Snowmass LOI: Precision Calibration of Large LArTPC Detectors

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1 Introduction

The Deep Underground Neutrino Experiment (DUNE) [1–3] at the Long-Baseline Neutrino Facility is an international project that will be the largest particle physics experiment ever built in North America. The DUNE project will use massive liquid argon time projection chambers (LArTPCs) to address fundamental questions such as the origin of the matter/antimatter asymmetry in the universe. Another upcoming neutrino oscillation experiment is the Short-Baseline Neutrino (SBN) Program [4], which will use multiple LArTPC detectors (SBND [4], MicroBooNE [5], and ICARUS [4]) to investigate the anomalous phenomenon of neutrino oscillation over shorter distances that could lead to the discovery of "sterile" neutrinos.

LArTPCs image particles produced within the detector volume by detecting ionization signals at the anode wires over the course of a readout window several milliseconds in duration. Subsequent assignment of energy to these reconstructed particles is done by a careful measurement of the amount of ionization charge detected at the wire planes. In order to obtain accurate energies, a correction must be made to account for charge loss/smearing that occurs due to various detector effects within the LArTPC and associated electronics readout chain. Some of these detector effects are particularly difficult to isolate in large underground detectors (such as the DUNE far detector LArTPC) given a relatively low cosmic muon flux.

A failure to pin down these detector effects could result in a bias in reconstructed particle energy scale/resolution, which could significantly impact the physics programs of LArTPC neutrino experiments such as DUNE and SBN. In the case of measuring the amount of CP violation in the neutrino sector at DUNE, a bias in energy scale or resolution of reconstructed neutrino candidates could lead to a significant reduction in sensitivity of the measurement or even a bias in the estimated amount of CP violation in comparison to the true value. The impact of detector effects has been identified as a limiting factor on the ultimate precision of the measurement, with an energy scale uncertainty of 1–2% as the preliminary goal [6]. Furthermore, the low-energy physics program at DUNE, including study of solar and supernova neutrinos [7], requires precise knowledge of energy scale and resolution at low energies to prevent bias in extracted physics parameters [8, 9]. As a result, precision calibration of the DUNE LArTPC detectors is absolutely essential for DUNE to achieve its physics goals. Similarly, the physics measurements to be done at the SBN Program will require precision energy measurements that likewise require precise calibration of the LArTPC detectors.

This Letter of Intent summarizes various activities and interests related to LArTPC detector calibration for DUNE and the SBN Program. We wish to highlight the need for precise detector calibration in enabling precision physics with large LArTPC detectors, and accordingly the need for funding dedicated efforts focusing on unleashing the true potential of this detector technology. This concerns not only DUNE and the SBN Program but also the broader community making use of liquid argon detectors, including both neutrino and dark matter experiments.

2 Topics of Interest

A number of calibration topics are relevant for the success of DUNE and/or the SBN Program. Below is a list of some of these topics:

- **Identification of "Standard Candles" from Natural Sources for Calibrations:** Identifying "standard candles" or particles of known energy deposition (as a function of measurable kinematic variables) in the detector is necessary as it allows for the constraint of other detector parameters of interest, some of which are listed below. Examples include ^{39}Ar beta decays [10] and other radiological sources in the argon, stopping and through-going muons from cosmic rays [11], delta rays [12] from cosmic muons, Michel electrons [13], photons from neutral pion decay [14], and neutrons [15].

- **Modeling of Electron-Ion Recombination:** Charge loss from prompt electron-ion recombination, occurring immediately after ionization is initially created, is important to quantify and account for in particle energy measurements. This effect is dependent on the local electric field magnitude, local ionization density, and potentially the angle of the ionizing particle trajectory with respect to the electric field direction. While measurements have been made at ArgoNeuT [16] and ICARUS [17], more work is needed to precisely constrain this effect to the 1–2% level. Global constraints from NEST [18], including characterization of recombination fluctuations, may be helpful.

- **Measurement of Electric Field Distortions:** Electric field distortions, such as those introduced by space charge effects from positive argon ions created by cosmic rays via ionization, or from detector misalignment, can lead to complications in particle energy reconstruction. This includes impact from variations in electron-ion recombination (dependent on electric field magnitude) and spatial squeezing/stretching of particle tracks [19]. Measurements from MicroBooNE [20, 21], ICARUS [22], and ProtoDUNE-SP [23], the single-phase prototype detector [24] for the DUNE far detector, are informing this calibration effort.

- **Electron Lifetime Measurements:** The impact of charge attenuation from attachment of ionization to impurities in LArTPC detectors, quantified by the electron lifetime, must be carefully accounted for in particle energy measurements. This effect can vary substantially as a function of time and position within the detector, and so fine-grained measurements are needed. Detectors located near the surface, such as ProtoDUNE-SP and the SBN Program detectors, benefit from a high cosmic muon flux in making these measurements using cosmic muons [23]. The DUNE far detector will see a much lower cosmic muon flux, and so it may be difficult to pin down this effect precisely in time/space, though ^{39}Ar beta decays will enable more fine-grained measurements [10].

- **Wire/Pixel Field Response Estimation:** A detailed modeling of the wire field response in LArTPC detectors has been carried out at MicroBooNE [25], using TPC ionization data to validate the model [26]. This modeling may need to be improved further in order to reduce bias in energy measurements, using data from running LArTPC experiments or small R&D setups for tuning/validation. A similar program should be carried out for LArTPC detectors using pixels for electrodes, such as the LArTPC concept to be used in the DUNE near detector [27].

- **TPC Front-End Electronics Characterization:** TPC front-end electronics located inside the liquid argon [28] (or outside of the cryostat in the case of ICARUS [29]) must be carefully characterized and calibrated in order to ensure accurate charge measurements that are stable throughout the lifetime of the experiment. Studies of gain and peaking time variations/stability [26], as well as measurements of noise levels [30], have been carried out at MicroBooNE; preliminary studies have also been carried out at ProtoDUNE-SP [23]. Further study will be necessary for different TPC electronics designs to minimize associated uncertainties in particle energy scale/resolution.

- **Scintillation Light Yield and Light Detector Response Determination:** Scintillation light detectors at LArTPC neutrino experiments are often used for timing measurements and triggering on non-beam events (e.g. proton decay). Additionally, they may provide better energy measurements when combined with ionization data from the TPC. In all of these applications, there must be precise understanding of initial scintillation light yields, effects of Rayleigh scattering, and light detector acceptance and quantum efficiency beyond what current measurements [23] can provide.

- **Dedicated Calibration Hardware:** Dedicated calibration hardware can be useful as it provides coverage in constraining certain low-level detector effects when it is difficult to do so with standard candles from natural sources, which are especially limited in underground detectors such as the DUNE far detector. A UV ionization laser system is used at MicroBooNE for measuring electric field distortions [20, 31], and a similar system is planned for SBND; a different design is being explored for the DUNE far detector [3]. In addition, a pulsed neutron source (DD neutron generator), argon purity monitor hardware, and deployable radiological sources are being explored for the DUNE far detector for use in energy calibrations [3].

- **Use of Prototype Detectors:** Many of the detector effects listed above can be studied at prototype LArTPC detectors, such as ProtoDUNE-SP, which has already produced preliminary calibration results [23]. Calibration studies at MicroBooNE will greatly benefit future experiments such as DUNE and the SBN Program. Additionally, dedicated calibration hardware can be tested in advance using prototype detectors, as is planned for the second run of ProtoDUNE-SP for R&D toward deployment at the DUNE far detector. Finally, some measurements, including measurement of electron-ion recombination and wire/pixel field response, might be better made with smaller R&D LArTPCs in a more controlled environment.

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