ANALYSIS OF THE MUON AND TWO PROTON FINAL STATE WITH THE SHORT-BASELINE NEAR DETECTOR

NADIA TALBI as mentored by DR. MINERBA BETANCOURT

ABSTRACT. The neutrino remains an enigma within the Standard Model. The Short-Baseline Near Detector (SBND) at Fermilab probes these particles by examining essential regions of research such as oscillation measurement and searches for sterile neutrinos. This research intends to further our understanding of neutrino properties by establishing selection criteria for the one muon two proton final state (µ2p) at SBND. Using Monte Carlo simulation data, various kinematic variables are analyzed to optimize detection efficiency and purity. These findings will be compared with data collected by SBND to study how our models compare to experimental results.

1. INTRODUCTION

The Standard Model of particle physics conveys our fundamental understanding of matter and its interactions in the universe. However, it does not account for phenomena such as matter-antimatter asymmetry, dark matter, dark energy, gravity, or the origin of neutrino mass.

The neutrino is the host of a multitude of enigmas: origin of mass, mass hierarchy, flavor oscillation & mixing parameters. The open questions of the neutrino may be hints at fundamental properties of the universe we have yet to understand. Thus, further insight into the neutrino may result in resolutions to quandaries of the Standard Model. For this reason, neutrino research is becoming increasingly relevant, with various strategies being developed to detect these elusive particles. Liquid Argon (LAr) detectors are emerging for neutrino experiments, as they offer powerful resolution and detailed imaging capabilities. Understanding neutrino interactions within LAr detectors, particularly neutrino-nucleon interactions, is essential to reduce uncertainties and improve the accuracy of neutrino measurements.

This research intends to probe the neutrino interaction signature of one muon and two protons through SBND. Previous studies at ArgoNeuT[1], MicroBooNE[2], and ICARUS[3] have examined the µ-2p final state, but more research is necessary to achieve a sufficient understanding of this signature. The dense LAr nuclei in SBND enable numerous neutrino interactions, resulting in sufficient µ-2p statistics, demonstrating strong protential to examine this final state. This capability additionally allows SBND to observe a range of interactions from quasi-elastic production (QE), meson exchange current (MEC), resonant pion production (RES), neutral current (NC), deep inelastic scattering (DIS), & cosmic muons.

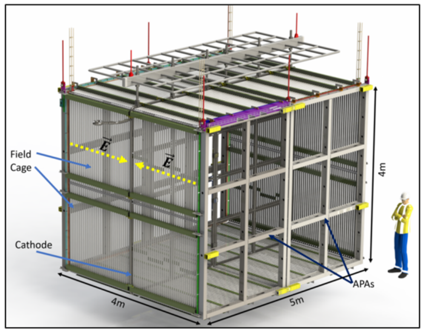

Figure 1. *The design of the Time Projection Chambers (TPC) of the Short-Baseline Near Detector*

µ-2p events should be produced by QE & MEC processes; however, RES may produce a similar topology with a µ-p-π final state. Consequently, the pion tracks may often be misidentified as protons. This source of uncertainty exhibits the importance of studying the µ-2p final state. To accurately identify the µ-2p signature, it is necessary to develop precise selection criteria, sensitive cuts, and a detailed analysis of kinematic variables. Ultimately, this study aims to minimize misidentification & further the precision of neutrino analyses.

2. Detector

The Short-Baseline Neutrino Program studies the neutrino through their interactions with charged particles. This analysis focuses on the Short-Baseline Near Detector (SBND) (Figure 1). The detector is situated just over 100 meters away from the Booster Neutrino Beam (BNB) neutrino source. Liquid Argon Time Projection Chambers (LArTPC) among other components allow SBND to detect charged decay products, perform comprehensive LAr neutrino studies, and inform future neutrino experiments such as DUNE. The detector compares yields of neutrino flavors with other detectors on the beamline to measure oscillation parameters and identify potential discrepancies.

3. Analysis

Throughout this analysis, the µ-2p final state is selected, as generated by Monte Carlo simulation and reconstructed using Pandora. This final state was examined with multiple variables. By comparing the contributions of certain production methods, namely RES, QE, and MEC, one can determine essential information about neutrino-nucleon interaction modeling.

The µ-2p event selection was adapted from Jack Smedley from ICARUS[4] to the following criteria, informed by Figure 2. The following cuts were used in this analysis:

- **Fiducial:** the vertex of this interaction is contained within the detector
- **Muon selection µ:** $\chi^2_\mu > 30$; $\chi^2_p < 60$; Track length > 50 cm
- **Proton selection µ-(2)p:** $\chi^2_\mu \neq 0$; $\chi^2_p < 65$ ($p_{leading}$ as longest track)

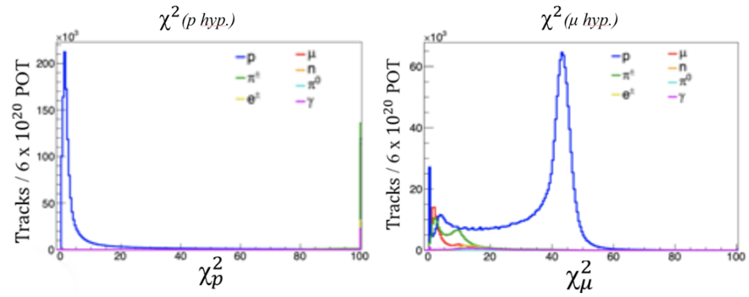

FIGURE 2. *Event tracks as a function of χ^2 values created by Shweta Yadav*[5] *for muon (right) & proton (left) hypotheses. The legend distinguishes the yields of each particle relative to each χ^2.*

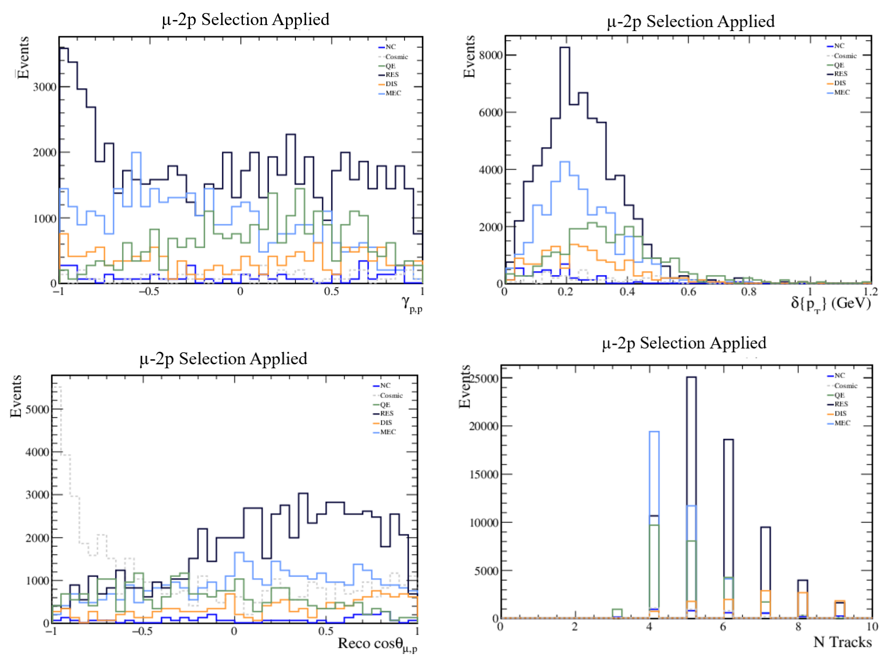

FIGURE 3. *Event yields of δ_{pT} (upper left), reco. cos $\theta_{\mu,p}$ (lower left), reco. cos $\gamma_{p,p}$ (upper right), and N Tracks (lower right) following the μ-2p selection*

- **Pion Cut:** $\chi^2_\mu \neq 0$; $\chi^2_p < 50$; $\chi^2_\pi < 30$; Track length < 10 cm

The selection criteria listed above are applied sequentially. Following this selection, it was a common finding in each variable for QE processes to dominate until the second proton cut. At this point, RES production dominates, hinting that an additional cut to eliminate pions may be essential to optimize accurate event selection. Figure 4 demonstrates the results of such a cut. Prior to the pion cut attempt, it is quite difficult to distinguish μ-2p processes (i.e. quasi-elastic & meson exchange current) from contributing background (i.e. resonant pion production). The pion cut attempt decreases the background contribution and demonstrates the Number of Tracks as a distinguishing observable for the production modes.

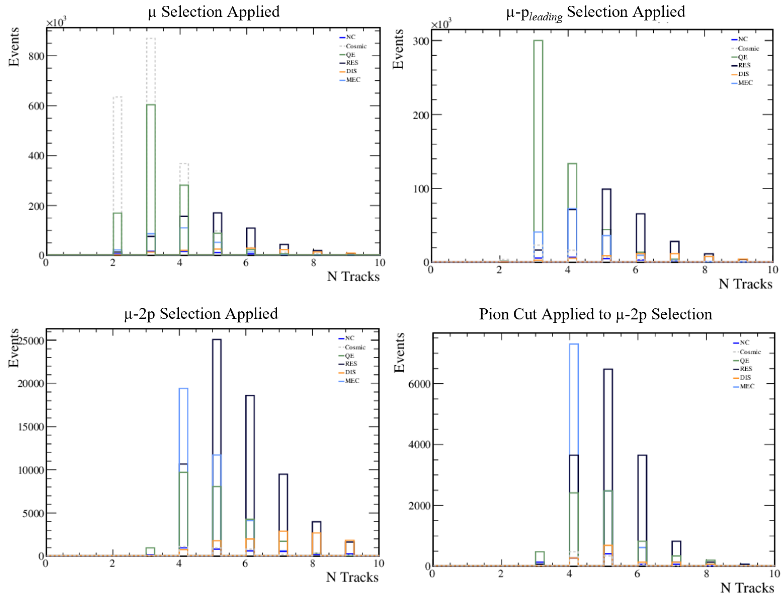

FIGURE 4. *Event yield progression in the N Track variable. The MEC & QE contribution in the fourth bin is favorable once the π cut is applied.*

An interesting feature among the cut progression in Figure 5 is the improved ratio of (QE+MEC)/RES following the added pion cut. This ratio goes from 0.886 with the μ-2p selection to 1.17 with the additional cut on pions. Despite improved purity, one must acknowledge the significant decrease in statistics following the pion cut. The future of μ-2p analysis will focus on examining real SBND data and comparing the results to our simulation.
Additionally as data collection commenced, I have scanned several μ-2p candidate events with SBND such as Figure 6.

4. Conclusion

The μ-2p final state is a promising site to study neutrino interactions within LAr detectors. The selected sample for one year shows around 144000 events in the muon and two proton final state. Within simulation, the μ-2p final state demonstrates a surplus of resonant pion events, implying the need for further cuts to improve data purity. Refining μ-2p criteria will increase precision of neutrino studies from oscillation measurements to sterile neutrino searches.

References

[1]Acciarri et al. (2014) arXiv:1405.4261 [nucl-ex] *The detection of back-to-back proton pairs in Charged-Current neutrino interactions with the ArgoNeuT detector in the NuMI low energy beam line*

Yields in True E_ν *(per year)*

6e20	RES	QE	MEC	DIS	NC	Total
No Cut	2053020	2990000	772450	469420	934777	7219667
Proton	295316	497519	162258	48897	24311	1028301
Two Protons	69490	25137	36432	10743	3099	144901
Pion Cut	14807	6749	10537	1033	826	33952

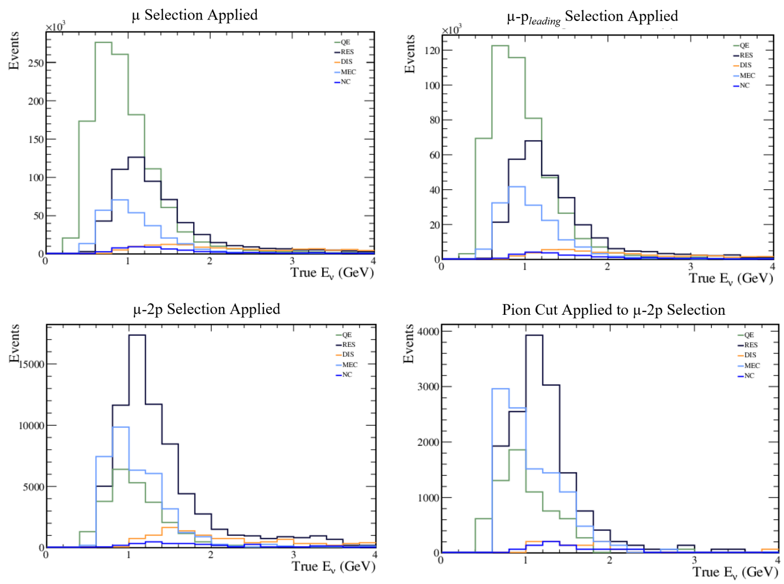

FIGURE 5. *MC simulated progression of event yields after each cut in True* E_ν

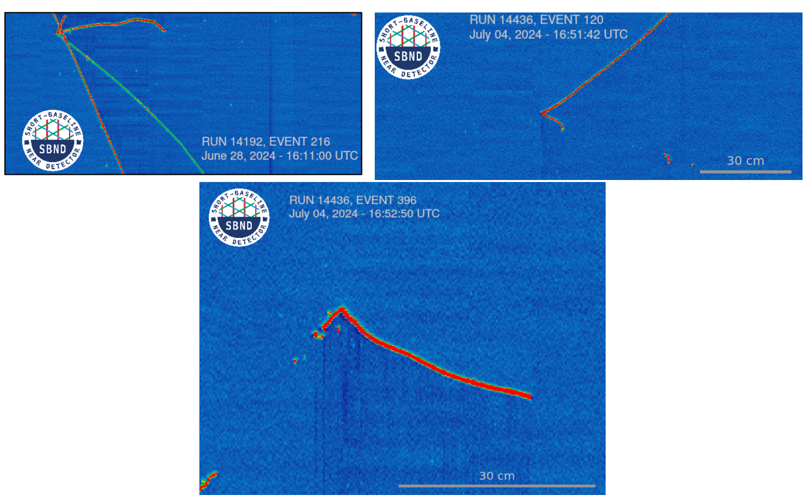

FIGURE 6. *Event displays of μ-2p and μ-p candidates among the first data collected by SBND*

[2]Abratenko et al. (2023) arXiv:2211.03734 [hep-ex] *First Measurement of Differential Cross Sections for Muon Neutrino Charged Current Interactions on Argon with a Two-proton Final State in the MicroBooNE Detector*

[3]Howard et al. (2024) *Charged Current Mesonless Analysis with the off-axis NuMI beam at ICARUS*

[4] *Current Status of CC2p0π Selection* SBN-doc-35781-v2

[5] *Strategy for Event Selection for the (SB)ND Constraint in the Oscillation Analysis* SBN-doc-31313-v2

Thank you to Dr. Minerba Betancourt, Shweta Yadav, Jack Smedley, Dr. Tom Junk, Dr. Jaesung Kim, Dr. Henry Lay, Terry Kim, & the SIST program for your wisdom and generous support.