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The MicroBooNE Detector: Status After Three Years of Data Taking

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MicroBooNE is a 100-ton scale liquid-argon time projection chamber (LArTPC) neutrino experiment located on the Booster neutrino beamline at Fermilab. The experiment first started collecting neutrino data in October 2015. The detector, the first in the short-baseline neutrino program at Fermilab, is the longest operating LArTPC to date and plays an important role in a phased program towards the construction of massive kiloton scale detectors for future long-baseline neutrino physics (DUNE). We present results on the performance of the detector after three years of data-taking, highlighting operational accomplishments such as the high electron lifetime and signal-to-noise levels achieved. Additionally, we describe the current state of MicroBooNE reconstruction, presenting results which show the detector's ability to perform sub-millimeter tracking and produce accurate momentum and calorimetric measurements capable of enabling the analyses needed to explore the exciting neutrino interaction physics this detector was built for.

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1. Introduction

Neutrino oscillations are an empirically established beyond the Standard Model phenomenon. The field has rapidly been moving from an era of discovery to precision measurements which aim to test neutrino mixing unitarity, CP violation in the lepton sector, and resolve anomalies which have been associated with possible sterile neutrinos. One method via which these tests can be carried out aims to use intense and controlled muon neutrino beams of $\mathcal{O}(1)$ GeV energies combined with large-scale LArTPC detectors capable of producing fine-grained images of neutrino interactions, which in turn can enable precision oscillation measurements.

MicroBooNE contributes to this program in two ways. First, the detector was specifically built to investigate the nature of the excess of low-energy electron-like neutrino events recorded by the MiniBooNE collaboration [1]. This can be achieved by relying on spatial and calorimetric information provided by a LArTPC, enabling the suppression of beam-induced γ backgrounds which impact MiniBooNE's analysis. Percent level measurements of ν-Ar interactions such as this are necessary in order to answer the open questions in the field. In addition, as the first large-scale LArTPC neutrino experiment in the US, MicroBooNE serves an important R&D role in developing the scalability and know-how required to operate this detector technology, with an eye in particular to the construction of the DUNE experiment.

This note summarizes the status of the MicroBooNE detector, providing a description of how the experiment's operations and event reconstruction are enabling its physics program.

2. Detector Overview and Operations Status

MicroBooNE is the longest-ever running LArTPC detector in a neutrino beam. Throughout its three years of operations, MicroBooNE has collected over 9E20 POT, corresponding to $\mathcal{O}(10^5)$ neutrino interactions in the fiducial volume.

The detector is comprised of a cylindrical cryostat filled with liquid argon which encloses a 75 ton TPC. A -70 kV potential applied to the TPC's cathode allows ionization charge to drift in a 273 V/cm field towards the anode in 2.3 ms. Roughly eight thousand wires, distributed over three planes and spaced 3 mm apart, measure induced currents caused by drifting electrons. An array of 32 PMTs complement the measurement of ionization signals by detecting prompt scintillation light, used for triggering and cosmic-ray background rejection. Details on the MicroBooNE detector can be found in Ref. [2].

Key to the successful operation of the MicroBooNE detector are the high argon purity (NOTE-1003-PUB, NOTE-1026-PUB [7]) and high signal-to-noise [3] delivered by its cold electronics. The detector's cryogenic engineering and purification system have resulted in an electron lifetime consistently greater then 18 ms, providing a uniform detector response. MicroBooNE's employment of electronics kept in the cold argon are also a first, resulting in signal-to-noise levels of 20 and 40 on induction and collection wires respectively [3]. This enables su-MeV thresholds, opening a physics program at low energy which expands on the already rich study of GeV neutrino interactions.

The fine granularity and broad dynamic range of the MicroBooNE TPC leads to large data-volumes. MicroBooNE employs an online trigger which makes use of its PMT system to require light be seen in coincidence with the 1.6μs BNB neutrino beam. This trigger removes empty beam-spills from the data in which no neutrino interaction occurred, reducing rates by a factor of x20, and performing a powerful role in reducing backgrounds.

Operating on the surface requires dealing with a constant flux of cosmic-ray particles. Cosmic rays dominate the data collected by the experiment, both by producing scintillation light in time with the beam, forcing a trigger, as well as by depositing charge in the TPC volume during the long drift time, causing a "pileup" of cosmic-ray tracks which overlap the neutrino interaction. Cosmic interactions dominate the issuing of a trigger over neutrinos by a factor of 10-to-1, and for each recorded spill roughly a dozen cosmic interactions obfuscate the recorded event. Cosmic-ray suppression is a key aspect of MicroBooNE analyses: it is achieved by employing pattern recognition algorithms which make use of TPC information, and the use of scintillation light to time cosmic-ray tracks and separate them from any energy deposition associated with the beam. MicroBooNE is incorporating into its analyses an external Cosmic Ray Tagger, installed in 2016, to help further mitigate cosmic backgrounds.

3. Reconstruction Status

The goal of event reconstruction is to collect the information necessary to recover the flavor and energy of the interacting neutrino. Physics analyses in LArTPC detectors depend on a robust pattern-recognition capable of identifying different signal topologies and characterizing the kinematics of neutrino interaction final state particles. The ability to perform millimeter tracking and accurate calorimetric energy reconstruction are key to achieving this physics. MicroBooNE is the first detector of its kind to perform analyses employing solely fully-automated reconstruction and event selection, also an important milestone in the context of the broader LArTPC neutrino program. This section reports on the status of the MicroBooNE signal-processing and pattern-recognition performance.

The first step required to analyze MicroBooNE's data consists of identifying the spatial position and energy of ionization charge deposited in the detector volume. Key to this is the processing of signals from TPC wires. While designed as a fully-active calorimeter, a wire-instrumented TPC can exhibit a complex non-isotropic response caused by the relative orientation of ionization tracks and wires. MicroBooNE has developed novel signal-processing techniques which make use of cross-plane signal coincidences to extract ionization energy deposition information [4, 5]. This work goes beyond the basic removal of noise and electronics response features, improving signal response uniformity and the detector's efficiency in a phase-space otherwise difficult to access.

Pattern recognition algorithms are subsequently used to identify and reconstruct individual interactions occurring in the detector. MicroBooNE's current reconstruction, based on the Pandora multi-algorithm suite [6], and complemented by Kalman and vertex-fitting algorithms (NOTE-1049-PUB [7]) achieves sub-millimeter tracking and vertexing resolution. These in turn enable accurate reconstruction of kinematic variables as well as the identification of low-threshold particles associated with neutrino interaction vertices. MicroBooNE is also leading the development of novel reconstruction approaches, making use of deep neural networks for neutrino and particle identification [8, 11] as well as tomographic imaging (NOTE-1040-PUB [7]).

Millimeter tracking and accurate energy reconstruction allow reconstruction of the kinematics associated with particles produced in neutrino interactions with the accuracy required to perform precision neutrino measurements. Range-based momentum determination provides energy resolution of a few percent for contained tracks of several hundred MeV in energy. Additionally, MicroBooNE has refined a technique for the determination of muon momentum via multiple Coulomb scattering which provides an energy estimate for un-contained tracks, achieving momentum resolution of 10-20% (NOTE-1049-PUB [7]). This, combined with its calibration strategy (NOTE-1048-PUB [7]), allows for particle identification techniques capable of distinguishing protons from minimally ionizing pions and muons.

Central to the oscillation physics objective of MicroBooNE and other LArTPC experiments is the study of ν_e interactions from $\nu_\mu \to \nu_e$ oscillations. Identifying and reconstructing ν_e events requires being able to measure electromagnetic showers produced by the outgoing lepton. In the few-hundred MeV energy range (key to MicroBooNE's physics program) the sparse and stochastic nature of EM showers in liquid argon make this a non-trivial task. The experiment is developing important techniques for the reconstruction of EM showers and their energy determination, with results focusing on calibration sources such as Michel electrons [10] and photon showers from neutral pion decays (NOTE-1049-PUB [7]). Pioneering machine learning techniques for this purpose are also being developed to better identify and isolate EM activity [11]. These studies are enabling current measurements of interactions with final state EM activity.

4. Conclusions and Outlook

After three years of data-taking the MicroBooNE experiment has demonstrated stable and successful performance, achieving many important operational milestones and results. A wide range of sophisticated tools have been developed which are enabling MicroBooNE's current physics program. These techniques are having an impact on the broader LArTPC community and are being shared within the SBN and DUNE collaborations. As MicroBooNE continues to operate, improvements are being pursued in order to achieve its primary goal of investigating the MiniBooNE excess, with a particular focus on increasing reconstruction efficiencies with increased background rejection power.

References

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