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The νPRISM Detector

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Abstract

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I. INTRODUCTION

Now that neutrino appearance has been observed by the T2K experiment [1], it is possible to determine the neutrino mass hierarchy and CP phase with current (T2K [2], NOνA) and proposed (Hyper-K [3], LBNF, LBNO) long baseline accelerator experiments. To make precision measurements of neutrino mixing parameters, including the CP violating phase, future experiments must achieve systematic uncertainties on neutrino event rate predictions at the 2% level or better. The current T2K ν_e appearance measurement, the combined uncertainty on the neutrino flux and interaction modeling is 8.8%. Significant improvements are therefore needed to reach the level necessary for precision oscillation measurements.

Substantial reduction to the overall systematic uncertainty is typically provided through the use of a near detector, which measures the initial rate of neutrino interactions prior to oscillation, however there are limitations to this technique as it is used currently. First, the near detector measures abundant ν_μ interactions to predict the oscillated ν_e event rate. In the T2K analysis, 3% of the total uncertainty is based on theory calculations of the ratio of ν_e to ν_μ cross sections; it is difficult to directly measure with comparable precision at the near detector as the ν_e component of the flux is significantly smaller by design. Second, uncertainties associated with the modeling of nuclear effects in neutrino interactions are significant in the T2K analysis; 7.5% are uncertainties which do not cancel in the extrapolation. Third, reports of non-standard physics, such as sterile neutrinos, would modify the near detector event rate and affect the extrapolation; alternate explanations such as nuclear effects would also be relevant for the long baseline program.

In recent years, the incorporation of nuclear effects into the modeling of neutrino interactions at the GeV scale has been a significant challenge. The MiniBooNE "excess" of CCQE-like ν_μ candidate events, particularly at large Q^2, has been interpreted as previously un-modeled nuclear effects which produce multi-nucleon final states with no final state pions. However, attempts to calculate these nuclear effects have provided disparate results, and there is still no model that postdicts all of the experimental data. Uncertainties associated with the modeling of nuclear effects in neutrino interactions are expected to be a dominant systematic uncertainty for future neutrino oscillation measurements.

Even if a model can correctly postdict observed event rates and kinematic distributions for a particular measurement an ambiguity often remains because the broad energy spectrum of neutrinos in neutrino beam presents an under-constrained problem, *ie.* it is not possible to find a unique solution for the energy dependent neutrino interaction rate and final state particle kinematics that satisfies the data. In one approach, the under-constrained problem is addressed by combining constraints from different experiments with spectra peaked at different energies. However, the effectiveness of this approach can be limited due to systematic differences in measurements from multiple experiments. A recent example is the seeming discrepancy in pion production spectra measured by MiniBooNE and MINERνA which can be interpreted as unexplained energy dependence of the cross-section or merely systematic effects unique to each experiment.

An experimental solution to these problems is to have a single experiment that over-constrains the problem by measuring the cross-section and final state particle kinematic distributions for a range of spectra peaked at varying neutrino energies. By making these measurements in a single experiment, the relative systematic effects can be well understood. If the neutrino flux can be predicted with enough accuracy, it may even be possible to extract the cross-section and final state particle kinematics over the energy region of interest in a largely model-independent way (as one could do with a mono-energetic neutrino beam).

A. The off-axis neutrino beam

Current long base-line experiments such as T2K and NOνA use off-axis beams that take advantage of the two-body decay kinematics of the charged pion to sample a narrow band beam. Fig. 1 shows the spectra of ν_μ neutrinos as a function of off-axis angle for the J-PARC neutrino beam. An experiment that samples off-axis angles ranging from 1 to 4 degrees observes neutrino spectra peaked between 400 MeV and 1000 MeV. These off-axis spectra are relatively narrow in energy compared to on-axis fluxes (MiniBooNE, K2K) at similar peak energies. Hence they can be used to provide a stronger constraint on the energy dependence of the cross section and relationship between neutrino energy and final states.

A detector with a base line of $\sim$ 1 km and off-axis spectra may also be used to search for short-baseline neutrino oscillations consistent with the LSND [4] or MiniBooNE [5] ν_e appearance anomalies. The observed excess in MiniBooNE may arise from oscillations associated with one or more sterile neutrinos, or more mundane mis-modeling of neutral current (NC) or charged current (CC) cross sections. If sterile neutrinos are the cause of the excess,

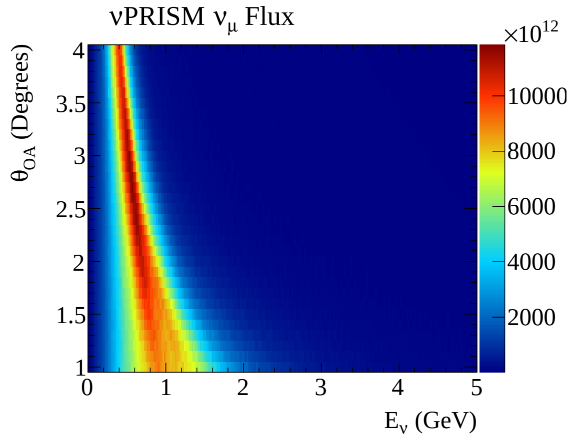

FIG. 1: The ν_μ flux spectra in the J-PARC neutrino beam for a range of off-axis angles.

the energy dependence of the oscillations will lead to a unique pattern over the range of off-axis spectra that can be differentiated from mis-modelled interactions.

B. The electron neutrino cross-section

The neutrino oscillation channel used to probe for CP violation is $\nu_\mu(\bar{\nu}_\mu) \rightarrow \nu_e(\bar{\nu}_e)$. While the beam observed by near detectors is $\sim 99\%$ $\nu_\mu(\bar{\nu}_\mu)$, the signal at the far detector is $\nu_e(\bar{\nu}_e)$. Hence uncertainties in the relative cross-section of muon and electron neutrinos are also critical. Electron neutrinos of energy 1 GeV can be produced in the decays of muons, however, in conventional beams a beam dump stops most muons before they decay. In the absence of a stored muon beam, the study of the ν_e cross sections at 1 GeV is challenging. Since the ν_e component of the beam is only 1%, a detector with a large fiducial mass and very pure particle identification capabilities is required. Recent improvements in electron and π^0 separation in water Cherenkov detectors, and the capability of water Cherenkov detectors to scale to very large fiducial masses suggest that they can be used to measure the electron neutrino cross section with unprecedented precision in a conventional neutrino beam.

II. THE νPRISM DETECTOR CONCEPT

The concept for the νPRISM detector is illustrated in Fig. 2. It is a tall water-Cherenkov detector located 1-2 km from the neutrino source in J-PARC neutrino beam. At 1 km, the detector is $\sim$50 m tall, covering the off-axis angle range of 1-4 degrees. The base-line to the detector is set to at least 1 km to control event pile-up rates and to reduce the line source effect of the pion beam. A water-Cherenkov detector is chosen since measurements on H_2O are most relevant for T2K and Hyper-K and the detector technology scales to large fiducial masses well. The detector diameter is set to 10 m based on the need to contain forward going muons with momentum up to 1.5 GeV/c to probe the relevant phase space for T2K and Hyper-K. More details of the design considerations and construction techniques for νPRISM are given in Section VI.

In νPRISM, a new off-axis angle, θ_{OA} observable is introduced. This observable is estimated by using the reconstructed vertex position for each event in νPRISM and calculating the angle between the average beam direction and the vector from the average neutrino production point to the reconstructed vertex. A given θ_{OA} corresponds to a predicted neutrino spectrum, and this additional information can be used to overconstrain the cross-section models or derive cross-sections in a model independent way.

A. Measurments in νPRISM

Charged current muon and electron neutrino interactions in νPRISM are identified by observing Cherenkov rings that are consistent with penetrating or showering particles respectively. Muon and electron candidates are further separated by the presence of a delayed Michel electron from the muon decay. Events with a single prompt muon or electron candidate ring are used for the oscillation candidate samples in T2K or Hyper-K oscillation measurements. Table I shows the number and purity of these events in νPRISM at 1 km with a 1e21 proton-on-target exposure.

The ν_μ neutrino statistics and purity are high enough that the final state particle response can be derived for an almost arbitrary input spectrum using the information from the various off-axis spectra. For example, the final state muon momentum and scattering angle distributions for a nearly mono-energetic spectrum or an oscillated spectrum can be

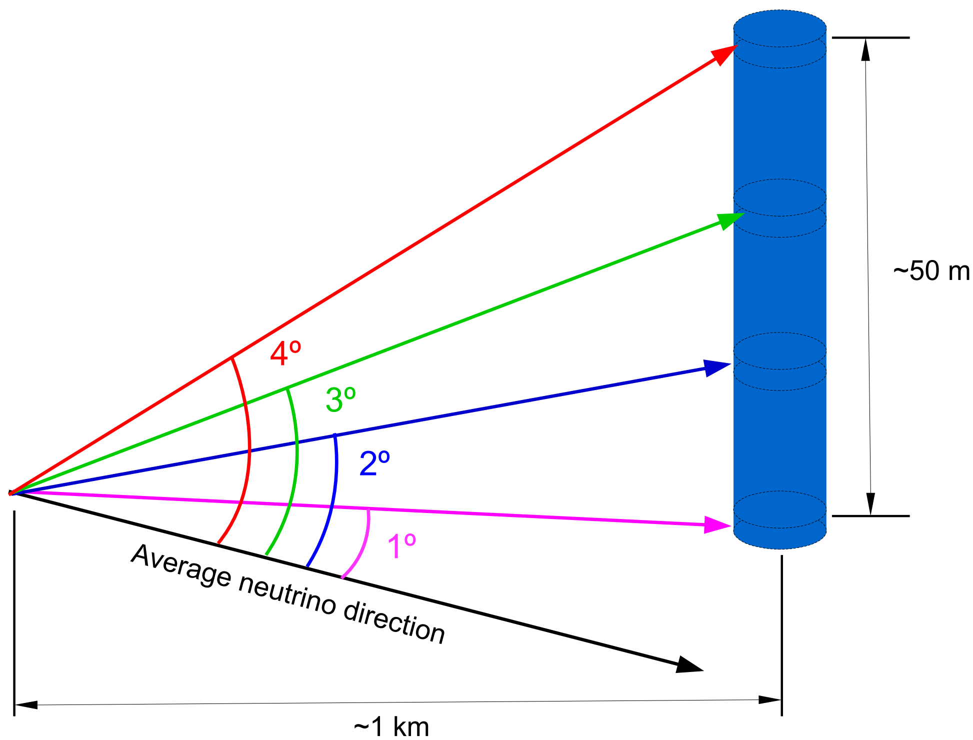

FIG. 2: The νPRISM detector concept.

TABLE I: The νPRISM candidate event rates for single ring muon and electron like samples for 1e21 protons on target in the J-PARC beam.

Off-axis Range	1 Ring Muon Candidates	CC ν_μ Purity	1 Ring Electron Candidates	CC ν_e Purity
1°-2°	7.8e5	97.3%	5.4e3	32.5%
2°-3°	4.3e5	97.7%	4.5e3	51.8%
3°-4°	1.9e5	97.2%	2.9e3	65.0%

derived, as described in Section III.

The ν_e statistics and purities in Table I are derived using the same photo-coverage (40%) and PMT size (20 inch) as Super-Kamiokande. As was shown in the proposal for a 2 km water Cherenkov detector for T2K, smaller PMTs with finer granularity can improve the performance, and that approach is being investigated for νPRISM. Regardless, even with 1e21 protons on target and large PMTs, a measurement of the ν_e cross section with a 3% statistical uncertainty on the normalization is possible. The ν_e candidate events will be used to measure the cross-section ratio relative to CC ν_μ interactions and to search for short baseline ν_e appearance, as described in Section III.

It is also possible to reconstruct events with two or more rings in νPRISM. Events with a lepton candidate and additional charged particle ring can be used to measure the cross-section for single charged pion production in charged current interactions. Events with two rings consistent with showering particles may be reconstructed as NCπ^0 events, and events with a muon-like particle that undergoes a hadronic scatter can be reconstructed as NC$\pi^\pm$ events. For the neutral current events, νPRISM provides a unique opportunity to directly measure the energy dependence of the cross-section in a single experiment. These additional measurements with νPRISM are described in Section V.

B. Flux modeling for νPRISM

νPRISM takes advantage of the off-axis angle observable θ_{OA} to predict the underlying neutrino spectrum for each interaction in νPRISM. The predicted spectrum is based on the flux model. For T2K the flux is predicted based on a data-driven simulation of the neutrino beamline from the interaction of protons in the target to the decay of hadrons and muons that produce neutrinos [6]. The dominant uncertainties in the flux modeling arise from modeling of hadronic interactions in the target, the magnetic horns and the decay region walls. However, dedicated measurements from hadron production experiments such as NA61/SHINE are significantly reducing these uncertainties. These hadron production measurements include measurements of particle production multiplicities on replica targets. By fully incorporating the replica target data, it is expected that experiments will be able to reduce uncertainties on the flux prediction even lower than the $\sim 10\%$ that has already been achieved by T2K and MiniBooNE [7]. With a precise flux prediction for νPRISM, the dependence of the neutrino spectra on θ_{OA} can be determined independently from νPRISM measurements, and that information can be incorporated in the derivation of neutrino cross-sections from the νPRISM data.

III. MEASUREMENTS WITH CC ν_μ CANDIDATES

As discussed in the previous section, νPRISM can reconstruct large, pure samples of charged current events with a muon candidate and no other particles above Cherenkov threshold. For each event, the off-axis angle θ_{OA} is reconstructed and this observable implies additional information about the distribution of possible neutrino energies based on the prior flux model. Data binned in θ_{OA} and the usual muon observables of momentum (or kinetic energy) and scattering angle are used to constrain the cross section model. In the typical approach, the data may be unfolded to find the cross-section in the true variable of neutrino energy, muon momentuma and muon scattering angle. However, unfolding relies on regularization to deal with the ill-defined nature of the problem, and may not perform well when unfolding for θ_{OA} to the neutrino energy.

We take an alternative approach of using the off-axis neutrino spectra impinging on νPRISM as a set of basis functions. We then write a spectrum of interest as a linear combination of the off-axis spectra:

$$F_{\nu_\mu}(E_\nu) = \sum_i c_i \phi^i_{\nu_\mu}(E_\nu). \tag{1}$$

Here $F_{\nu_\mu}(E_\nu)$ is an arbitrary function of interest, $\phi^i_{\nu_\mu}(E_\nu)$ is the predicted spectrum in the i^{th} off-axis angle bin and c_i are simply coefficients. The challenge is to find a set of c_i that approximatly satisfy the equation while minimizing the statistical and systematic uncertainties that are propagated through the linear combination. Once the c_i are found, we can write a similar equation for the observables:

$$N(p_\mu, \theta_\mu | F_{\nu_\mu}(E_\nu)) = \sum_i c_i N^i(p_\mu, \theta_\mu). \tag{2}$$

In this way, the final state particle multiplicities and kinematics can be measured for an given choice of of the input neutrino energy spectrum. For neutrino cross section measurements, one may choose an input spectrum that approximates a mono-energetic beam. For neutrino oscillation

A. Pseudo-monoenergetic beams

IV. MEASUREMENTS WITH CC ν_e CANDIDATES

V. OTHER MEASUREMENTS IN νPRISM

VI. DETECTOR DESIGN AND CONSTRUCTION CONSIDERATIONS

VII. CONCLUSION

ACKNOWLEDGMENTS

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