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How to do a $\nu_e \rightarrow \nu_\mu$ measurement in a SK-like detector

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In the future neutrino experiments, a beta-beam, which can produce pure electron neutrino beam, is expected to achive precise measurement of the neutrino oscillation parameters. In the ν_μ appearance measurement of a beta-beam, a detector does not need to identify particle charge and thus, a water Cherecov detector will be a candidate for the far detector. In this paper, we study the expected signal detection efficiencies and background at the proposed beta beam facilities with the water Cherenkov detector. In the estimation, we use the current simulation and analysis tools developed for the Super-Kamiokande experiment. Depending on the beta beam setups, the signal detection efficiencies are found to vary from 36.4% to 75.3% in the standard ν_μ search. The major source of background was found to be neutral current pion production, and the fraction of the background increases with the mean energy of the neutrino beam.

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1. Introduction

Various neutrino experiments are in operation or in preparation to measure neutrino oscillation parameters precisely. These experiments are expected to provide the mass squared differences or oscillation angles. However, the mass hierarchy of neutrinos or the CP phase parameter of neutrino mixing still remains unkonwn. In order to investigate these properties of neutrinos, it is essential to have a much more intense and pure neutrino beam. Among the proposed beam lines, the beta-beam has several unique features. Since the beta-beam facility can produce pure electron neutrinos or anti-neutrinos from the decay of stored radio-active ion beams, it is not necessary to identify the charge of leptons in the far detector, this will ease the requirements of the far detector. In this paper, we study the performance of the water Cherencov detector with a beta-beam in light of experience gained from the Super-Kamiokande analysis.

2. Neutrino Measurement in a Ring Imaging Water Cherenkov Detector

Super-Kamiokande(Super-K) [1] is a 50 kt water Cherencov detector, which detects the Cherencov ring image induced by charged particles and gamma rays. Atmospheric neutrino oscillations have been established by the observation in Super-K [2]. The energy spectrum of neutrinos from the beta-beam facility spreads from a few hundred MeV to a few GeV. Therefore, it is possible to use the same method as used in the study of atmospheric neutrinos. Since the beam direction is fixed, the incoming neutrino energy is reconstructed as follows, by assuming charged current quasi-elastic(CCQE) interaction;

$$E_\nu^{rec} = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + P_\mu \cos\theta_\mu},$$

where m_N is the nucleon mass, E_μ is the muon energy, m_μ is the muon mass and P_μ is the muon momentum. The actual steps to search for CCQE events is as follows [2]: (1) search for an event with a single Cherenkov ring of a lepton produced by neutrino charged current interaction, (2) classify the ring into two categories, e-like and μ-like, using the photon distribution of the ring pattern, and (3) reconstruct the momentum and direction of the lepton using the observed ring image. The resolution of neutrino energy for CCQE events is shown in Fig. 1.

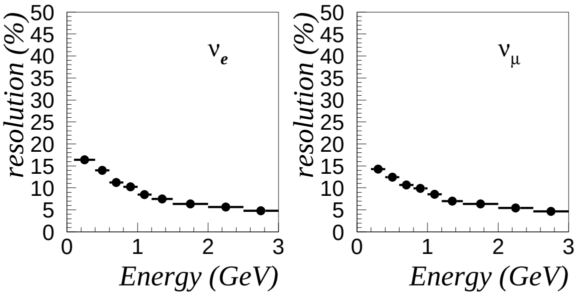

Figure 1: Resolution of neutrino energy as a function of the true neutrino energy for 1-ring, e-like, CCQE ν_e events(left) and 1-ring, μ-like, CCQE ν_μ events(right).

3. Analysis

The aim of this study is to estimate the detection efficiencies and the background in the search for ν_μ appearance with a beta-beam and water Cherencov detector. As the tools to study these items, we use available simulation and analysis programs from the Super-Kamiokande experiment because their performances have been verified in the past atmospheric neutrino and accelerator neutrino studies.

3.1 Neutrinos from the beta-beam facility

The properties of the neutrino beam from a beta-beam facility is determined by the type of ion and its relativistic γ. It is possible to estimate the energy spectrum of the neutrino beam very precisely because the kinematics of beta decay is very well understood. The mean energy of the neutrino beam needs to be adjusted to maximize the sensitivities for neutrino observation. Usually, the peak energy of the neutrino beam is adjusted to the oscillation maximum, which is determined by the baseline together with the energy of the neutrinos. In this study, two baseline distances (L) are selected as described in [4]. One of them is 130km corresponding to the distance from CERN to Frejus, and the other is 700km corresponding to the distance from CERN to Gran-Sasso. For the shorter baseline case, the oscillation maximum is around $0.4GeV$, and for the other case, it is around $1.5GeV$. So here the neutrino beam of peak energy of $\sim 0.4GeV$ is referred to as the 'LE beam' configuration, and peak energy of $\sim 1.5GeV$ as the 'HE beam' configuration. Also both ν_e and $\bar{\nu_e}$ beams are necessary to study CP violation and the mass hierarchy. These four sets of ion and γ combinations have been identified as the candidate configurations, as described in [4].

3.2 Event selection criteria and signal efficiencies

At first, we apply standard event selection to eliminate the cosmic ray muons and the very low energy events. The selection criteria are that there is no activity in the outer detector(FC event), the reconstructed vertex is in the fiducial volume(FV), and the electron equivalent energy(evis) is larger than 30MeV. The neutrino energy spectra for each beam configuration after this selection are shown in Fig. 2. It should be noted that events other than CCQE interactions will be dominant in the HE beam configurations.

In the following analysis, the CCQE events need to be selected as discussed before. Because the Cherenkov threshold of the proton in a water cherenkov detector is 1.1 GeV, only the lepton is identified as a clear ring in this energy range. Therefore, an event with a single ring is selected. Ring candidates are searched for based on the Hough transformation method [3] and the number of rings are determined by the likelihood method. The selected ring is classified into two types [2], e-like and μ-like, by using the difference of the shape of the ring. The misidentification probability is about 1% for both atmospheric ν_e and ν_μ of CCQE events. The μ-like selection probability in the beta-beam neutrino sample after 1-ring selection is about 90% for <400MeV, 95% for >400MeV energy region. However, the events selected as a μ-like event sample contain the charged pions because the ring shape of the charged pions are similar to the muon rings, rather than the electron rings. So the events except CCQE interaction are contaminated. In order to eliminate those charged pion events, events with 1 decay electron are selected. Because the interaction probability of charged pions in water is quite large, a large fraction of the charged pions interact before decaying. The efficiency of detecting decay-electrons in Super-K is 80% (63%) for μ^+ (μ^-). The summary table of event selection efficiencies is shown in Tab. 1.

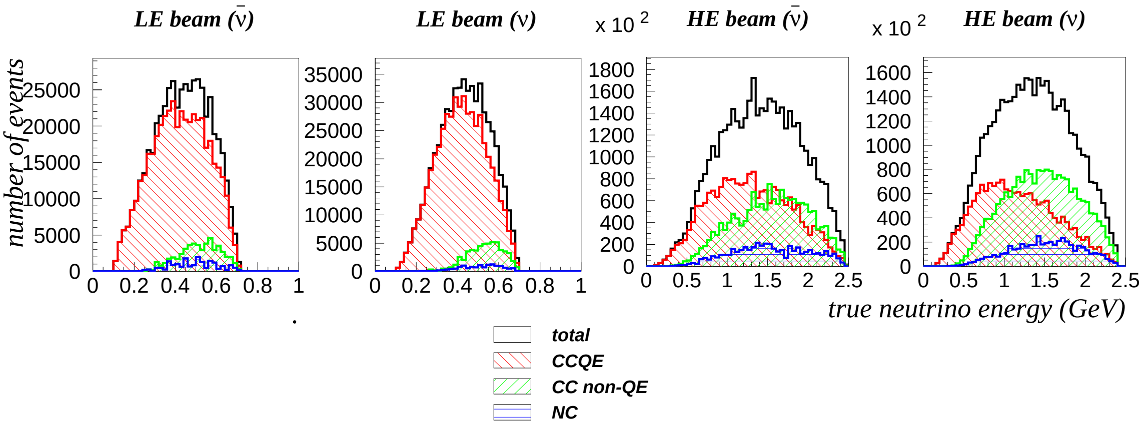

Figure 2: The rate of neutrino interactions in water Chrencov detector for each beam setup.

	LE beam				HE beam			
selection	CC $\bar{\nu}_e$	CC $\bar{\nu}_\mu$	CC ν_e	CC ν_μ	CC $\bar{\nu}_e$	CC $\bar{\nu}_\mu$	CC ν_e	CC ν_μ
FC, FV, evis	100%	100%	100%	100%	100%	100%	100%	100%
1-ring	94.8	96.6	94.4	95.8	81.3	79.6	72.7	68.0
μ-like	1.2	95.7	1.2	95.1	0.9	98.8	0.7	97.6
decay-e	<0.0	81.4	2.4	65.2	6.6	66.7	15.1	54.8
final sample	<0.1	75.3	<0.1	59.4	<0.1	52.5	<0.1	36.4

Table 1: Summary of selection efficiencies of CC events for each beam set. After standard selection(FC, FV and evis>30MeV), the numbers in each selection step show the probabilities after the previous step.

3.3 Background events

Major background events in the search for ν_μ appearance signal are produced by NC interactions, beacause pions are selected as μ-like events. The cross-section of the NC pion production is larger of higher neutrino energies and thus, the fraction of the backgournd events get higher in the HE beam as shown in Fig. 3-(c),(d), in which true paramteres are assumed: $\sin^2 2\theta_{13} = 0.15$, $\sin^2\theta_{23} = 0.5$, $\Delta m^2 = 2.5\times 10^{-3} eV^2$ and $\theta_{12} = 0$ (no matter effect). Moreover, the momentum of the pions are rather low because most of the pions are produced via decay of resonances. Therefore, the reconstructed energy using the misidentified pions is rather low and not sensitive to the energy of the parent neutrino.

But, in case of the reconstructed energy distributions (Fig. 4-(1)), the NC events are peaked at lower energy because of the different kinematics between QE and NC events. It is therefore easy to distinguish these background events from the signal. For the $\sin^2 2\theta_{13} = 0.01$ case (Fig. 4-(2)), it is difficult to see ν_μ signal, especially in the HE beam(Fig. 4-(2-d)).

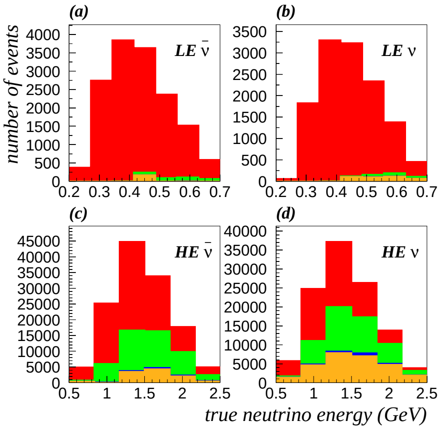

Figure 3: The final sample neutrino true energy distributions for each beam type, in case of $\sin^2 2\theta_{13} = 0.15$. The different event types are shown in different colors as shown right side.

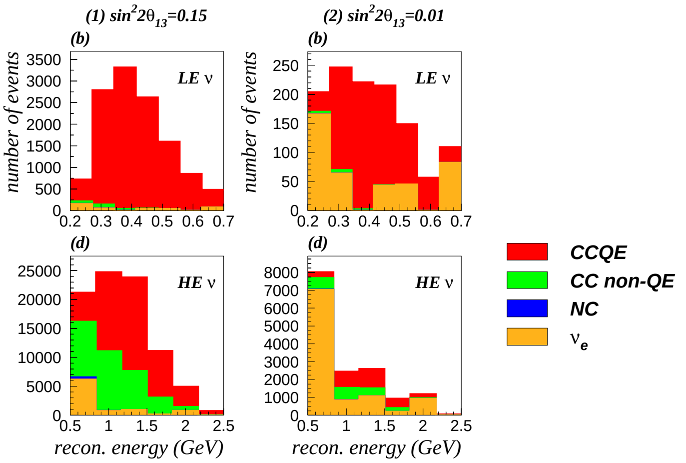

Figure 4: (1) are the reconstructed energy distributions in case of $\sin^2 2\theta_{13} = 0.15$. (2) are in case of $\sin^2 2\theta_{13} = 0.01$.

4. Conclusion

ν_μ appearance measurement by using beta-beams and water Cherencov detectors is very promising as a future neutrino oscillation experiment. In these experimental configurations, the signal detection efficiencies of a water Cherencov detector are expected to be 75.3%(59.4%) for $\bar{\nu_\mu}(\nu_\mu)$ from the LE beam and 52.5%(36.4%) for $\bar{\nu_\mu}(\nu_\mu)$ from the HE beam. Meanwhile, becasue the interactions other than CCQE interaction become dominant at high energy, the rate of background increases in the HE beam configurations. Mainly, misidentification of the pion's rings from NC ν_e pion production is the cause of the background.

References

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