Selection of Muon Neutrino Charge-Current Interactions with Single Pion Production in the Upgraded Near Detector ND280 of the T2K Experiment

Отбор Событий с Одним Заряженным Пионом от Взаимодействий Мюонных Нейтрино по Каналу Заряженного Тока в Модернизированном Ближнем Детекторе ND280 Эксперимента T2K

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The leading systematic uncertainties of the T2K's oscillation analysis stem from the modeling of neutrino-nucleus interactions and are largely constrained by the measurements with the near detector ND280. The recent completion of the ND280 upgrade in 2024 has significantly enhanced its tracking capabilities. This paper presents a novel event selection targeting muon neutrino charged-current interactions with single positively charged pion production in the new detector modules of ND280. The selection was designed to maximize the acceptance of the kinematic phase space, providing superior constraints for neutrino interaction models. This work is a critical step towards reducing the dominant systematic uncertainties for the next generation of high-precision oscillation measurements in T2K.

Основные систематические неопределенности в осцилляционном анализе эксперимента T2K связаны с моделированием нейтрино-ядерных взаимодействий и в значительной степени ограничиваются измерениями на ближнем детекторе ND280. Модернизация ND280 в 2024 году существенно улучшила трековые возможности детектора. В статье представлена новая методика отбора событий от взаимодействий мюонных нейтрино по каналу заряженного тока с образованием одного положительно заряженного пиона в обновленном ND280. Отбор был оптимизирован для охвата максимально возможной области фазового пространства, что обеспечивает получение строгих ограничений на модели нейтринных взаимодействий. Эта работа представляет собой важный шаг на пути к снижению доминирующих систематических неопределенностей для следующего поколения измерений осцилляционных параметров в T2K.

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The T2K Experiment

Tokai-to-Kamioka (T2K) [1] is a long-baseline neutrino oscillation experiment in Japan with the goal of precisely measuring neutrino mixing parameters. This is achieved through the study of ν_μ and $\bar{\nu}_\mu$ disappearance and the observation of ν_e and $\bar{\nu}_e$ appearance channels. The experiment comprises three key components: the neutrino beam line at J-PARC, the near detector complex, and the Super-Kamiokande water Cherenkov detector [2], located 295 km to the west J-PARC.

T2K utilizes a high-intensity ν_μ ($\bar{\nu}_\mu$) beam. The experiment employs a 2.5° off-axis beam design. Such a configuration yields a narrow energy spectrum with a peak around 600 MeV, matching the first oscillation maximum for the 295 km baseline, and additionally helps to suppress background processes.

Near Detector ND280

The ND280 near detector is a crucial off-axis component of the T2K experiment, located 280 m from the neutrino production target. It serves to constrain the dominant systematic uncertainties in T2K's neutrino oscillation analysis (OA). This is achieved by characterizing the unoscillated neutrino flux and measuring neutrino-nucleus interaction cross-section with a high-precision. For instance, when ND280 constraints are applied, the total systematic uncertainty on signal events at the far detector is reduced from

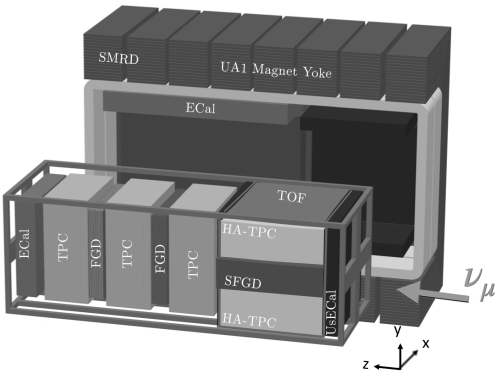


Figure 1. The schematic view of the Upgraded Near Detector ND280.

16.7% to 3.4% for the ν_μ-like (single muon ring) sample and from 17.3% to 5.2% for the ν_e-like (single electron ring) sample in neutrino beam mode [3].

Despite this success, the classic ND280 design (in place from 2010) had several limitations affecting its capability to constrain neutrino interaction models. Its detection efficiency was non-isotropic compared to the 4π coverage of the Super-Kamiokande far detector. Furthermore, it had a relatively high detection threshold of interaction products.

The ND280 upgrade was designed to overcome these limitations [4]. For the upgrade, the upstream components were replaced with a new, high-granularity system. All sub-detectors remain housed within the refurbished UA1 magnet. The key components of the upgraded ND280 are (Fig.1):

- The Tracker: this section, located downstream of the beam, is retained from the original ND280. It consists of two Fine-Grained Detectors (FGDs) serving as neutrino targets, interleaved with three Time Projection Chambers (TPCs) for precise particle tracking and identification.

- The Upstream Tracker (Upgrade): The core of the upgrade is a new upstream system, featuring a novel 3D Super Fine-Grained Detector (SFGD) as the primary neutrino target. It is surrounded by two High-Angle TPCs (HA-TPCs) and Time-of-Flight (TOF) panels, significantly improving the acceptance for wide-angle tracks and enhancing particle identification.

- The tracker and upgrade are surrounded by an electromagnetic calorimeter (ECal) to measure electromagnetic showers and contain neutral particles. The Upstream ECal serves as a veto detector.

- UA1 dipole magnet yokes host a side muon range detector (SMRD). Its purpose is to identify muons exiting the main detector.

Neutrino charged-current interactions resulting in single charged-pion production ($\nu_\mu + N \rightarrow \mu^- + \pi^+ + X$), denoted as CC1$\pi^+$, contribute to the signal samples in the far detector. Its imperfect modeling currently limits the precision of the T2K's neutrino OA. To address this, high-precision measurements of the CC1π^+ cross-section and final-state kinematics are essential. These can be achieved using the new upstream tracker with the SFGD as the neutrino target. The foundation of these measurements is a robust event selection, which is necessary to isolate a clean CC1π^+ signal from other interaction processes.

The selection of CC1π^+ events is initiated by first identifying the muon candidate. There are three topologies for muon candidates based on their trajectory: forward (to vertical TPC), high angle (to HA-TPC), and contained in SFGD. All candidates are required to originate within the SFGD fiducial volume (FV). Forward and high-angle muon candidates are the highest momentum negative tracks in the corresponding detectors that satisfy particle identification (PID) criteria. To remove tracks from events that originate out of FV, time information between SFGD and TOF is used. For contained tracks, the muon candidate is the longest fully-contained track in the SFGD that passes PID and has a tagged Michel electron (ME) at its endpoint. Muon finding is performed simultaneously across all topologies. In the case of multiple muon candidates, the track with the highest reconstructed momentum is chosen as the main track.

Following the identification of the muon candidate, the analysis proceeds to find the positive pion. Similar to the muon, pion candidates are also classified into three topologies based on their trajectory. The procedure to select TPC and HA-TPC pions is the same as in muon selection. SFGD contained pion candidates are divided into three categories: those with a tagged ME, those without a tagged ME, and trackless pions. Pion candidates with or without tagged ME should pass pion PID criteria. Trackless pions are selected based on the presence of a ME tagged in proximity to the interaction vertex (reconstructed start point of the muon candidate). This selection accounts for pions with momentum too low to produce a track. In SFGD a track is reconstructed only if it passes at least 3 cm, corresponding to a minimum pion momentum of approximately 100 MeV/c. As a result, trackless pions constitute a small subset of the overall pion sample, as most pions are produced above this momentum threshold. This category is important for extending the signal phase space to include low-momentum pion events, and its selection efficiency remains robust, as it depends only on a tagged ME near the vertex. After identifying all charged pions in an event, additional criteria to select exactly one pion is applied. Events featuring a neutral pion are treated as background in the analysis. Rejection of these events is done by searching for an electron-positron pair in the Upgrade or Tracker detectors, or for a shower-like energy deposit in the ECal.

The analysis classifies events into 15 exclusive samples based on the combination of muon and pion topologies. This approach provides comprehensive coverage of the kinematic phase space: TPC samples probe the forward,

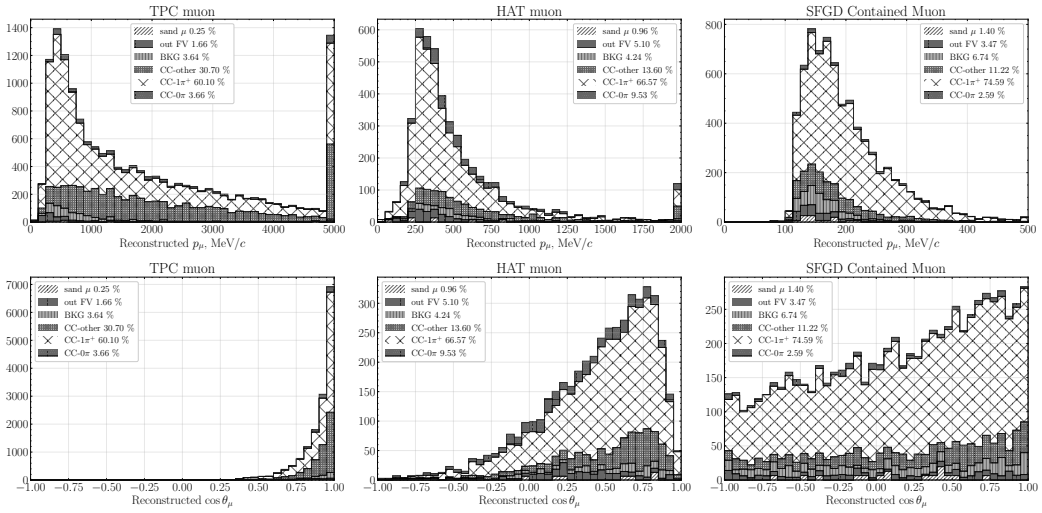


Figure 2. Distributions of the reconstructed momentum and the cosine of the angle with respect to the beam axis for muon candidates from the selected CC1π^+ events, categorized by muon topology.

high-momentum region; HA-TPC samples cover intermediate angles and momenta; and SFGD-contained samples are sensitive to backward-going, low-momentum tracks. Distributions of the reconstructed muon kinematics are shown in Figure 2.

A total selection purity of 75% is achieved, with individual sample purities ranging from 51% to 94%. Samples exhibiting lower purity will be further examined to assess their suitability for inclusion in the final cross-section analysis. The dominant background in these samples comes from events containing multiple pions, whether charged or neutral. The overall CC1π^+ selection efficiency is approximately 30%. A key feature of this efficiency is its flatness across kinematic variables: it is stable as a function of both the muon's momentum and its angle relative to the initial neutrino direction. When considering pion kinematics, the efficiency also remains flat across the pion angular distribution. However, the efficiency shows a strong dependence on pion momentum: it reaches 40% at low momenta (below 300 MeV/c) and then decreases progressively to 20% with higher momenta. This decline stems from the increasing difficulty of identifying high-momentum pions. For SFGD-contained pions, the probability of secondary interactions rises with momentum, degrading particle identification performance. For pions that reach the TPC or HA-TPC, identification becomes challenging above 1 GeV/c, where pions and protons are easily misidentified.

Conclusion

The T2K near detector ND280 plays a crucial role in constraining systematic uncertainties for the experiment's oscillation analysis. ND280 Upgrade, which includes new upstream detectors, significantly expands the kinematic

phase space and enhances the reconstruction of neutrino interaction products. This work presents a high-purity selection of charged-current single-pion (CC1π^+) events in the upgrade modules. The resulting samples will enable a precise measurement of the CC1π^+ cross-section, leading to improved neutrino interaction models and a direct reduction of the dominant systematic uncertainties in T2K's oscillation analysis.

Acknowledgements

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