Search for Electron Neutrino Appearance in a 250 km Long-baseline Experiment

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We present a search for electron neutrino appearance from accelerator produced muon neutrinos in the K2K long baseline neutrino experiment. One candidate event is found in the data corresponding to an exposure of 4.8×10^{19} protons on target. The expected background in the absence of neutrino oscillations is estimated to be 2.4 ± 0.6 events and is dominated by mis-identification of events from neutral current π^0 production. We exclude the ν_μ to ν_e oscillations at 90% C.L. for the effective mixing angle in 2-flavor approximation of $\sin^2 2\theta_{\mu e} (\simeq \frac{1}{2}\sin^2 2\theta_{13}) > 0.15$ at $\Delta m^2_{\mu e} = 2.8 \times 10^{-3}\text{eV}^2$, the best fit value of the ν_μ disappearance analysis in K2K. The most stringent limit of $\sin^2 2\theta_{\mu e} < 0.09$ is obtained at $\Delta m^2_{\mu e} = 6 \times 10^{-3}\text{eV}^2$.

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In 1998, the Super-Kamiokande (SK) collaboration reported evidence of neutrino oscillation based on atmospheric neutrino observations favoring large mixing between ν_μ and ν_τ and a Δm^2 near $2.2 \times 10^{-3}\text{eV}^2$ [1]. Subsequently, solar neutrino data from various experiments have indicated ν_e disappearance as a result of neutrino oscillations to other active neutrino flavors (ν_μ or ν_τ) with large mixing and a Δm^2 near $5 \times 10^{-5}\text{eV}^2$ [2, 3]. The KamLAND experiment also observes a deficit of reactor $\overline{\nu}_e$ consistent with the same parameter values [4] as those in the solar neutrinos. Recently, the KEK to Kamioka long-baseline neutrino oscillation experiment (K2K) [5] reported indications of $\nu_\mu \to \nu_x$ oscillation using an accelerator produced ν_μ beam. The measurement of ν_μ disappearance in K2K results in neutrino oscillation parameters which are consistent with the values derived

from the atmospheric neutrino oscillations.

Measurements of atmospheric and solar neutrinos suggest mixing between all neutrino flavors. The ν_e appearance is predicted at the same Δm^2 as the one measured using the atmospheric neutrinos (Δm^2_{atm}) in the framework of 3-flavor neutrino oscillations with certain parameter values. The probability of ν_e appearance in the 2-flavor approximation is expressed by

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta_{\mu e} \sin^2(1.27\Delta m^2_{\mu e} L/E), \quad (1)$$

where $\theta_{\mu e}$ and $\Delta m^2_{\mu e}$ are the effective mixing angle and mass squared difference between the mass eigenstates involved, respectively, for ν_e appearance; L is neutrino path length in kilometers; and E is the neutrino energy in GeV. In 3-flavor framework with "one mass scale dominance" [6], the effective mixing parameter is related to the mixing angle θ_{13} by

$$\sin^2 2\theta_{\mu e} \simeq \sin^2\theta_{23} \sin^2 2\theta_{13} \simeq \frac{1}{2}\sin^2 2\theta_{13}, (\theta_{23} \simeq \pi/4). \quad (2)$$

In this letter, we report results from the first search for ν_e appearance using ν_μ beam in the K2K experiment sensitive to the Δm^2_{atm} region.

In K2K, an almost pure (98%) ν_μ beam with a mean energy of 1.3 GeV is produced with the KEK proton synchrotron (KEK-PS) [7]. The fraction of ν_e is approximately 1% and the remainder are $\overline{\nu}_\mu$. Twelve GeV protons from the KEK-PS hit an aluminum target embedded inside a pulsed magnetic horn system which focuses positively charged secondary particles, mainly pions, toward a far detector located 250 km far from KEK. The secondary particles decay to produce a neutrino beam. The stability of the pulse-by-pulse beam direction is checked by monitoring muons from pion decay with a set of ionization chambers and silicon pad detectors following the beam dump. The measurements from these monitors show that the beam is directed to within 1 mrad of the far detector, SK [8], which is a 50 kt Water Cherenkov detector located in Kamioka, Gifu Prefecture in Japan.

To reject cosmic-ray and atmospheric neutrino background, the global positioning system is employed at both the KEK and SK sites to synchronize between beam spills and events observed in SK [9]. The neutrino flux at KEK is measured by a near detector complex consisting of a 1 kt water Cherenkov detector (1KT) and a fine-grained detector (FGD) system. The FGD consists of a scintillating fiber detector with segmented water targets (SciFi) [10], a plastic scintillator hodoscope (PSH), a lead-glass calorimeter (LG), and a muon range detector (MRD) [11]. The ν_μ flux at SK is estimated by extrapolating the measured flux at KEK using predicted flux ratio between SK and KEK (far/near ratio). The far/near ratio is evaluated by a beam Monte Carlo (MC) simulation as a function of neutrino energy and is validated using secondary pion kinematic distributions measured with a gas Cherenkov detector [12] downstream of the horn system.

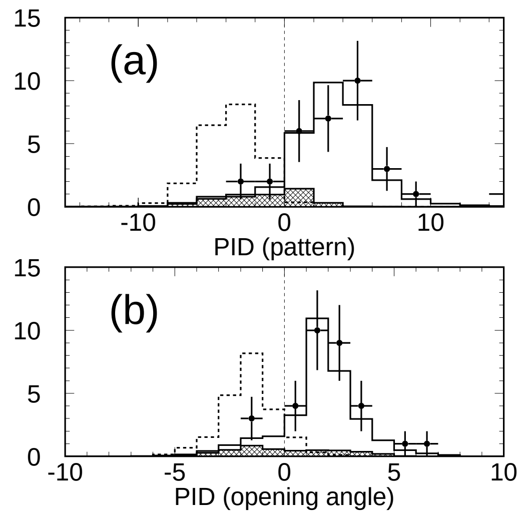

FIG. 1: Distributions of PID parameters for 32 single-ring events based on (a) Cherenkov ring pattern, and (b) Cherenkov opening angle. The distributions for the data (closed circles), oscillated ν_μ MC with $(\sin^2 2\theta_{\mu\mu}, \Delta m^2_{\mu\mu}) = (1.0, 2.8 \times 10^{-3}\mathrm{eV}^2)$ (solid histograms) and expected ν_e signal with full mixing (dashed histograms) are shown. Shaded histograms are the NC component of ν_μ MC.

Electron neutrino events in SK are selected assuming ν_e charged current quasi-elastic (CC-QE) interactions in an oxygen nucleus, i.e. $\nu_e + n \to e + p$. Since the proton momentum in the reaction is typically below Cherenkov threshold in water, only the electron is visible. Thus, a single electron-like Cherenkov ring is the signature of ν_e appearance. The ν_e contamination in the beam is estimated by the beam MC simulation which predicts the ratio of the number of ν_e interactions to that of ν_μ to be 0.9% in SK. This estimate is checked by a measurement of the ν_e fraction at KEK using the FGD system. A more serious background comes from neutral current (NC) interactions where a single π^0 is produced and one gamma-ray from its decay is not reconstructed. The NC π^0 production rate was measured using the 1KT, constraining the cross section.

This analysis is based on the data taken between June 1999 and July 2001, corresponding to 4.8×10^{19} protons on target (POT). A total of 56 fully-contained events are obtained in the 22.5 kt fiducial volume of SK. Single-ring events are selected to enhance CC-QE interactions against the π^0 production background. The details of the selection criteria for fully-contained single-ring events are found in Ref. [5]. Particle identification (PID) is applied to reduce ν_μ-induced backgrounds. A Cherenkov ring produced by an electron is diffused by its electro-

TABLE I: Summary of the event reduction for ν_e appearance search at SK. The first column lists each reduction step, and the second gives the number of observed events after each selection. The numbers of expected background from ν_μ and beam ν_e without neutrino oscillations are shown in the third and fourth column, respectively. The last column corresponds to the expected number of CC interaction events induced by ν_e oscillated from ν_μ with $(\sin^2 2\theta_{\mu e}, \Delta m^2_{\mu e}) = (1.0, 2.8 \times 10^{-3}\text{eV}^2)$.

	DATA	ν_μ w/o osc	beam ν_e	ν_e from ν_μ osc
FCFV	56	80	0.8	28
Single Ring	32	50	0.5	20
PID (e-like)	1	2.9	0.4	18
E_{vis} >100MeV	1	2.6	0.4	18
w/o decay-e	1	2.0	0.4	16

TABLE II: Systematic errors in the expected number of ν_μ background in SK.

	Jun.1999	Nov.1999∼Jul.2001
NC cross-section	$^{+22\%}_{-27\%}$	$^{+20\%}_{-25\%}$
Ring Counting	$^{+15\%}_{-13\%}$	$^{+15\%}_{-13\%}$
Particle ID	±11%	±11%
ν_μ Energy Spectrum	±14%	±1%
Far/Near ratio	$^{+15\%}_{-11\%}$	±6%
ϵ_{1KT}	±4%	±4%
ϵ_{SK}	±3%	±3%
POT normalization	±0.9%	±0.6%
CC-nQE cross-section	±1%	±0.4%
Total	±36%	$^{+33\%}_{-31\%}$

magnetic shower and multiple scattering, while that produced by a muon has a clear edge, and a low energy muon has a smaller opening angle than an electron. Both the Cherenkov ring pattern and opening angle are required to be consistent with an electron event. PID parameters are calculated from a log-likelihood difference for the electron and the muon hypothesis. Distributions of these PID parameters are shown in Fig.1. Negative values of the parameters indicate an electron-like event. Distributions of data are consistent with the oscillated ν_μ MC with $(\sin^2 2\theta_{\mu\mu}, \Delta m^2_{\mu\mu}) = (1.0, 2.8 \times 10^{-3}\text{eV}^2)$, the best-fit parameters of the ν_μ disappearance analysis in K2K [5], where $\theta_{\mu\mu}$ is the effective mixing angle in 2-flavor approximation for $\nu_\mu \to \nu_x$ oscillation. The visible energy is required to be larger than 100 MeV to reject low momentum charged pions and electrons from muon decays in which muons are below Cherenkov threshold. Finally, events which are followed by a decay electron signal within a 30 μsec time window are rejected. A small fraction of ν_e interactions are also rejected by this cut when they are accompanied with decay electrons originating from pions in inelastic interactions. The overall efficiency to select CC interactions from the oscillated ν_e is 57 % for $\Delta m^2 = 2.8 \times 10^{-3}\text{eV}^2$.

One event is selected as an electron candidate as summarized in Table I. While ring-counting algorithms evaluate this event as a single-ring event, under a careful manual examination it reveals that the remaining PMT hits out of the reconstructed ring form an additional ring, and the invariant mass of these two rings is found to be consistent with the π^0 mass. Thus, we conclude that the observed event is consistent with a π^0 background event from NC interaction.

In our simulation to predict the number of background events, NC and CC pion production are modeled following Rein and Sehgal [13] for the resonance region, and GRV94 [14] with the correction of Bodek and Yang [15] for the deep inelastic scattering region. The axial vector mass for QE and resonance pion production in the simulation are 1.1 GeV/c^2 and 1.2 GeV/c^2, respectively. The interaction models used in this analysis are the same as in the ν_μ disappearance analysis in Ref. [5] except for the normalization of NC with respect to CC-QE cross-section. The reduction of the background events is summarized in Table I.

The expected background from ν_μ interactions in the case of no oscillation is estimated to be 2.0 events where the normalization is determined by extrapolating the observed number of events in the 1KT [5]. It is estimated to be 1.9 events in the case of $\nu_\mu \to \nu_\tau$ oscillation with $(\sin^2 2\theta, \Delta m^2) = (1.0, 2.8 \times 10^{-3}\text{eV}^2)$. Since the background is dominated by NC π^0 production (87%) and the oscillated ν_τ has the same NC interactions, it is insensitive to the ν_μ disappearance oscillation parameters.

The NC π^0 production cross-section in the MC simulation is checked by a 1KT measurement of π^0 events. In the 1KT, π^0 events are selected by requiring two e-like rings whose invariant mass is between 85 MeV and 215 MeV. Muon events are also collected by requiring a single μ-like ring in the 1KT as a reference to ν_μ flux. The NC/CC-QE cross section ratio is calculated from the ratio of the number of π^0 events to that of muon events. The π^0 sample in the 1KT is dominated by NC interactions (87%), while the muon sample is dominated by CC interactions (97%). The measured NC/CC-QE ratio is consistent with the MC simulation; the ratios of data to MC is $1.07^{+0.20}_{-0.15}$. To cover the allowed range, from 0.92 to 1.27, without changing the NC cross-section model in our MC, an uncertainty of 30% is assigned on the NC/CC-QE ratio. This error is used to estimate the systematic uncertainty in the ν_μ background. The uncertainty in the cross-section ratio of CC interactions other than QE (CC-nQE) to CC-QE is estimated to be ±20% as in Ref. [5]

The uncertainty in the ν_μ-induced background is esti-

mated to be ±0.6 events for the 2.0 events. Contributions from various sources to the systematic error are summarized in Table II. Since the horn current and target diameter were different in June 1999 from the other period, systematic errors are estimated separately for these two periods and properly weighted to obtain the total systematic error. The uncertainty in the NC cross-section gives the largest contribution of $^{+20}_{-25}\%$. Systematic errors from ring counting and PID are estimated by comparing the shape of the MC and data likelihood distributions for cosmic-ray muons and atmospheric neutrino events. They are assigned to be $^{+15}_{-13}\%$ and ±11%, respectively. Systematic errors from the neutrino energy spectrum (±1.0%) and far/near ratio (±6.0%) are estimated in the same manner as in Ref. [5]. Systematic errors from the fiducial volume definition and detection threshold in the 1KT (ϵ_{1KT}) and SK (ϵ_{SK}) are estimated to be ±4% and ±3%, respectively.

The expected background from beam ν_e interactions in SK is estimated to be 0.4 events, which is derived from the ν_e/ν_μ flux ratio predicted by the beam MC simulation and the ν_μ flux extrapolated from the 1KT measurement. The systematic uncertainty in the number of beam ν_e events is estimated to be 0.11 events, which is dominated by the uncertainty in the ν_e energy spectrum. The ν_e/ν_μ ratio has been verified by a measurement of ν_e events in the FGD [16]. The ν_e events in the FGD are selected by requiring 1) a vertex inside the SciFi fiducial volume, 2) an energy deposit in the PSH of greater than 20 MeV, 2.5 times larger than expected from a muon, 3) an energy deposited in the LG of greater than 1 GeV, and 4) no corresponding hits in the MRD. During an exposure of 2.9×10^{19} POT, 51 electron candidates are selected with an estimated background of 24 ν_μ induced events. The ν_e/ν_μ interaction ratio is measured to be $1.6 \pm 0.4(stat.)^{+0.8}_{-0.6}(sys.)\%$ which is in agreement with the beam MC prediction of 1.3%.

The observation of one electron event in SK is consistent with the expected background of 2.4 events in the case of no oscillation. A constraint on neutrino oscillations from ν_μ to ν_e is obtained by comparing the observed number of electron events with the expectation assuming oscillations. The expected number of electron events is calculated by

$$N_{exp} = N^{OSC}_{\nu_e} + N^{BG}_{\nu_\mu} + N^{BG}_{\nu_e}, \tag{3}$$

where $N^{OSC}_{\nu_e}$ is the number of electron events induced by oscillated ν_e, $N^{BG}_{\nu_e}$ is that induced by beam ν_e, and $N^{BG}_{\nu_\mu}$ is that induced by both CC and NC interactions of ν_μ and NC interactions of ν_e and ν_τ from oscillations. The $\nu_\mu \to \nu_e$ oscillation signal, $N^{OSC}_{\nu_e}$, depends on the probability of ν_e appearance expressed by Eq. 1. The number of beam ν_e induced background, $N^{BG}_{\nu_e} = 0.4$, is treated as a constant, since a contribution of $\nu_e \to \nu_x$ oscillation is negligible. The CC component of $N^{BG}_{\nu_\mu}$ decreases

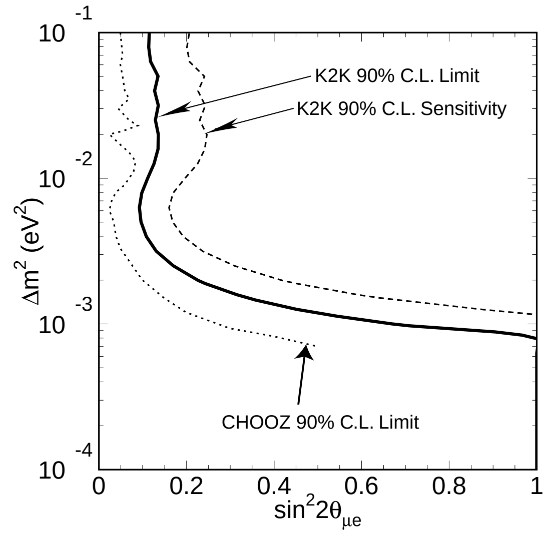

FIG. 2: The confidence interval for $\nu_\mu \to \nu_e$ oscillations as a function of the effective $\Delta m^2_{\mu e}$ at 90% C.L. (solid line). Dashed line indicates 90% C.L. sensitivity of the experiment for the current statistics. The area to the right of each curve is excluded. Dotted line shows the limit at 90% C.L. by CHOOZ assuming $\sin^2 2\theta_{\mu e} = \frac{1}{2}\sin^2 2\theta_{13}$.

with ν_μ disappearance observed in K2K and atmospheric neutrino experiments , depending on the survival probability,

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{\mu\mu} \sin^2(1.27\Delta m^2_{\mu\mu} L/E), \tag{4}$$

where $\theta_{\mu\mu}$ and $\Delta m^2_{\mu\mu}$ are the effective mixing angle and mass squared difference for ν_μ disappearance, respectively. In the present analysis, we assume $\theta_{\mu\mu} = \frac{\pi}{4}$ based on the nearly full mixing observed by atmospheric neutrino experiments, and $\Delta m^2_{\mu\mu} = \Delta m^2_{\mu e}$, which is implied in the framework of 3-flavor neutrino mixing by the small mass difference found in solar neutrino experiments [17]. Thus, N_{exp} reduces to a function of two parameters, $\theta_{\mu e}$ and $\Delta m^2_{\mu e}$.

A probability density function (PDF) for N_{exp} is constructed from the Poisson distribution convoluted with the systematic uncertainty. Given the observation of one electron event, the systematic uncertainty has a very small effect on the derived confidence interval. The confidence interval of $\sin^2 2\theta_{\mu e}$ is calculated using the method suggested in Ref. [18]. In the calculation, the best-fit parameters are searched for in the 2-dimensional parameter space with $\sin^2 2\theta_{\mu e}$ bounded in [0,1].

Figure 2 shows the limit on $\sin^2 2\theta_{\mu e}$ as a function of $\Delta m^2_{\mu e}$. The experimental limits on the neutrino mixing for the $\nu_\mu \to \nu_e$ oscillation hypothesis are given at 90% C.L. for a parameter region with $\Delta m^2_{\mu e} > 6 \times 10^{-4}$ eV^2. Neutrino oscillations from ν_μ to ν_e are excluded at 90%

C.L. for $\sin^2 2\theta_{\mu e} > 0.15$ at $\Delta m^2_{\mu e} = 2.8 \times 10^{-3}\text{eV}^2$. The most stringent limit of $\sin^2 2\theta_{\mu e} < 0.09$ is set for $\Delta m^2_{\mu e} = 6 \times 10^{-3}$ eV^2. The sensitivity of the experiment for the current statistics is also shown in Fig. 2.

Assuming 3-flavor neutrino oscillations and CPT invariance, our results can be compared to reactor experiments. CHOOZ has excluded $\sin^2 2\theta_{13} > 0.1$ at $\Delta m^2_{13} \sim 3 \times 10^{-3}\text{eV}^2$ [19]. This corresponds to a limit of $\sin^2 2\theta_{\mu e} < 0.05$ at $\Delta m^2_{\mu e} \sim 3 \times 10^{-3}\text{eV}^2$ assuming $\theta_{23} = \pi/4$, and consistent with the present analysis as shown in Fig.2. The limit on $\sin^2 2\theta_{13}$ by CHOOZ is converted by assuming $\sin^2 2\theta_{\mu e} = \frac{1}{2}\sin^2 2\theta_{13}$.

The K2K experiment searched for $\nu_\mu \to \nu_e$ oscillations with accelerator-produced muon neutrinos traveling 250 km. This is the first experimental search for ν_e appearance with sensitivity down to the Δm^2 suggested by atmospheric neutrino oscillations. A single electron candidate is found in SK. The observed event is consistent with the expected background event. The limit on the ν_e appearance is obtained. At the best-fit parameter values of the K2K ν_μ disappearance analysis, we set the 90% confidence limit of $\sin^2 2\theta_{\mu e} < 0.15$.

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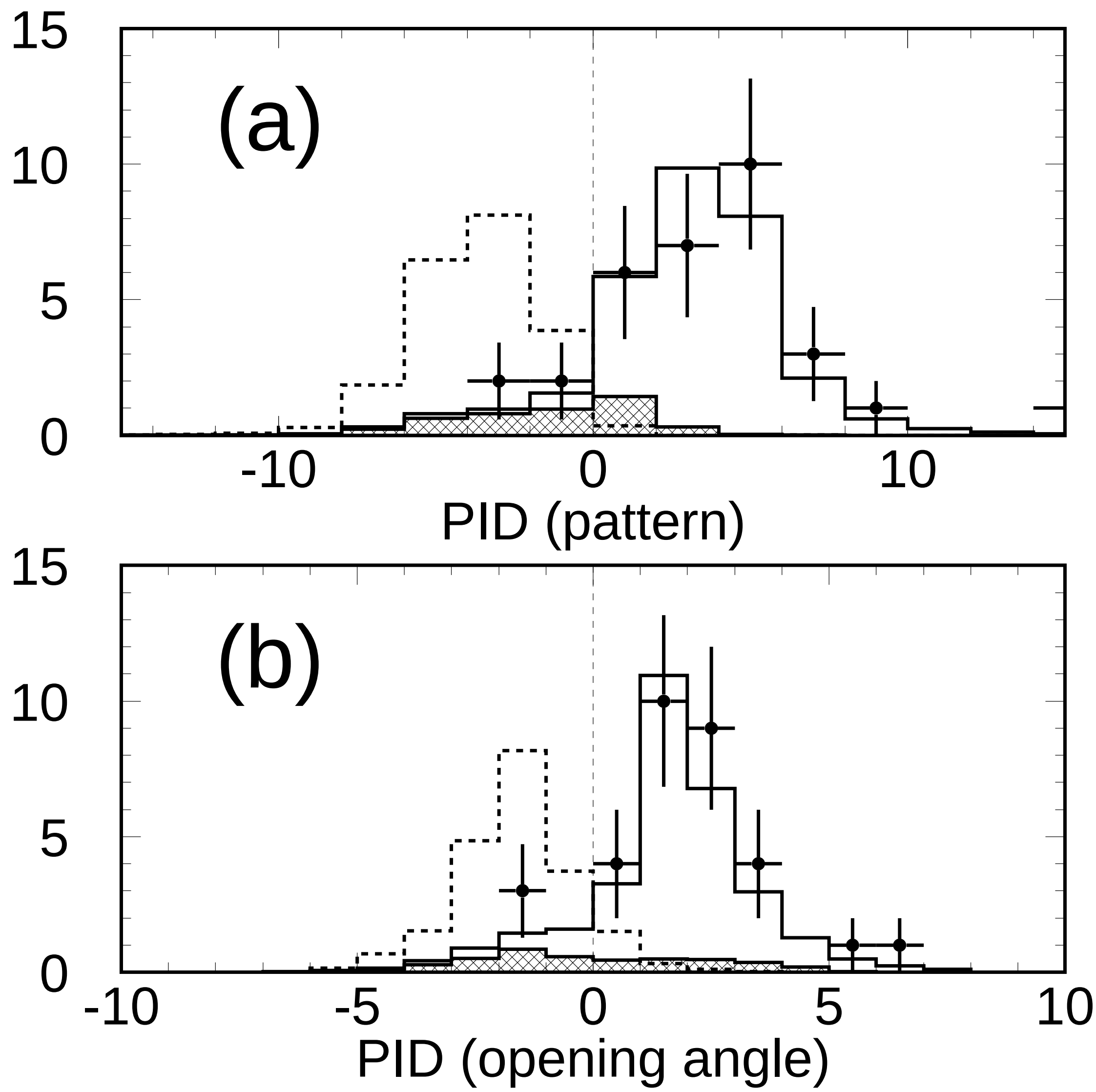
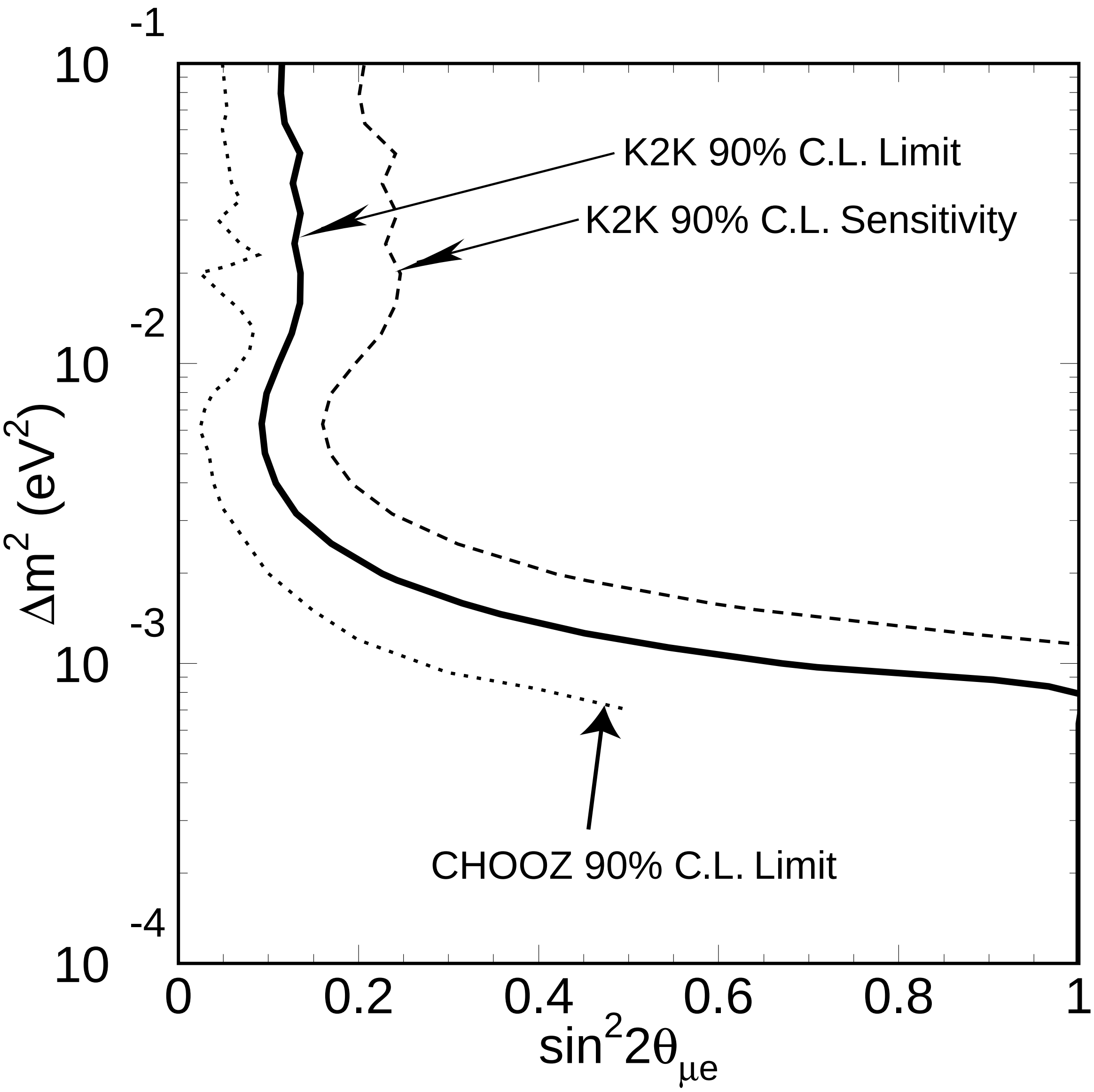


15
10
5
0
(a)
-10
0
10
PID (pattern)
15
10
5
0
(b)
-10
-5
0
5
10
PID (opening angle)

Figure 1



K2K 90% C.L. Limit
K2K 90% C.L. Sensitivity
CHOOZ 90% C.L. Limit
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Δm^2 (eV^2)
0
0.2
0.4
0.6
0.8
1
$\sin^2 2\theta_{\mu e}$

Figure 2