π^0 IDENTIFICATION ANALYSIS FOR THE LAr DETECTOR IN 2 km STATION OF T2K EXPERIMENT* **

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This article presents methods of distinguishing ν_μ NC π^0 production from ν_e CC electron production events in liquid argon TPC detector. This is important in estimation of the intrinsic ν_e component in the beam in long-baseline neutrino experiments. One of the methods — based on finding a gap between primary vertex of interaction and the beginning of electromagnetic shower — is evaluated for T2K experimental setup with liquid argon TPC in 2 km station of the experiment.

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1. Introduction

In long-baseline electron neutrino appearance experiments aiming to estimate θ_{13} mixing angle it is important to measure the number of electron neutrinos appearing as a result of oscillations. The beam consists mainly of muon neutrinos which, during their flight to the far detector, oscillate into electron neutrinos; however, electron neutrinos are also present in small amount in the beam. To estimate this electron component, one needs to measure it before the oscillation phenomenon occurs, in the near detector(s) of the experiment.

In the T2K experiment [1], such measurement can be carried out using 100 ton liquid argon detector (T2KLAr), which will be a part of intermediate, 2 km station of the experiment. T2KLAr is an ideal instrument for that

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purpose. It is a time projection chamber (TPC) — an aluminium cryostat filled with liquid argon — recording ionization signals from charged particles traversing the detector. More detailed description can be found in [2]; it is enough to say here that it is an imaging detector, with precisely reconstructable topology of events. It also has particle type recognition capability and good calorimetric features. These allow for precise reconstruction of events and can lead to good estimation of ν_e component in the ν beam. It can also supplement measurements carried out using other detectors in the 2 km station: water Cherenkov detector and muon ranger.

2. Neutrino interactions in the detector

Neutrinos interact weakly with the medium (liquid argon), exchanging charged (CC) or neutral (NC) currents.

Charged current interaction of electron neutrino leads to production of an electron (and perhaps some other particles, almost certainly hadrons):

$$\nu_e + N \to e^- + N'(+\,\text{hadrons}).$$

The electron initiates an electromagnetic shower, clearly distinguishable from other types of particles in the detector. Thus, it can serve as a signature for electron neutrino events.

The only significant background to the aforementioned process is π^0 production, occurring in NC muon neutrino interactions:

$$\nu_\mu + N \to \nu_\mu + N + \pi^0(+\,\text{other hadrons}).$$

A π^0 decays, in most cases, into two gamma quanta which form electromagnetic showers similar to the cascades produced by electrons. The typical event display for CC electron neutrino interaction (electron event in short)

Fig. 1. A pi zero event. Two electromagnetic showers are visible.

and NC muon neutrino interaction with π^0 production (π^0 event) are shown in the Figs. 1, 2. If one shower in π^0 case is for some reason invisible, the NC muon neutrino event can easily be confused with one induced by an electron neutrino.

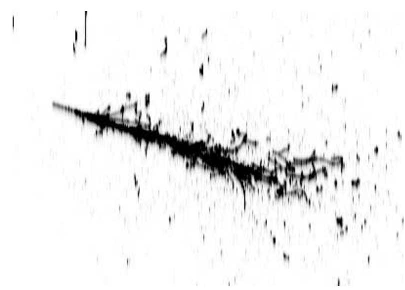

Fig. 2. An electron event with one cascade visible.

3. π^0 separation methods

Since our aim is to identify electron events in the detector, we have to develop methods of distinguishing them from their main background, *i.e.* π^0 events. Three following methods can be used:

- Two showers method — the easiest way to recognize π^0 events is to check whether one or two showers can be seen on the display. If we can see two showers, the event is a π^0 one. Unfortunately, some π^0 events can have only one shower visible, and these cannot be identified using this method.

- Gap method — π^0 events have showers originating from the different location than the primary vertex. Seeing the gap identifies the event as π^0 one. However, if the gap is small, it is sometimes hard to notice. Also note that one has to know where the vertex is located, and this is only possible if other particles coming from the vertex are visible.

- dE/dx method — one can examine the ionization energy loss pattern of a visible shower. In a π^0 case the loss should be twice as large as in the electron case — the shower is formed by a electron–positron pair. However, sometimes a gamma induces a single-electron shower due to Compton scattering effect.

To achieve best results, these three methods should be combined. In this study the effectivity of the gap method is evaluated.

4. Gap method

For π^0 events, we expect a gap between the vertex and the point at which the showers begin. This is because the gammas during their flight before converting into electron–positron pair are not visible in LAr detector. We can use this fact to distinguish such events from electron ones, which have their shower origin precisely in the vertex. However, to carry out such an analysis, we have to deal with two issues:

- The position of the vertex is not *a priori* known. We have to have at least one visible particle originating from the vertex. This is usually a proton or charged pion. This limits our capability to events that have at least one proton or charged pion with sufficiently high energy to show up in the detector.
- If a gap is small, one can easily make a mistake and decide that there is no gap at all. Therefore, we have to consider only events for which the gap is large enough. Fortunately, taking into account events with the gap larger than 1cm excludes only 5.4% of all the events. This number is obtained by assuming exponential gamma decay probability (conversion length of photon in LAr λ_{pair} is equal to 18 cm):

$$P(x) = \frac{1}{\lambda_{\text{pair}}} \, \exp\left(-\frac{x}{\lambda_{\text{pair}}}\right).$$

The analysis was divided into two stages. First, the visibility criterion for a particle marking the vertex was conservatively assumed to 3 wires lit up by the particle. This condition is usually utilized when reconstruction of the direction of a particle is necessary. Then, in the second stage, the events which were discarded in the first stage as not containing any visible particle in the vertex underwent a scanning procedure. Its aim was to decide how many of them are really invisible in the real detector environment.

5. First stage — three wire criterion analysis

5.1. Simulation

In order to perform such an analysis, one has to simulate neutrino events inside the detector volume. Usually, the procedure is a sequence of the following steps:

$$\text{Neutrino simulation} \rightarrow \text{Detector simulation} \rightarrow \text{Data analysis}\,.$$

Neutrino simulation takes beam characteristics (energy spectra of all flavors of neutrinos in the beam) as an input. It simulates primary interactions in the detector medium. The products of an interaction are then propagated further in the medium by detector simulation, which takes into account all the design subtleties of the detector. The detector simulation produces output which is identical to the output of the real detector — in this case, collection and induction images composed using wire signals. This output is finally processed (noise subtraction, event reconstruction, *etc.*) by data analysis routines.

In the analysis described here we used Nuance as a neutrino interaction generator. Nuance is a widely used tool developed by Dave Casper from UCIrvine. The technical details regarding physical models used in the program can be found in Ref. [4]. The simulation process includes primary interactions on independent nucleons and secondary interactions of hadrons inside nucleus (intra-nuclear or final state interactions).

In the analysis, version 3.006 of Nuance was used, which is capable to simulate interactions on nucleus of user's choice — this is important, because intra-nuclear interactions are strongly dependent on number of protons and neutrons in the nucleus (and other factors associated with the type of nucleus). For the analysis, argon was set as a target. The results were cross-checked with NUX+FLUKA simulation. FLUKA [5] is a widely known and thoroughly checked simulation package for nuclear and particle physics; in the NUX+FLUKA simulation it is responsible for intra-nuclear interactions. Since the results given by Nuance and NUX+FLUKA are generally in agreement, one can conclude that the Nuance neutrino simulation on argon can be trusted.

The beam characteristics used are taken from the data available in the T2K Collaboration web repository. 25.000 NC muon neutrino events were generated, and they were used in the analysis below.

5.2. Visibility analysis

Usually, as a detector simulation, one uses fully fledged simulation package. However, to simplify the procedure, a program using ROOT libraries was used instead of detector simulation at this stage of the analysis. The program calculated number of wires which the ionizing signal from each particle produced can be observed on. This gives us a hint whether the particle considered is visible or not. The program utilized the following algorithm:

- It takes into account every charged particle (protons, charged pions, muons, electrons, charged kaons), and calculates length of its track using known energy-range dependence for each type of particle
- It makes two consecutive projections: first onto the wire plane, and then second onto 2 directions perpendicular to the wires' directions ($45°$, $-45°$). This way, two quantities are obtained, corresponding to the length of track in two directions perpendicular to the wires.

- If greater of these quantities exceeds 9 mm (3 wires times 3 mm wire pitch) we conclude that the track is visible.

The results for all protons and pions present in the sample are shown in the Figs. 3, 4.

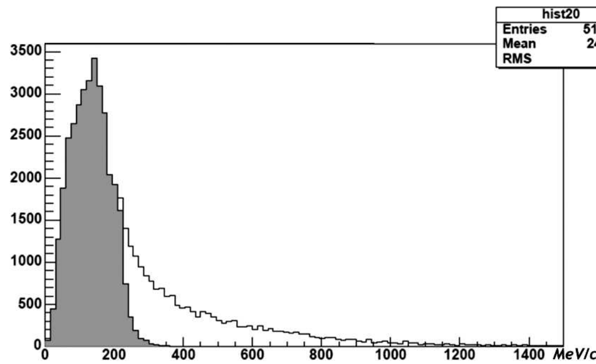

Fig. 3. Three wire criterion: visible (white) and invisible (gray) protons in the sample on the momentum histogram.

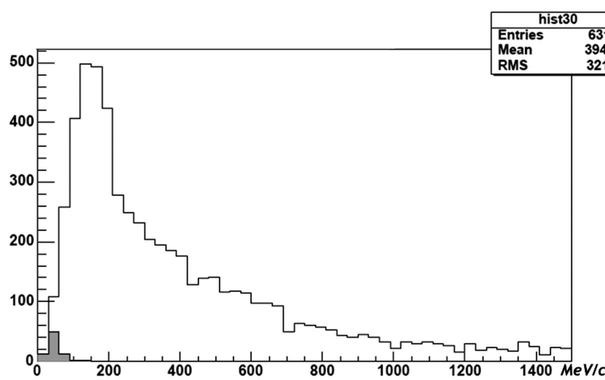

Fig. 4. Three wire criterion: visible (white) and invisible (gray) charged pions in the sample on the momentum histogram.

One can see that even though there is so many protons in the low energy range, most of them are in fact invisible. Other particles are almost always visible (but they are so rare, that they do not significantly contribute to the visibility analysis).

To conclude this part of the study, one has to check how many π^0 events have at least one visible particle in the vertex. The results are presented in the TABLE I below. We see that 64% of all π^0 events have the primary vertex visible, which enables us to use the gap method. Remaining 36% cannot be identified using this method.

TABLE I

Description	Number of events
All events in the sample	25636
Events with 1 or more π^0s	4301 (17%)
π^0 events with 1 or more visible tracks	2762 (64% of all π^0 events)
Unidentifiable π^0s (vertex not visible)	1539 (36% of all π^0 events)

6. Second stage — visual scanning

Since the main contribution to visibility of the vertex comes from protons, and their invisibility in the lower energy range is the main problem, in the second stage of the analysis the visibility of those low energy protons have been carefully examined. 60 NC ν_μ events were selected. The following conditions were imposed to select events which are of interest here:

- At least one pi zero produced;
- One proton with kinetic energy less than 20 MeV (corresponds to 200 MeV/c in momentum);
- Any number of neutrons.

The second condition is a result of observation that all protons below 200 MeV/c momentum threshold are recognized as invisible in the three wire criterion analysis. Our aim is to check if this is indeed the case.

The selected events were transferred to full detector simulation, implemented in the Geant4 environment. The analysis was based on visual scanning of selected events — looking at collection and induction views of each event and deciding whether the vertex is really visible or not.

The results discussed here should be considered preliminary. In 31 of 60 cases (over 50%) we were able to identify the vertex location, despite the fact that all the events chosen here were discarded by the three wire analysis as invisible. This shows that the results given by three wire analysis are too conservative; in fact, a large amount of protons in the vertex can be visually recognized even though they do not produce three wire signal.

7. Summary results and conclusions

Three wire analysis shows that 61% of π^0 events can be properly identified on the basis of 1 cm gap. These results can be significantly improved, as our preliminary scanning analysis shows. The results should be combined with results of analyses using other methods, *e.g.* energy loss pattern analysis performed for ICARUS liquid argon detector [3]. Additionally, one should also consider performing two showers analysis, which should also improve the overall results. The accuracy needed in the experiment is about 1%. Three methods described in the article should reach this level, if they are used together.

The analysis presented here is still in progress. More events have to be scanned and electronic detector noise should be considered. Two showers analysis is also planned in the future.

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