Oscillation analysis with NuPRISM

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Abstract. NuPRISM is a proposed intermediate water Cherenkov detector for the T2K and Hyper-K long baseline neutrino oscillation experiments. The detector makes use of the off-axis effect, where the peak energy of the neutrino flux falls with increasing perpendicular distance from the neutrino beam axis. By spanning the 1 – 4 degree off-axis angular range NuPRISM can sample neutrino fluxes with peak energies from 1200 to 400 MeV respectively. These samples can be linearly combined to create an effective neutrino flux, such as the muon neutrino flux at the far detector for some choice of the neutrino oscillation parameters.

This proceedings presents the NuPRISM muon neutrino disappearance analysis, showing that this technique is unaffected by mis-modelled neutrino cross-sections. It also presents the electron neutrino appearance analysis, showing the preliminary uncertainty on a measurement of the $\nu_e/\nu_\mu$ cross-section ratio at NuPRISM.

1. Introduction
Long baseline neutrino oscillation experiments are starting to enter the precision era, with new, high power neutrino beams and kiloton scale detectors expected to provide large samples of oscillated neutrino events. The sensitivity of these future experiments to CP violation will depend strongly on the control and understand of systematic uncertainties. This is demonstrated by the studies performed for the proposed T2K Phase-II [1], where reducing the T2K systematic uncertainty by a factor of $\frac{2}{3}$ reduces the number of protons-on-target needed to reach a $3\sigma$ measurement of CP-violation (assuming CP is maximally violated) by 25%.

1.1. NuPRISM 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 the “off-axis” effect. By measuring neutrino interactions across a range of off-axis angles NuPRISM samples many different neutrino spectra, each of which peaks at a different energy. Events selected at different off-axis angles can be weighted and linearly combined to create an arbitrarily shaped neutrino spectrum. NuPRISM thus provides a direct link between reconstructed event information and neutrino energy. The NuPRISM detector concept is explained in more detail in Reference [2].

1.2. Muon neutrino disappearance analysis
The muon neutrino spectrum at the T2K far detector, Super-Kamiokande (SK), for a given value of the oscillation parameters is shown in Figure 1(a). The predicted oscillated spectrum using a linear combination of off-axis slices at NuPRISM is included in the plot, showing
excellent agreement with the true spectrum around the oscillation minimum. The selected event distribution predicted by NuPRISM is shown by the coloured, stacked histogram in Figure 1(b), and can be compared to the event distribution selected at SK in black. The differences between the NuPRISM linear combination and the oscillated SK flux are corrected for using predicted events at SK, and are shown in blue, green and magenta in Figure 1(b).

Figure 1. Comparisons of the NuPRISM linear combinations to the oscillated SK distributions for the true muon neutrino flux (a) and for the selected events (b).

The impact of nuclear effects on the measurement of neutrino oscillation parameters has been highlighted many times [3] and the T2K collaboration has performed a study to quantify the effect of a specific nuclear model choice on their muon neutrino disappearance analysis. The study has been reproduced using NuPRISM and the results compared, shown in Figure 2, demonstrating that the NuPRISM linear combination technique is insensitive to mis-modellings of neutrino-nucleus interactions. More details on this study can be found in Reference [2].

Figure 2. The difference in extracted values of $\sin^2 \theta_{23}$ between oscillation analyses using the nominal MC as data and those using an alternative MC, for the T2K oscillation analysis on the left and the NuPRISM analysis on the right.

1.3. Electron neutrino appearance analysis
Measuring electron neutrino appearance is a necessary first step towards measuring $\delta_{CP}$. At NuPRISM this is done using a three-step analysis. Step 1, shown in Figure 3(a), uses a linear combination of NuPRISM $\nu_\mu$ fluxes to recreate the far detector $\nu_e$ flux. Step 2, which converts the predicted rate from muon neutrinos to electron neutrinos, requires an accurate measurement
of the $\frac{\nu_e}{\nu_\mu}$ cross-section ratio. At present the uncertainties on this ratio stand at approximately 4% and come from theory alone — there are no experimental measurements approaching this level of precision. To measure this at NuPRISM we match the NuPRISM $\nu_\mu$ flux to the NuPRISM off-axis $\nu_e$ flux, shown in Figure 3(b). Taking the ratio between the linear combination and the electron events provides a direct measure of the cross-section ratio while matching the fluxes ensures that any difference observed is due to the different neutrino flavour, rather than coming from the different fluxes. Using a preliminary detector simulation and reconstruction NuPRISM can select a large, pure sample of electron neutrino interactions and can measure this ratio to the 5% level, as shown in Figure 3(c). This is a preliminary analysis, improvements to the reconstruction and in-situ constraints on the dominant backgrounds are expected to improve this in the future. Together steps 1 and 2 give a prediction for the expected signal events, shown in red in Figure 3(d). The final step is to measure the backgrounds to the appearance signal, which can be done directly using the NuPRISM events at the same off-axis angle as the far detector. Given that NuPRISM and SK use the same detector technology and reconstruction this measurement will provide a very precise prediction on the intrinsic background in the analysis.

References
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