Charged-current muon neutrino shape and rate analysis at the T2K off-axis near detector

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Abstract. The experimental evidence that neutrinos can convert from one flavour to another and therefore have non-vanishing mass, has been recently honoured by a Nobel Prize. However, the completeness of the three-neutrino mixing paradigm, parametrised by the PMNS matrix, was challenged in the last two decades. Sterile neutrinos - singlet fermions that contribute to weak interactions only through mixing with active neutrinos - might help to explain some anomalies to the three-neutrino scenario reported by several experiments. However, the existing results are puzzling and the existence of such particles is still an open question.

The T2K off-axis near detector (ND280), located at 280m from the proton target, can contribute to the search for sterile neutrinos. Shape and rate measurements for charged-current muon neutrino interactions are studied and tested against the current cross-section model uncertainties to see whether it’s possible to detect short-baseline neutrino oscillations within the 3+1 model.

1. Introduction

Neutrino oscillations provide an interesting hint of physics beyond the Standard Model (SM) by requiring neutrinos to have non-vanishing masses. The Pontecorvo-Maki-Nakagawa-Sakata formalism parametrises oscillations between three flavour eigenstates ($\nu_e, \nu_\mu, \nu_\tau$) and three mass eigenstates. However, the completeness of the three-neutrino paradigm has been challenged in the last two decades by indications of short-baseline (SBL) oscillations that might be explained by introducing a new type of neutrino: the sterile neutrino.

Sterile neutrinos do not interact via the weak interaction and their existence can be studied by their mixing with the SM neutrinos. The simplest theoretical model considers only one sterile neutrino in addition to the SM neutrinos (the 3+1 model). The additional sterile neutrino should be heavier than the other neutrinos. The related mass-squared difference is then much larger than the other mass differences ($\Delta m_{41}^2$ of the order of 1 eV$^2$) and therefore, the other mass differences can be considered degenerate. As a result the two neutrino approximation can be used and the disappearance probability of muon neutrinos becomes:

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta_{\mu\mu}) \cdot \sin^2 \left( \frac{1.267 \Delta m_{41}^2 [eV^2] L_\nu [km]}{E_\nu [GeV]} \right)$$

where $L_\nu$ and $E_\nu$ are the neutrino oscillation distance and energy respectively.

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The T2K Experiment, with its off-axis near detector (ND280) located at 280 m from the proton target, can participate in the search for sterile neutrinos.

2. Event selection and analysis strategy
ND280 plays a key role in constraining the flux and cross-section systematics [1]. Thanks to the ND280 tracker (TPCs and FGDs) a clean sample of CC muon neutrinos can be selected. The events are then classified into three topologies by the number of pions in the final state: zero (CC0\(\pi\)), one positive pion (CC1\(\pi\)), and any other combination (CCOther). This classification reflects the three interaction modes dominant at T2K energies: quasi-elastic interactions dominate the CC0\(\pi\) sample, resonance pion production dominates the CC1\(\pi\) sample and deep inelastic scattering dominates the CCOther sample.

Presented is a description of the analysis, which is a Monte Carlo (MC) based sensitivity study, and the checks that have been performed to test the robustness of the analysis [2]. The MC data is normalised to the T2K statistics collected between January 2010 and May 2013 (6 \times 10^{20} \text{ POT}).

The sensitivity study is performed using a binned likelihood fit to the neutrino energy, reconstructed assuming CC Quasi Elastic (QE) interactions. The dependency on the oscillation parameters (\(\sin^2 2\theta_{\mu\mu}\) and \(\Delta m^{2}_{41}\)) is introduced by re-weighting the number of signal events by the survival probability (Eq. 1). The different sources of systematic uncertainties are considered in the fit by including nuisance parameters with gaussian constraints, similar to other T2K analyses [1].

3. Challenges of the analysis
One of the challenges of this analysis is working with a limited knowledge of the neutrino cross-section. T2K uses data from external experiments (e.g. MiniBooNE) to tune the theoretical cross-section model implemented in the MC simulations. When performing such tuning, the hypothesis of no SBL oscillations is assumed. If this assumption is incorrect, it could lead to a bias in the modelling of the neutrino cross-section, significantly impacting the exclusion limits coming from this analysis.

For example, if a SBL oscillation was present in the MiniBooNE experiment, the flux used to extract the MiniBooNE cross-section data would be incorrect, then to reliably extract cross-section parameters we must first fold a sterile mixing signal into our MC cross-section model before tuning the model. Since the true mixing parameters are unknown, the tuning was repeated with different SBL oscillation assumptions folded into the MC cross-section model prediction to see how the choice of mixing can vary the fitted parametrisation. The differences observed were used to calculate residual scans relative to the null hypothesis parametrisation to see if the nominal uncertainties can cover any variation of the cross-section model introduced by possible sterile mixing (see Figure 1). A residual value outside \(\pm 1\) signifies regions where the parametrisation doesn’t cover possible variations in the external data.

A second study was performed to probe the robustness against variations of the cross-section parameters. Variations will introduce shape and rate distortions, which might mimic a SBL oscillation signal. The study probed whether the use of three sub-samples (CC0\(\pi\), CC1\(\pi\), and CCOther) disentangles the effects of the cross-section parametrisation from those of the oscillations. Figure 2 shows the comparison between the distortions introduced by different values of the parameter \(M^{QE}_{A}\) (the axial mass in the CCQE cross section calculation) and the effect coming from oscillations at an arbitrary point in the phase-space. The study then uses an Asimov [3] dataset to test the distortions in the entire phase-space. This study showed that variations of cross-section parameters introduce distortions over specific energy ranges, depending on the typical energy range of the interaction. Thus the three sub-samples where affected differently whereas SBL oscillations affect the three samples similarly.
Figure 1. (Left) Best fit cross-section predictions when different sterile mixing hypotheses are folded into the MC. (Right) Parameter residuals for the axial mass ($M_{AE}^Q$) fits performed over a range of mixing parameters.

Figure 2. Neutrino reconstructed energy $E_{\nu}^{Reco}$ distribution for the CC0$\pi$ (left), CC1$\pi$ (middle) and CCOther (right) samples. The nominal spectrum (black line) is shown together with the spectra obtained varying the $M_{AE}^Q$ parameter by -1, -2 and -3$\sigma$ (yellow, orange and red lines respectively). For comparison the expected spectra corresponding to $\sin^22\theta_{\mu\mu} = 0.7$, $\Delta m_{41}^2 = 2$ eV$^2$ are shown in blue.

4. Conclusions
A new analysis to search for sterile neutrinos using a sample of CC muon neutrinos in the T2K off-axis near detector has been presented. It has been tested against possible biases due mismodelling of the neutrino cross-section. The analysis is found to be robust with respect to the cross-section parametrisation used for the T2K oscillation analyses. The analysis is currently undergoing an internal collaboration review in order to obtain approval to run the analysis on T2K data.

References
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