Final results from K2K and status of T2K

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The K2K (KEK-to-Kamioka) neutrino oscillation experiment is the first accelerator-based experiment with more than 100 km baseline. Data taking of K2K started in 1999 and finished in 2004. Final results for oscillation analyses are presented. The next generation long baseline experiment in Japan, T2K (Tokai-to-Kamioka), which aims for the observation of ν_e appearance from ν_μ beam with an order of magnitude improved sensitivity, is in preparation for startup in April 2009. The status of experiment and related efforts are reported.

1 Introduction

In early 1990s, 'anomaly' of ν_μ/ν_e ratio in atmospheric neutrino was reported by Kamiokande[1] and other experiments. In 1998, Super-Kamiokande (Super-K) collaboration announced famous evidence for neutrino oscillation in atmospheric neutrinos[2,3]. Together with excellent results from solar (and later reactor) neutrino experiments, neutrino oscillation rapidly became 'standard' explanation of former neutrino 'anomalies.' However, in order to firmly establish this picture, it was necessary to have independent experiments, especially with controlled, artificial neutrino source. K2K (KEK-to-Kamioka) was the first experiment which confirmed the neutrino oscillation using accelerator-produced neutrino beam.

The neutrino oscillation among 'standard' three flavors can be characterized by three phases (θ_{12}, θ_{23}, θ_{13}) and difference of mass-squared between corresponding mass eigenstates (Δm^2_{12} and Δm^2_{23}). With the approximation of two-flavor oscillation, the survival probability of muon neutrino with energy E_ν (GeV) after traveling distance L (km) is written as

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2[1.27 \times \Delta m^2_{23} \times L(\mathrm{km})/E_\nu(\mathrm{GeV})], \quad (1)$$

where θ_{23} and Δm^2_{23} are the mixing angle and mass-squared difference between second and third generation neutrinos, respectively. For this mode, ν_μ is considered to oscillate primarily into

ν_τ [4]. With neutrinos below τ production energy threshold, this is observed as ‘disappearance’ of charged current events.

One can also consider ‘appearance’ of ν_e from ν_μ as a sub-dominant contribution, with probability

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{23} \sin^2 2\theta_{13} \sin^2[1.27 \times \Delta m^2_{23} \times L(\mathrm{km})/E_\nu(\mathrm{GeV})]. \qquad (2)$$

This mode is sensitive to θ_{13}, the last mixing angle to be measured and primary goals of next generation neutrino oscillation experiments.

In this article, we report final results from K2K on both ν_μ disappearance and ν_e appearance analyses, as well as neutrino-nucleus interaction studies. Then, the status and prospects of the next long baseline neutrino oscillation experiment in Japan, T2K (Tokai-to-Kamioka), will be given.

2 K2K – first long baseline experiment

Triggered by atmospheric neutrino ‘anomaly’, K2K (KEK-to-Kamioka) experiment was proposed in 1995. Data taking for K2K started in 1999 and finished in 2004.

2.1 Experimental setup

A schematic picture of the K2K beamline is shown in Fig 1. Almost ($\simeq$98%) pure ν_μ beam with a mean energy of 1.3 GeV is produced by 12 GeV proton synchrotron (PS) at High Energy Accelerator Research Organization (KEK) in Tsukuba, Japan. Protons extracted from PS hit an aluminum target. Secondary particles, mainly pions, are focused into Super-K direction by a set of magnetic horn system and decay into neutrinos in 200 m long decay volume. Properties of neutrino beam are measured at two points 250 km apart, with near detector (ND) system at KEK and with Super-K, a 50 kton water Čerenkov detector. The timing of accelerator extraction, 1.1 μsec every 2.2 sec, was synchronized to event timing at the far site using Global Positioning System (GPS). By using near detector data to characterize neutrino beam properties just after production, systematics related to e.g. uncertainties from absolute neutrino flux and absolute cross-section are greatly reduced.

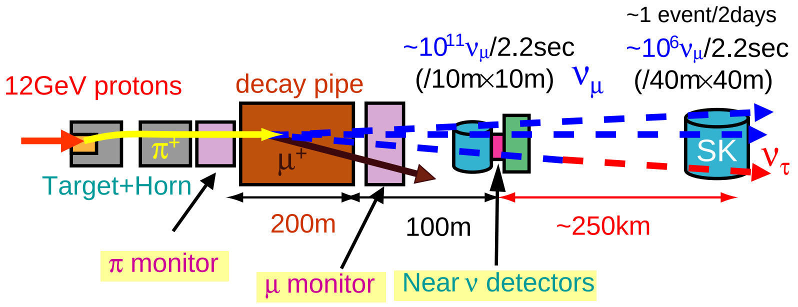

Figure 1: Schematic layout of K2K experiment.

Several instruments are placed in the beamline in order to monitor the beam quality [5]. Intensity and position of proton beam are measured by monitors located along the primary beamline. The kinematics of secondary pions just before the decay volume are measured using a specially-designed gas Čerenkov counter (pion monitor) in the early stage of the experiment. The intensity, profile and direction of tertiary beam are monitored by muon monitor system located just after the beam dump. Throughout the experiment, beam properties are stable and well within requirements not to affect oscillation measurements. For example, the stability of beam direction has been better than 1 mrad, while requirement is 3 mrad. In total, 1.05×10^{20} protons on target (POT) are delivered and data corresponding to 0.92×10^{20} POT are used for the analysis.

2.2 ν_μ disappearance final result

Events recorded with Super-K are selected with criteria similar to those with Super-K atmospheric neutrino analysis. We select events where the event vertex is inside fiducial volume and all the final state particles are fully contained inside the detector. Figure 2 shows the timing distribution of events observed in Super-K, after subtracting expected time of flight from KEK to Kamioka (Δt). In the left figure, open, hatched and shaded histograms are after removing pre-activity, requiring greater than $\sim$20 MeV energy deposit, and final selection, respectively. A clear peak is seen at $\Delta t = 0$, with negligible and expectation-consistent background from atmospheric neutrinos. Right figure shows zoom-up view around the expected timing (without fiducial volume requirement). Nine-bunch structure of KEK-PS is clearly seen, which gives us confidence that those events are due to neutrinos produced 250 km away.

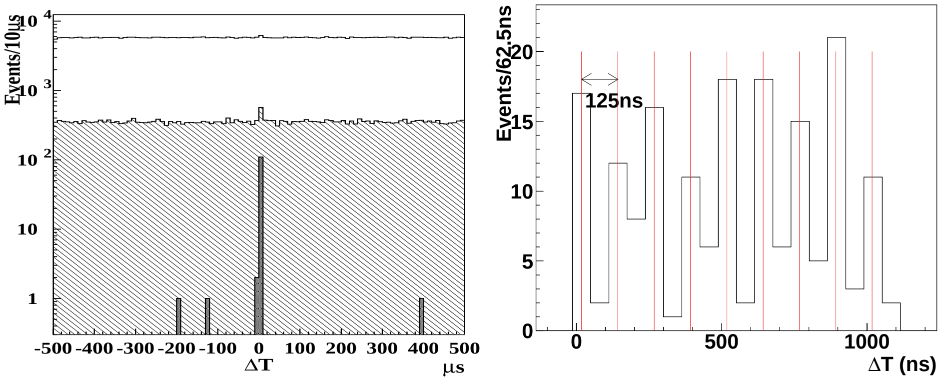

Figure 2: Timing distribution of events observed in Super-K.

In the signal timing region of $-0.2 < \Delta t < 1.3$ μsec, 112 events are observed. From near detector measurements extrapolated to the far site, the expected number of events in case of no oscillation is $158.1^{+9.2}_{-8.6}$ events. For the near to far extrapolation, HARP hadron production data[6] is used to constrain uncertainties from secondary pion kinematics. Further, for 58 events in which single Čerenkov ring identified as muon-like (against electron-like) is observed, we reconstruct the neutrino energy assuming two-body charged current quasielastic (CCQE) interaction, $\nu_\mu + n \rightarrow \mu + p$. Figure 3 (left) shows the reconstructed energy distribution, together with expectation without oscillation (dashed) and best-fit result with neutrino oscillation hypothesis (solid). The observed spectrum is consistent with oscillation best-fit parameters (Kolmogorov-Smirnov test probability of 37%) while not compatible with null oscillation (0.07%). We find evidence of neutrino oscillation from both reduction in number of events and distortion of energy spectrum[7].

Using both number of events and reconstructed energy spectrum, we performed maximum likelihood analysis to find best fit parameters of mixing angle ($\sin^2 2\theta_{23}$) and mass-squared difference (Δm^2_{23}). Best fit parameters are found to be $(\Delta m^2, \sin^2 2\theta) = (2.8\times10^{-3}\mathrm{eV}^2, 1.0)$. Figure 3 (right) shows allowed regions of oscillation parameters with 68, 90, and 95% confidence level. Result from Super-K atmospheric neutrino L/E analysis[3] is also shown. The null oscillation case is excluded with 4.3σ significance from difference in the log likelihood. K2K has confirmed the neutrino oscillation result reported by Super-K. Recently, MINOS collaboration also confirmed K2K and Super-K results[8].

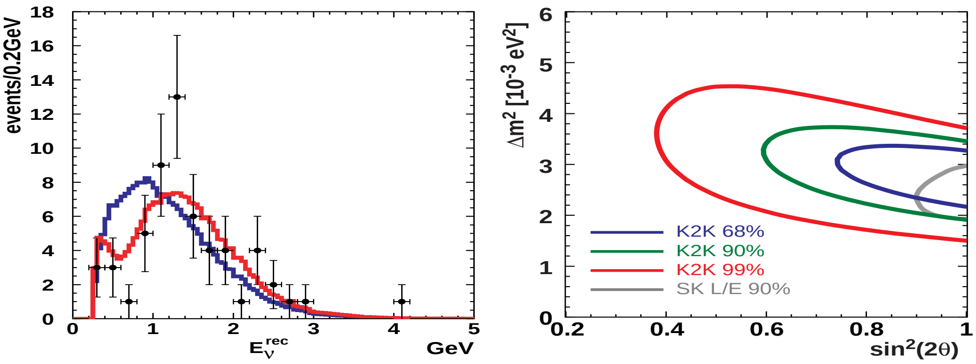

Figure 3: Left: Distribution of reconstructed neutrino energy. Points, solid line and dashed line are data, the best fit spectrum and expectation without oscillation, respectively. Right: Allowed region of neutrino oscillation parameters. Result from Super-K atmospheric neutrino L/E analysis is overlaid.

2.3 Search for ν_e appearance

Appearance of ν_e from ν_μ beam is searched for by utilizing the excellent e/μ separation capability of water Čerenkov detector [9]. Single ring, showering (electron-like) type events in Super-K are selected as candidates of ν_e charged current events.

The dominant background to this search is expected to be ν_μ neutral current interaction, where only π^0 is generated ($\nu_\mu + N \rightarrow \nu_\mu + \pi^0 + N'$) and one of γ from π^0 decay is missed in the reconstruction. Early result using about half of K2K data [10] indicated that we needed better π^0 rejection efficiency to improve the sensitivity. Thus, we have developed a new algorithm for π^0 identification. A second gamma-ray ring candidate is reconstructed by comparison of the observed charge and expected light patterns calculated under the assumption that two showering rings exist. Thus, it always 'finds' the second ring in an event. We use the invariant mass of reconstructed π^0 to discriminate ν_e signal from π^0 background events. The performance of algorithm is verified using Super-K atmospheric neutrino data. The efficiency for expected ν_e signal is 70%, while 70% of π^0 background is rejected.

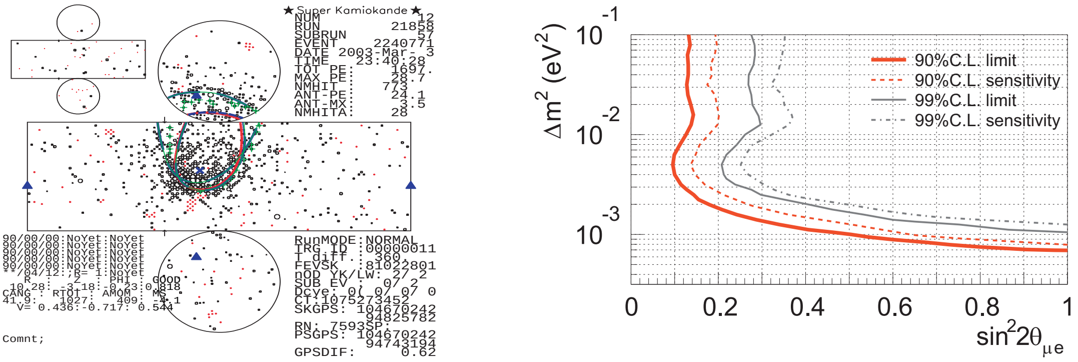

Figure 4: Left: remaining candidate for ν_e appearance search at K2K. Two rings reconstructed by π^0 identification algorithm are also shown. Right: Upper bound on $\nu_\mu \rightarrow \nu_e$ oscillation parameters at 90 and 99% confidence levels.

After all selection, we have found one candidate event, while 1.7 events of background are expected from MC simulation. Among them, 1.3 events are from ν_μ interaction, dominated by NC π^0 production, and rest is from intrinsic ν_e contamination in the beam. Figure 4 (left) shows an event display of the remaining candidate. Because the observation is consistent with expected background, we derive excluded region on $\sin^2 2\theta_{\mu e}$, where $\theta_{\mu e}$ is mixing angle between ν_μ and ν_e measured in $\nu_\mu \rightarrow \nu_e$ transition and $\sim \frac{1}{2}\sin^2 2\theta_{13}$, as a function of Δm^2. Figure 4 (right) shows the excluded region. At $\Delta m^2 = 2.8 \times 10^{-3}$ eV^2, upper limit on $\sin^2 2\theta_{\mu e}$ is set at 0.13 with 90% confidence level[11].

2.4 Neutrino-nucleus interaction studies

In addition to the oscillation analyses, we study neutrino-nucleus interaction using high statistics near detector data. Because we always need to interpret data using neutrino interaction model, it is highly important to understand the neutrino interaction with nuclei to perform neutrino oscillation experiments. We have published three interaction studies:

1. As described above, NC π^0 production is a main background for ν_e appearance search. The cross-section ratio of this mode to the total charged current is found to be $\sigma(\mathrm{NC}\pi^0)$ / σ(CC)=0.064±0.001(stat.)±0.007(syst.), consistent with our MC simulation[12].
2. CCQE is the main signal for oscillation analysis and also used for normalization of other modes. The axial vector mass M_{A}, parameter to characterize the axial form factor in this interaction, is measured to be $M_{\mathrm{A}} = 1.20 \pm 0.12$ GeV[13].
3. From early stage of experiment, K2K had observed significant deficit in the forward scattering events, which limits the prediction accuracy of the neutrino energy spectrum at the far detector. The cross section of CC coherent pion production is found to be much less than the predicted value, which explained the observed discrepancy. The cross-section ratio to the total charged current is found to be $\sigma(\mathrm{CC\ coherent}\ \pi)/\sigma(\mathrm{CC})<0.060$ at 90% confidence level[14].

Several other analyses are still ongoing and will be published in future.

3 SciBooNE – a bridge between K2K and T2K

One of K2K near detectors, SciBar[15] has been disassembled and shipped to U.S. for a new experiment at Fermilab, E954 (named SciBooNE)[16]. The main goal of SciBooNE is measurements of neutrino-nucleus scattering cross sections below 1 GeV. Booster Neutrino Beamline at Fermilab, where currently MiniBooNE[17] is running, can provide a neutrino beam with very similar energy spectrum to that anticipated in T2K. Using well understood SciBar detector and intense, well understood beam from Booster Neutrino Beamline, precise study of neutrino interaction will be performed. In SciBooNE, run with anti-neutrino beam mode is also planned, which will help designing future CP violation study in long baseline experiments.

The experiment was approved by Fermilab PAC in December 2005. In summer 2006, detectors were moved from KEK to Fermilab and construction of the detector hall was started. As of April 2007, the hall construction has been finished and detectors are commissioned with cosmic ray. The experiment is expected to start data taking before summer 2007.

4 T2K – first 'superbeam' experiment

Based on the successful experience with K2K, T2K (Tokai-to-Kamioka) experiment[19] was proposed to further improve our knowledge on neutrino oscillation. The experiment was approved in 2003 and started the beamline construction in 2004. The primary goals of T2K are search for $\nu_\mu \to \nu_e$ oscillation with more than an order of magnitude better sensitivity than K2K, and precise measurement of ν_μ oscillation parameters. The commissioning of beamline is planned to start in April 2009.

4.1 J-PARC facility

Intense neutrino beam will be produced by proton accelerators at Japan Proton Accelerator Research Complex (J-PARC)[18] in Tokai village, Ibaraki prefecture. J-PARC accelerator system is designed to deliver 0.75 MW of beam power with fast extraction from its main ring. It consists mainly three parts: a linac, a 3 GeV rapid cycle synchrotron (RCS) and a main ring. In January 2007, the J-PARC linac was successfully commissioned. Commissioning of RCS and the main ring are scheduled in Japanese fiscal year 2007 and 2008, respectively.

4.2 Off-axis beam

In order to achieve the physics sensitivity we aim at T2K, it is indispensable to reduce background such as neutral current π^0 production for ν_e appearance search. Because the neutrino interaction cross section increases at high energy while the oscillation is expected to take place in rather low energy region of < 1 GeV, it is desired to reduce unwanted high energy tail while keeping as high intensity as possible in the signal region.

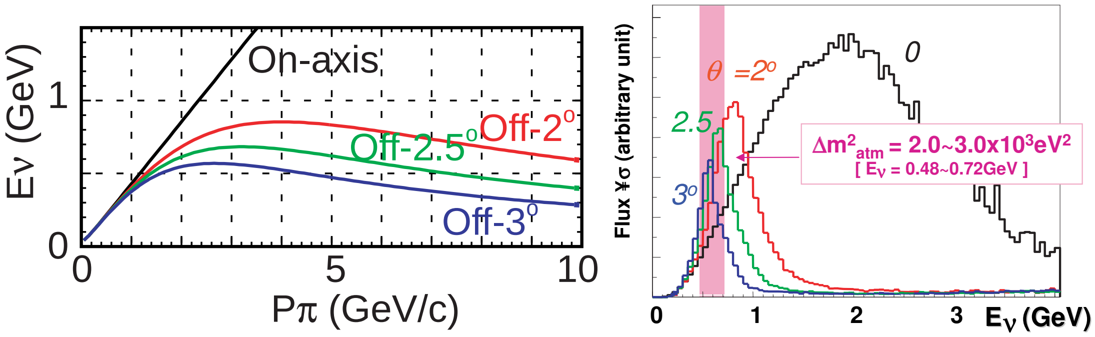

Figure 5: Left: Neutrino energy as a function of parent pion energy for various off-axis angle. Right: Neutrino energy spectrum for T2K beamline at various off-axis angle.

One of the characteristic feature of the T2K experiment is its ‘off-axis’ beam configuration. Figure 5 (left) shows the energy of neutrino emitted to certain angles with respect to the parent pion flight direction as a function of pion energy. At off-axis angles, the neutrino energy is rather independent of parent pion energy but dependent on the off-axis angle from the pion direction. Thus, by intentionally displacing the average direction of the secondary pions from the far detector direction, one can realize intense, narrow band beam tuned to the expected oscillation maximum at the far detector.

T2K is the first experiment to adopt this method, originally invented by BNL-E889 group[20]. Figure 5 (right) shows the expected neutrino spectrum at the far detector. Currently the off-axis angle at startup is planned to be 2.5°, although the beamline is designed to accommodate off-axis angles of 2–2.5°.

4.3 Beamline construction status

The construction of J-PARC neutrino beamline started in 2004. The primary beamline to transport protons to target was connected to the J-PARC main ring in Nov. 2006. The design and fabrication of beamline components, such as superconducting magnets, beam monitor, and power supply are on schedule.

The excavation of the target station, where the target and magnetic horns will sit, is ongoing. The upstream half of decay volume was already constructed. The target is made of graphite to withstand collision with intense proton beam. Design and test of the target cooling system is in progress. A set of three magnetic horns will be used to focus secondary particles. A prototype of the first horn has been tested with the design current of 320 kA (cf: K2K horns were operated with 250 kA, NuMI horns with ∼200 kA) for 850,000 pulses. Currently the third horn prototype is being configured to be included in the test. The design of beam dump is fixed and the first module of cooling core is assembled in March 2007.

4.4 Near and far detectors

The near detectors, consisting of two detector systems, will be placed about 280 m from the proton target. The 'on-axis' detector will monitor the beam direction, while 'off-axis' detector system will measure the neutrino flux, energy spectrum, and interaction cross-sections. The off-axis detector consists of several sub-detectors housed in a magnet, which will be reused from UA1/NOMAD experiments at CERN. The design of detectors is fixed and prototyping/test/fabrication is ongoing. The construction of detector hall will start from summer 2007.

The far detector, SuperKamiokande, recovered the original photo coverage and has been taking data from summer 2006.

4.5 Sensitivity to ν_μ disappearance (Δm^2_{23}, θ_{23})

With the design intensity of 0.75 MW, we expect about 2,200 (1,600) ν_μ (charged current) interactions in the fiducial volume of Super-K per a year if we had no neutrino oscillation. Using large statistics data optimized to the oscillation maximum, T2K aims to measure Δm^2_{23} and θ_{23} with precisions of $< 10^{-4}$ eV^2 and 0.01, respectively.

4.6 Sensitivity to ν_e appearance (θ_{13})

With 5×10^{21} protons on target of data (∼5 years with design intensity), 103 ν_e appearance signal is expected for oscillation parameters of ($\Delta m^2_{23} = 2.5 \times 10^{-3}$, $\sin^2 2\theta_{13} = 0.1$). The expected background is 23, of which 13 is from intrinsic ν_e contamination and 10 from ν_μ interaction, dominated by mis-identified NC π^0 production. The 90% confidence level (CL) sensitivity, assuming 10% uncertainty in background estimation, is shown in Fig. 6. At $\Delta m^2_{13} = 2.5 \times 10^{-3}$, the 90% CL limit of $\sin^2 2\theta_{13} = 0.008$.

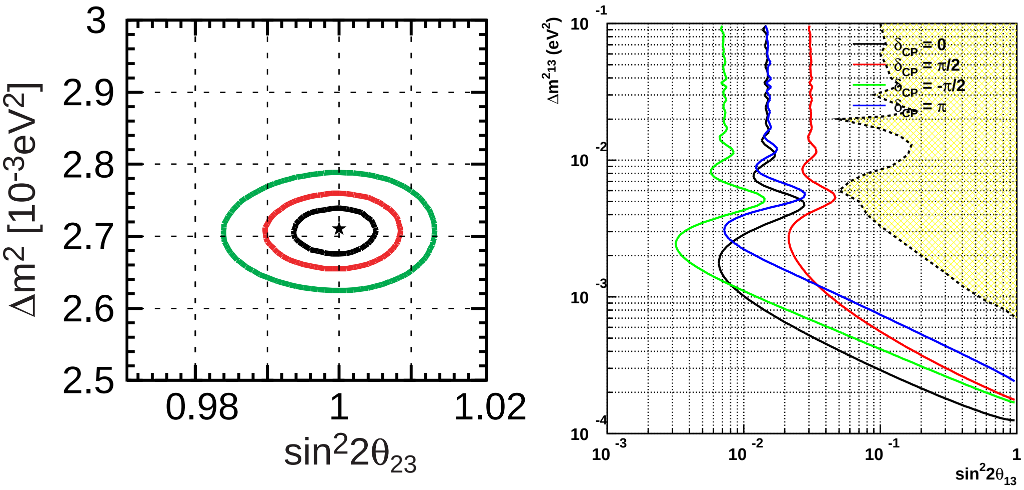

Figure 6: Left: Expected 68, 90 and 95% confidence level allowed region for ν_μ disappearance parameters with 5×10^{21} POT. Right: 90% confidence level sensitivity for ν_e appearance signal at T2K.

5 Summary

We have successfully completed the K2K long baseline neutrino oscillation experiment. K2K confirmed ν_μ oscillation reported by Super-K and set a limit to $\nu_\mu \to \nu_e$ oscillation in appearance mode. As the first experiment of this kind, K2K established validity and usefulness of long baseline experiment.

Based on this successful experience, the next generation long baseline experiment in Japan, T2K, is in preparation. The main goals of T2K are observation of ν_e appearance and precise measurement of ν_μ oscillation parameters. Accelerator and beamline are being constructed. The design of near detector system is fixed and engineering design, prototyping and production of detector component are ongoing. The far detector, Super-K, recovered its full photo-coverage and is running. We expect the first beam for T2K in April 2009.

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