Design of an LBNF Hadron Flux Measurement Experiment

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The Long Baseline Neutrino Facility (LBNF) will send a neutrino beam of unprecedented intensity from Fermilab in Illinois to the Deep Underground Neutrino Experiment (DUNE) at the Sanford Underground Research Facility in South Dakota. In doing so, it will facilitate a new era of precision neutrino physics and function as the centerpiece of accelerator-based particle physics in the United States. LBNF will be a conventional neutrino beam and will therefore be subject to substantial uncertainties in the number of neutrinos in the beam and their energy spectrum. Current estimates of the neutrino flux at DUNE are uncertain at the level of 8-40% depending on neutrino energy (see Figure 1), and these estimates rely on rough guesses of hadron production model accuracy in many areas of phase space. The PI proposes to design an experiment that will precisely measure the LBNF neutrino flux through measurement of neutrino parent hadrons and muons downstream of the focusing horns, using a replica setup of the LBNF beamline in a low intensity testbeam at Fermilab. The eventual measurement would reduce flux uncertainties to 2-6% depending on energy, and ground them firmly in data rather than guesswork. The goal of the work proposed here is a full technical design of the spectrometer, ready to begin construction at the end of the award term, as well as construction and testbeam testing of a critical component of the design: a Ring Imaging Cherenkov detector.

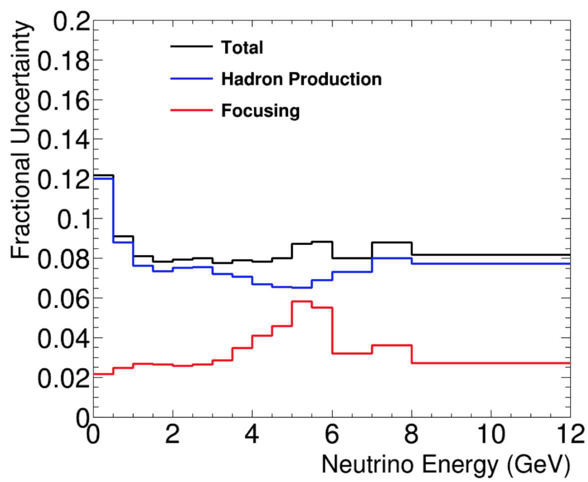

Figure 1: Estimated fractional uncertainty in the muon neutrino flux at the DUNE far detector, as a function of neutrino energy. This figure was made by the PI for the DUNE collaboration, with inputs from students Peter Madigan (University of Colorado) and Amit Bashyal (Oregon State University).

The DUNE experiment has a wide range of physics goals, including measurement of the CP-violating phase of the neutrino mixing matrix, which will be measured via electron-neutrino appearance in the muon-neutrino dominated beam. The experiment's sensitivity to the CP-violating phase will be strongly coupled to its ability to control systematic uncertainties. For example, a 3% uncertainty in the normalization of the electron neutrino signal relative to other neutrino species would require $\sim$600 kt-MW-years of additional exposure to reach 5σ sensitivity to 50% of δ_{CP} phase space, relative to a 1% uncertainty on the same quantity [1]. Achieving this level of precision in a neutrino experiment will require extreme control of all systematic sources, including neutrino flux, cross sections, and detector effects. The DUNE near detector will provide powerful constraints on these parameters, but will be hindered both by the significant *a priori* uncertainties on the near detector flux and by the fact that the flux at the near detector is not identical to the flux at the far detector. In addition to benefiting DUNE's basic goals of oscillation parameter measurements in the three-flavor mixing paradigm, small and well-understood flux uncertainties will be absolutely critical in the event of a DUNE measurement that is not consistent with our current three-flavor mixing model.

The LBNF neutrino beam will be created by impinging a high intensity proton beam on a graphite target, focusing the resulting hadrons through a set of magnetic focusing horns, and allowing them to decay in a long decay volume. Uncertainties in the neutrino flux created by this beam arise from two primary sources: uncertainties in models of hadrons created by the primary proton-carbon interaction and subsequent secondary interactions, and uncertainties in the alignment of the neutrino beam components. Although control of alignment uncertainties requires *in situ* beam monitoring, the dominant hadron production uncertainties can be controlled through external hadron production measurements, such as the one proposed for design here.

Measurements of hadron production off replica targets have become common, but measurement of hadron flux after focusing horns has not yet been attempted, partially because high particle rates in neutrino beamlines make it impossible to operate a traditional high energy particle detector. The experiment the PI proposes to design mitigates this difficulty by using a replica of the LBNF target and horn system in a low-intensity beamline at Fermilab. The replica would be as similar as possible to the LBNF beamline, making use of spare LBNF targets and horns, which would be pulsed at the same current and repetition rate as those in the LBNF beamline, but operated at much lower proton intensity. A precise measurement of hadrons after the focusing horns would reduce the hadron production systematics in Figure 1 such that the total flux uncertainty would be dominated by the 2-6% focusing uncertainties (which cannot be measured in a replica setup).

Figure 2: Sketch of LBNF target/horn system and one possible LBNF spectrometer design. Not to scale.

The hadron flux measurement will require a suite of detectors capable of identifying and measuring the position and three-momentum of charged pions, kaons, and muons, as well as distinguishing backgrounds such as neutral particles. A schematic for one possible design is shown in Figure 1. Time of flight (TOF) counters would correlate primary protons and their charged daughters. Immediately downstream of the second TOF counter would be a magnetized spectrometer instrumented at the front and back with silicon strip arrays, allowing precise momentum measurements. Background discrimination and separation of pions, kaons and protons would be accomplished through a combination of the TOF counters and a ring imaging Cherenkov detector (RICH) downstream of the spectrometer; a Silicon-Tungston calorimeter would provide muon/pion separation. The figure depicts detectors with relatively small aperture ($\sim$10 cm) with the entire system downstream of the horns movable in the plane transverse to the beam, in order to scan across the aperture of the decay volume. Construction of the entire experiment is outside of the scope of a single Early Career Award. The specific scope of this proposal is a full technical design of the entire experiment, as well as construction and testing of one component. Because particle identification of hadrons in the 5-15 GeV region will be extremely critical to the success of an eventual flux measurement, the PI proposes to build and test a RICH detector that would provide particle identification in this region.

The PI has been a leader of the LBNF/DUNE beam design and simulation effort for five years, and has acquired detailed knowledge of the beamline and an excellent working relationship with Fermilab neutrino beam engineers and scientists. As part of this work, she developed a genetic algorithm that identified LBNF horn designs that dramatically increase neutrino flux in the DUNE region of interest and were recently chosen as the horns that will be built for LBNF. Relative to the previous NuMI-like design, the configuration identified by the PI shortens the time to reach key oscillation figures of merit by an amount equivalent to increasing the DUNE far detector mass by 70%. The PI has also spent nine years understanding and limiting the impact of systematic uncertainties on neutrino measurements on the MINERvA experiment, including two years as analysis coordinator and two years as Co-Spokesperson. The PI therefore possesses the technical and leadership experience needed to lead the design of this experiment, and to build the collaboration necessary to see the resulting design made a reality.

References

[1] R. Acciarri *et al.* [DUNE Collaboration], arXiv:1512.06148 [physics.ins-det]. See Fig 3.23.

List of Collaborators

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  John Back (University of Warwick), Mary Bishai (Brookhaven National Laboratory), Helio da Motta (Centro Brasileiro de Pesquisas Fsicas), Milind Diwan (Brookhaven National Laboratory), Steve Dytman (University of Pittsburgh), Julian Felix (University of Guanajuato), Hugh Gallagher (Tufts University), Richard Gran (University of Minnesota Duluth), Satyajit Jena (IISER-Mohali), Mike Kordosky (College of William and Mary), Chuck Lane (Drexel University), John LoSecco (University of Notre Dame), Emily Mahar (Massachusetts College of Liberal Arts), Steve Manly (University of Rochester), Tony Mann (Tufts University), Alysia Marino (University of Colorado), Kendall Mahn (Michigan State University), Kevin McFarland (University of Rochester), Tony Mann (Tufts University), Joel Mousseau (University of Michigan), Donna Naples (University of Pittsburgh), Jeff Nelson (College of William and Mary), Ryan Patterson (Caltech), Vittorio Paulone (University of Pittsburgh), Ron Ransome (Rutgers University), Heather Ray (University of Florida), Lu Ren (University of Pittsburgh), Dave Wark (Oxford University), Lisa Whitehead (University of Houston), Alfons Weber (Oxford University), Elizabeth Worcester (Brookhaven National Laboratory), Jaehoon Yu (University of Texas Arlington), Eric Zimmerman (University of Colorado)

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