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Charged current interactions on hydrocarbon with a single positively charged pion in the final state at the T2K off-axis near detector with 4π solid angle acceptance.

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The long-baseline neutrino experiment Tokai-to-Kamiokande (T2K) is in Japan and measures neutrino oscillation parameters. The muon neutrino charged current interactions in the near detector (ND280) are used to predict the far detector's event rate, particularly constraining the neutrino flux and neutrino-nucleus interaction cross sections, the dominant systematic uncertainties in the oscillation analysis.

We present a study of charged current interactions on carbon with a muon and a single positively charged pion in the final state (CC1π^+) at the T2K off-axis near detector with a 4π solid angle acceptance. This channel constitutes the main background for the muon neutrino disappearance measurement when we do not observe the charged pion in the Super-Kamiokande water Cherenkov detector. A precise understanding of it is relevant for all current and planned neutrino oscillation experiments. Single positive pion production is primarily sensitive to resonant processes, non-resonant contributions, and coherent pion production. Additionally, final-state interactions in the nuclear target have to be considered.

A fascinating characterization of CC1π^+ interactions through the measurement of Adler Angles is presented. These observables carry information about the polarization of the Δ resonance and the interference with the non-resonant single pion production.

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1. The T2K experiment

T2K (Tokai to Kamioka) [1] (Figure 1) is a long-baseline neutrino experiment in Japan. An accelerator (J-PARC) [2] is used to produce neutrinos, which are then detected in a near detector complex (which includes these detectors: ND280, INGRID, WAGASCI) [3], at 280 m from the beam production point, which characterizes the beam and the interactions of the neutrinos before oscillations. The beam then propagates through the Earth until the T2K far detector, Super-Kamiokande (SK) [4] at 295 km. T2K is the first experiment to use an off-axis neutrino beam configuration allowing a narrow-band ν_μ beam. The narrow-band ν_μ beam generated toward the far detector peaks at $\sim 0.6\,GeV$, which maximizes the effect of the neutrino oscillation at 295 km and minimizes the background to ν_e appearance detection.

It looks explicitly for two oscillation channels:ν_μ disappearance and $\nu_\mu \to \nu_e$ appearance, the latter channel is sensitive to θ_{13} and the CP phase δ_{CP}. T2K has some sensitivity on neutrino mass hierarchy. Most recently, T2K reported a measurement that favors maximal CP violation and excludes at 3σ a large range of possible values of δ_{CP} [5].

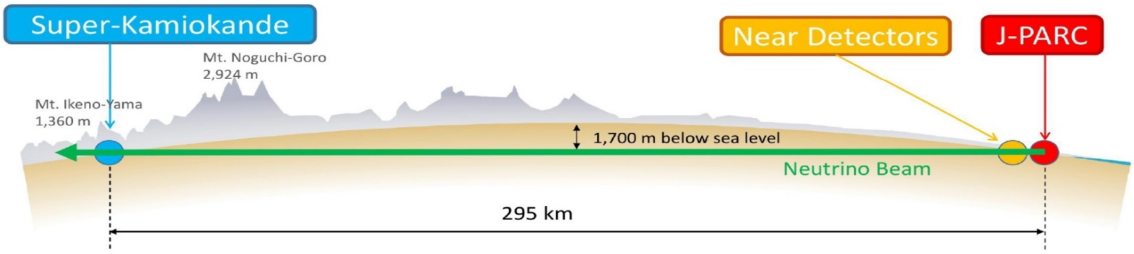


Figure 1: A schematic of a neutrino's journey from the neutrino beam-line at J-PARC [2] (red dot), through the near detectors complex [3] (yellow dot) and then travels 295 km underneath to Super-Kamiokande [4] (blue dot).

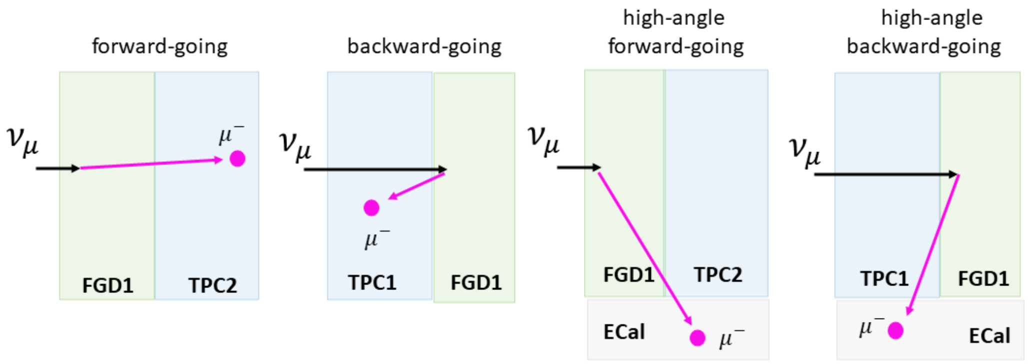
1.1 The T2K off-axis near detector: ND280

The ND280 off-axis detector is formed by a water-scintillator detector optimized to identify π^0 (the P∅D), three time projection chambers (TPCs), and two fine-grained detectors (FGDs). An electromagnetic calorimeter (ECal) surrounds the P∅D, TPCs, and FGDs. The whole off-axis detector is placed inside a magnetic field provided by the recycled UA1 magnet and a side muon range detector (SMRD).

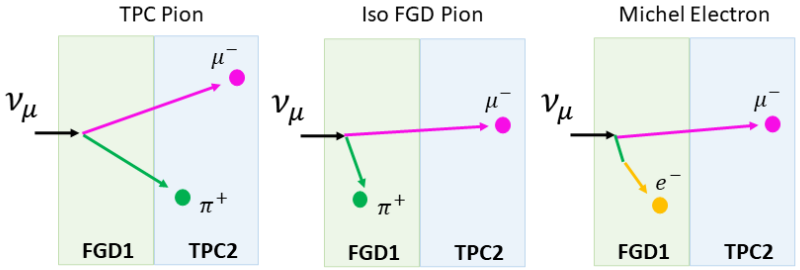
The main objective of the near detectors in a neutrino oscillation experiment (like T2K) is the reduction of systematic errors in the oscillation analysis. Therefore the events selected at the near detector are used to constrain the flux and cross-section parameters.

2. CC1π^+ event selection

The CC1π^+ signal is sensitive mainly to resonant (RES) processes, with non-resonant and coherent pion production (COH) contributions. CC1π^+ events consists of one negatively charged muon (with 4π solid angle acceptance (Figure 2a)), one positive charged pion (that can be observed in the TPC, as an isolated track in the FGD or via Michel electron tagging as shown in Figure 2b), no additional mesons, and any number of nucleons.



(a) Four directions of interest



(b) Positive pion detection

Figure 2: Schematic of the four directions of interest (a) and sub-detectors where the positive pion can be detected (b). TPCs are shown in light blue, FGD1 in light green, and ECals in light gray.

By studying the CC1π^+ interactions, we can reduce the main background for the ν_μ disappearance measurement. When the charged pion is not observed, the CC1π^+ events are misidentified and induce a bias because their energy is wrongly reconstructed. Since the signal events are defined in terms of the experimentally observable particles exiting the nucleus, final-state interactions (FSI) can alter the multiplicity of mesons and nucleons in the final state, the kinematic of these, and the classification of the event. In addition, the neutrino energy (E_ν) of CC1π^+ event is reconstructed, assuming that the target nucleon is at rest and considering the neutrino as massless. All this introduces a bias in the reconstruction of E_ν.

There are some challenges when studying these interactions, our incomplete understanding of the nuclear effects contributing to the cross-section and inaccuracies in reconstructing the neutrino energy [6, 7]. Thus it is essential to understand these nuclear effects. These studies aim to provide results in a model-independent way, facilitate their comparison to other experiments, and improve the current models.

3. Adler angles

The Adler reference system describes the p + π^+ final state in the Δ reference system. These observables carry information about the polarization of the Δ resonance and the interference with the non-resonant single pion production, and they can provide hints of parity violation due to the lack of preference in the Δ direction. These Adler angles can allow us to investigate the effects of pion re-scattering, high-mass resonances, and deep inelastic processes. The two angles are properly defined at the nucleon interaction level, but the FSI and the Fermi momentum of the target nucleon will alter them [6, 7]. The problem is that the nuclear effects are considerable. Figure 3 shows the Adler angles definition at the nucleus level, where they are measured by looking at the μ^- and the π^+ that escape the nucleus, so we already have nuclear effects influencing those measurements.

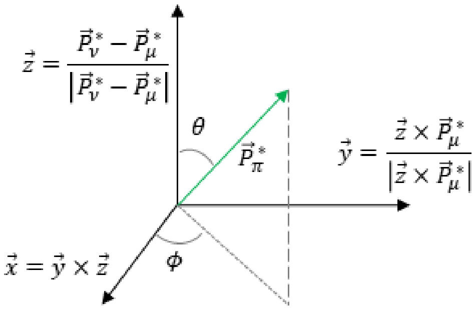
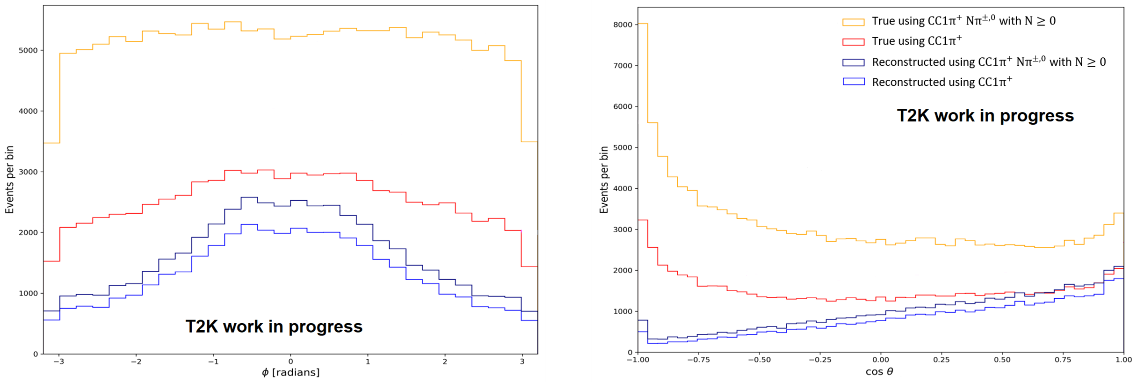


Figure 3: Definition of the Adler angles at the nuclear level. The momenta of the particles are defined in the $q = p_\nu$ - p_μ rest frame [6, 7].



(a) **(b)**

Figure 4: Comparison between reconstructed and true Adler angle distributions for ϕ (left) (a) and cos θ (right) (b).

The Rein-Sehgal model [9] assumes that these angular distributions should not have a preferred direction, which translates to a flat distribution observed in previous results. Contrary to this, in T2K we do not see flat distributions (Figures 4a and 4b). The main difference between our analysis and the analysis by ANL [8] is the target used. ANL used a target of deuterium, minimizing the FSI effect. Considering these differences, the observed non-flat behavior could be coming from nuclear medium effects and FSI due to the heavier target used.

Figures 4a and 4b show the comparison between reconstructed and true Adler angle distributions for ϕ and cos θ using CC1π^+ signal events. The comparison allows us to see the effect that the reconstruction and the selection of CC1π^+ events have in the Adler angle distributions. In this case, we observe that when plotting the true distribution, we have the flat-ish distribution that was expected and that the constraints in the samples will affect the number of events, but the shape will be very similar (orange and red curves in Figures 4a and 4b).

For the cos θ reconstructed distribution (violet and blue curves in Figure 4b), the number of events decreases for negative values; this corresponds to positive pions with low momentum after the boost, resulting from mis-reconstructing low momentum pions. In general, when applying the further criteria to select $CC1\pi^+$ events, the distributions start to look non–flat.

4. Conclusion

A new selection was developed to study the $CC1\pi^+$ signal with a full solid angle coverage of the ND280 detector. The upcoming ND280 detector upgrade [10] will improve the timing information and the detector efficiency for backward and high-angle tracks, and this will allow us to improve the event selection further. The study of $CC1\pi^+$ signal events can reduce the systematic errors for the oscillation analyses in Super-Kamiokande. These signal events are even more critical now that pion samples are being added to the far detector analysis.

Adler angle observables are presented. They have the potential to improve our interaction models by allowing us to investigate the effects of pion re-scattering, high-mass resonances, deep inelastic processes, and the interference between resonant and non-resonant single pion production. They will be most helpful for comparison with different neutrino interaction models.

In general, when applying the further criteria to select $CC1\pi^+$ events, the distributions start to look non–flat. The non-flat behavior observed in the reconstructed Adler angle distributions could be coming from nuclear medium effects, and FSI due to the heavier target used with respect to reference [8]. The lack of events with negative values of the cos θ points to the missing low momentum pions due to nuclear effects and FSI.

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