeks to answer is whether the oscillations of neutrinos differ from those of anti-neutrinos, testing whether "CP symmetry" is violated in the leptonic sector. It is known that the degree of CP-invariance violation that occurs in the interactions of quarks is insufficient to explain why our universe is comprised entirely of matter rather than antimatter. In long-baseline neutrino oscillation experiments the rate of oscillations and the way the oscillation rate varies with energy can be exploited to observe for the first time CP-violation in the leptonic sector, thereby determining the "CP-violating phase" of the PMNS mixing matrix, with potentially profound implications for our understanding of the matter-antimatter asymmetry in the Universe.

Access to this potentially ground-breaking science is only now possible because of the important window of opportunity provided by the expected availability of a new intense neutrino beam and underground infrastructures in the US, making viable the experimental physics program needed for the elucidation of the fundamental questions described above. Fermilab is willing to host a Long-Baseline Neutrino Facility (LBNF) strongly recommended by the P5 review. As host, Fermilab will provide the infrastructure required to carry out a long-baseline neutrino oscillation experiment with the combination of the required large instrumented target mass, high beam power and requisite protons on target. The LBNF will include:

- The LBNF accelerator complex: a pulsed high-energy proton source capable of delivering a peak beam power of 1.2 MW sourced by the PIP-II improvement program, and a proton transfer line to a conventional neutrino beam infrastructure (target, horn, decay channel);

- The LBNF far site infrastructure with a newly expanded underground space at the Sanford Underground Research Laboratory which is foreseen to be created after the complete refurbishing of the Ross shaft in 2017 and other site improvements necessary to house the massive LAr-TPC experimental apparatus.

- The conventional infrastructure at both the near and the far detector sites as well as the primary infrastructure such as the cryostat and associated cryogenics for the liquid argon detector.

The above conditions are necessary for the previously independent worldwide experimental options to converge on a single facility and for the creation of a unique international collaboration with the necessary capabilities to develop a world-class experiment with FNAL acting as host. The new collaboration supporting this LOI includes key international players in ongoing supporting programs (such at the CERN Neutrino Platform) and is in the unique position to propose a credible and suitable experimental plan by the FY18.

To address the exciting physics program made possible by the LBNF, the large international collaboration (referred to here as ELBNF), identified in the author list presented in Appendix A, proposes to construct a deep-underground neutrino observatory based on a 40 kton liquid-argon (LAr) time-projection chamber (TPC) at the Sanford Underground Research Laboratory. The massive far detector will offer a wealth of key measurements and potentially ground breaking discoveries beyond the search for CP- invariance violation, including: atmospheric-neutrino measurements of exquisite precision; extremely sensitive searches for nucleon decay; and the possibility of detecting a neutrino burst from a core-collapse supernova explosion in our galaxy. Searches for proton decay are also sensitive to physics at very high- energy scales and provide unique clues about theories that unify the electromagnetic, weak and strong forces. The atmospheric-neutrino and proton- decay measurements complement and enhance the oscillation program based on precise measurements of the oscillations of neutrinos provided by the LBNF neutrino beam from FNAL.

Overall Scope

- As a large international collaboration, we propose to construct a deep-underground neutrino observatory for long baseline neutrino oscillations, neutrino astrophysics and proton-decay searches that will use a LAr TPC as its primary detector technology.

- The ELBNF collaboration will construct the detector apparatus at the near and far sites that is necessary for the experiment to meet its goals.

- This proposed program will have a fine-grained highly capable near detector facility as well as a 40 kton far detector located deep underground.

- The near detector facility must ultimately include a flexible high precision tracker with argon as the primary target material, in order to reduce key experimental systematic uncertainties.

- The far detector may employ the single-phase LAr TPC technology, the two-phase LAr technology, or a combination of both.

- The experiment proposed in this LOI (the ELBNF near and far detectors), and the LBNF facility (beam components and infrastructure at Fermilab and Sanford) are two distinct entities. The international partners may contribute to either or both.

- A machine-detector interface group will be established to provide a strong connection between the LBNF facility and the ELBNF experiment.

- The initial operational model will follow the model used by CERN in the construction and exploitation of the LHC where the laboratory operates the facility and the experiment's operational costs will be paid by an established common fund.

- We expect to start the full data-taking period around 2025 and extend until ~ 2035 in order to fully exploit this remarkable facility.

- The construction of the first 10 kton of the underground far detector is our highest priority and this should be operational by 2021 at the very latest, with the detector modules for the full 40 kton far detector being installed shortly afterwards. This strategy is essential to place the experimental collaboration at the heart of the global neutrino program as early as possible and start gathering science.

- Our experiment is a unique, exciting and challenging program that adopts a modular approach to get construction and first science early and form the facility that will lead the scientific discoveries in our proposed disciplines.

Science Case

The long-baseline physics case is compelling and competitive. The proposed experiment will have discovery opportunities as well as the capability to perform measurements with unprecedented precision. The high-power beam and large underground LAr-TPC detector will enable a broad science program across a range of scientific frontiers, such as: neutrino oscillation physics (including sensitivity to new as yet undiscovered phenomena), the physics of core-collapse supernova, proton decay, and detailed measurements of neutrino interactions in the near detector.

The experimental program has two flagship neutrino measurements; the most important being the potential discovery of CP violation in the lepton sector, followed by the determination of the neutrino Mass Hierarchy (with a statistical significance of greater than five standard deviations). To perform these measurements:

- Spectral information is critical to achieve the desired experimental precision;
- Information from the 1st and 2nd oscillations maxima is important in resolving possible ambiguities.
- Further work to be performed for the TDR will assess how these requirements can be addressed with a 1300 km baseline by a further optimization of the beam profile properties and a further investigation on the systematic errors reachable with the near detector complex as well as external measurements (hadro-production, neutrino cross sections, etc. …).
- Other experiments worldwide may be complementary to parts of the science program.

The experimental program has two additional flagship science goals enabled by the large underground LAr-TPC detector:

- The search for baryon number non-conservation.
- The possibility to detect supernova neutrinos.

A more complete list of the scientific aims of the experiment includes:

- Determination of CP violation in the neutrino sector and direct precise measurement of δ_{CP}, the CP violating phase.
- Direct detection of matter effects and definitive determination of neutrino mass ordering.
- Precision measurements of oscillation parameters of the PMNS matrix including θ_{23} and the determination of the octant in which it lies.
- Precise tests of standard three-neutrino paradigm achieved by over-constraining the PMNS matrix through measurements of ν_μ disappearance, ν_e and ν_τ appearance. Such tests provide sensitivity to a number of new phenomena, including non-standard neutrino interactions (through the high sensitivity to matter effects) and sterile neutrinos.
- The large underground LAr-TPC detector enables a range of key scientific opportunities, including the search for baryon

number nonconservation and the possibility to detect supernova and atmospheric neutrinos.

- The highly capable near detector will provide a broad program of measurements, including the determination of neutrino cross-sections as well as electroweak precision measurements.

Scientific and Experimental Strategy

We are proposing a strong and timely strategy to benefit from the unique opportunity provided by LBNF:

- The ELBNF collaboration will rapidly establish itself as a world-class player in the deep underground physics field (accelerator and non-accelerator) through the construction of a modular set of detectors that are not necessarily identical but are of the similar mass.

- The construction of an initial 10-kton detector deep underground at Sanford lab on a timescale of about 2021 is the top priority to begin the physics program and establish the collaboration in the neutrino landscape. This early first module installation will engage the collaboration, test all the aspects of the underground installation and operation, and will provide an early underground physics program as well as be ready for beam physics as soon as PIP-II is implemented.

- Remaining modules will follow in rapid succession in order to complete the 40-kton detector in a timely fashion. We expect to start full data taking period in 2025 and extend until ~2035.

- The new international collaboration will leverage the CERN Neutrino Platform as an important facility for detector design and development and the collaboration will benefit from participation of its members in related ongoing and planned experiments and R&D efforts worldwide.

- The collaboration will have the necessary expertise intellectual resources and critical mass to accrete the financial resources to design and implement this challenging plan.

Strategic Issues to be addressed in the CDR

There are a number of key strategic decisions that will need to be addressed in the Conceptual Design Report. This includes the following questions:

- What are the advantages of a single large cavern compared to multiple smaller, modular caverns?

- Is it better to clone identical modules or to construct detectors with increasing volumes (as risks are retired)?

- What are the scientific or programmatic arguments for starting with a relatively crude near detector that is then followed by a finely segmented detector rather than a full-functionality near detector required from the start?

- When does the neutrino beam line need to be complete – when PIP-II is ready or earlier?

- Should the LAr technology be single phase, two-phase, possible new implementation or a combination of both, constructed sequentially?

- What are the benefits of constructing a small (100 ton) demonstrator before 2021 in the underground laboratory at SURF in order to retire technical/implementation risks?

- What is the timeline for key decisions and milestones, such as CD-2/3 reviews?

- What is the roadmap to produce "CD-1" like documentation (with detailed costing) within the year?

Plan Moving Forward

Given the scientific motivation and the large US and large non-US interest, the intention is to form the full EBLNF collaboration structure on a rapid timescale. In particular, as soon as possible, we intend to:

- Establish the collaboration, implement a governance model, and choose leadership for the collaboration.
- Determine a roadmap that completes the writing of a CDR and provides the "CD-1 like" supporting material including a cost and schedule within the coming year.

Summary

This LOI establishes the first step in the creation of new, international collaboration that unifies the world's two very long-baseline neutrino collaborations and other interested scientists from all over the world in order to build a state-of-the-art liquid argon detector deep underground for the purpose of unraveling the mysteries about the neutrino as well as study proton decay and provide an important detection tool for supernovae. This collaboration will exploit the major and expanded facilities foreseen at Fermilab and Sanford Underground Research Laboratory in order to carry out its science. To quickly establish itself on the "world stage", the collaboration aims to have a 10-kton module underground by 2021. The goal is to begin beam operations with the full scope detector in mid 2020's and operate the experiment for more than a decade.

Appendix A – Signatures