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νPRISM: A new way of probing neutrino interactions

Mark Scott[*†]
TRIUMF
E-mail: mscott@triumf.ca

In both neutrino interaction and neutrino oscillation measurements the rate of events you observe directly depends on the energy of the incident neutrino. Unfortunately this energy cannot be measured directly, and experiments rely instead on the outgoing lepton and observed nucleons. To translate these observables into a neutrino energy we must assume knowledge of the neutrino interaction and average over the neutrino flux. Current measurements of neutrino-nucleon interactions do not agree well with existing models and indicate that the relationship between neutrino energy, true underlying interaction and particle kinematics is not well determined.

νPRISM is a proposed near detector for a long baseline neutrino beam experiment. Sited 1km from the beam production point, the detector spans a range of off-axis angles relative to the neutrino beam direction. As the off-axis angle changes so does the beam energy spectrum, providing a way of directly relating the neutrino energy to the experimental observables. This talk discusses the νPRISM concept, showing how it can be used for neutrino cross section measurements and showing how it reduces neutrino interaction uncertainties in oscillation measurements.

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*Speaker.
†for the νPRISM collaboration

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1. Introduction

In the last decade neutrino physics has entered the 'precision era'. The discovery of large θ_{13} by Daya Bay [1], RENO [2] and T2K [3] has opened the door to observing CP violation in the lepton sector, and the next generation of long baseline neutrino experiments, Hyper Kamiokande (Hyper-K) and LBNF, are being designed to make this measurement. The Particle Physics Project Prioritization Panel (P5) report [4] set a requirement for any future long baseline neutrino experiment, stating that

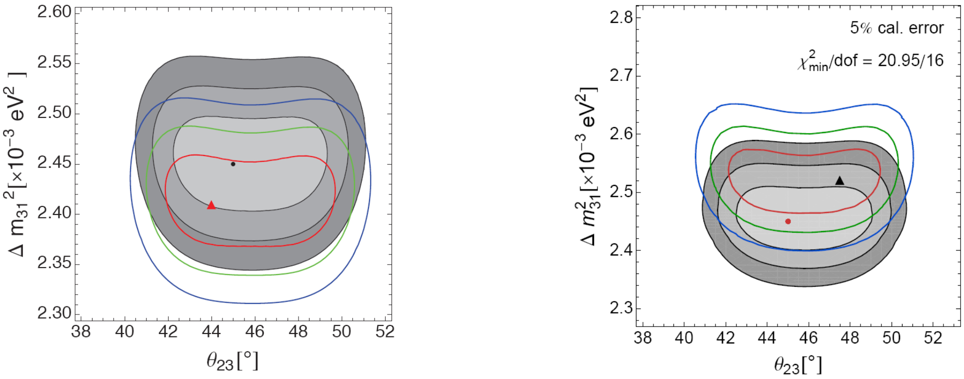
> ...we set as the goal a mean sensitivity to CP violation of better than 3σ (corresponding to 99.8% confidence level for a detected signal) over more than 75% of the range of possible values of the unknown CP-violating phase δ_{CP}.

To meet the P5 requirement, both LBNE [5] and Hyper-K [6] require the total systematic uncertainty on their far detector rate prediction to be less than 3%. This can be compared to the systematic uncertainty currently demonstrated by the T2K experiment, which has achieved a systematic uncertainty of around 7% on their far detector event rate prediction, with the greatest part of this coming from nuclear interaction uncertainties.

Recent work by, amongst others, P. Coloma *et al.* [7] and C.-M. Jen *et al.* [8] has helped highlight further obstacles that must be overcome to achieve the systematic uncertainty demanded by the next generation of oscillation experiments. In these papers the authors have simulated a "T2K-like" experiment and then used the GLoBES [9] framework to perform a muon neutrino disappearance analysis, fitting fake datasets using a given Monte Carlo (MC) model to extract the atmospheric oscillation parameters. In both cases the aim is to explore what happens to the oscillation parameter fit when the nuclear model present in the MC does not match the "true" model in nature. This was done by using two sets of fake data, one generated from the nominal MC and the other generated using a different nuclear model. The fake datasets are then each fit using the nominal MC and the 1, 2 and 3 σ confidence intervals, along with the best fit point, are plotted in the $\Delta m^2_{31} - \theta_{23}$ space. The results of this are shown in Figure 1, with results from the fit to the nominal MC shown with the shaded contours and circular point whilst the coloured contours and triangular best fit point come from the fit to the other fake dataset.

In Figure 1a a modified verion of the GENIE neutrino event generator [10] provided the nominal MC, which used the relativistic Fermi gas (RFG) model to describe the target nucleon momentum distribution. The fake data was generated using the same, modified, version of GENIE but with the RFG model replaced by O. Benhar's spectral function [11]. This study shows that if the MC used in an oscillation analysis does not use the same nuclear model as the data being fit then the oscillation parameters that are extracted can be shifted compared to their true values. In this case the measurements of both Δm^2_{31} and θ_{23} are about 2% below their true values.

In the paper by P. Coloma *et al.* they again used GENIE as their nominal MC but this time used the GiBUU [12] generator to create their fake dataset. These two generators implement essentially the same charged current quasi-elastic (CCQE) interaction model, with the major difference between the two coming from their treatment of final state interactions, described in more detail in Ref. [7]. It is also worth bearing in mind that both generators have been tuned to match the MiniBooNE CCQE cross section data. Figure 1b again demonstrates that if the MC model used in



(a) Nominal MC uses the RFG nuclear model whilst the SF was used for one fake dataset. Taken from Ref. [8]

(b) Using GENIE as the nominal MC and GiBUU to generate one fake dataset. Taken from Ref. [7]

Figure 1: The 1 (red), 2 (green) and 3 (blue) σ confidence intervals, along with best fit points, from the fake data fits described in Ref. [8] (left) and Ref. [7] (right). In both cases the solid intervals where created when fitting the fake data generated from the nominal MC whilst the coloured intervals come from the fit to the fake data generated using a different nuclear model.

the oscillation fit does not match the model present in the fake data then the oscillation parameters obtained are significantly shifted from their input values.

A third study was performed by the T2K collaboration, which used the full set of detector, flux and neutrino interaction systematic uncertainties from the published T2K disappearance analysis [13]. For this analysis three different MC models were tested, all of which used the NEUT neutrino interaction generator [14] and the T2K detector and flux simulations as their base. The first was the nominal NEUT generator, which provided the baseline oscillation fit results for the comparison. For the second MC model, any events that proceeded through the NEUT pionless delta decay (PDD) interaction channel were removed and replaced by events generated using the Nieves *et al.* [15] meson exchange model (MEC). For the third MC the same procedure was followed, but the Nieves MEC events were weighted so that the total MEC cross section matched that calculated by Martini *et al.* [16].

For each MC model the analysers applied the same throws of the flux, detector and neutrino interaction systematic uncertainties to produce a large number of fake datasets. Each dataset had the same variation applied to its neutrino flux, the detector systematics and the underlying neutrino interactions, but would either contain PDD events, Nieves MEC events or Nieves MEC events scaled to the total Martini cross section. An oscillation fit was then performed for each throw, and the oscillation parameters extracted using the nominal data set compared to the parameters from the two data sets containing MEC events.

This study showed that fitting either the Nieves or Martini MEC events introduces an additional 3% uncertainty on the value of $\sin^2\theta_{23}$ and for the Martini events in there is an additional bias in the extracted oscillation parameter of -2.9%. For the current T2K analyses these additional uncertainties are much smaller than the statistical uncertainty on the far detector event sample, but as more data is collected they will become more relevant.

The studies discussed above reflect some of the difficulties facing neutrino oscillation experiments due to imperfect knowledge of the underlying neutrino interaction physics. They also help show how hard it is to constrain the nuclear models used by today's neutrino generators, since even when two generators are tuned to the same cross section data they produce different predictions for the observed, oscillated, neutrino spectrum at an experiment like T2K. In order to measure neutrino oscillations precisely one needs to know the neutrino interaction cross section as a function of neutrino energy, since it is the observed L/E dependence of the neutrino spectrum that is used to measure the oscillation parameters. Unfortunately, it is exceedingly hard to measure the absolute energy of a neutrino experimentally without depending upon some model of neutrino and nuclear interactions. νPRISM is a proposed near detector for a T2K-like experiment that would provide a direct link between the neutrino energy and the experimental observables, allowing the determination of the neutrino energy without relying on an interaction model.

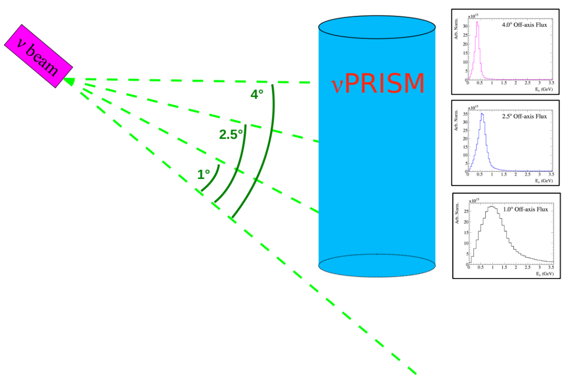
2. The νPRISM concept

The neutrinos in a conventional neutrino beam come from the two-body decay-in-flight of charged pions. As one moves further from the beam axis the observed neutrino energy spectrum narrows and peaks at a lower energy; this is called the "off-axis" effect. By measuring neutrino interactions across a range of off-axis angles νPRISM would sample many different neutrino spectra, each of which peaks at a different energy. A cartoon of this is shown in Figure 2a. The detector is split into slices, each at a different off-axis angle, which can be weighted and combined to create an arbitrarily shaped neutrino spectrum. Reconstructed events are selected in each slice, and applying the chosen linear combination to these events gives the expected reconstructed event distribution for the desired neutrino flux. An example of this is shown in Figure 2b, where a Gaussian flux centred at 700 MeV is created. The 1D histograms on the right show the different off-axis fluxes whilst the 2D histograms show the corresponding reconstructed lepton momentum and angle to the neutrino beam. The two lowest plots show the result of applying the linear combination, with the Gaussian flux on the right and the expected lepton kinematic distribution for that flux on the right. Using this technique, νPRISM provides a direct link between the observed reconstructed event information and the neutrino energy.

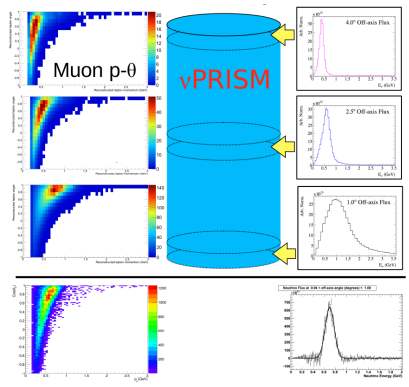
3. Neutrino physics with νPRISM

3.1 The νPRISM ν_μ disappearance analysis

Creating Gaussian neutrino beams demonstrates most clearly the process of linking neutrino energy to reconstructed observables, but for an oscillation analysis one must construct an *oscillated* neutrino spectrum. The muon neutrino disappearance spectrum is shown in Figure 3b, which also shows the predicted oscillated spectrum using a linear combination of off-axis slices at νPRISM. The reconstructed lepton kinematics predicted by νPRISM for the given set of oscillation parameters is shown in Figure 3a, clearly displaying the oscillation dip. For any set of oscillation parameters νPRISM can provide the expected lepton kinematic distribution that would be measured after oscillation without relying on neutrino interaction models to give the neutrino energy.

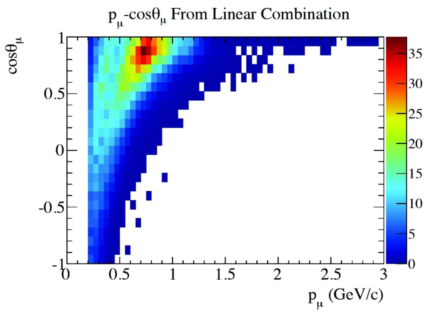


(a) The different neutrino energy spectra across the νPRISM detector.

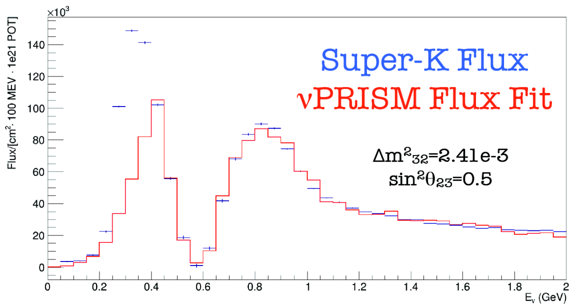


(b) An example of the linear combinations required to produce a Gaussian neutrino flux.

Figure 2: Cartoons showing the variation in the neutrino flux across the νPRISM detector and how measurements of these can be combined to produce a Gaussian neutrino flux.



(a) The predicted lepton kinematics that would be observed at the T2K far detector for the given set of oscillation parameters.

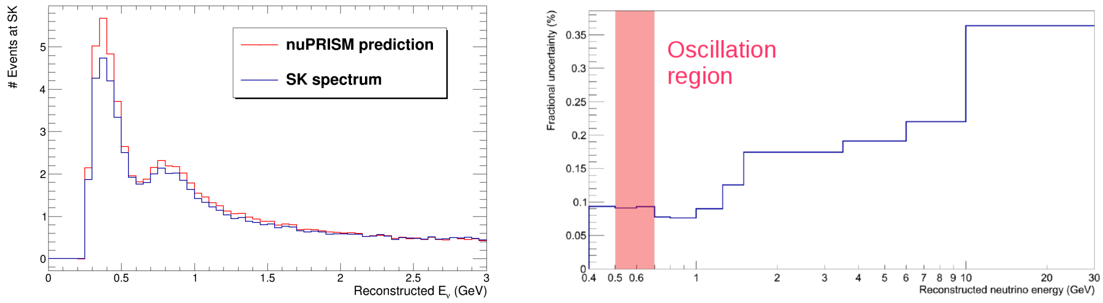


(b) A comparison between the true oscillated muon neutrino spectrum and the predicted spectrum from linear combinations at νPRISM.

Figure 3: The predicted and true oscillated muon neutrino spectrum at the T2K far detector, for a given flux prediction and set of neutrino oscillation parameters

Using this process a muon neutrino disappearance analysis was performed in the context of the T2K experiment, taking into account the full T2K flux and cross section uncertainties in addition to the statistical uncertainty from the linear combination. The oscillated Super-Kamioande (SK) reconstructed neutrino energy spectrum is shown in Figure 4 alongside the prediction from νPRISM and the total uncertainty on that prediction. The νPRISM prediction has a less than 10% total uncertainty in the oscillation region (between 500 - 700 MeV) and well reproduces the oscillated SK events.

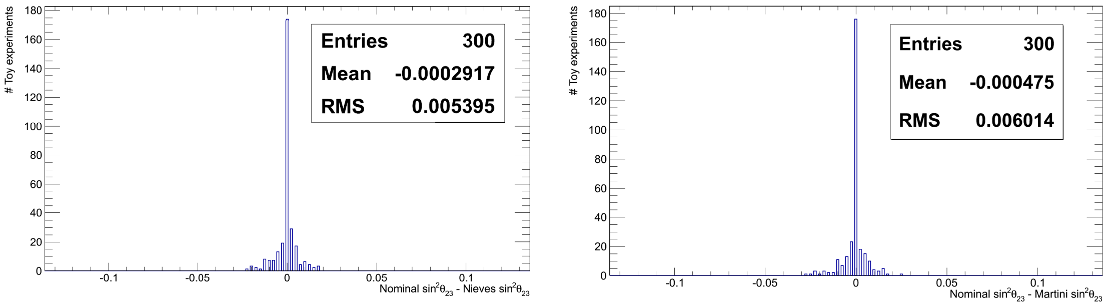
To quantify the model dependence of the analysis, using the same method as the T2K analysis discussed earlier, MEC events from the Nieves and Martini model were added to many νPRISM and SK fake datasets. The three-flavour muon neutrino disappearance probability was applied to the SK fake datasets, using $\Delta m^2_{32} = 2.41 \times 10^{-3}$ and $\sin^2\theta_{23} = 0.5$ with the other oscillation parameters set to the best fit values from the particle data group [17]. A disappearance fit was performed using the νPRISM prediction for both the nominal fake datasets and those containing Nieves and Martini



(a) The reconstructed neutrino energy spectrum simulated at SK after oscillation and the predicted spectrum from linear combinations at νPRISM.

(b) The total uncertainty on the number of selected events at SK from the νPRISM prediction.

Figure 4: The oscillated neutrino event sample at SK as predicted by νPRISM and its associated uncertainty.



(a) Difference for Nieves fake data fits. The distribution bias is less than 0.1% and the RMS equal to 1.1%.

(b) Difference for Martini fake data fits. The distribution bias is less than 0.1% and the RMS equal to 1.2%

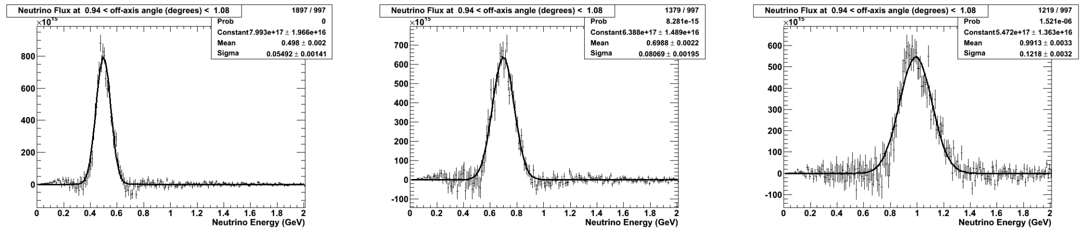
Figure 5: The difference between the value of $\sin^2\theta_{23}$ extracted from the fit to the nominal fake data and that from the fit to the fake data containing MEC events.

events, and the difference in the extracted value of $\sin^2\theta_{23}$ is shown in Figure 5.

This shows that, for both the Nieves model (Fig. 5a) and Martini model (Fig. 5b), the νPRISM technique gives the same value for the fitted neutrino oscillation parameters whether or not the MEC events are present.

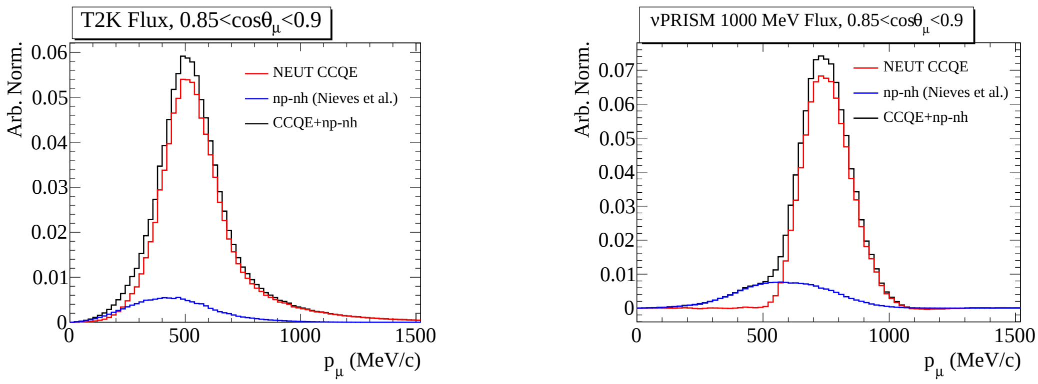
3.2 Neutrino cross section physics

Besides oscillation physics, νPRISM affords a unique way of studying neutrino interactions as a function of neutrino energy. If the detector spans the $1^\circ - 4^\circ$ off-axis angle range then peak energy of the observed neutrino flux varies from 400 MeV to 1 GeV. Using the linear combination method described above one can create a Gaussian neutrino flux across this range of energies, as shown in Figure 6. These neutrino fluxes give the neutrino energy, and measuring the lepton information from charged current events gives the 4-momentum tranfer (Q^2) of the interaction. This allows νPRISM to measure neutrino cross sections across a range of neutrino energies using the same detector and neutrino beam, with a known, correlated, uncertainty between those measurements.



(a) 500 MeV (b) 700 MeV (c) 1 GeV

Figure 6: Gaussian neutrino fluxes at νPRISM, centred at 500 MeV, 700 MeV and 1 GeV with a 10% width.



(a) T2K flux (b) 1 GeV Gaussian flux

Figure 7: Reconstructed muon momentum for CCQE and Nieves MEC events (labelled np-nh) in the T2K neutrino flux (left) and for the 1 GeV Gaussian flux at νPRISM (right).

νPRISM can also perform the first ever energy dependent cross section measurements of neutral current interactions, which can constrain the large uncertainties on neutral current backgrounds in oscillation analyses.

3.2.1 Separating nuclear models

A neutrino flux with a narrow energy spread also provides a powerful tool to discriminate between different neutrino interaction models. Looking again at the Nieves MEC model, Figure 7 shows the reconstructed lepton momentum for both true CCQE events and those coming from MEC interactions for the T2K flux (Fig. 7a) and the νPRISM Gaussian flux at 1 GeV (Fig. 7b). For the T2K flux the NEUT CCQE events sit atop the Nieves MEC events, so the total spectrum is little changed when including the new model. On the other hand, for a Gaussian neutrino flux, the MEC events reconstruct with much lower lepton momentum than the CCQE events and are clearly separable. Making these measurements over the available neutrino energy range will be a strong test of any new nuclear model.

3.2.2 Measuring the ν_e/ν_μ cross section ratio

As stated earlier, the νPRISM linear combination method can be used to create a neutrino flux of almost any shape. To measure the ν_e/ν_μ cross section ratio the different off-axis slices of

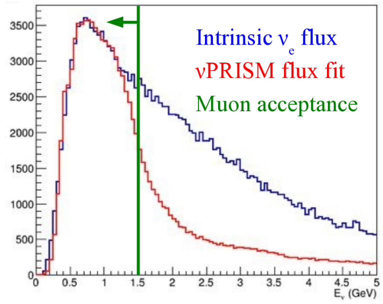


Figure 8: The intrinsic ν_e contamination in the T2K neutrino beam (blue) compared to the νPRISM fit to this flux (red) and the approximate neutrino energy at which any muons produced from neutrino interactions are not contained within νPRISM.

the detector are combined to recreate the intrinsic ν_e contamination present in the neutrino beam. Figure 8 shows that it is possible to model this flux well within the neutrino energy region where any muons produced by the interaction are contained within νPRISM. This allows νPRISM to predict the expected lepton distribution for ν_e appearance measurements directly from the data, without relying on the neutrino interaction models and the large uncertainties that come with them.

4. Conclusion

The analysis described above has shown that the νPRISM concept can be used to remove any bias arising from the choice of neutrino interaction model and reduce any additional uncertainty that choice introduces.

We have also shown that the linear combination method can successfully create Gaussian neutrino fluxes over a range of neutrino energies, which can be used to distinguish nuclear models and measure neutrino cross sections as a function of neutrino energy. Finally, νPRISM is able to directly compare electron and muon neutrino cross sections with the same flux, leading to a data driven prediction for the electron neutrino appearance spectrum after oscillation. Though not discussed here, νPRISM will also be a robust probe of sterile neutrino oscillations [18] by testing the sterile oscillation hypotheses over a range of known energies using the same beam and detector.

Precision neutrino physics demands we achieve a better understanding of neutrino interactions, particularly if we want to realise the projected sensitivities of the next generation of oscillation experiments. The νPRISM detector concept can provide this understanding, remove the potential biases and uncertainties introduced by our nuclear models and explore short baseline oscillations.

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