November 18, 2014

Experimental program at the Long-Baseline Neutrino Facility (ELBNF)

Letter of Intent to Form an International Collaboration

Executive Summary

This Letter of Intent (LOI) brings together a global neutrino community to pursue an accelerator-based long-baseline neutrino experiment, as well as neutrino astrophysics and nucleon decay, with an approximately 40-kton (active mass) modular liquid argon TPC (LAr-TPC) detector located deep underground and a high-resolution near detector. 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 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 2024 to drive a new neutrino beam line at Fermilab. With the availability of space for expansion and improved access at the Sanford laboratory, 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. This plan is aligned with the European Strategy Report and the US HEPAP P5 report.

Science Case

The study of the properties of the neutrino has already provided many surprises, representing the first evidence in particle physics 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 mass eigenstates are mixtures of the flavor eigenstates.

With the exception of the possible hints for the existence of sterile neutrinos, the current data can be described in terms of the three-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 Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix.

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 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, the way the oscillation rate varies with energy, and the differences between neutrinos and antineutrinos can be exploited to observe for the first time CP violation in the leptonic sector. In the three-neutrino paradigm, CP violation is determined by the value of a complex phase δ_{CP} in the PMNS matrix, whose sign is opposite for neutrinos and antineutrinos; CP violation occurs if the value of δ_{CP} is not zero (or π). Discovery of CP violation in the neutrino sector would have potentially profound implications on our understanding of the matter-antimatter asymmetry in the Universe.

Current neutrino oscillation data tell us about differences in the squared masses of the neutrino mass states, and about the sign of the mass-squared difference between two of the states, but not about the difference of those with respect to the third, which may be heavier (normal ordering) or lighter (inverted ordering) than the other two. Resolving this neutrino mass hierarchy ambiguity, along with precise measurements of neutrino mixing angles, would be a potent discriminator between various classes of models which attempt to take physics beyond the standard model and would have significant theoretical and cosmological implications. It is also an important input into the interpretation of results from other future neutrino experiments. Long-baseline neutrino oscillation experiments can determine the mass ordering by exploiting the matter effect on the oscillation probabilities, which affects the electron-neutrino component of the neutrino beam, with different effect on neutrinos and antineutrinos, and with opposite sign depending on the mass ordering.

Even without CP violation, electron neutrinos and antineutrinos propagating through the Earth behave differently due to the fact that the material through which the beam passes contains electrons but no intrinsic positrons. This effect must be distinguished from the differences that arise from true CP violation. To unfold these two effects from each other in a single experiment requires a baseline, the distance from the neutrino source to detector, >1000 km. Discrimination can be further enhanced, remaining ambiguities resolved, and the precision of the measurements improved by measuring the oscillation spectrum as a function of neutrino energy, ideally covering both first and second oscillation maxima.

An important goal of the proposed experimental program is to precisely measure other parameters of the PMNS matrix and to test the three-neutrino paradigm and the validity of the PMNS matrix as the description of neutrino mixing and oscillations. This involves measurements of ν_μ disappearance and both ν_e and ν_τ appearance, with the goal of measuring all of the PNMS matrix elements in this single experiment.

A long-baseline experiment requires a massive, high-precision far detector located deep underground. Such a detector can be exploited to make additional crucial measurements and searches for physics beyond the Standard Model. These include searches for baryon number non-conservation (proton decay); measurements of thousands of neutrinos from a core-collapse supernova if one should occur in our galaxy during the operational lifetime of the experiment that would shed light on the formation of a neutron star; and measurements with atmospheric neutrinos, which complement and enhance the oscillation measurements made with beam neutrinos and can provide extended sensitivity to physics beyond the Standard-Model, through the wide range of neutrino energies and distances traveled through the earth that they offer.

To achieve the precision required to make a significant advance in the measurement of neutrino oscillation parameters over current experiments and to reach the desired 5σ sensitivity to CP violation, a highly-capable, high-precision near detector is required to measure the unoscillated flux spectrum to a few percent for all neutrino species in the beam (ν_μ, $\overline{\nu}_\mu$, ν_e, $\overline{\nu}_e$) and to precisely measure neutrino cross sections necessary to interpret the far detector signal and backgrounds. This requires a high resolution, magnetized near neutrino detector with high efficiency for identifying and measuring electrons and muons. To measure the small ν_e contamination in the beam with greater precision, the detector would need to be able to distinguish e^+ from e^-; this would require a low-density detector with a commensurately long physical radiation length. Use of a target nucleus similar to the far detector would allow cancellation of systematic errors and inclusion of other target nuclei would provide constraints for accurate modeling of nuclear effects. Such a detector, placed in the high-intensity neutrino beam needed for the oscillation measurements, will collect a vast sample of neutrino interactions, which will enable a rich program in neutrino scattering physics addressing many non-oscillation topics, such as precision electroweak measurements.

Design of the Experiment

To address this broad and exciting physics program, a number of key elements are required:

- A high-intensity, megawatt class, wide-band, sign-selected muon neutrino beam.
- A massive, high-precision neutrino detector, placed deep underground.
- A baseline sufficiently long to simultaneously determine the mass hierarchy and measure CP-violating effects.
- A highly capable near detector located close to the neutrino source.

Access to this potentially groundbreaking science is now possible because of the important opportunity provided by the expected availability of a new intense neutrino beam at Fermilab and of underground infrastructures at the Sanford Underground Research Facility, which is at a distance of 1300 km from Fermilab. These facilities will make viable the experimental physics program needed for the elucidation of the fundamental questions described above.

Fermilab is prepared to host the Long-Baseline Neutrino Facility (LBNF), strongly recommended by the P5. As host, Fermilab will provide the infrastructure required to carry out a long-baseline neutrino oscillation experiment with the combination of the required accelerators, beamline, target and horn. The LBNF will include:

- A conventional horn-focused neutrino beam, including a proton transfer line target, horns, decay pipe and absorber, capable of operating at 1.2 MW initially, and with the potential to be upgraded to 2.4 MW. This beam will be driven by the existing Fermilab Main Injector complex, including the planned PIP-II injector upgrades.

- The LBNF far site infrastructure with newly expanded underground space at the SURF, 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 LBNE near site infrastructure required to house the near detector complex.

- The conventional infrastructure, including the primary technical infrastructure such as the cryostat and associated cryogenics for the liquid argon detector.

To address the groundbreaking 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 Facility. Potential designs for the ELBNF far detector have been developed by a number of groups, who now have come together within ELBNF, including both single-phase and dual-phase readout technology. The far detector may employ just one of these technologies, or possibly different technologies in a phased implementation, depending on the performance and developing maturity of the candidate designs. These options are being explored by several groups at the CERN Neutrino Platform (e.g. WA105) as well as Fermilab's short-baseline neutrino program.

The collaboration also proposes to build a fine-grained highly-capable near detector located on the Fermilab site. The reference design consists of a large-volume straw-tube tracking detector (STT) and electromagnetic calorimeter inside of a dipole magnet, and resistive plate chambers for muon identification located in the magnet yoke and upstream and downstream steel absorbers. High-pressure argon gas targets and other nuclear targets are embedded in the upstream part of the tracking volume. This system may be augmented by a magnetized LAr or GAr TPC.

Status of the Development of the Experimental Design

The designs of LBNF and ELBNF build on considerable detailed work already done by a number of collaborations, groups and laboratories who have been working for a number of years to developing designs and plans to address the crucial and fascinating physics program proposed here. This includes work done by the LBNE and LBNO collaborations, which have developed comprehensive designs for long-baseline experimental programs, including beam, near detector, far detector and civil engineering designs to support them, as well as other groups that have developed ideas relevant to this program.

The LBNE Collaboration is developing a design for a single-phase LAr-TPC using wire-plane readout, which is based on the successful INFN ICARUS design. It takes a modular approach based on factory-built anode planes, which can be assembled in configurations and quantities depending on the total size of the far detector. A small-scale prototype, utilizing reduced-scale anode planes, is currently being assembled inside a cryostat at Fermilab that can hold 35 tons (fiducial) of LAr. An Expression of Interest contemplating a full-scale prototype for an engineering as well as a beam test has been reviewed by the CERN SPSC and they have invited submission of a full technical proposal.

The LBNO Collaboration is developing a dual-phase readout LAr-TPC, whose anode is assembled from modules that can be combined to produce a detector of any size. A test of a TPC with the scale of 1 m x 3 m anode plane and a 1-meter drift is currently under construction at CERN. It is planned to build a 6 m x 6 m x 6 m TPC demonstrator (WA105) inside a 8 m x 8 m x 8 m cryostat, illuminated by a charged particle test beam, in the CERN Neutrino Platform. Construction has started for an extension of the EHN1 building in the North Area at CERN to house this and potentially the LBNE test., with the goal of executing initial beam tests before the start of the next long shutdown for LHC upgrades.

Other world-wide efforts on LAr TPC development which will also benefit the development of the LBNF far detector include the upgrades of the ICARUS detector (WA104) for possible use in a short-baseline program at Fermilab, MicroBooNE, the proposed LAr1-ND experiment at Fermilab, the LArIAT test beam program, and other smaller scale R&D programs.

The strategy for integrating these efforts and deciding on the type and configuration of the LBNF far detector system, including the possibility of phased implementation which may involve modules of different design, will be developed and presented in the full LBNF proposal that is anticipated to be submitted in mid-2015.

A complete conceptual design for a fine-grained near detector in a large dipole magnet with argon and other nuclear targets, as described above, has been developed by the LBNE collaboration[ND-DPR LBNE-doc-6704]. LBNE also has a conceptual design for a LAr TPC inside a similar magnet [LBNE-doc-4724-v10]. A design for a near detector based on a high-pressure gas Ar TPC is under development by LBNO [https://laguna.ethz.ch/indico/getFile.py/access?contribId=53&sessionId=5&resId=0&materialId=slides&confId=59].

A complete design for a beamline utilizing the Fermilab Main Injector has been developed by the LBNE team. It is optimized for the 1300 km baseline from Fermilab to SURF. It is designed for initial operation with the 1.2 MW beam that will be available thanks to the PIP-II project, and with the ability to be upgraded to at least 2.4 MW beam power if future upgrades to the Fermilab accelerator complex are accomplished. The LBNO team has developed designs for beamlines that would utilize the CERN SPS or a proposed 50 or 75 GeV high power PS (HPPS) that are optimized for a 2300 km baseline. Preliminary studies suggest that the horn focusing system developed for the HPPS beam, if applied to the 1300 km baseline from Fermilab to Sanford Lab, would improve the reach for both CP violation and mass hierarchy determination relative to the LBNE-designed beam.

Organization

It is envisioned that the experiment proposed by the ELBNF detector collaboration in this LOI and the LBNF facility and the ELBNF detector collaboration would be two distinct entities. The international partners may contribute to either or both

The ELBNF Collaboration will be responsible for:

- The definition of the scientific goals and corresponding scientific and technical requirements on the detector systems and neutrino beam line.
- The design, construction, commissioning and operation of the detector systems.
- The scientific research program conducted with the ELBNF detectors and LBNF neutrino beam.

Fermilab will provide the high-intensity proton source that will drive the long-baseline neutrino beam, utilizing the existing Main Injector with upgraded injectors (PIP-II). Fermilab, working with and with the support of international partners, will be responsible for the Long-Baseline Neutrino Facility, including:

- Design, construction and operation of the LBNF beamline, including the primary proton beam beamline and the neutrino beamline including target, focusing structure (horns), decay pipe, absorber, and corresponding beam instrumentation.
- Design, construction and operation of the conventional facilities and technical infrastructure on the Fermilab site required for the ELBNF Near Detector complex.
- Design, construction and operation of the conventional facilities and technical infrastructure within the Sanford site, including cryostat and cryogenic systems, required for the ELBNF Far Detector.
- Fermilab, as the host lab, will pay for the operating costs of the facility.

Close and continuous coordination between ELBNF and LBNF will be required to ensure the success of the combined enterprise. An Experiment-Facility Interface Group will be established (by Fermilab) to oversee and ensure the required coordination both during the design and construction and the operational phases of (E)LBNF. This Group will cover areas including

- Interface between the Near and Far Detectors and the corresponding conventional facilities.
- Interface between the detector systems provided by ELBNF and the technical infrastructure provided by LBNF.
- Design and operation of the LBNF neutrino beamline. This is a particularly important activity, since the neutrino-energy spectrum and other characteristics of the neutrino beam, and the ability to measure those characteristics, are a crucial part of the long-baseline experimental program.

The successful model used by CERN for managing the construction and exploitation of the LHC and its experiments will be used as a starting point for the joint management of LBNF and ELBNF. Fermilab, as the host laboratory, will have responsibility for the facilities, and for oversight of the experiment and its operations. Mechanisms to ensure input from and coordination among all of the funding agencies supporting ELBNF, modeled on the CERN Resource Review Board, will be adopted. The same (or similar) structure will be employed to coordinate among funding agencies supporting the LBNF construction and operation.

Scientific and Experimental Strategy

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 as the CERN Neutrino Platform) and this collaboration is in the unique position to propose a credible and effective experimental plan supported by a "Conceptual Design Report" (CDR) to be submitted in the summer of 2015, followed by a fully established cost and schedule (CD-2) by the end of 2017.

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 laboratory on a timescale of 2021 is a 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.

- The new international collaboration will leverage the CERN Neutrino Platform as an important facility for detector design and development. The collaboration will also utilize the infrastructure of both its University partners and science laboratories located around the world.

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

- We expect to start data taking from accelerator operations in 2024 and extend until around 2035 (a decade of beam operations) in order to fully exploit this remarkable facility.

- Our experiment offers a unique, exciting and challenging program that adopts a modular approach to get first science early and drive the establishment of the facility that will lead to the scientific discoveries that are core to the LBNF programme.

Strategic Decisions to be addressed in the CDR

There are a number of key strategic decisions that will need to be addressed by the ELBNF collaboration as part of the writing of the CDR. For illustration, a sample of the issues to be addressed include:

- Examine the trade offs between a single large cavern as compared to multiple smaller, modular caverns.

- Determine the optimal construction strategy. Is it better to clone identical modules or to construct detectors with increasing volumes (as risks are mitigated)?

- Based on a given funding profile, how should the funds be allocated to optimize the scientific impact. When does a finely segmented near detector need to be in place?

- When does the neutrino beam line need to be completed – when PIP-II is ready or earlier in order to exploit 700 KW beam currently serving NOvA which could be deployed in the LBNF beamline as soon as the beamline is done?

- Define the final mix of technologies. Should the LAr technology be single phase, two-phase, or a combination of both?

- Consider the benefits of constructing a small (approximately 100 ton) demonstrator before 2021 in the underground laboratory at Sanford in order to retire technical/implementation risks.

- Determine the timeline for key decisions and establish milestones, such as CD-2/3 reviews to drive the program forward.

- Determine the roadmap to produce “CD-1 like” documentation (with detailed costing) within the coming year.

Immediate Plan Moving Forward

Given the scientific importance and urgency, the intention is to form the full

EBLNF collaboration structure on a rapid timescale. In particular, as soon as possible, we as the newly forming collaboration intend to:

- Establish the collaboration, implement a governance model, and choose leadership for the collaboration.
- Determine the roadmap for the completion of the writing of a CDR and for the provision of 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. It proposes to build a state-of-the-art liquid argon detector deep underground for the purposes of unraveling the mysteries of the neutrino, observing proton decay, and detecting thousands of neutrinos coming from a supernovae explosion, and a high-resolution near detector to support the measurements with the far detector and enable a rich program in neutrino scattering physics. This collaboration will exploit the major and expanded facilities foreseen at Fermilab and Sanford Underground Research Facility 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 in 2021. The goal is to begin beam operations with the full scope detector in 2024 and the plan is to operate the experiment for more than a decade.

Appendix A – Signatures