第19回「宇宙ニュートリノ」研究会

Search for $\nu_\mu \rightarrow \nu_e$ oscillation in the K2K experiment

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Outline

- Motivation for $\nu_\mu \to \nu_e$ search
- The K2K experiment
- Search for $\nu_\mu \to \nu_e$ oscillation
- Constraint on neutrino oscillation parameters
- Summary

Motivation for $\nu_\mu \to \nu_e$ search

- No measurement of θ_{13}, but a limit of θ_{13} <12° (reacotor ν)
- We c $\to\nu_e$ oscillation

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\left(\Delta m^2_{31} \frac{L}{4E}\right)$$

~0.5 ~2.8×10^{-3}eV^2

- First experimental search with a ν_μ beam and a long baseline
- If $\theta_{13} \neq 0$, LBL experiments can prove CPV in lepton sector
- Pioneering research toward the next generation LBL experiment (T2K)
  - Neutral pion rejection (crucial background for $\nu_\mu \to \nu_e$ search)

The K2K Experiment

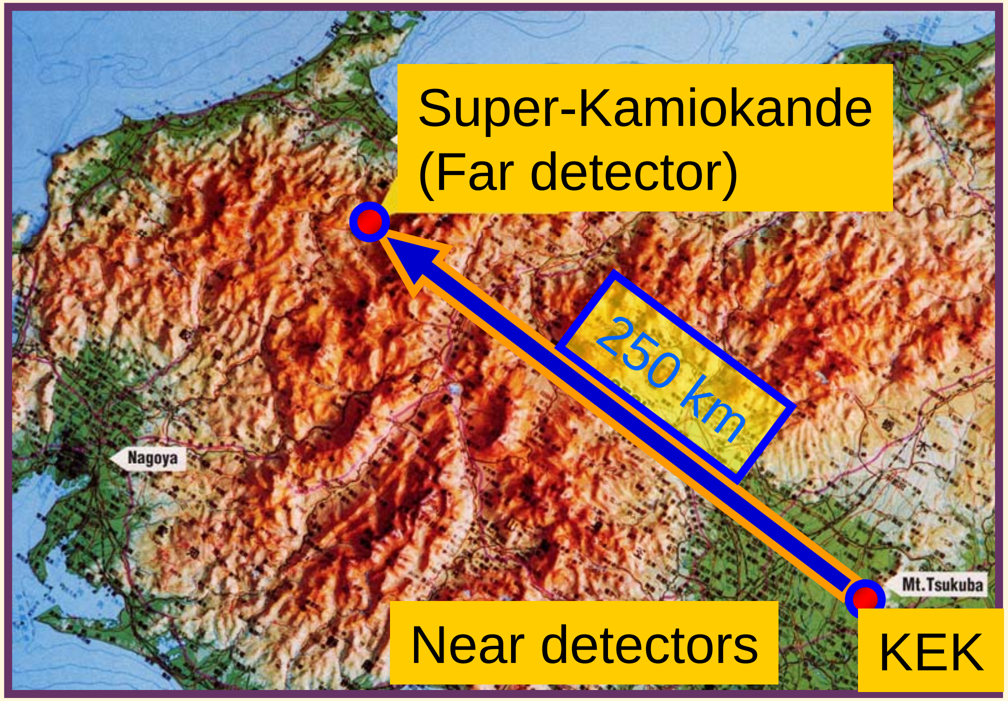
"KEK to Kamioka long baseline neutrino oscillation experiment"

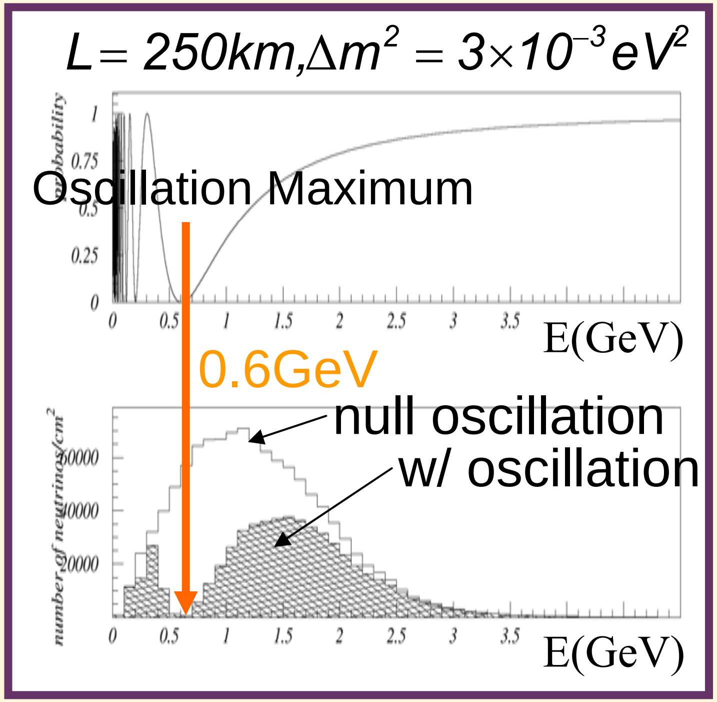
- ν_μ beam (~98% purity)
- E_ν= ~1.3GeV (in average)
- 250km baseline

compared w/ the expectation from near detector measurement.

→ ν_μ disappearance (confirm atm-ν result)

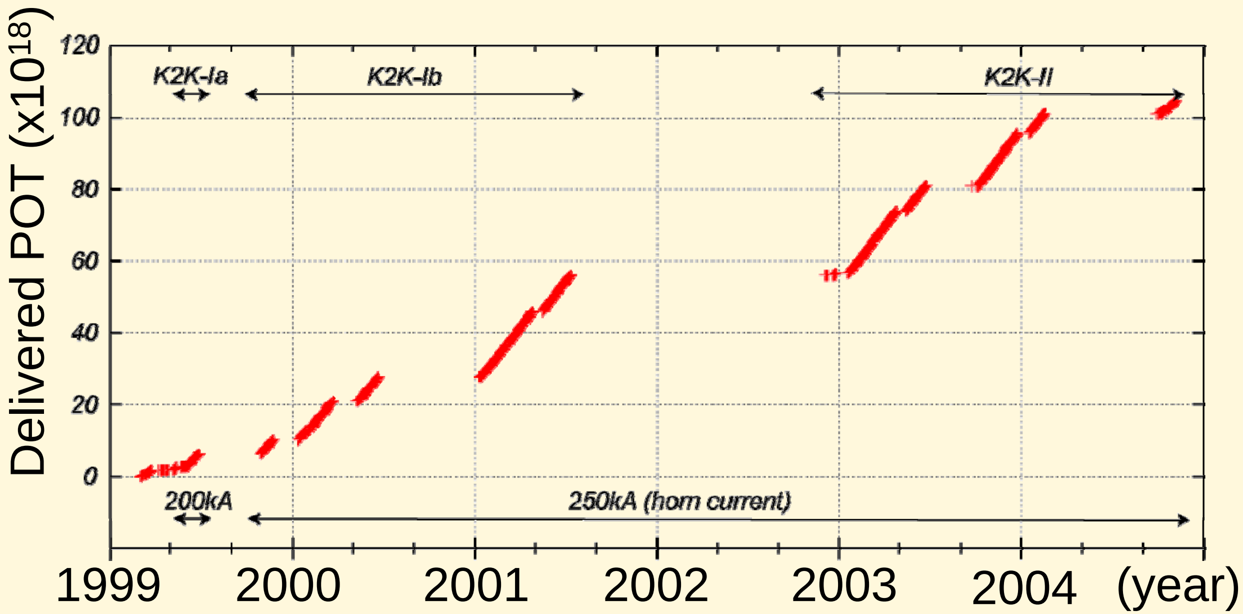
→ ν_e appearance





Data Sample

- 2 experimental phases
  - 1999.6-2001.6 with SK-1 → K2K-1
  - 2002.12-2004.11 with SK-2 → K2K-2
- Protons on target (POT): 9.2×10^{19} (entire data sample)
  - 4.8×10^{19} POT in K2K-1
  - 4.4×10^{19} POT in K2K-2



Search for $\nu_\mu \rightarrow \nu_e$ oscillation

- Look for the excess of ν_e events at SK
  - Find ν_e signal candidates in SK

  - Predict # of background events
- Prediction of SK events

$$N_{SK} \times \frac{MC\ event\ rate\ of\ \nu_e\ signal}{MC\ total\ event\ rate}$$

  - N_{SK}: total number of ν events estimated from ND event rate.
    - Cancellation of syst. uncertainties of cross-section and absolute flux

Estimate of SK event rate

- Neutrino interaction rate meas. with 1KT (N_{KT}^{int})
- The same detector technology as Super-K.

Total num. of SK events:

$$N_{SK} = \Phi_{SK} \times \sigma \times \varepsilon_{SK}$$
$$= N_{KT}^{int} \times \frac{\int \Phi_{SK}(E_\nu)\sigma(E_\nu)dE_\nu}{\int \Phi_{ND}(E_\nu)\sigma(E_\nu)dE_\nu} \times \frac{M_{SK}}{M_{KT}} \times \varepsilon_{SK}$$

≡Far/Near Ratio ~1×10^{-6}

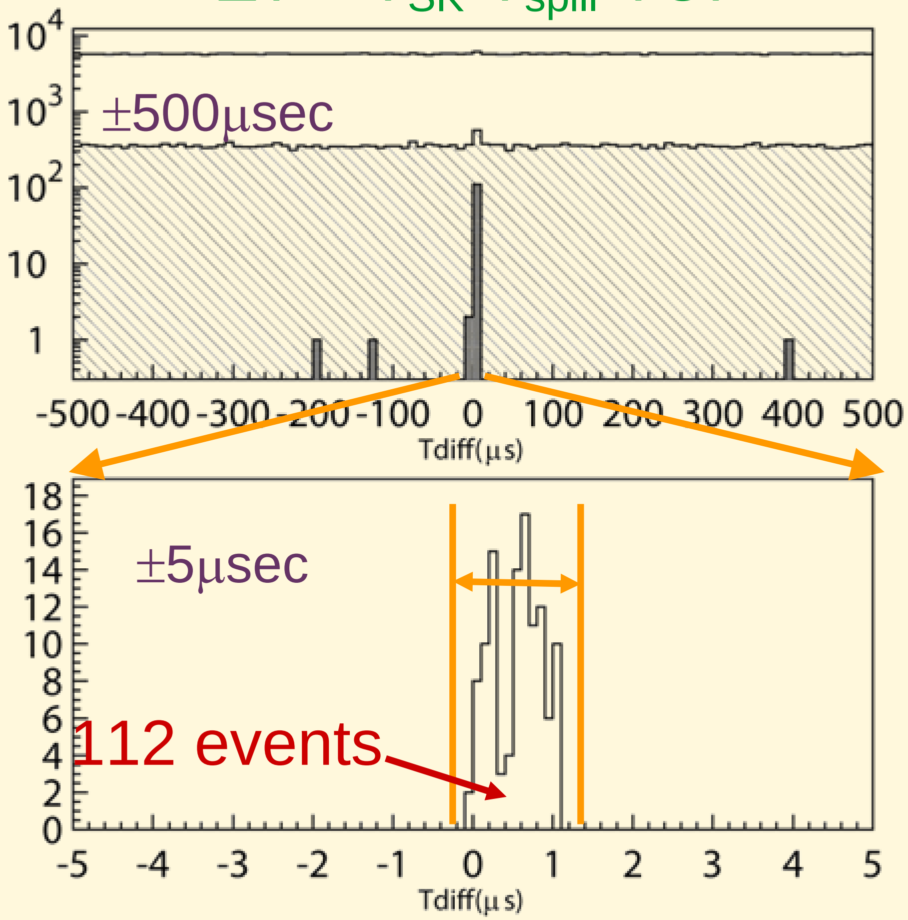
M: Fiducial mass M_{SK}=22.5kt, M_{KT}=25t

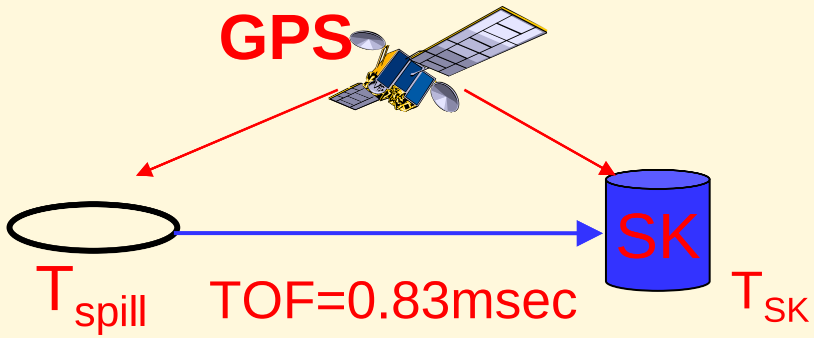
ε_{SK}: detection efficiency =77.0 (78.2)% for K2K-I (K2K-II)

$$N_{SK} = 158.4^{+9.4}_{-8,7}$$

Observation of beam neutrinos

$\Delta T = T_{SK} - T_{spill} - TOF$





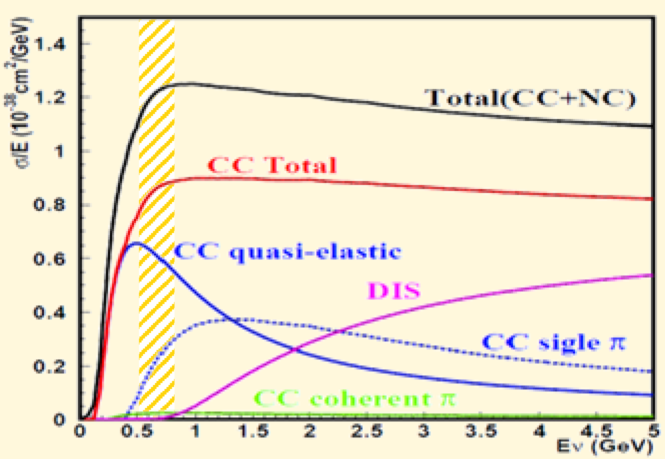
(BG: 1.6events within ±500ms
2.4×10^{-3} events in 1.5μs)

Observe: 112 events

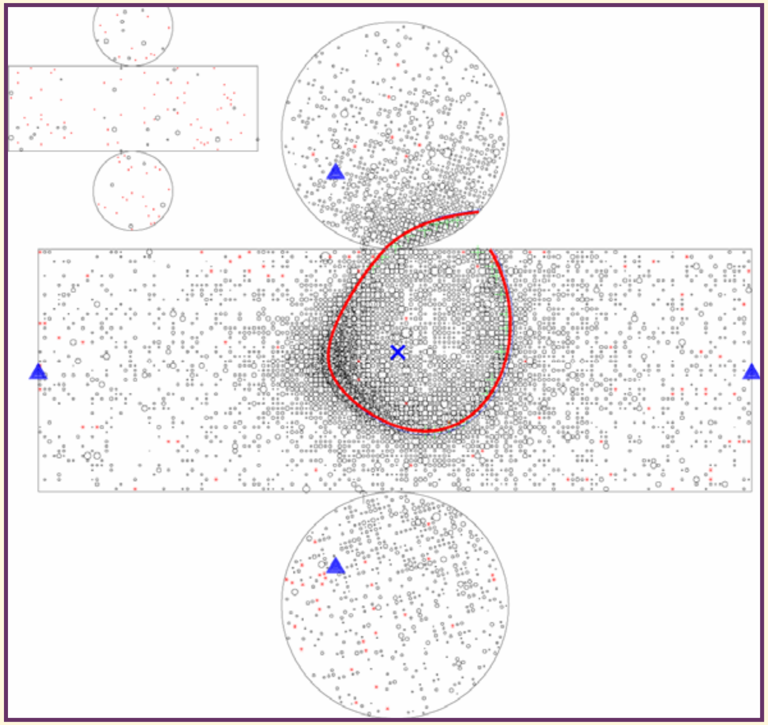
Signature of $\nu_\mu \rightarrow \nu_e$ oscillation

- ν_e CC quasi-elastic interaction
  - Dominant process at E~0.6GeV.
  - Only an electron is visible.

Select single-ring shower-type events

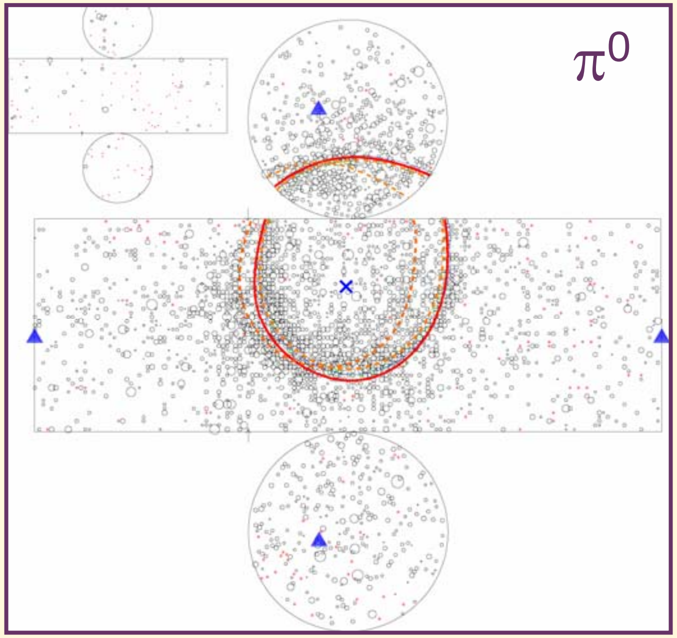


Event display of ν_e CC-QE event



Background for $\nu_\mu \to \nu_e$ search

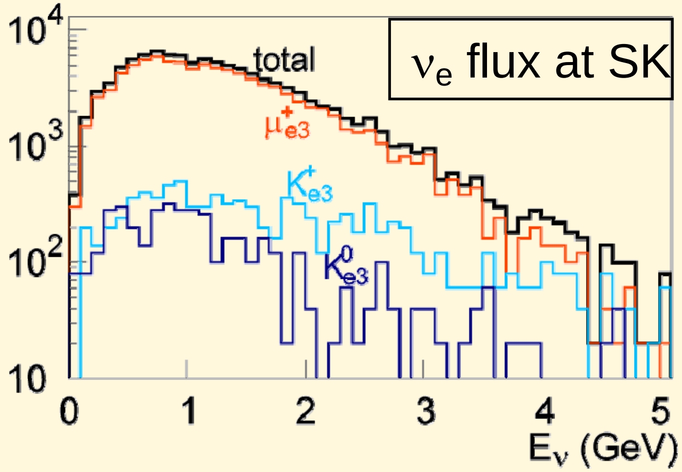
- Dominant background
  - π^0 production event with one reconstructed gamma-ray



- Remaining background originates from ν_e in the beam

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu \quad (\mu^+_{e3})$$
$$K^{+(0)} \to \pi^{0(-)} + e^+ + \nu_e \quad (K^{+(0)}_{e3})$$

  - Intrinsically irreducible.
  - A fraction of 0.9% at SK
  - Beam- ν_e contribution is estimated with MC
    - MC is validated by the near detector measurements.

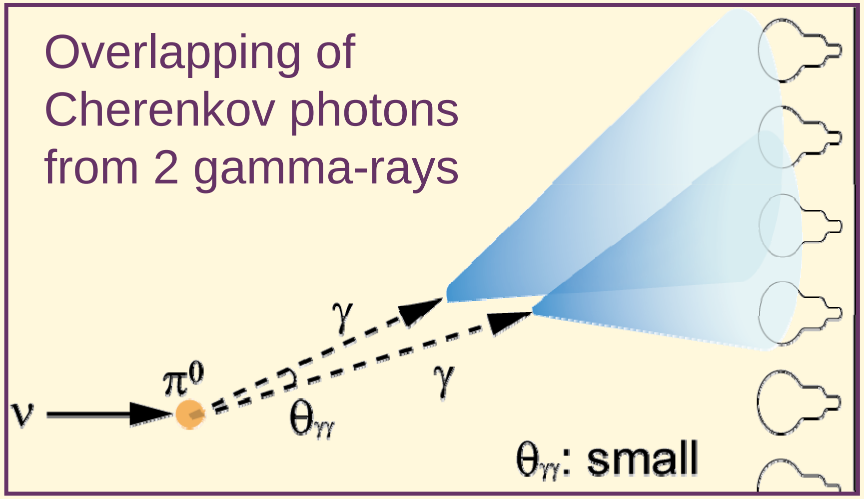


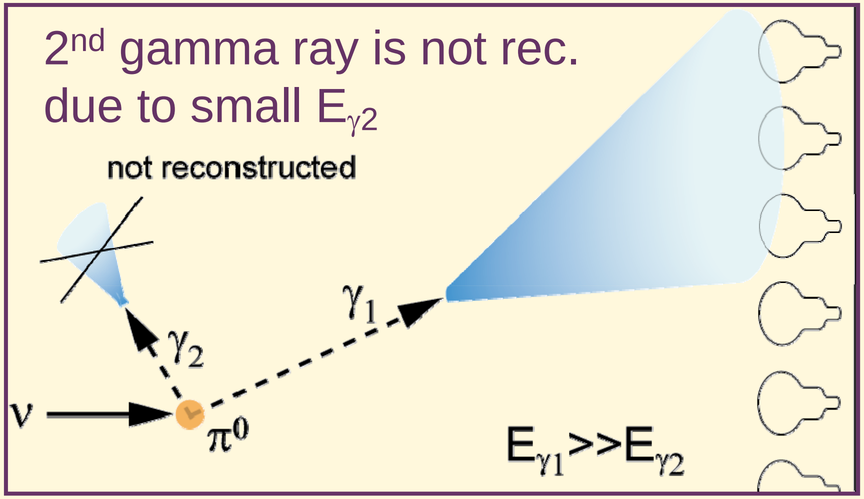
Neutral pion background

- Dominant process: single π^0 production such as Δ resonance via NC interaction (NC1π^0)

$$\nu + N \rightarrow \nu + \Delta(\rightarrow \pi^0 + N')$$

- Characteristics of π^0 background
  - Small opening angle of 2 gamma-rays
  - Small energy of 2nd gamma-ray





π^0 reconstruction algorithm

- Assume 2 emitted gamma-rays from a vertex
- Inputs to the fitter
  - Event vertex
  - Visible energy (E_{vis}, electron-equivalent energy)
  - Direction of 1st ring ($\mathbf{r}_{\gamma 1}$)
- Outputs
  - Momentum vectors of 2 gamma-rays ($E_{\gamma 1}$, $E_{\gamma 2}$, $\mathbf{r}_{\gamma 2}$)
- Fitting method
  - Share E_{vis} with 2 gamma-ray (no kinematical constraint of π^0 decay)
  - Compare the observed charge dis
    expectations based on Poisson χ

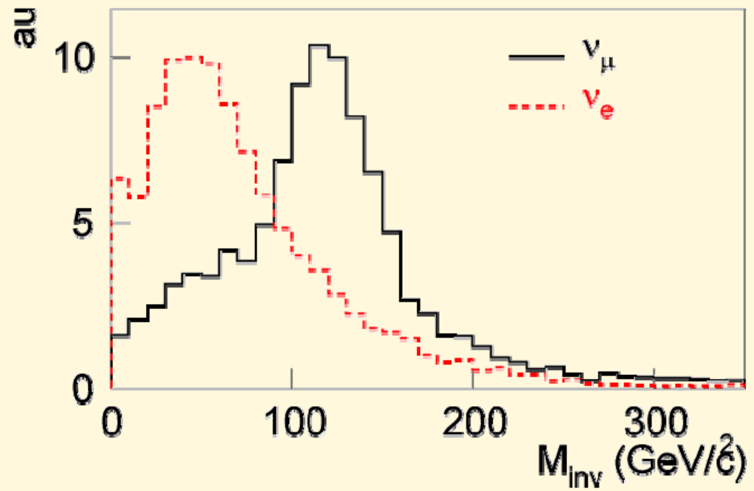
$$\chi^2 = \sum_{PMT} 2(q_i^{exp} - q_i^{obs}) + 2q_i^{obs} \ln \frac{q_i^{obs}}{q_i^{exp}}$$

e/π^0 separation

- e/π^0 separation using invariant mass of 2 gamma-rays:

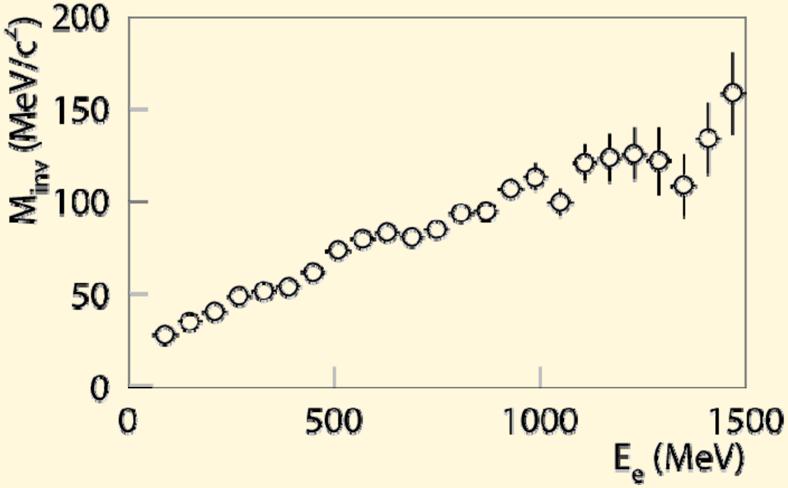
$$M_{inv} = \sqrt{2E_{\gamma 1}E_{\gamma 2}(1-\cos\theta_{\gamma\gamma})}$$

  - M_{inv}~π^0 mass for π^0 events
  - M_{inv} <100MeV/c^2 for single-electron events



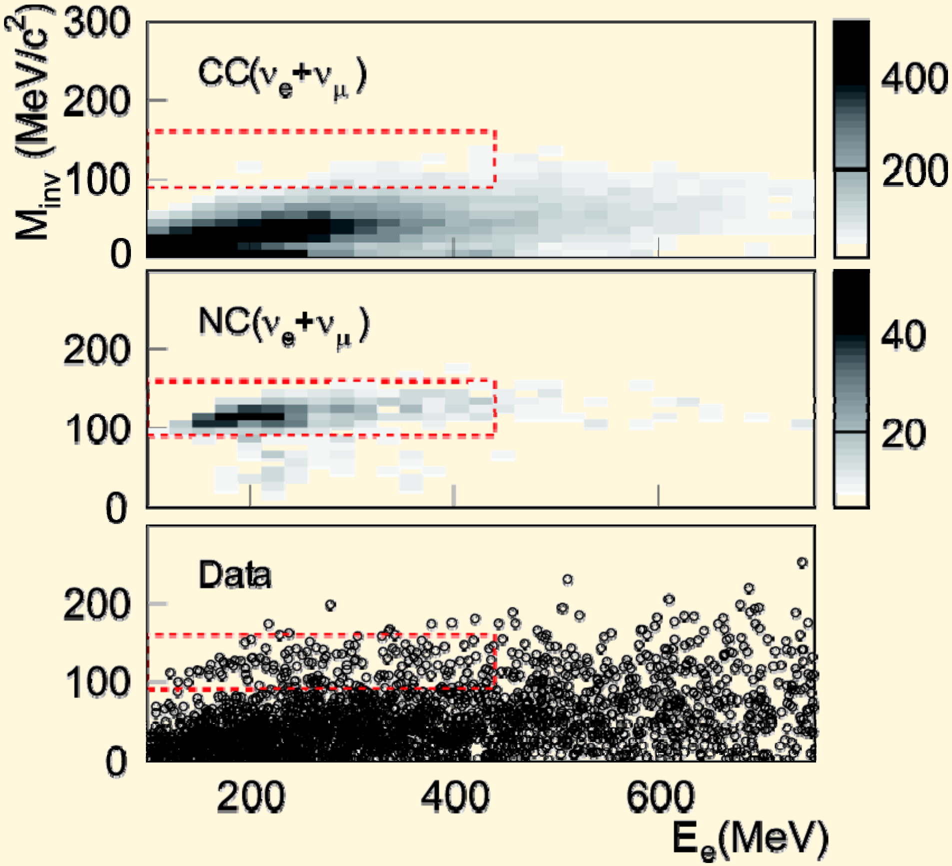
- Reconstruct 2nd fake ring for single-electron events:
  - Small $\theta_{\gamma\gamma}$ ~20°
  - Small $E_{\gamma 2}$ ($E\gamma 2/(E\gamma 1+E\gamma 2)$~0.2)

  → M_{inv} depends on electron energy (E_e)



Validation of π^0 fitter

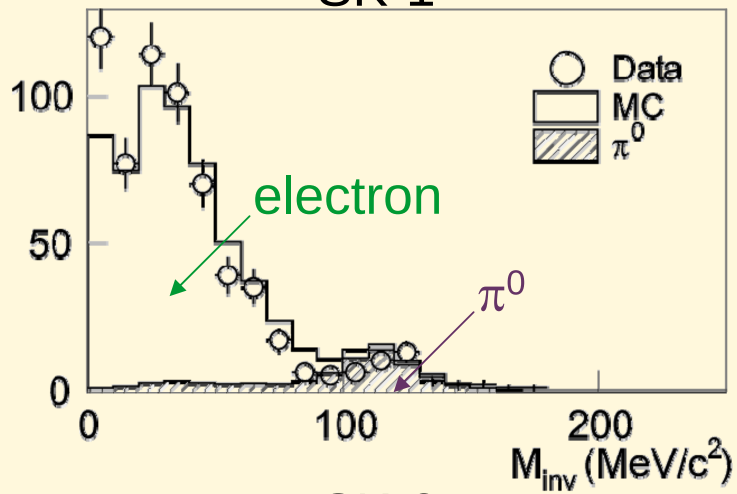
- Atm. ν 1-ring shower-type events
  - ~94% fraction of electron (ν_e)
  - ~6% fraction of π^0 via NC
- M_{inv}~π^0 mass for π^0 events
  - Events clustered around M_{inv}~π^0 mass in data, as we expecte according to MC NC interaction events.



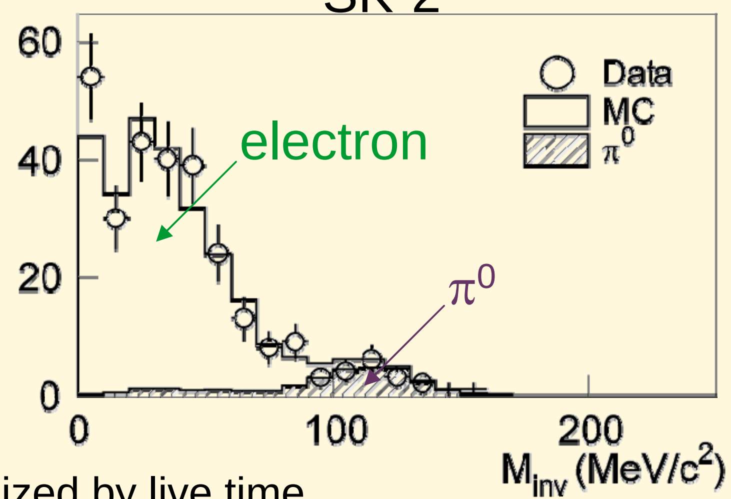
Validation of π^0 fitter

- Good agreements for both ν_e and $\pi 0$ compositions
- M_{inv} peak for π^0's:
  - 122(118)MeV/c^2 for SK-1(2) data
  - 116(117)MeV/c^2 for MC events
  - → Good agreement btw/ data & MC
    - Energy scale error: ~3MeV
    - Stat. error: 2~3MeV

SK-1

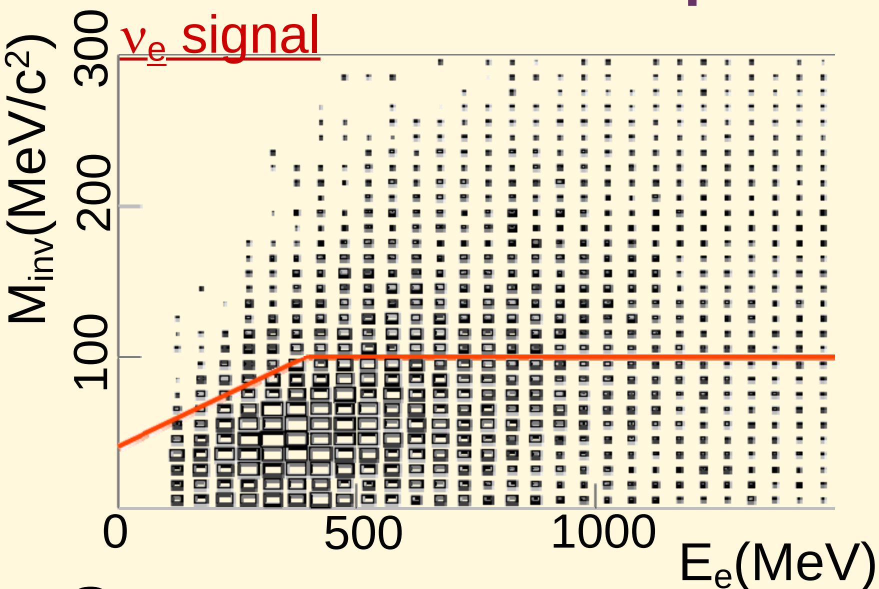


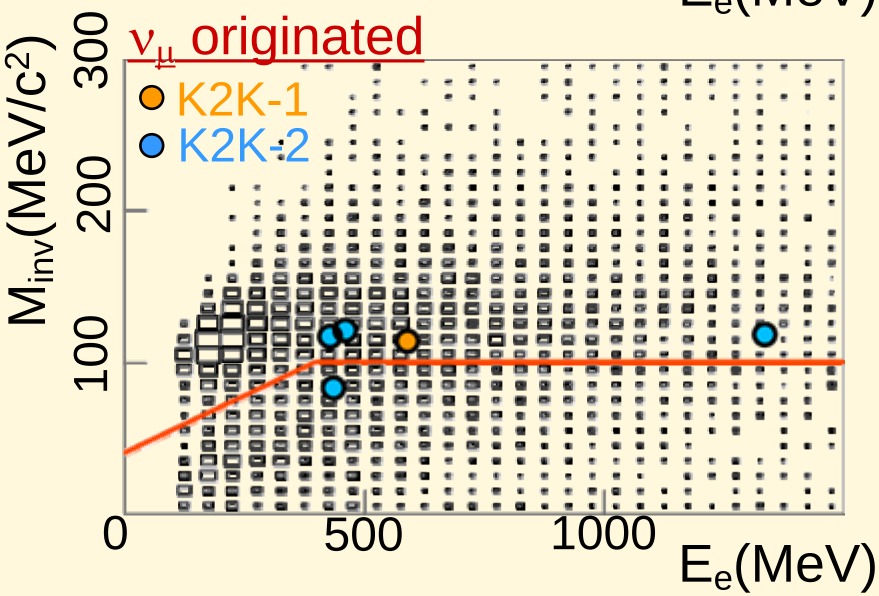
SK-2



MC events are normalized by live time
SK-1: 1492 days, SK-2: 627 days

Neutral pion rejection cut





- Apply a π^0 rejection cut in K2K data sample

$$\begin{cases} M_{inv} < \frac{3}{20} E_e + 40MeV & \text{for} \quad E_e < 400MeV \\ M_{inv} < 100MeV & \text{for} \quad E_e \geq 400MeV \end{cases}$$

- Optimized to maximize the sensitivity on $\sin^2 2\theta_{\mu e}$
- 4 of 5 remaining events are rejected.
  - Rejection capability is consistent w/ MC prediction of 70%

Numbers of observed & expected events

— K2K-1 —	ν_μ MC	beam ν_e	Data
Fully contained	81.1	0.81	55
Single ring	50.92	0.47	33
Shower-type ring	2.66	0.40	3
Visible energy cut	2.47	0.40	2
No decay electron	1.90	0.35	1
Non-π^0 like	**0.58**	**0.17**	**0**

— K2K-2 —	ν_μ MC	beam ν_e	Data
Fully contained	77.4	0.86	57
Single ring	49.41	0.52	34
Shower-type ring	3.21	0.44	5
Visible energy cut	2.93	0.44	5
No decay electron	2.17	0.39	4
Non-π^0 like	**0.74**	**0.21**	**1**

Signal selection eff:
- 47% for K2K-1
- 55% for K2K-2

ν_μ BG rejection:
- 0.55% for K2K-1
- 0.74% for K2K-2

#observed = 1
#expected B.G. = 1.70

Consistent w/ the BG expectation

Calculating upper limits

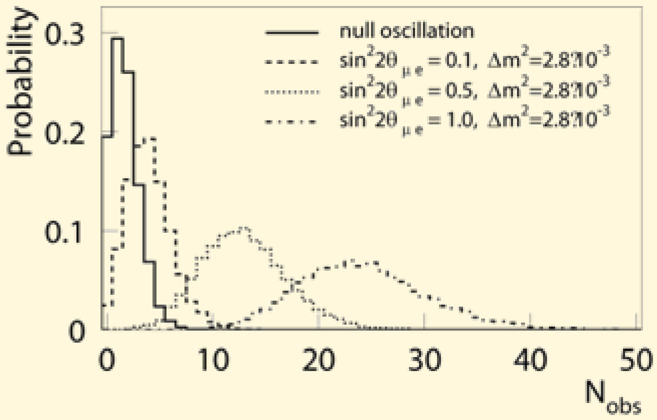
- Assume 2-flavor mixing: $P(\nu_\mu \to \nu_e) = \begin{cases} \sin^2 2\theta_{\mu e} \sin^2(1.27\Delta m^2 \frac{L}{E}) & \text{for CC} \\ 0 & \text{for NC} \end{cases}$

- Confidence interval with Poisson dist. using N_{obs} and

$$N_{exp}(\sin^2 2\theta_{\mu e}, \Delta m^2) = S_{\nu_e}(\sin^2 2\theta_{\mu e}, \Delta m^2) + B_{\nu_\mu}(\sin^2 2\theta_{\mu e}, \Delta m^2) + B_{\nu_e}$$

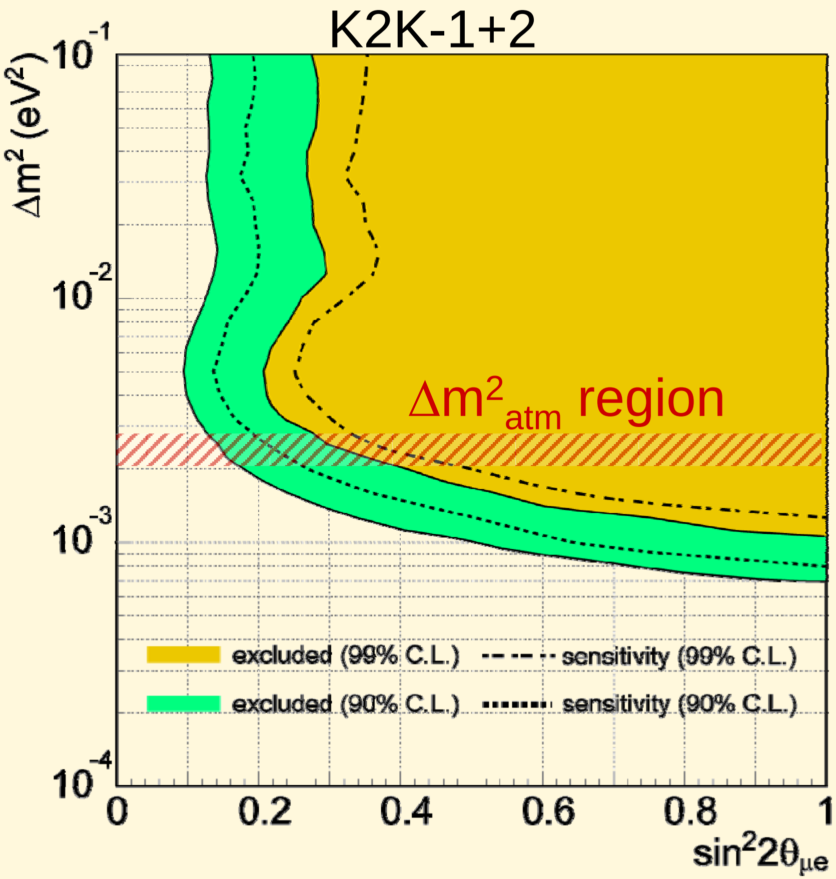
ν_e signal — ν_μ-originated BG — beam-ν_e BG

PDF



- Syst. uncertainties are implemented in prob. densities. (~±30%)
  - –Many virtual exp. with random syst. parameters
  - –Observe N_{obs} events in Poisson regime
- Confidence interval calc. with Feldman & Cousins method

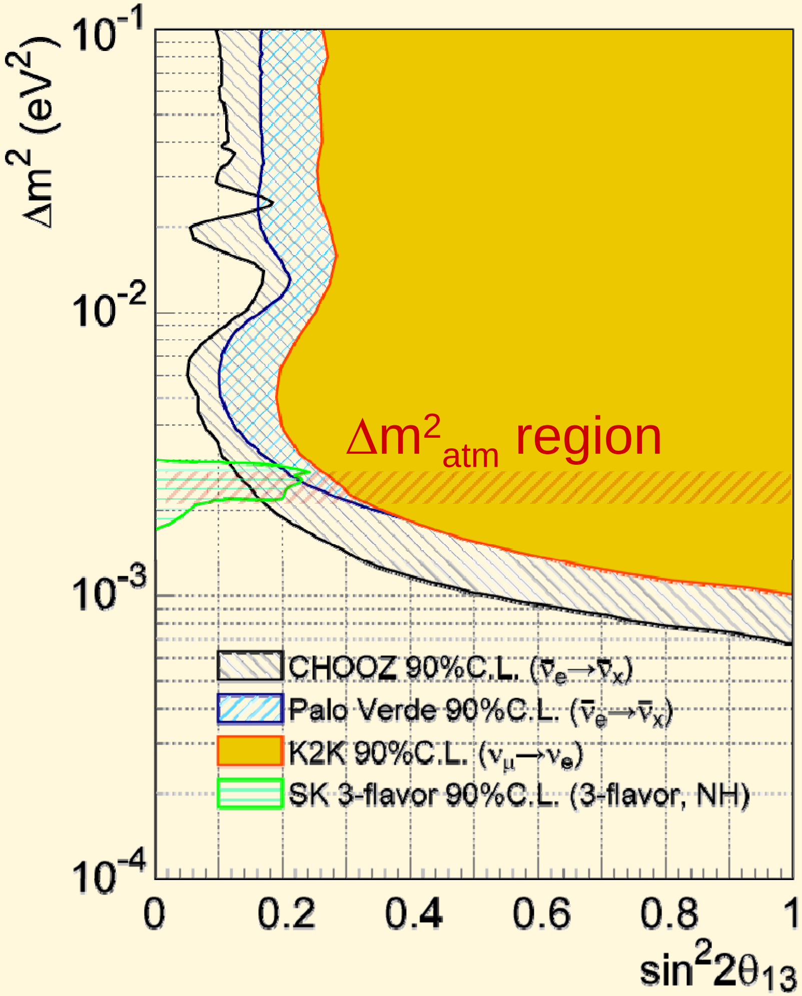
Constraint in Δm^2-$\sin^2 2\theta_{\mu e}$ space



N_{obs} = 1event
N_{exp}(no osc.) = 1.7events

Constraint on oscillation parameters (90% C.L.):
$\sin^2 2\theta_{\mu e} < 0.13$ at $\Delta m^2 = 2.8 \times 10^{-3}$ eV^2

Constraint on the mixing parameter θ_{13}



$$\sin^2 2\theta_{\mu e} \approx \frac{1}{2} \sin^2 2\theta_{13}$$

- Comparison w/ reactor neutrino experiments:
  - $\sin^2 2\theta_{13} < 0.13$ (CHOOZ)
  - $\sin^2 2\theta_{13} < 0.20$ (Palo-Verde)

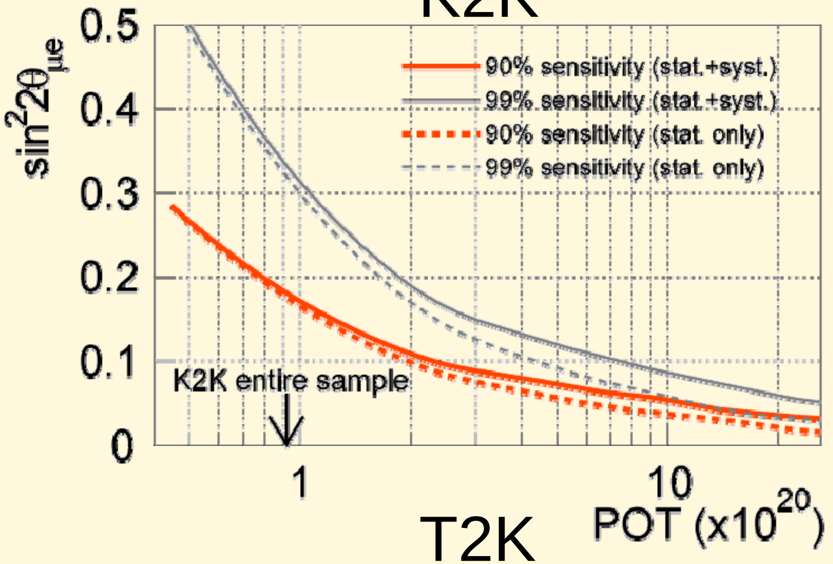
  →Consistent results
- The most strict limit in ν_e appearance mode
- The only result using a ν_μ beam at $\Delta m_{atm}{}^2$ region

Future prospects

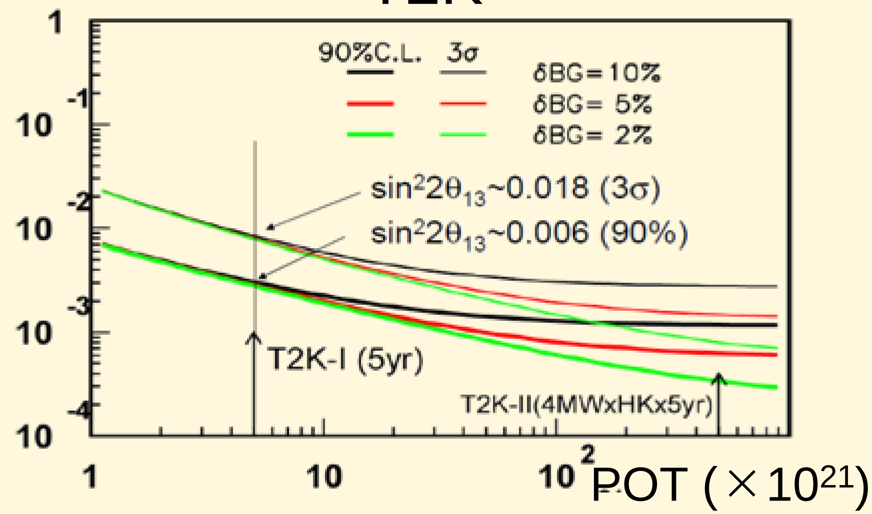
- The K2K sensitivity reaches $\sin^2 2\theta_{\mu e}=0.1$ with 10 times stat. (90%CL, $\Delta m^2=2.8\times10^{-3}eV^2$)
- The projected sensitivity of T2K: $\sin^2 2\theta_{\mu e}\sim O(10^{-3})$
  - Intense neutrino beam
    - → ×50 statistics for 5 years
  - Narrow band, lower energy (<1GeV)
    - → Suppress π^0 production

<u>Demonstrated the π^0 rejection as the pioneering work</u>

K2K



T2K



Summary

- We have searched for $\nu_\mu \rightarrow \nu_e$ oscillation using the entire K2K data sample of 9.2×10^{19} POT.
- We have developed a new reconstruction algorithm for π^0's.
  - Validated the performances with atmospheric neutrinos.
  - Achieved ν_μ background rejection by 70%.
  - Pioneering works for the future long-baseline experiment.

  → Improved sensitivity for $\nu_\mu \rightarrow \nu_e$ oscillation
- New constraints on neutrino oscillation parameters
  - $\sin^2 2\theta_{\mu e} < 0.13$ (90% C.L.) at $\Delta m^2 = 2.8 \times 10^{-3}$ eV^2
    - Most strict limit in ν_e appearance mode
  - $\sin^2 2\theta_{13} < 0.26$ (90% C.L.) at $\Delta m^2 = 2.8 \times 10^{-3}$ eV^2 in 3-flavor framework
    - Consistent with the results from the reactor neutrino experiments (CHOOZ, Palo-Verde)