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The role of ProtoDUNE-SP in future oscillation physics

Richard Diurba for the DUNE Collaboration[1,*]
[1] *University of Bern*
E-mail: rdiurba@fnal.gov

Long-baseline oscillation experiments are entering a new phase where neutrino beams can provide ultra-high fluxes over long distances. These beams will lead to an era of high statistics in large neutrino detectors, creating new systematic uncertainty-limited analyses. The Deep Underground Neutrino Experiment (DUNE) plans a high flux beam to travel 1300 km to 10-kT liquid argon detector modules. While neither the near detector nor the far detector has been constructed, prototypes of the DUNE Far Detector have been built and operated at CERN. One prototype, ProtoDUNE Single-Phase, is a full-scale mockup of the first 10-kT DUNE Far Detector module and can inform DUNE on detector performance and particle passage in argon. The proceedings discuss some published and in-progress results from ProtoDUNE-SP and how these results can impact current sensitivity studies and future analyses.

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*Speaker

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1. Introduction

The Deep Underground Neutrino Experiment (DUNE) represents an international collaboration building a long-baseline neutrino oscillation experiment using liquid argon time projection chambers (LAr TPCs) as Far Detector modules. To prototype the first module for the Far Detector, DUNE constructed ProtoDUNE Single-Phase (ProtoDUNE-SP), a 770-ton LAr TPC, at CERN Neutrino Platform [1]. The detector ran from 2018 to 2020 and took two months of hadron beam data from a tertiary hadron beam originating from the CERN Super Proton Synchrotron [1, 2]. It then took almost a year and a half of cosmic data.

Intended as both an engineering prototype and a test beam experiment, ProtoDUNE-SP can have a more prominent role in DUNE oscillation physics through ProtoDUNE-SP data. The proceedings summarize the talk from NOW 2022 on how both detector physics data and particle passage data taken from ProtoDUNE-SP can push forward the field's projections of DUNE sensitivities for determining the neutrino mass hierarchy and measurements of the mixing parameters in the leptonic sector.

2. DUNE Sensitivity Studies

DUNE's most recent complete oscillation sensitivity study was published in 2020 [3]. Instead of discussing the results, the Far Detector simulation remains the focus. DUNE simulated a Far Detector module using LArSoft, GENIE, and GEANT4. It required decisions on detector performance, detector-related systematic uncertainties, reconstruction-related uncertainties, and neutrino interaction modeling-related systematic uncertainties. For example, the simulation set the purity of liquid argon at 100 ppt O_2 equivalent, referred to as a drift electron lifetime of 3 ms. Other uncertainties included the electric field stability, limited to 1% across a 10 kT module, and the resolution of reconstructed neutrino-induced final state particle energies, which came from a parameterized formula with different parameters for different particle species.

ProtoDUNE-SP can prove the reasonableness of the uncertainties used, improve uncertainties with constraints and methods developed at ProtoDUNE-SP, and inform choices for detector parameters used on future simulation samples. The following sections cover some relevant measurements and analyses from ProtoDUNE-SP.

3. Detector Physics of ProtoDUNE-SP

The detector physics requirements necessary for the Far Detector module were guidelines for what ProtoDUNE-SP must prove. These requirements were written in the DUNE Technical Design Report [4]. ProtoDUNE-SP's detector performance paper reported that each primary requirement had been accomplished for electric field stability, cold electronics noise, measured liquid argon purity, and the timing and detection capabilities of the scintillation light detectors used [1].

The ProtoDUNE-SP surpassed the highest-level technical specifications for the first DUNE Far Detector module. The detector operated at 500 V/cm successfully. The drift electron lifetime was measured above 20 ms, significantly higher than the 3 ms technical specification. The cold electronics noise was below 1000 electrons ENC (550 for collection wire channels, 650 for induction

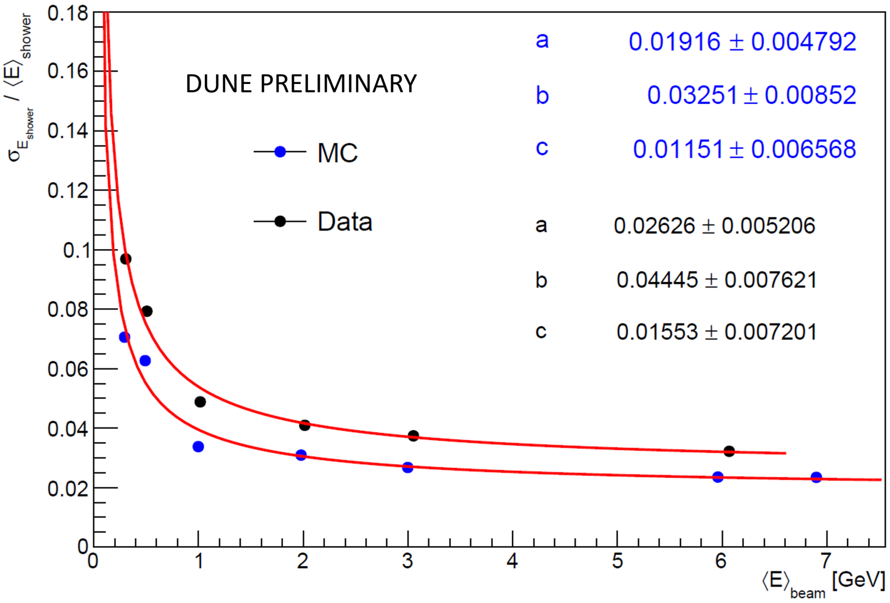

Figure 1: Measured positron energy resolution across the beam momentum settings of the test beam. The distributions are fitted to the equation: $\frac{\sigma_E}{E} = \sqrt{a^2 + (b/\sqrt{< E >})^2 + (c/<E>)^2}$.

wire channels), and the light detectors had photons detected per MeV and timing resolutions above requirements. These ultimately confirm the initial assumptions used to simulate the Far Detector.

Furthermore, these results can guide alternative samples with different low-level detector parameters, specifically the high and low limits used for fluctuating the simulation parameters. These alternative samples enable studies on the impacts and correlations of detector effects on oscillation analyses. Evaluating detector-related and calibration-related uncertainties through these alternative samples provide comparisons more informed by current and past LAr detector development.

4. Particle Passage Data of ProtoDUNE-SP

ProtoDUNE-SP took data of charged hadrons, muons, and positrons at energies measured by the beamline instrumentation [1, 2]. The energy information allows ProtoDUNE-SP to study the calorimetric response of the detector to these test beam particles and to measure a cross section of charged hadrons on argon.

The first involves measuring the calorimetric response of particles in the liquid argon, which improves track and shower energy reconstruction. An example would be the ongoing analysis of the positron energy reconstruction that can test energy resolution uncertainties, as shown in preliminary Figure 1.

The measurement of cross sections of charged particles on argon feeds back to long-baseline oscillation physics in two ways. The cross section can be used to evaluate systematic uncertainties associated with secondary interactions of final state particles re-scattering off the argon while traversing the detector. These cross sections can also inform neutrino event generators by providing external data to tune final state interaction modeling inside the nucleus. Pions represent one of the

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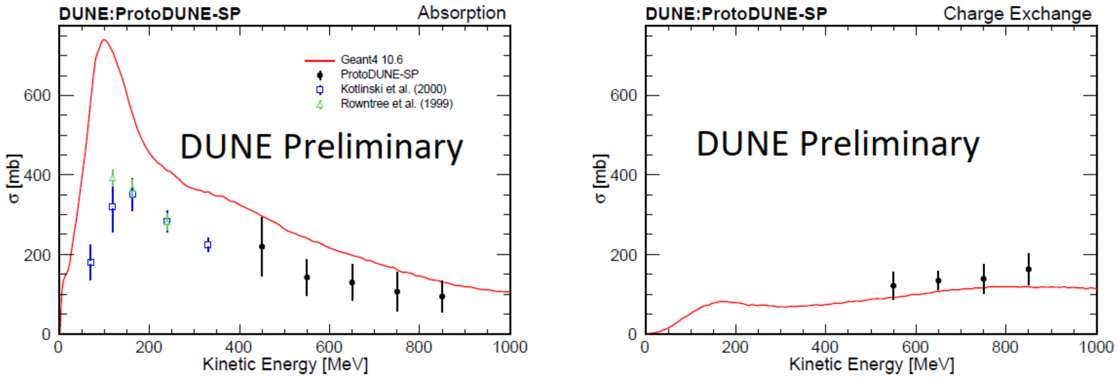

Figure 2: Measured cross section on argon for pions using a likelihood fitter with a regularized result. Shown are the pion absorption cross section (left) and the pion charge exchange cross section (right).

most pertinent particles for DUNE due to their high expected frequency as final state particles in neutrino interactions. ProtoDUNE-SP has measured exclusive cross sections of pions around the energy ranges of 0.5 GeV to 1 GeV. The channels include pion charge exchange and pion absorption on argon. Figure 2 shows the preliminary cross section compared to GEANT4.

Publications on particle passage for positrons, kaons, pions, and protons are all planned soon from ProtoDUNE-SP. They can inform the simulations of the calorimetric response and tune the modeling of neutrino-induced and hadron-induced scattering off argon.

5. Conclusion

ProtoDUNE-SP is a prototype to inform the design and performance of the first DUNE Far Detector module. The measurements from ProtoDUNE-SP provide an insight on the precision of the first Far Detector module, and these measurements of precision can act as modeling parameters in long-baseline oscillation sensitivities. These studies will continue with future studies from ProtoDUNE-SP and ProtoDUNE Horizontal Drift, ProtoDUNE-SP's successor, on the performance of large, monolithic wire-based liquid argon detectors.

References

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