A letter of intent to extend T2K with a detector 2 km away from the JPARC neutrino source

Submitted by the T2K collaboration to the JPARC PAC

June 27th 2007

Abstract

This Letter of Intent describes the motivation for and feasibility studies of a detector site 2km from the neutrino production point of the the T2K experiment. At this distance, almost the same neutrino energy spectrum is measured as the unoscillated spectrum would be at Super-K 295 km away. We describe a plan to measure this spectrum with both a 1 kton water Cherenkov detector which has been optimized to match Super-K resolution, and a 100 ton fiducial volume fine-grained tracking detector which will provide fine grain imaging and low particle detection thresholds for a precise study of neutrino interactions at the relevant energies. A reference design for the fine-grained detector utilizing a liquid argon time projection chamber is described. High energy muons which exit the water Cherenkov detector will be measured by an iron muon ranger. The 2KM detector, in combination with measurements from a detector located 280 m from the neutrino source, and results from the NA61 hadron production experiment at CERN, will allow for the best constraint on the prediction of the unoscillated neutrino rate at the Super-K far detector.

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Contents

1 Project Description

The T2K experiment (Tokai-to-Kamioka) is a long baseline neutrino oscillation experiment that will measure several parameters that describe neutrino mixing at the scale set by atmospheric neutrino oscillation. These include precision measurements of Δm^2_{23}, θ_{23}, and most importantly, θ_{13}. From reactor experiments such as Chooz and Palo Verde, we believe θ_{13} to be fairly small (less than $\sim 12^\circ$), which implies that electron neutrino appearance will be a statistically small effect. On the other hand, θ_{23} is known to be nearly maximal, and it is of great theoretical interest to measure a small difference from $\pi/2$. For both cases, the T2K experiment requires detailed understanding of systematic effects.

The T2K experiment utilizes a high intensity beam being constructed at the J-PARC facility in Tokai. The beam is first measured by a set of detectors 280 m from the neutrino source, and the far detector is Super-Kamiokande, a 50 kton water Cherenkov detector with 11,000 photomultiplier tubes, 295 km distant. For $\Delta m^2 \sim 2.5 \times 10^{-3}$ eV^2, the maximum oscillation effect is at a neutrino energy of 0.6 GeV. Unlike previous long-baseline experiments, T2K will use the off-axis technique to produce a sharp peak in the energy spectrum of neutrinos at the critical energy. This will maximize the signatures for the disappearance of muon neutrinos and the appearance of electron neutrinos.

To best cancel systematic uncertainties, it is desirable to measure the neutrino beam with the same type of detector as Super-K near the neutrino production point before neutrino oscillations have taken place. For a water Cherenkov detector, we find that the minimum size is set by the length needed to contain muons produced by ~ 1 GeV neutrinos, and corresponds to a volume weighing approximately 1 kton. This size also readily contains the important event categories of intrinsic beam ν_e and neutral current single-π^0. For this size, a detector located 2 km away from the neutrino source will have one event or fewer in the water volume for every pulse of the accelerator.

Both the neutrino flux and energy spectrum change as one moves farther from the beam axis. At a distance of 295 km, the far detector will sample a very narrow interval of the beam profile. A detector at 2 km will sample a very similar interval of the neutrino profile. Therefore, the event rates measured at 2 km can be simply extrapolated to the Super-K site with small corrections.

A valuable event category at these energies are two-prong quasi-elastic scatters with both μ and p reconstructed in the final state. This allows a precise measurement of neutrino energy, and allows us to isolate a non-quasi-elastic sample that contributes to the background for θ_{23}. To use these events most effectively, it is also necessary to have a fine-grained detector that is sensitive to tracks which might not be seen in a water Cherenkov detector. For this purpose, a design is presented for a large (150 ton) liquid argon TPC with an embedded frozen water target. Such a detector will record 200,000 events per year, affording very detailed studies of the complicated region near $E_\nu \sim 1$ GeV, where resonant pion production is significant, the hadronic part cannot be calculated perturbatively, and nuclear effects are important.

Finally, there is important information in the high energy tail of the neutrino spectrum which can constrain both the ν_μ and ν_e components of the beam. High energy muons exit the water Cherenkov detector, but we will measure them with a downstream muon range stack. High energy events will also be detected with high efficiency in the liquid argon detector. In this case, the high energy muons escaping the liquid argon volume can still be detected and measured in the water Cherenkov detector.

In this letter, we express our interest in constructing an intermediate detector complex located off the J-PARC site near the small village of Tokai. We believe this facility will be a important element of T2K in the high intensity period of running where careful control of the systematic errors are required. The facility considered would be located about 2 km away from the target, and would extend ~50 m below ground level to reach the proper position in the neutrino beam at that location. Environmental studies and sample core drilling have already been conducted and have confirmed the suitability of the chosen site. The local government, which owns the property, approved the proposed facility and granted use of the property at no cost to the experiment.

2 Physics Goals of T2K

2.1 Introduction

There is now a strong consensus that neutrinos have mass and their flavor states mix with each other. Strong evidence exists from atmospheric neutrinos [1], solar neutrinos [2, 3], reactor experiments [4], and long baseline oscillation experiments [5, 6].

The next generation of experiments must take the step towards making precision measurements of the neutrino parameters that are already known, and attempt to measure effects that have not yet been seen, because the values of the parameters that govern them are either zero or too small. Electron neutrino appearance is an as yet unobserved aspect of neutrino oscillation; in addition, if interpreted in a three neutrino oscillation framework, the observation of electron neutrino appearance would mean that more refined measurements could explore CP violation in the lepton sector using neutrinos.

The main goals of the T2K experiment are:

- to observe ν_e appearance in an oscillation experiment for the first time,
- to measure $\sin^2 2\theta_{13}$ or improve the limit by a factor of 10 to 20,
- to measure $\sin^2 2\theta_{23}$ to better than the few percent level, perhaps resolving whether it is only large, or very nearly maximal, and
- to continue to refine the precision measurements of Δm^2_{23} begun by Super-K, K2K and MINOS.

Fig. 1 shows the expected sensitivity of the experiment to θ_{13}, for different values of CP-violating phase δ. Fig. 2 taken from the T2K LOI [8] shows expected sensitivities for different values of Δm^2_{23} to the atmospheric mixing parameters.

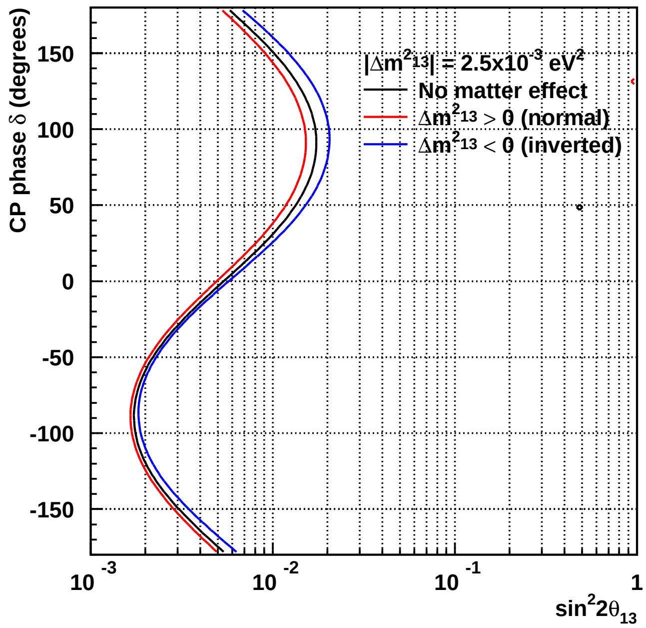


Figure 1: Expected reach of T2K in $\sin^2 2\theta_{13}$ and CP phase δ.

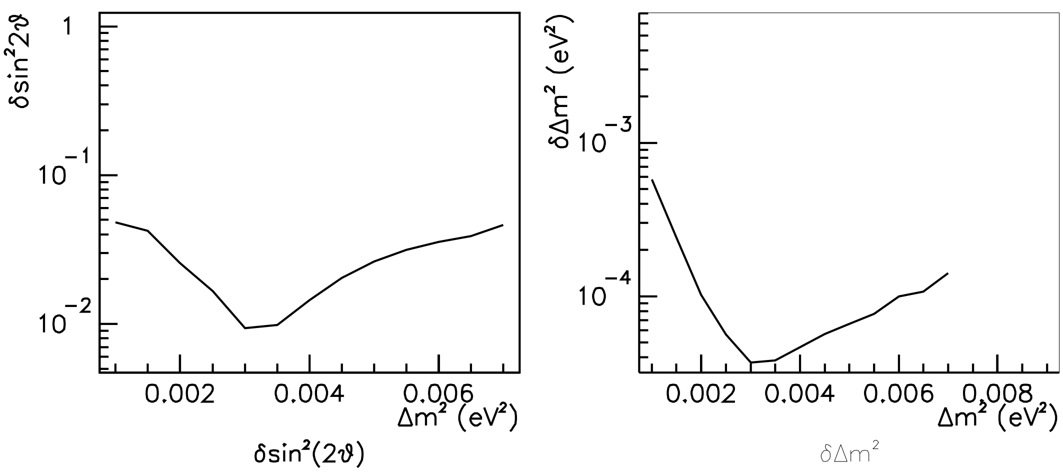


Figure 2: T2K's expected fractional sensitivity to $\sin^2(2\theta_{23})$ and Δm^2_{23} as a function of Δm^2_{23} from the T2K LOI [8].

The value of θ_{23} is of particular interest. Our current knowledge from Super-K tells us that $\sin^2 2\theta_{23}$ is consistent with unity but could be as small as 0.95. If the value is unity this corresponds to a mixing angle of 45°, which is an exactly equal mixture of mass states known as "maximal mixing." One of the major goals of the experiment is to measure $\sin^2 2\theta_{23}$ to high enough precision to distinguish between a mixing which is merely large from one which is so close to maximal that it would appear to indicate some underlying symmetry.

3 Motivation for the 2KM Detector

T2K is a challenging experiment. The goal is to believably measure a very small amount of ν_e appearance on top of background of true ν_e interactions, along with a comparable amount of neutral current interactions. Unfortunately, some of these backgrounds are irreducible. However, the 2KM detectors together with the ND280 and Super-K detectors make the T2K experiment uniquely situated in the world to make the most convincing measurement of non-zero θ_{13}. We are fortunate to be able to build the 2KM complex at the JPARC facility due to the relatively shallow depth 2 km away from the T2K neutrino source.

All of the proposed elements of the T2K detector are shown in Fig. 3. As described in the introduction, T2K is an off-axis experiment, which is specifically designed to select a narrow energy band by exploiting the change in energy spectrum as a function of angle from the central beam axis. Since the part of the neutrino beam measured by Super-K is only a small portion of the entire beam, the neutrino energy spectrum seen at Super-K is quite different from the energy spectrum of the entire beam. Even along the off-axis angle, the finite size of any detector subtends a different fraction of the entire beam depending on the size of the detector and the distance from the production point. This is demonstrated by Fig. 4 which compares the neutrino beam spectrum 2 degrees off-axis for the anticipated detectors at 280 m, at approximately 2 km, and at 295 km.

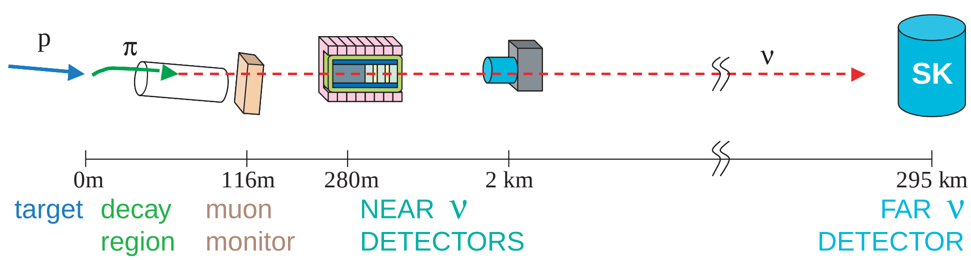


Figure 3: An overview of all of the proposed elements of the T2K experiment. The CERN T2K/NA61 pion production experiment will be used to predict the pion momentum in the decay region.

By using the results from the T2K/NA61 experiment at CERN and estimated differences due to efficiency and targets, the detector at 280m will make a prediction of the unoscillated flux at Super-K. This prediction can be directly checked by the 2KM detector since it has the same technology and target as Super-K, and the flux seen at the 2KM is almost the same as that seen by Super-K before oscillations. The detector is close enough to the target that the neutrinos still will not have oscillated, giving a direct check of the prediction from NA61 and the 280m detector.

In addition, the water Cherenkov detector at the 2KM site will use almost the same reconstruction algorithms as Super-K. The choice of a large unsegmented water Cherenkov detector is only possible this far away from the neutrino production source. The similarities of the detectors and algorithms, combined with the similarity of the fluxes at 2 km and 295 km, allows a direct prediction of the ν_e appearance search background at Super-K using the 2KM with small corrections.

The most convincing case to be made by the T2K experiment for non-zero θ_{13} will be a comparison of the predictions at Super-K of the energy spectrum of backgrounds to the ν_e search by both the 280m and 2KM detectors,

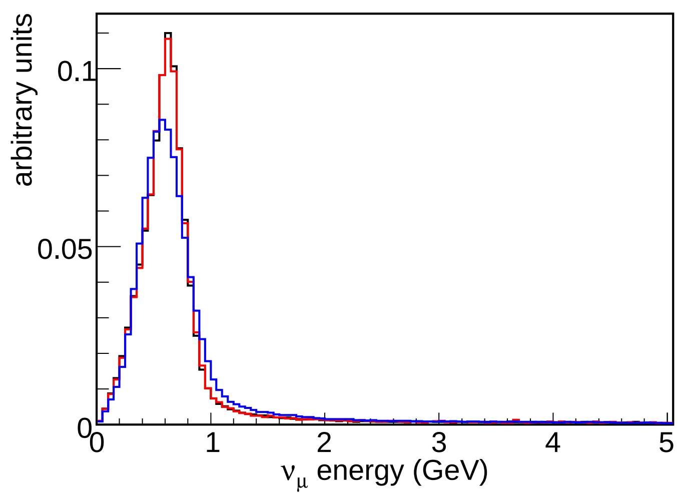


Figure 4: The expected T2K neutrino flux at 280 m(blue line), 2km(red line), and Super-K (black) line.

3.1 The Neutrino Flux at 2 km

The background for the ν_e search at Super-K comes from both electron neutrinos that are intrinsically in the beam at production, and misidentified events at Super-K that were produced by neutral current (NC) and ν_μ charged current (CC) interactions. Therefore, in order to maximize the potential of the experiment it is important to measure carefully the expected neutrino spectrum for both ν_μ and ν_e in a place where the spectrum is as similar to that at Super-K as possible. This allows both a careful check of the NA61/280m prediction and a direct prediction of the background at Super-K.

Although the proposed detector at 2 km subtends a 30× larger solid angle than Super-K at 295 km, it is distant enough so that the neutrino energy spectra at 2KM and Super-K are similar in shape. The differences in flux as measured at 280 m and 295 km can be seen more clearly by looking at the ratio of near ν_μ flux to far flux (N/F ratio) as a function of energy. The left and right panels of Fig. 5 show this ratio at 280 m and 2 km respectively. Because the energy of peak positions are shifted at 280 m relative to that at Super-K the N/F ratio changes drastically exactly in the region of the oscillation maximum. On the other hand, we can see that by moving to about 2 km, the N/F ratio is flat to about 5%.

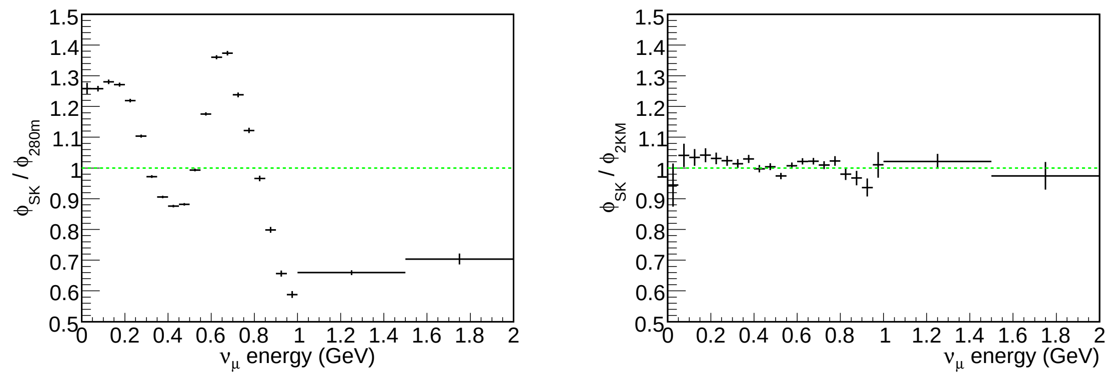


Figure 5: (left) The near/far neutrino flux ratio as a function of energy 280 m from the T2K target. (right) The near/far neutrino flux ratio as a function of energy 2 km from the T2K target.

3.2 Water Cherenkov Detector

The profile and properties of the beam near the target will be measured by the detector complex 280 m from the neutrino source. Super-K is a water Cherenkov device, and optimally a similar detector will measure the neutrinos before they have a chance to oscillate. Having a large unsegmented water Cherenkov detector at 2 km from the T2K target will be a valuable addition to the experiment because it:

- **Has the same target material as Super-K**
- **Uses the same detector technology as Super-K**
- **Uses almost the same reconstruction algorithms as Super-K**
- **Sees almost the same unoscillated neutrino spectrum as Super-K**

The size of the water Cherenkov detector is driven by two factors. First of all, we want to contain most muons which interact inside the fiducial volume. At the same time the detector must not be so large that there is more than one neutrino interaction per spill on average. At 2 km this sets a size of approximately 13 m with a 9 m diameter and a 100 ton fiducial volume.

Extensive design studies have been performed using a GEANT4 based Monte Carlo. Data were simulated and fully reconstructed using tools based on the Super-K reconstruction chain. The basic parameters of the simulation were tuned by first simulating the water

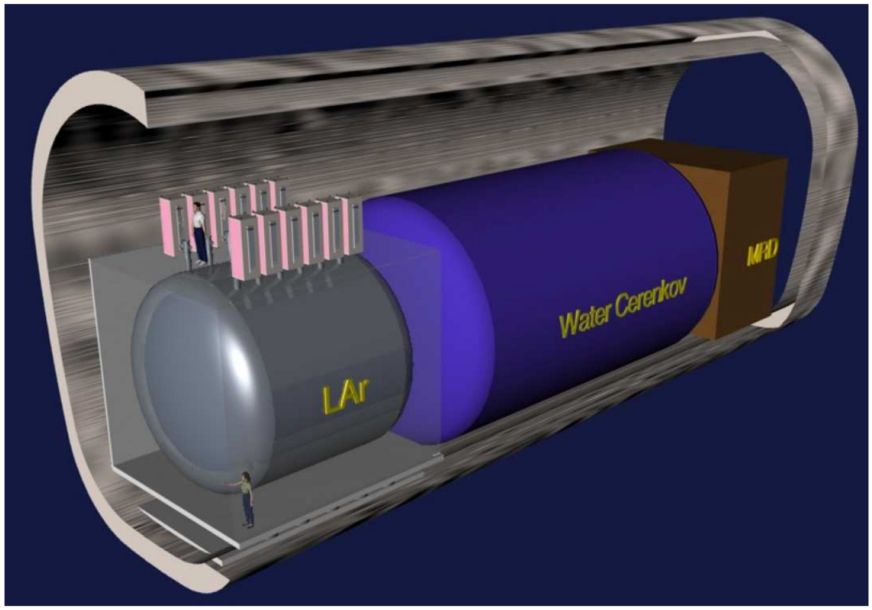


Figure 6: A schematic view of the baseline design of the 2KM detector complex composed of a liquid argon TPC, a water Cherenkov detector and a muon ranger.

Cherenkov tank from the 1 kton tank at the K2K experiment. Then important parameters of the design were varied. A configuration was chosen which has the most similar response to Super-K when reconstructing physics quantities. An example of this is the choice of the size and number of PMTs. One option is to use the same size PMTs as K2K and Super-K (841 tubes). However, the number of PMTs, and hence the ring resolution is greatly reduced due to the relatively large "pixel" size. Another option is to use a larger number of 8-inch PMTs (5660 tubes). Although the physical size of the PMT is different, the number (5660 vs. 841) is much closer to Super-K's (11146 tubes), and the relative pixel sizes are similar. Fig. 7 demonstrates this effect. In these figures, a π^0 is simulated decaying in the Super-K detector, and in a 2KM water Cherenkov detector with 8-inch and 20-inch PMTs. As can be seen, qualitatively the 8-inch case looks more like Super-K.

We have done quantitative studies to determine the optimum configuration for matching relevant Super-K resolutions and efficiencies. We have studied single-ring muon selection efficiency, ring-counting and particle identification (PID: classification into e-like (showering) or μ-like (non-showering) particles). In order to apply this reconstruction software to a detector equipped with 8-inch PMTs, careful modifications had to be made to the reconstruction code. We conclude from these studies that a configuration with a larger number 8-inch PMTs is superior to one with fewer 20-inch PMTs.

Mono-energetic $e^-$and μ^-events ranging from 30 MeV/c (150 MeV/c for μ^-) to 1500 MeV/c, emitted isotropically from random vertices, were simulated and reconstructed using the Super-K/K2K software suite. All stages of the reconstruction were checked: first the vertex (and first ring) fitter finds the position of the vertex (and the direction of the

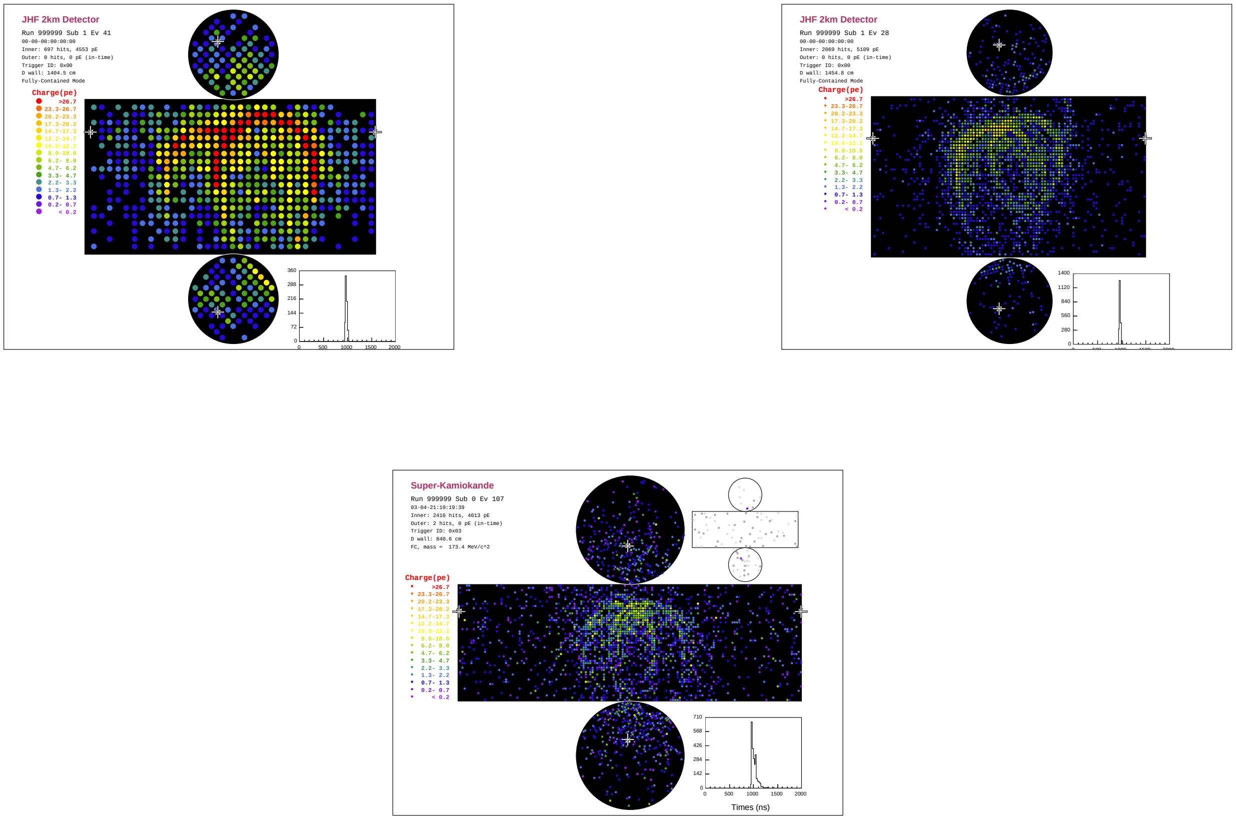


Figure 7: A simulated NC π^0 event in the 2KM WC detector with 20-inch PMTs (top left) and 8-inch PMTs (top right). A simulated NC π^0 event in the Super-K detector is shown for comparison (bottom). Based on studies with this simulation, we have concluded that it is preferable to use a larger number of small 8-inch PMTs than a smaller number of 20-inch PMTs.

most visible ring) using timing and charge information. Then, using the vertex position information, the ring counting program determines the number of Cherenkov rings and their directions by a maximum likelihood method. Rings are classified by the PID program which determines whether the ring is e-like (a showering particle) or μ-like (a non-showering particle) using another maximum likelihood method. Using this PID information the vertex of single-ring events is further refined. Throughout the entire process a ring separation program is used to apportion the charge of each PMT between the rings. The momentum of each track is then estimated from the amount of charge detected in a 70° half-opening angle around the reconstructed direction. These Monte Carlo and reconstruction tools were used in the analysis presented in section 5.

3.3 Muon Range Detector

To measure any neutrinos with interaction products that leave the water detector, and to better match the acceptance of Super-K, we will have a muon ranger. The muon ranger must be large enough to contain almost all of the high energy muons produced in the water Cherenkov detector that escape, and must cover enough of the solid angle to intersect most of those muons. The high energy portion of the ν_μ tail is dominated by the decays of kaons which are also a source of ν_e backgrounds. Measuring this flux will give an additional exclusive constraint on this component of the background.

3.4 Fine Grained Detector

The fine grained detector at the 2KM site is used to measure both quasi-elastic (QE) and non-quasi-elastic (non-QE) neutrino interactions at 2 km. The non-QE interactions serve as a source of background to both the ν_e appearance and ν_μ disappearance searches. Having a spectrum which is as similar as possible to that seen in the water Cherenkov detector is important, as cross-sections are energy-dependent and what is measured in a detector is a folding of the flux $\times$ the cross-section. Water Cherenkov detectors are not sensitive to all particles that are produced in neutrino interactions, and are not optimized for complicated multi-track events.

We also need to characterize the NC and intrinsic ν_e backgrounds to the ν_e search with high resolution. This will allow us to directly test the efficiency and systematic errors of the water Cherenkov analysis. The more finely-grained and low-energy threshold the detector, the better we can measure pions, protons and other particles produced in non-QE interactions and characterize both the intrinsic ν_e in the beam and misidentified ν_e background. We know from our experiences with the K2K experiment [15] that different detectors and analysis techniques yielded approximately a 20% difference in the inferred non-QE cross-section fraction. For this reason we believe it is important to measure the amount of non-QE interactions in as many targets and detectors as possible with our flux.

The statistics of events reconstructed in the fiducial volume of the fine grained detector needs to be comparable to that of the water Cherenkov detector (~200,000 events/year). This means that the fiducial volume of such a detector needs to be on the order of 100 tons and any proposed detector technology must be able to scale to this size for reasonable cost.

3.4.1 Liquid Argon TPCs

For the reasons described above, one of the options being actively explored by the T2K collaboration is the use of a liquid argon TPC as the 2KM fine grained detector. Extensive

R&D has been carried out demonstrating that a liquid argon TPC would provide a unique and fundamental input for the experiment. Specifically, liquid argon:

- is already known to scale to the 100 ton mass scale.
- provides bubble-chamber-like imaging with ≈ 3 mm resolution.
- has a very low momentum threshold making all particles in neutrino interactions visible.

The event and particle identification in the liquid argon detector gives clean e/μ and e/π^0 separation with an unbiased reconstruction. Preliminary studies show ν_e and π^0 components of the background separable to approximately 99.8%. This will provide an independent measurement of the ν_e contamination, well separated from the π^0 background. Combined with the NC background, it will yield independent and separated ν_e and π^0 background components at the far detector. For the muon neutrino disappearance search, the good muon identification makes the selected sample very clean. The low momentum detection threshold in LAr compared to water Cherenkov allows for an independent classification and measurement of event samples in the GeV region. This will provide independent systematic uncertainties on the non-QE/QE ratio.

Since the energy spectrum measured by the water Cherenkov detector is based on measurements of the outgoing leptons, the final determination of the oscillation parameters is limited by systematic errors arising from the lack of knowledge of all the details of the neutrino interactions. The bubble-chamber-like imaging of the events will permit the study of these neutrino interactions with high quality and, given the flux and the large mass, with high statistics. This sample of events will allow the study of the deep inelastic scattering and resonance modeling, quasi-elastic modeling including interaction form factors, and the study of nuclear effects such as binding, Fermi-motion, Pauli exclusion, NN-correlations, PDF modifications, re-scattering, etc.

Finally, in order to experimentally measure and confirm the expected nuclear difference between the targets of argon and oxygen, we are studying the possibility of an embedded frozen water target in between the cathode plates which will provide enough statistics every year to track these differences.

4 The 2KM Laboratory Facility

4.1 Overview, Location and Size

At about 2 km from the target, the center of the detectors must be more than 40 m below the surface. Therefore, the laboratory facility must be constructed underground, in addition to relevant surface facilities. We searched for a candidate site for this laboratory facility, and found one 1.84 km down stream from the target.

Due to civil-construction constraints, the candidate site is not on the line that connects the target and Super-K. The 2KM detector detector will be located in a position which is left-right symmetric to Super-K with respect to the beam center. Since the beam is expected to be left-right symmetric, we expect almost the same flux as that in Super-K. In order to confirm the left-right symmetry of the beam, we hope to also install a set of compact neutrino event monitors at the ND280 experimental hall.

Fig. 8 shows the map near J-PARC. The candidate site is located 1.84 km down stream from the target. This place is owned by the local government (Tokai-village). We had many discussions with Tokai-village, and in 2003, Tokai-village agreed to provide this place to this experiment without any cost.

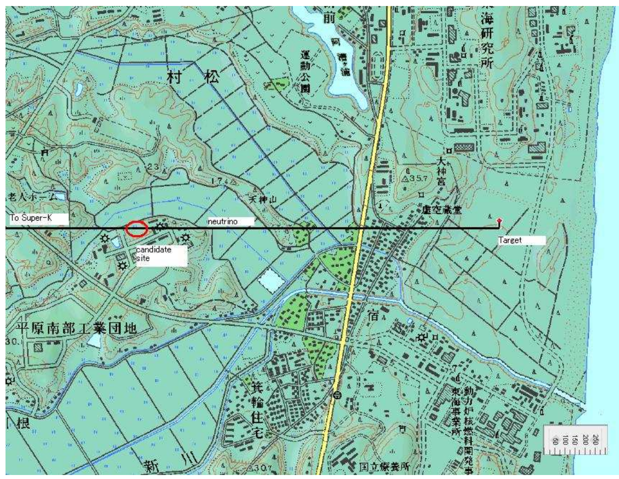


Figure 8: A map near the J-PARC accelerator facility and the candidate 2 km detector facility. The horizontal black line near the center shows the line that connects the target and the far detector. The candidate site is shown by a red circle. It is located 1.84 km from the target.

In order to design the underground facility and to estimate its cost, it is necessary to know the condition of the underground soil. For this reason, in 2003 we carried out a boring measurement at the site down to 65 m from the surface. The soil is not hard down to 7.5 m from the surface. However, below this level, the soil is hard enough to excavate the underground facility.

For cost reasons, the size of the experimental hall must not be larger than absolutely necessary. The floor where the neutrino detectors are installed is located 56.27 m below the surface. The center of the neutrino detectors is 51.62 m below the surface. The underground cavity is approximately 34.5 m long, 9.3 m wide and 14 m high. The liquid argon TPC, the water Cherenkov detector and the muon range detector will be installed in this underground cavity from upstream to downstream.

5 Physics with the Intermediate Detector

The goal of the 2KM detector is to constrain systematic uncertainties and provide a direct measurement of the un-oscillated event rate. We believe this facility will be a important element of T2K in the high intensity period of running where careful control of the systematic errors are required. This section describes the role of the 2KM detectors in characterizing the flux and interactions of neutrinos at the Super-K far detector. The primary concerns are prediction of the background for the ν_e appearance search and prediction of the ν_μ flux for the disappearance measurement. As described in section 3 the 2KM detector can be used both to predict the un-oscillated event rate at Super-K by itself and to check the predictions of T2K/NA61 and the 280m detector directly. Both of these scenarios are discussed in this section.

When searching for ν_e appearance in Super-K there will be both an irreducible intrinsic ν_e background and a background due to event mis-identification. Fig. 9 shows an example of the case where the ν_e appearance signal is found just above the expected sensitivity of the experiment.

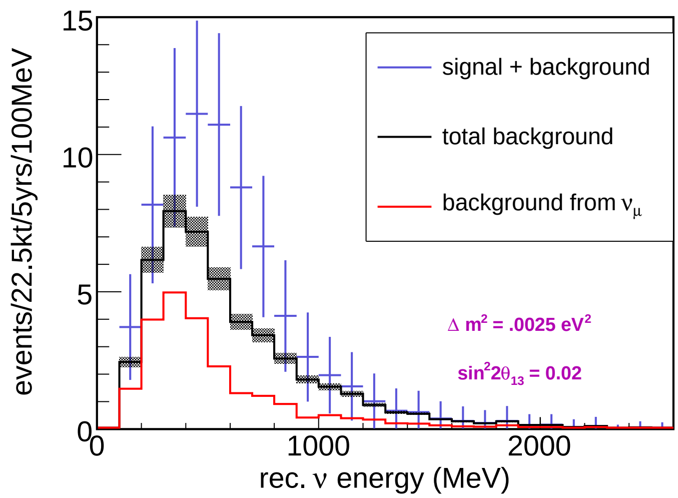


Figure 9: Expected ν_e signal in Super-K near the sensitivity of the T2K experiment. The error bars on the total spectrum are statistical and the background error bars were plotted assuming a 7.5% uncertainty.

It is clear from this figure that if there is no observed signal, or the signal is quite small, the error or sensitivity will be dominated by how well we can determine the background to the search. Fig. 10 shows this effect as a function of exposure for Super-K with several errors on the total background normalization assumed.

As can be seen, if the total background uncertainty is allowed to approach 20%, the θ_{13} sensitivity flattens out after 5 years of T2K running as the result becomes systematics-limited. Therefore our goal is to control the total uncertainty to better than 10%. Also

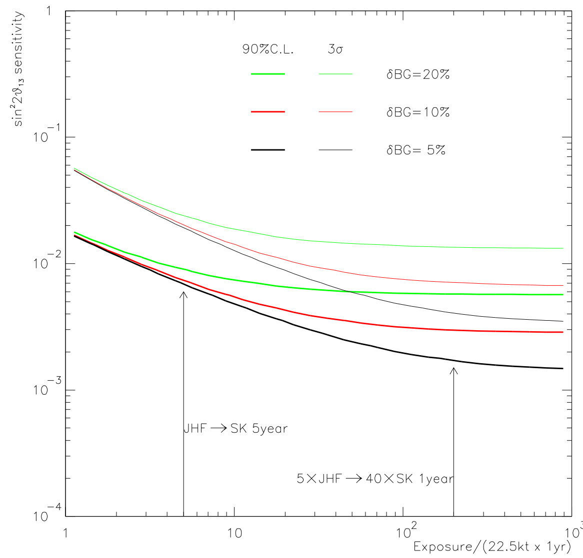


Figure 10: Sensitivity to θ_{13} as a function of exposure for three uncertainties in the background prediction. The first arrow is the exposure for a five year T2K run, the second for five years of a upgraded J-PARC beam with Hyper-Kamiokande as the target.

shown in Fig. 10 is the situation for the proposed second phase of T2K with an upgraded neutrino beam and a detector with approximately 20 times the fiducial volume (such as the proposed detector Hyper-Kamiokande). In this case the result is completely systematics-limited and the total uncertainty needs to be controlled to better than 5%. The ν_e appearance background at Super-K will also be predicted at the ND280 detector, with a goal of controlling the systematic error to 10%. The background measurements made by these two detectors rely on very different techniques, the two independent techniques will complement each other constraining the background even further.

5.1 Measurement of the Background for ν_e Appearance with the 2KM

The leading uncertainty in the background for ν_e appearance at Super-K is in the rate of NC single-π^0 interactions on water which fake a single-ring electron. In addition to the prediction for this rate made by the detectors 280 m from the target, the 2KM water Cherenkov detector will provide a direct measurement of these interactions using a detector with nearly identical response. We estimate from MC that approximately 1100 NC-π^0 will be misidentified as ν_e background in the 2KM after five years of operation, and another 29,000 NC-π^0 will be successfully reconstructed. These reconstructed events together with the π^0's observed by fine-grained detectors at the 280m and 2KM locations will allow us to explore the way in which these events become misidentified, as well as to develop improved reconstruction algorithms that can be applied in the far detector. In five years we should have excellent statistical sensitivity to the efficiency as a function of energy, angle, and opening angle, which will contribute to a well-understood prediction of the background rate at Super-K. This section describes the technique by which the 2KM can directly measure this background before oscillations and predict the background seen at Super-K.

5.1.1 Neutral Current π^0 Backgrounds

Neutral current π^0 events are a major source of background for a ν_e appearance search at Super-K. In a water Cherenkov detector, a π^0 should produce two e-like rings, corresponding to the electromagnetic showers from $\pi^0 \to \gamma\gamma$. If the Cherenkov ring from one EM shower is missed, the event would be misconstrued as single-ring e-like and then may fall in the acceptance window for ν_e appearance. We can predict the rate of these events by applying the same selection criteria used at Super-K to the 2KM data.

Certain selection criteria have been implemented to directly address the π^0 background. First, we expect that some π^0 production comes from coherent neutrino scattering off of the oxygen nucleus. To reduce the background from this source we restrict the angle between the e-like ring and the neutrino direction to have $\cos\theta < 0.9$. This is effective because in the case of coherent scattering there is very little momentum transfer and the π^0 is produced following the neutrino direction.

In order to remove the remaining NC events, a special π^0 fitter is used, based on a maximum likelihood method to test the π^0 hypothesis against the e^- hypothesis. The idea is that some π^0 decays are not identified and fully reconstructed by the standard ring counting algorithm because the low energy second γ cannot be easily distinguished from scattered/reflected light. The PMT light pattern is fit twice, first assuming that the light pattern comes from a single electron track, then assuming that the light pattern was produced by two showering tracks. This program returns the likelihood ratio for these hypotheses as well as the $\gamma\gamma$ invariant mass from the 2-track fit. The NC-π^0 background peaks at the π^0 mass, while the ν_e signal does not; events with a computed invariant mass larger than 100 MeV/c^2 are rejected. The likelihood ratio is also used for e/π^0 separation: events with high L_{π^0}/L_e are more likely to be π^0.

Fig. 11 shows the three special variables used to reduce NC-π^0 background. In each panel the distribution of the parameter is plotted, with the upper row for the case of ν_μ interactions (mostly NC), and the lower row is for the case of ν_e. All analysis cuts other than the one plotted have been applied, including the 1-ring e-like requirements and the neutrino energy window. One can see that the responses of the 2KM detector and the SK far detector are similar and that the effectiveness of these cuts can be readily studied. Remaining differences in the distributions are caused by differences in the detectors and algorithms. The patterns used for reconstruction are not yet fully tuned for the proposed water Cherenkov detector and we expect closer agreement with a more fully developed design. It should be noted that these differences are fully included in the analysis that follows.

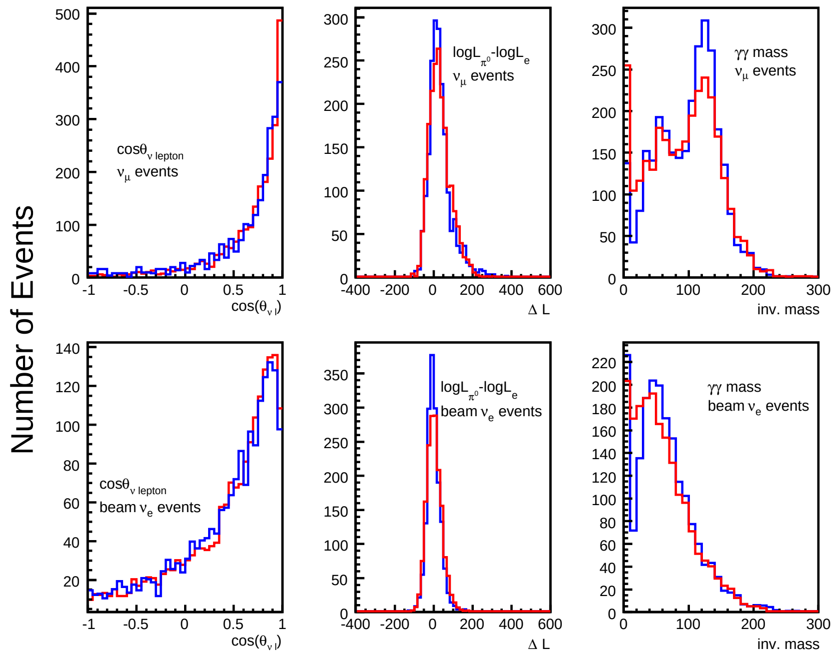


Figure 11: Distributions of the NC-π^0discriminating variables. The first column is the opening angle between the single e-like ring and the neutrino direction; the second the likelihood ratio from the π^0-fitter; and the third the reconstructed invariant mass. The top row is beam ν_μ and is mostly NC, the bottom is beam ν_e and mostly charged current ν_e. Super-K is blue and the 2KM water Cherenkov detector red.

5.1.2 Intrinsic Beam Electron Neutrinos

The second major contribution to ν_e appearance background is ν_e interactions from the intrinsic ν_e flux component of the T2K beam. These neutrinos originate from three main sources: muon decay, $Ke3$ decay of K^+ and $Ke3$ decay of K^0_L. Within the ν_e appearance window of $350 < E_\nu < 850$ MeV, the dominant contribution (89%) is muon decay. The intrinsic ν_e background will be an irreducible component of the total background measurement by the 2KM detector.

Although the ν_e background is irreducible, it is possible to study and limit this contribution. This can be done by the use of an extremely high-resolution tracking chamber like a LAr TPC. In this case, studies suggest the ν_e and π^0 components of the background should be separable to approximately 99.8%. Also the the superposition of the predicted shape of each background source can be considered.

To constrain the individual components of the ν_e flux, the smaller contribution (11%) from $Ke3$ decay to intrinsic ν_e background may be indirectly studied by measuring the rate of high energy muons at 2KM. High energy muons typically exit the WC and range out in the MRD. For muons with energy greater than 2.5 GeV, as shown in Fig. 12, the parent neutrino is predominantly from kaon decay, based on our Monte Carlo estimate. In a 5-year exposure at 2KM we will measure 85,000 such interactions.

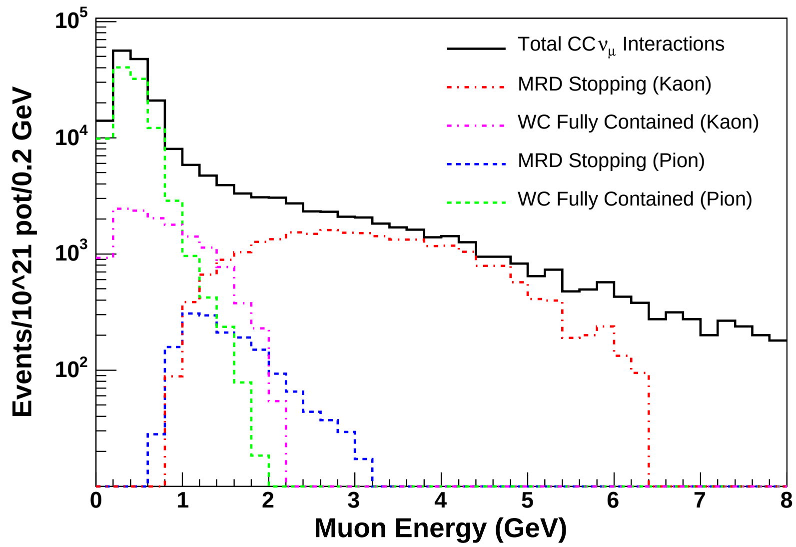


Figure 12: The spectrum of reconstructed muon energy at 2KM. The event sample requires either containment in the WC or for the muon to stop in the MRD. The parent neutrino component from π^+ and K^+ decay is separately identified. Above 2.5 GeV, the parent neutrino is predominantly from K^+ decay; almost all of these events exit the WC and stop in the MRD.

5.1.3 Misidentified Charged Current Background

The final background component – mis-identification of CC-ν_μ interactions – is smallest. Although these interactions should look very different than ν_e interactions, there is a very high rate of CC-ν_μ interactions. Single-ring μ-like events are distinguished from single-ring e-like events by a particle identification algorithm. We estimate that this algorithm is better than 98% efficient in rejecting muons from being classified as e-like.

To search for ν_e appearance using the 2KM water Cherenkov detector and Super-K, we apply a series of event selection cuts that aim at selecting CC QE ν_e induced events. First we select fully contained 1 ring e-like events, with a visible energy over 100 MeV, and no decay electron. We also select events with a reconstructed ν_e energy between 0.35 GeV and 0.85 GeV. After all cuts (including the π^0 cuts defined below) the remaining CC ν_μ contamination is estimated to be 0.05% in the 2KM water Cherenkov detector. At Super-K, the corresponding contamination is 0.03% (neutrino oscillations naturally reduce this background). The good e^-/μ^-separation performance of the water Cherenkov detectors is necessary to reduce this source of background.

5.1.4 Prediction of the Background for ν_e Appearance at Super-K Using the 2km Detector.

Using the water Cherenkov detector we will measure the total background for the ν_e appearance search. While for the real experiment, we will apply corrections to account for understood differences in response, the purpose of the study in this section is to get an idea of the size of the required corrections, by doing a simple scaling. We apply the same set of cuts to 2KM data as will be applied to the Super-K far detector data. Table 1 lists the event rates after each cut is applied, broken down by the three categories of background: NC-π^0, beam ν_e, and CC-ν_μ mis-identification. The statistics quoted are for a 5-year exposure of the T2K beam assuming 10^{21} protons-on-target per year. We expect in total approximately 3000 events at the 2KM detector.

	NC	beam ν_e	CC-ν_μ
1) FCFV, E_{vis} >100 MeV	93805	20250	564229
2) 1-ring e-like	20971	10113	12264
3) no decay-e	17241	8045	3284
4) 0.35 GeV < $E^{rec}_{\nu e}$ <0.85 GeV	6939	2430	1223
5) e/π^0separation	1122	1551	469

Table 1: Number of events in the 2KM water Cherenkov detector (5 yr exposure, 100.2t fiducial volume) after the standard cuts applied in the ν_e appearance analysis.

In this initial study, the expected backgrounds for the ν_e analysis at Super-K are extrapolated from the the measurement at 2KM using a simple scaling method:

$$N_{SK} = N_{2km} \times \left(\frac{L_{2km}}{L_{SK}}\right)^2 \times \frac{M_{SK}}{M_{2km}} \times \frac{\epsilon_{SK}}{\epsilon_{2km}}, \tag{1}$$

where L is the distance from the detector to the neutrino source and M the fiducial mass used in the analysis. For CC-ν_μ it is necessary to include the oscillation "survival" probability in the estimate (thereby reducing the background from misidentified ν_μ CC events). For this study we chose $\Delta m^2_{23} = 2.5\,10^{-3}\text{eV}^2$ and $\sin^2 2\theta_{23} = 1.0$ to describe the oscillation.

The extrapolated background is plotted in Figs. 13 and 14, where it is compared with the fully simulated and reconstructed background at Super-K. There is good agreement between the two shapes, suggesting that this simple scaling method is well-suited to predict the background at Super-K. Some difference in background spectrum shape at the two detectors can be seen above $\approx$ 1 GeV, corresponding to differences in detector response and rejection power between the two detectors. In the real experiment, corrections will be applied to account for any understood differences in response, and will improve agreement.

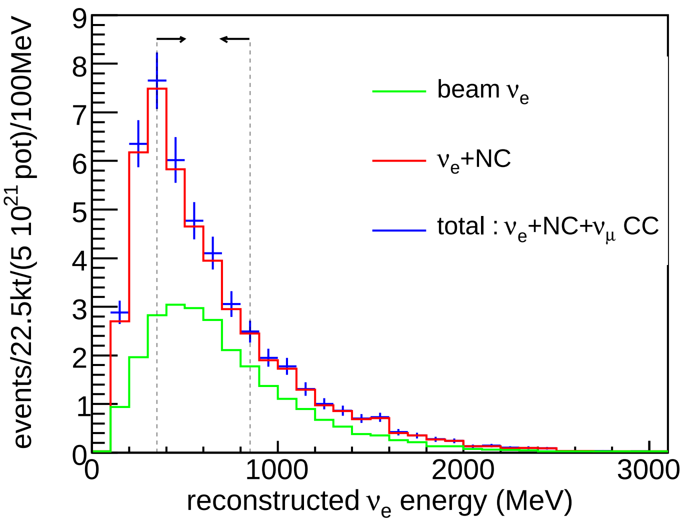


Figure 13: Extrapolated background for ν_e appearance at Super-K, using the scaling procedure described in the text. The reconstructed energy window is indicated by the dashed lines.

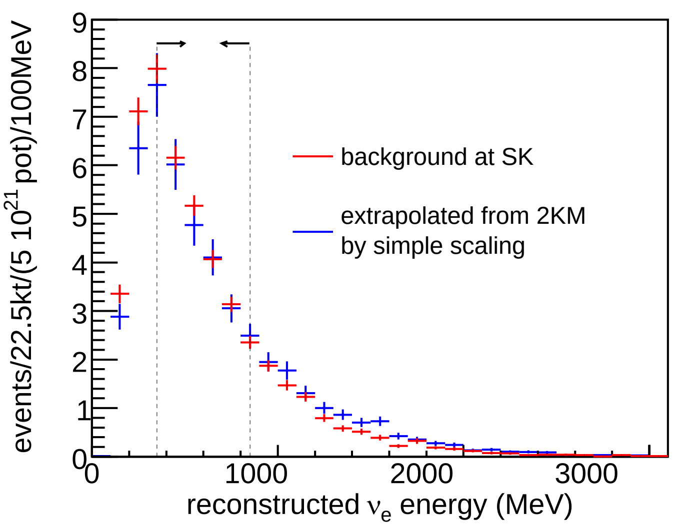


Figure 14: Total background for ν_e appearance at Super-K. The red points correspond to the results of the full T2K simulation and reconstruction at Super-K. The results from the 2KM extrapolation are shown in blue. The shapes are consistent.

5.2 Sensitivity of the T2K Experiment to Non-zero θ_{13} Including the 2KM Detector

As demonstrated in Fig. 10 in order for T2K to not be systematics limited, the total systematic error on background extrapolation at Super-K must be kept below 10%. The analysis described in Sec. 5.1 was performed assuming 5-year exposure of the T2K beam with 10^{21} protons-on-target per year. Applying this method, we obtain a predicted background of 23.0 events with a statistical uncertainty of 0.4 events (for $5 \cdot 10^{21}$ pot). The expected signal from the Super-K MC is 23.8 events. A breakdown of these numbers by event class is presented in Tab. 2. Detailed estimates of the detector related systematic errors for the ν_e appearance search is not yet finalized, However, based on the similar performance of the of the Super-K and 2KM detectors we expect that the the systematic error can be controlled to within 10%. By combining with the measurements made at the 280 m site, the extrapolation error could likely be kept below 5%. By employing a fine-grained detector at the 2KM site, which sees the same flux as the water target, we also hope to cross-check the systematic errors of the water Cherenkov detector.

	NC	beam ν_e	CC-ν_μ	Total
Monte Carlo estimate	10.2	13.2	0.35	23.8
Extrapolated from 2KM $\pm$ stat	9.4 ± 0.3	13.0 ± 0.3	0.67 ± 0.03	23.0 ± 0.4

Table 2: The number of background events for the ν_e appearance search at Super-K, based on 5 years of running at 10^{21} pot/yr. The first row was obtained with the T2K beam simulation, Super-K neutrino interaction Monte Carlo, detector simulation, and reconstruction. The second row was deduced from Table 1 by the geometrical scaling method. The uncertainties listed are statistical only, derived from the event rate at 2KM.

5.3 Measurement of the Unoscillated ν_μ Spectrum with the 2KM

By measuring ν_μ CC interactions at the 2KM, we have a reference for measuring the distortion at Super-K due to neutrino oscillations. This allows us to measure the parameters Δm^2_{23} and θ_{23}. Fig. 15 shows the percentage difference of the *flux shapes* at 2KM and Super-K as a function of neutrino energy, using the T2K beam Monte Carlo. As expected, this ratio is reasonably, but not exactly, flat with a spread of less than ±3% over the relevant energy range for oscillation studies.

5.3.1 Reconstructing the ν_μ Neutrino Spectrum

In order to reconstruct the energy of the incoming neutrinos from the outgoing interaction products, we must assume that we know the type of neutrino interaction that took place in the event, in order to describe the kinematics. To do this, cuts are performed on the data to obtain a sample with as high a QE purity as possible. In a water Cherenkov detector, this is done by requiring that the events have a single μ-like ring, are fully-contained with their vertex in the fiducial volume, and have more than 100 MeV of visible energy. If the event comes from a QE interaction, then its kinematics can be easily described and the energy of the neutrino can be reconstructed using only the outgoing lepton. If θ is the

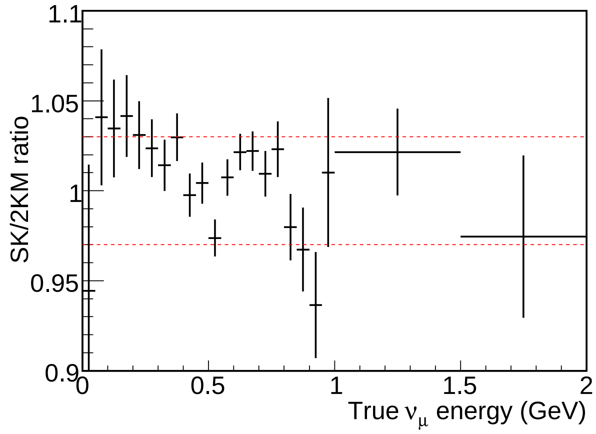


Figure 15: $\frac{F_{SK}}{F_{2KM}}\left(\frac{L_{SK}}{L_{2km}}\right)^2$ as a function of true ν_μ energy (where is F is the ν_μ flux). The deviations from unity are shown with dotted lines corresponding to $\pm 3\%$.

angle between the fitted muon direction and the beam direction, and P_μ and E_μ are the reconstructed muon momentum and energy, then:

$$E_\nu^{rec} = \frac{M_n E_\mu - 1/2(M_\mu^2 + M_p^2 - M_n^2)}{M_n - E_\mu + P_\mu \cos\theta}, \tag{2}$$

where M_p, M_n and M_μ are the masses of the proton, neutron and muon. Using this equation, and assuming an accumulated luminosity of $5 \cdot 10^{21}$ pot, we obtain the spectra of Fig. 16. In the same spirit as the ν_e analysis in this letter of intent, we compute the far-near ratio, simply scaling the 2KM spectrum by the ratio of fiducial masses and $1/L^2$ attenuation. Fig. 16 shows that the uncorrected 2KM water Cherenkov spectrum and Super-K spectrum are in excellent agreement, to $\pm 3\%$ up to 1 GeV. Above 1 GeV, the ratio increases because Super-K can contain muons up to higher energies than the smaller 2KM detector. In the real experiment a correction would be made for the geometrical efficiency differences and far-near ratios, further flattening the reconstructed event ratio.

One important fact to note in the above discussion is that the ν_μ spectrum will in fact be highly distorted at Super-K due to neutrino oscillations. However, by using the 2KM and ND280 detector together it will be possible to test the flux extrapolation technique before oscillations. The ND280 detector together with the NA61 experiment should be able to successfully predict the event rate at the 2KM site, thereby directly confirming our understanding of the extrapolation technique.

There is always some background in a QE-selected sample arising from other types of neutrino interactions. These events, when reconstructed with QE kinematics, will give an incorrect neutrino energy. For this reason, we need to carefully characterize the number of non-QE interactions in our beam. Since the expected event rate is approximately 120,000 QE ν_μ CC interactions per 100 tons per 10^{21} protons-on-target and 70,000 non-QE ν_μ

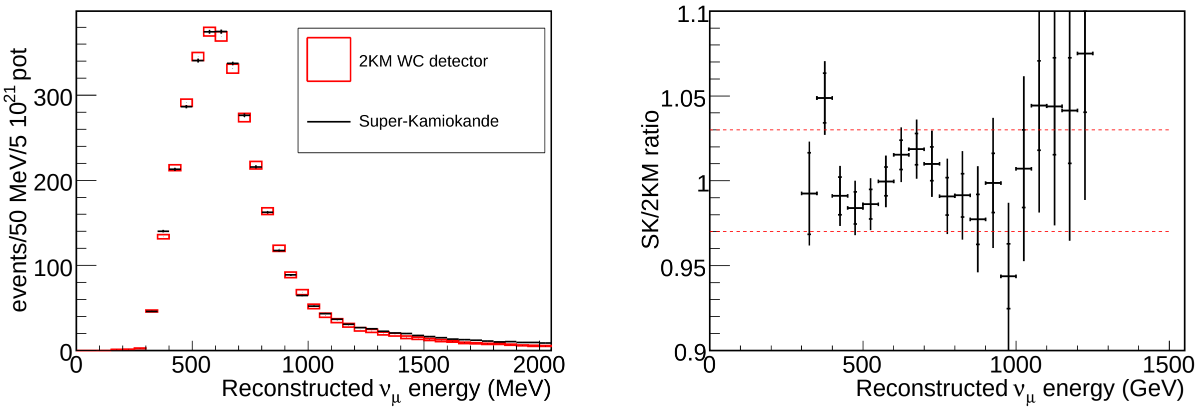


Figure 16: Left: Reconstructed muon neutrino spectrum for all events passing the selection criteria, assuming all are CCQE. Right: Corresponding far-near ratio, showing agreement to ±3%. The wide error bars take MC statistics into account. The ratio rises above 1 GeV, because Super-K contains more high-energy muons than the smaller 2KM tank.

CC interactions per 100 tons per 10^{21} protons-on-target, the event rate in both the water Cherenkov and fine grained detectors will be high enough to make careful studies of these backgrounds.

The WC detector and FGD elements complement each other. Since the 2KM detector is made of water, it has the same target material as Super-K and any nuclear target effects are the same between the two detectors. In the reference design, the liquid argon detector will have a comparable event rate on argon, and due to its exceptionally fine granularity, will make exclusive measurements of the non-QE reactions.

Since the target nucleus in the LAr is different than that of Super-K, we are investigating the option of embedding a frozen water target between the cathode planes of the LAr detector. By observing tracks which are initiated in the water target but are reconstructed in the liquid argon, we can compare the differences in our beam between water and argon targets and make any corrections necessary, even without input from external measurements. Even a small frozen water target will have a sizable number of reconstructed interactions.

5.3.2 Measurement of the Non-QE Component of ν_μ Interactions in Nuclear Targets.

As noted in section 3, in the K2K experiment [15] different detectors and analysis techniques yielded approximately a 20% difference in the inferred non-QE cross-section fraction. The error on this quantity is a leading driver in how well θ_{23} can be determined. For this reason, we believe it is important to measure the amount of non-QE interactions in as many targets and detectors as possible with our flux. In this section, we discuss the possible contribution of the 2KM detector complex to this measurement.

In order to estimate the contamination of non-QE background events in 1-ring μ-like events observed by the water Cherenkov detector, the non-QE/QE ratio can be measured by detectors other than the water Cherenkov detector, and then predicted for the water Cherenkov detector. The number of non-QE events should vary according to target material and a careful prediction and confirmation of this effect will give us confidence in our result.

The higher the probability for a pion produced by a neutrino interaction to be absorbed in the target nucleus, the larger the fraction of non-QE events that will be observed as 1-ring events. In our reference design, the non-QE/QE ratio will be measured in three targets, H_2O, Ar and CH (polystyrene), where CH is measured in the 280m detector [16]. Differences in neutrino interaction and nuclear effects between these target materials are summarized below.

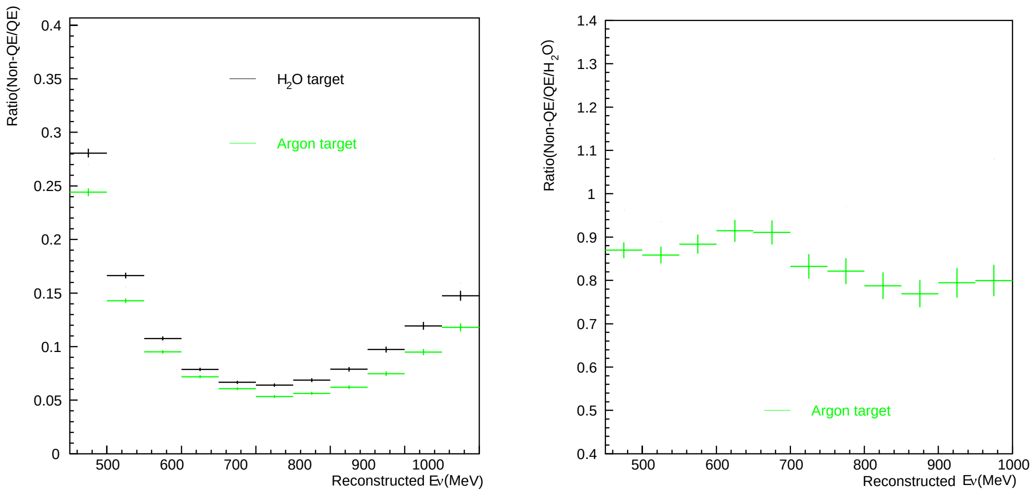
- The cross-section for neutrino interactions off bound nucleons is affected by the Fermi momentum of the target nucleus and the Pauli principle.
- The rate of exclusive neutrino interactions per unit weight depends on the proton/neutron ratio in the target nucleus.
- The probability of pion and recoil nucleon re-interaction in the target nucleus depends on the nucleus.

We studied this effect by simulating interactions in H_2O and Ar targets including the nuclear effects with the simulated 2KM flux. Fig. 17 shows the non-QE/QE ratio as a function of reconstructed E_ν for water and Argon at the 2KM site, along with the double ratio between argon and H_2O.

The non-QE/QE ratio is different by 10 to 20% for H_2O and Ar in the relevant energy range for the ν_μ disappearance measurement (500-800 MeV). This is due to the proton/neutron ratio difference and the difference in the pion re-interaction in the target nucleus between H_2O and Ar. This 10 to 20% difference in the ratio must be corrected for with the Monte Carlo simulation. The intrinsic uncertainty in the predicted non-QE/QE ratio for H_2O from the LAr measurement is likely to be 5 to 10%. The precise measurement of non-QE/QE ratio is a challenging task. Therefore, it will be important for the T2K experiment to have many independent measurements at both the ND280 and 2KM detectors with different systematic effects.

5.4 Sensitivity of the T2K Experiment to Δm^2_{23} and θ_{23} Including the 2KM Detector

In this section we have studied the impact of adding the 2KM detector on the measurement of the ν_μ disappearance parameters. We used the same extended maximum-likelihood method as the ND280 group in section 1.1.2 of [16]: two PDFs are used, one for QE events and one for nonQE events, taking into account several sources of systematic error. Fake data sets are produced at $\sin^2 2\theta_{23} = 1$ and different values of Δm^2_{23}, and then fitted. The



(a) Non-QE/QE ratio for H_2O and Ar targets.

(b) Ratio of non-QE/QE ratios between Ar and H_2O.

Figure 17: The non-QE/QE ratio for H_2O and Ar as a function of reconstructed neutrino energy.

variation of the systematic parameters leads to biases in the best fit point, which are plotted in Fig. 18.

We have evaluated the impact of the 2KM on 5 leading sources of systematics, known to have a potentially large impact on this measurement. These sources were also used in ND280 studies [16]. With the levels of systematics reached with a 2KM detector, the estimated systematic biases on the oscillation parameters are kept well under the statistical uncertainty (dashed line), clearly demonstrating the positive impact of an extra spectrum measurement at 2KM : combining 2KM and ND280 will minimize the impact of those sources of systematics.

These are the details of the systematic sources:

1. Uncertainty in the number of selected 1-ring, μ-like events. As in initial estimate, we do not try to make corrections for the efficiency difference between Super-K and the 2KM. Instead, we use the difference between Super-K and 2KM in selection efficiencies for fully-contained, 1 ring μ-like events, with Evis between 100 MeV and 1 GeV (for acceptance reasons). This is 1.9%, to which we add the fiducial volume errors: 2% at Super-K based on K2K experience, and 0.7% at 2KM. Our estimate of the total error is 2.9%. The effect of this error is shown in the red curve in Fig. 18.

2. Uncertainty in the contamination of nonQE events in the final sample (nonQE/QE ratio). The green curve of Fig. 18 results from varying this ratio. In section 5.3.2 we show that the differences between water and liquid argon in the relevant energy range are on the order of 10-20% in the absence of any correction. Combined with another measurement at ND280, we can reach 5% for this error. We are studying

how a water target in the LAr detector will further reduce uncertainties.

3. Uncertainty on the energy scale, resulting in the blue curve in Fig 18. Super-K's absolute energy scale systematic error is 2.1%. Taking advantage of the strong similarities between Super-K and 2KM, and the energy scale cross-checks between ND280 and 2KM, we expect to be able to reach a 1% relative uncertainty in the energy scale between the near and far detectors, thus leading to a total of 2.3% for this error. Specialized calibration tools such as artificial Cherenkov light generators are being designed for this purpose.

4. Uncertainty on the width of the predicted spectrum at Super-K, due to extrapolation errors in the far-near ratio. The difference in the full width at half-maximum between Super-K and 2KM is about 0.3% for the spectra of Fig. 16. The effect shown in the light blue curve of Fig. 18 corresponds to a 0.3% enlargement of the width of the reconstructed spectrum at Super-K.

5. Uncertainty on the spectrum at Super-K caused by uncertainties in the hadron production model in the graphite target. Our studies comparing GCALOR, FLUKA03 and MARS show that the variation of the far-near ratio between Super-K and 2KM is less than 1% when switching between these models. The combination of the similarities in spectra between Super-K and 2KM, the ability to extrapolate between ND280 and 2KM, plus additional information from NA61, make us confident that this source of uncertainty will be constrained to less than 1%. Following the model used in [16], we apply a weight varying linearly in neutrino energy, but with a slope of 1%.

6 Conclusion

Building a detector with the same target as Super-K, with almost the same detector response, and an extremely fine-grained tracking chamber sited in the T2K off-axis beam, will allow us to predict the events seen at Super-K with small corrections other than that of geometric acceptance. The 2KM detectors will help the ν_e appearance search at Super-K in two ways. First, it will allow a prediction of the unoscillated background at Super-K from the measurement 2 km away from the neutrino source. It will also allow the 280 m detectors along the the NA61 hadron production experiment to test their predicted event rate in water Cherenkov detector in the off-axis beam before it has a chance to oscillate.

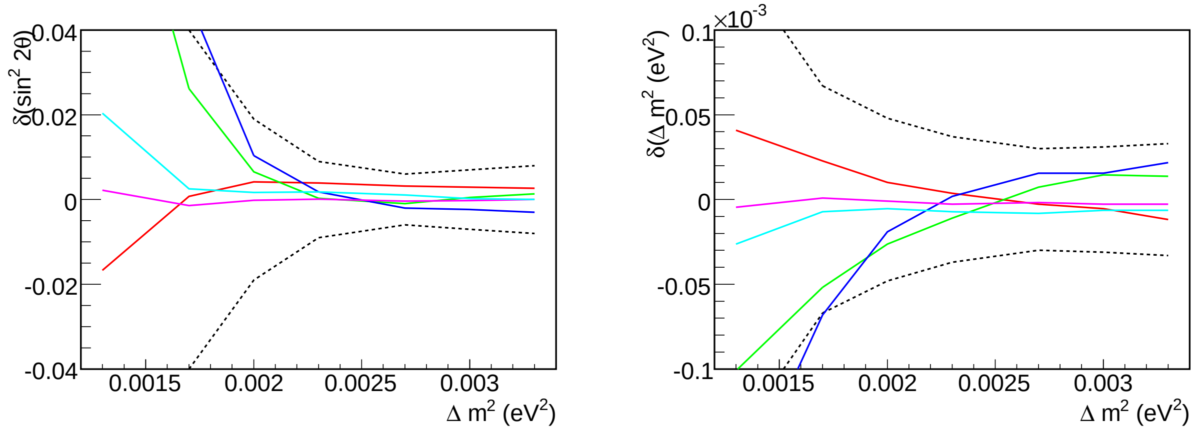


Figure 18: Biases in the ν_μ oscillation parameter reconstruction, caused by the main sources of systematics. The dashed lines show the statistical error on the measurements for $5 \cdot 10^{21}$ pot at 50 GeV. The fake data sets were produced at $\sin^2 2\theta_{23} = 1$, for the values of Δm^2_{23} given on the abscissa. Red: effect of a 2.9% uncertainty on the event normalization. Green: effect of 5% uncertainty on the nonQE/QE ratio. Blue: effect of a 2.3% shift in the energy scale. Light blue: effect of a 0.3% error on the width of predicted ν_μ spectrum at Super-K. Purple: effect of a 1% linear distortion in the spectrum, caused by uncertainties in the hadronic production models.

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