Probing kaon-originated neutrinos with the muons produced outside of the T2K near detector

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Abstract. One of the main backgrounds to the neutrino oscillations is the intrinsic electron neutrinos, which are produced in decays of muons and kaons, resulting in low and high energy components, respectively. The kaon-originated part of the spectrum can be measured using the Deep Inelastic Scattering of neutrinos inside of ND280, the T2K off-axis Near Detector or by looking at muons coming to ND280 from the interactions in the surrounding sand.

1. T2K experiment and its off-axis Near Detector
T2K experiment [1] is a long-baseline neutrino oscillation experiment located in Japan, that observes oscillations of muon neutrinos produced at J-PARC in Tokai and detected in Super-Kamiokande detector. One of the primary goals of the experiment is the observation of the $\nu_\mu \rightarrow \nu_e$ oscillation channel for neutrinos and antineutrinos. The main background to such searches comes from the irreducible intrinsic $\nu_e$ component of the beam, originating from the decay of muons (neutrinos with energy $E_\nu < 1.5$ GeV) and kaons ($E_\nu > 1.5$ GeV) [2]. Kaons also produce high-energy tail of the $\nu_\mu$ flux, responsible for the $\pi^0$ production in the neutrino interactions, being the second most important source of background [3].

The neutrino beam is measured by the ND280, a magnetized near detector, allowing a great reduction in the uncertainties related to neutrino flux and cross sections thanks to the fit of the predictions to the data. The ND280 consists of the P0D, a calorimeter optimized for $\pi^0$ detection, placed most upstream and followed by the tracker, composed of two Fine-Grained Detectors interleaved with three Time Projection Chambers. The inner detectors are surrounded by an electromagnetic calorimeter and the Side Muon Range Detector. The detailed description of ND280 can be found in [1].

To constrain the uncertainties in the already published analyses, three samples of CC $\nu_\mu$ interactions in tracker were selected, based on the number of pions in an event, which are a good indicator of the type of interaction (quasi-elastic, resonant or DIS), and covering different neutrino energy ranges. The description of the samples can be found in [4]. Since T2K started to collect data with $\bar{\nu}_\mu$ beam in 2014, four additional samples, measuring the $\nu_\mu$ and $\bar{\nu}_\mu$ components of the beam, were added to the fit in 2015. Their description can be found in [5].

2. Interactions in the surrounding sand
During the passage through the sand surrounding the ND280 pit and the pit itself, some of the beam neutrinos interact and if the interaction happened relatively close to the detector, the produced
particles may reach it and be detected. Muons from the interactions of high-energy beam tail can reach ND280 even from a distance of 40 m, as it was found from a dedicated simulation.

The sand particles can be a background for the neutrino interactions in the detector, if a neutral particle reinteracts in the fiducial volume or if a charged track is incorrectly reconstructed and not recognized as coming from outside. But the sand particles can also be used for calibration purposes and evaluation of the detector systematic errors.

The incoming sand particles are mostly muons and enter the detector through the front wall, thus they should be reconstructed as starting in the most upstream layers of the P0D. Cutting on the reconstructed starting position of a track gives a sample consisting of 84% of sand muons. Such a sample contains also particles produced in the outer inactive detector parts (coil, supporting structure and casing), which are indistinguishable from sand particles.

3. Sand muons and origin of parent neutrinos
The analysis presented here concerns another possible usage of the sand muons: exploiting them for better knowledge of the neutrino beam, in particular the high-energy tail, dominated by the neutrinos produced in the kaon decays.

For the selection of sand muon candidates, a cut on the starting position is applied. Then it is required that the track crossed at least one of the TPCs, in order to have reliable momentum measurement. For sand particles, such a condition means that they have to pass through the whole P0D, which contains brass and lead layers. Most of the particles other than muons stop inside P0D, and the surviving ones had to have momentum higher than about 1 GeV/c when they entered P0D.

TPC can distinguish the particle charge and thus look at muon neutrino and antineutrino components of the beam. This is important particularly for antineutrino beam mode, having a large contamination from neutrino component, which has to be measured in ND280, as the Far Detector is not sensitive to the particle charge.

Over 99% of negatively charged sand particles entering TPC are muons. For the positively charged particles, this fraction is worse, in particular in the neutrino beam mode, where it drops to 82% due to the contamination from protons and pions, while for antineutrino beam mode it is equal to 98%. For this reason, this study will not include the positive track sample for neutrino beam mode.

High momenta of the selected sand muons indicate that they were produced by the (anti)neutrinos from the high energy tail of the flux, which originate mostly from the decays of kaons. This can be seen in Fig. 1, which shows the true energy of the parent neutrino, where the origin of the neutrinos is marked in colors: the neutrinos and antineutrinos produced in kaon decays are indicated in magenta and green, respectively. The distributions are peaked at about 4 GeV, while the tracker samples probe mostly the flux around 1 GeV.

![Figure 1](image_url)

**Figure 1.** The distributions of the true energy of the neutrinos being the parents for the selected sand muons. Plot a) is for the negative tracks in the neutrino beam mode (for \(8.6 \times 10^{19}\) POT), plots b) and c) for positive and negative tracks in the antineutrino beam, respectively (for \(4.3 \times 10^{19}\) POT).

The number of sand muons in the presented samples is very high, compared to the samples of interactions selected in tracker. The comparison of rates per POT and the fraction of the selected
muons with kaon-originated neutrino parents is shown in Table 1 both for sand muons and tracker samples used in present T2K oscillation analysis.

Table 1. Comparison of the muon rates per POT and the fraction of kaon-originated neutrino being the parents of muons for the sand muons sample and the FGD samples used in the present T2K analysis.

| Neutrino beam mode    | sample                  | rate ($10^{19}$ POT) | fraction of kaon grandparents |
|-----------------------|-------------------------|-----------------------|-------------------------------|
| negative sand tracks  | $> 6000$                | 80%                   |
| $\nu_\mu$ CC-0$\pi$   | 600                     | 20%                   |
| $\nu_\mu$ CC-1$\pi^+$ | 127                     | 44%                   |
| $\nu_\mu$ CC-Other    | 145                     | 70%                   |

| Antineutrino beam mode | sample                  | rate ($10^{19}$ POT) | fraction of kaon grandparents |
|------------------------|-------------------------|-----------------------|-------------------------------|
| positive sand tracks   | $> 1100$                | 66%                   |
| $\bar{\nu}_\mu$ CC-1 track | 192                  | 12%                   |
| $\bar{\nu}_\mu$ CC-N tracks | 55                  | 44%                   |
| negative sand tracks   | $> 2100$                | 72%                   |
| $\bar{\nu}_\mu$ CC-1 track | 73                  | 26%                   |
| $\bar{\nu}_\mu$ CC-N tracks | 72                  | 48%                   |

The high fraction of kaon-originated neutrinos which are the parents of sand muons and their high rate indicate that the sand muons sample may be a unique and valuable tool to study the high energy part of the neutrino beam. The study presented here is ongoing and further results are expected in the future.

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