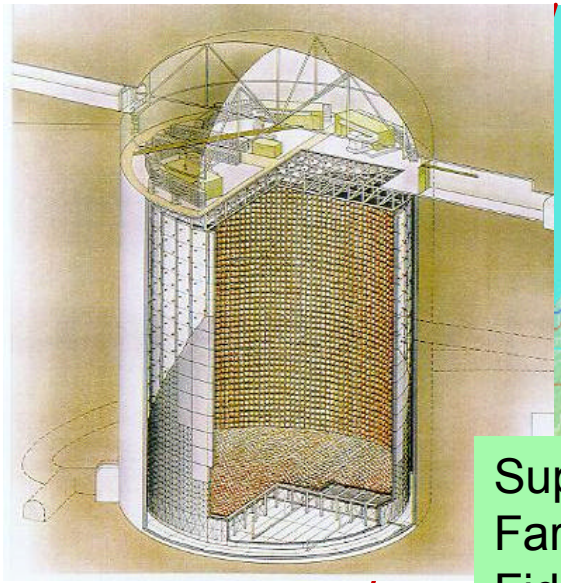
Results from the K2K experiment

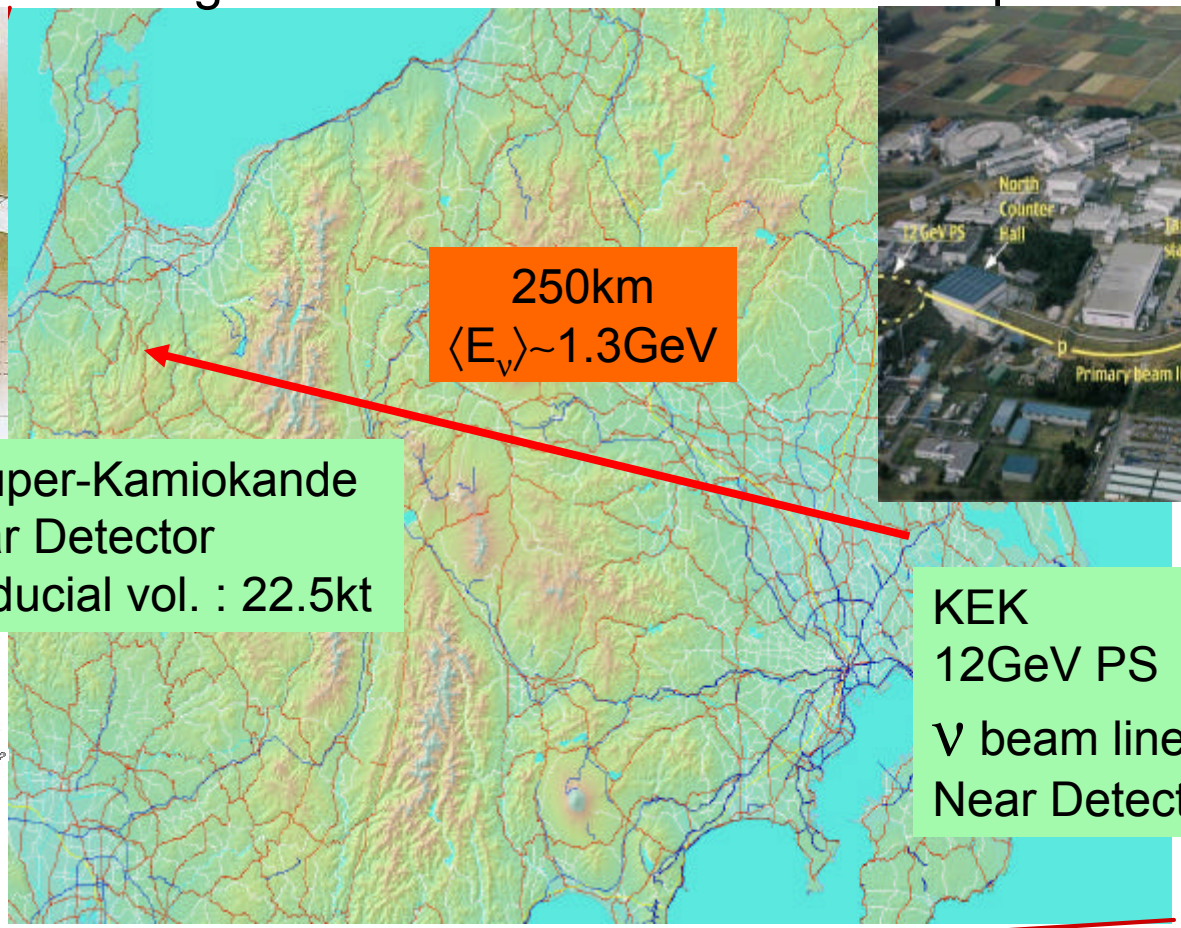
T. Nakadaira

KEK

K2K experiment

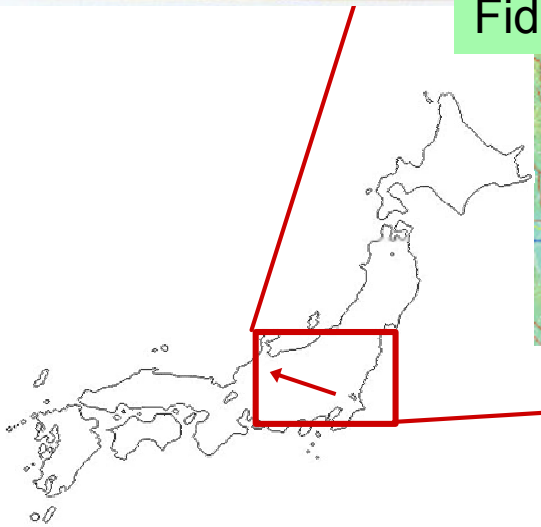
- KEK to Kamioka long baseline Neutrino Oscillation Experiment





Super-Kamiokande
Far Detector
Fiducial vol. : 22.5kt

KEK
12GeV PS
ν beam line
Near Detector(ND)



Started in 1999

K2K Collaboration

JAPAN: High Energy Accelerator Research Organization (KEK) / Institute for Cosmic Ray Research (ICRR), Univ. of Tokyo / Kobe University / Kyoto University / Niigata University / Okayama University / Tokyo University of Science / Tohoku University

KOREA: Chonnam National University / Dongshin University / Korea University / Seoul National University

U.S.A.: Boston University / University of California, Irvine / University of Hawaii, Manoa / Massachusetts Institute of Technology / State University of New York at Stony Brook / University of Washington at Seattle

POLAND: Warsaw University / Solton Institute

Since 2002

JAPAN: Hiroshima University / Osaka University

CANADA: TRIUMF / University of British Columbia

ITALY: Rome

FRANCE: Saclay

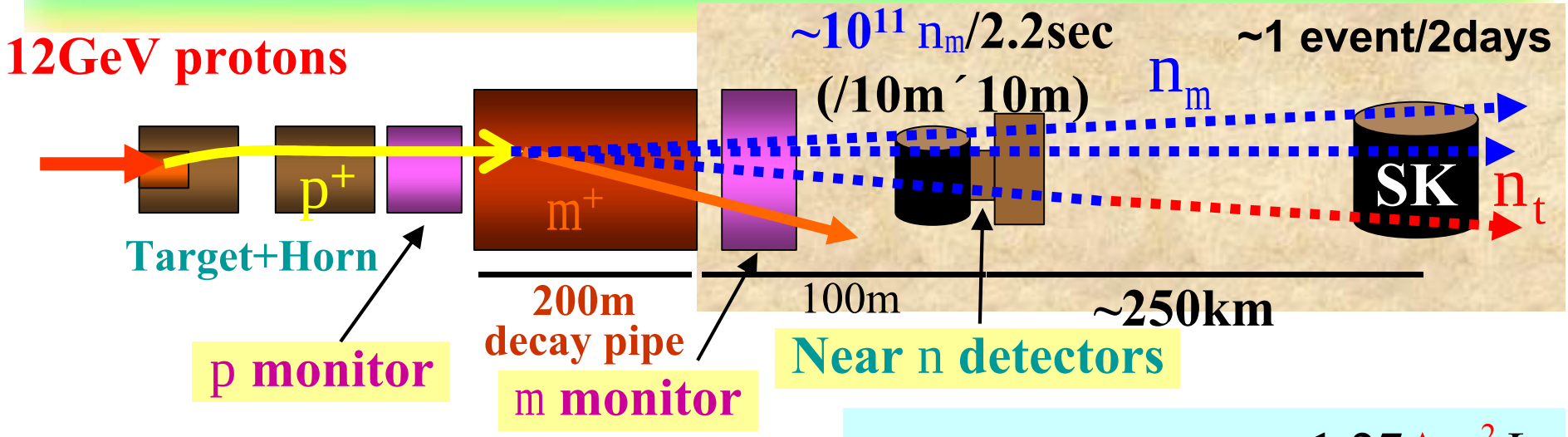
SPAIN: Barcelona / Valencia

SWITZERLAND: Geneva

RUSSIA: INR-Moscow

U.S.A.: Duke University

Principle of K2K



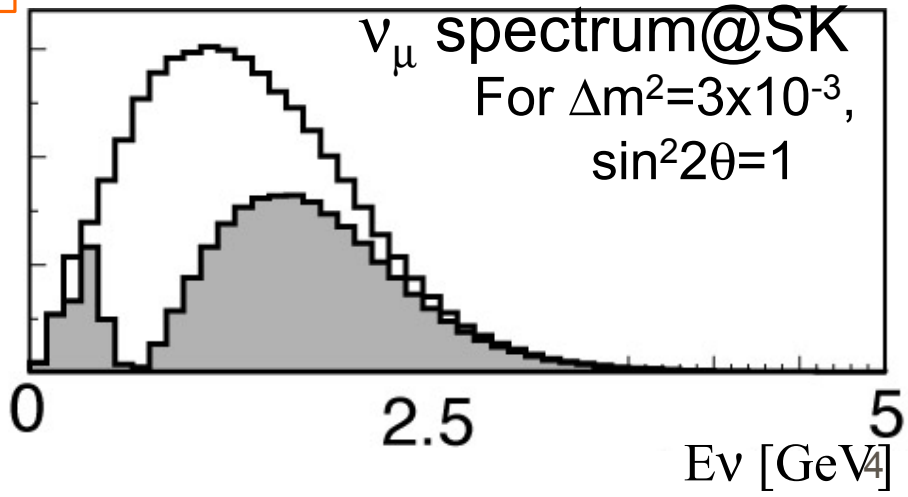
- Confirmation of $\nu_\mu \rightarrow \nu_x$ oscillation reported by Super-K atm-ν

$$\text{prob.} = \sin^2 2q \cdot \sin^2\left(\frac{1.27\Delta m^2 L}{E_n}\right)$$

Observables:

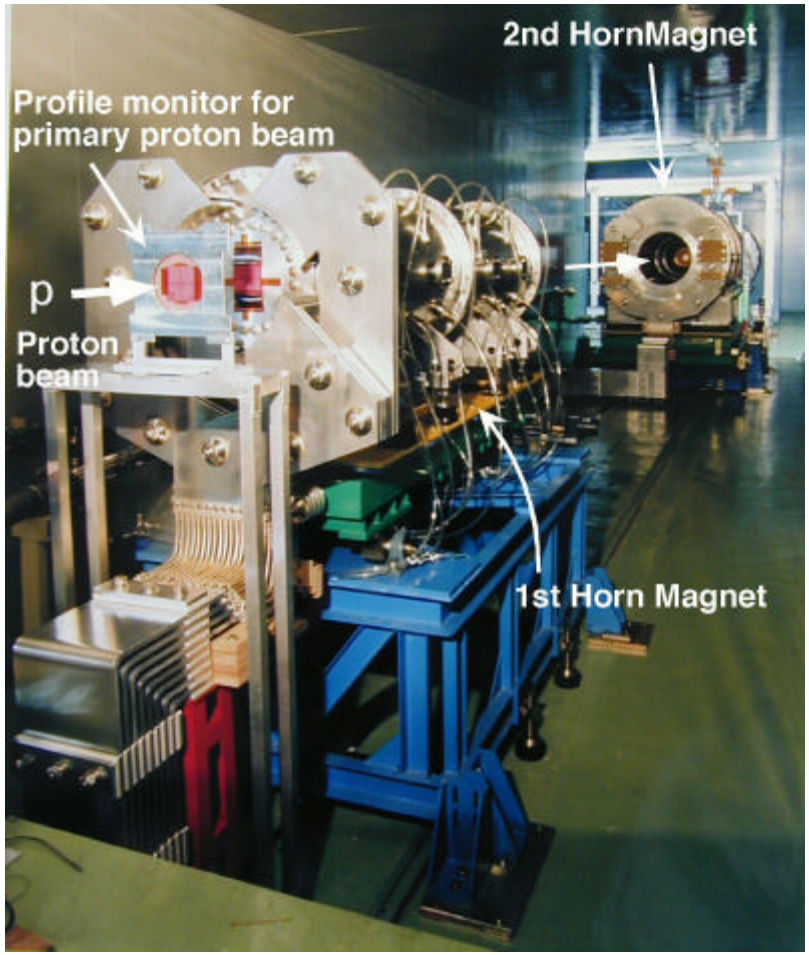
- Reduction of events
- Distortion of spectrum

→ If $\sin^2 2\theta \neq 0$ and $\Delta m^2 \neq 0$, Neutrino oscillation.

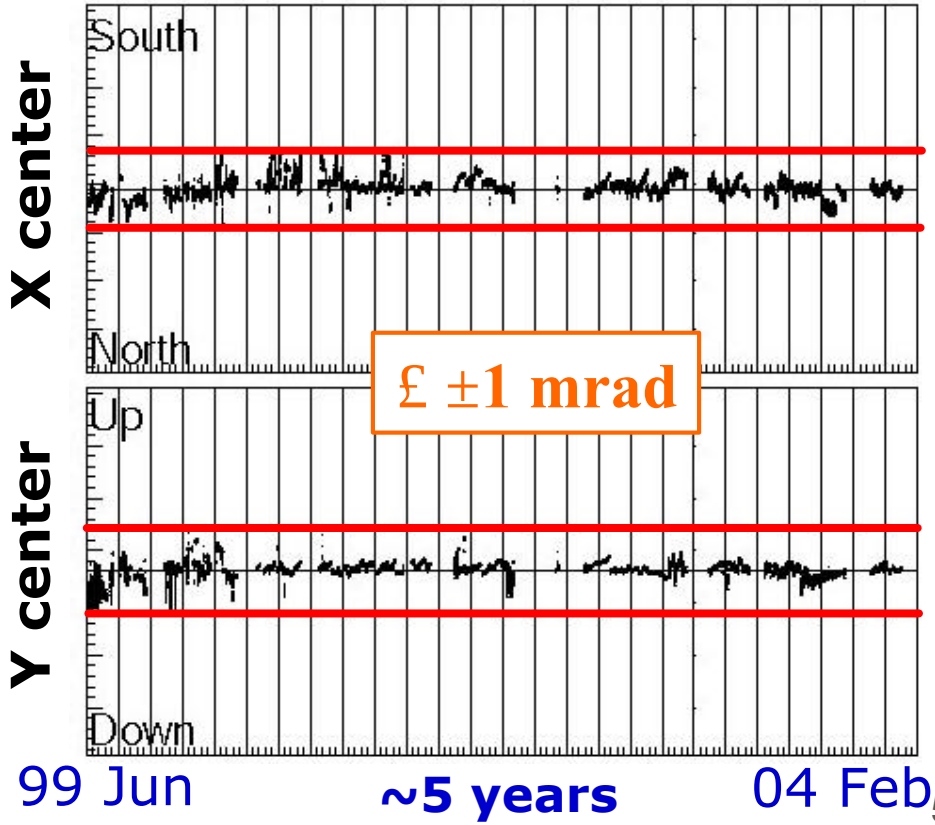


Neutrino beam and the directional control

- ~1GeV neutrino beam by a dual horn system with 250kA.



The beam direction monitored by muons spill by spill

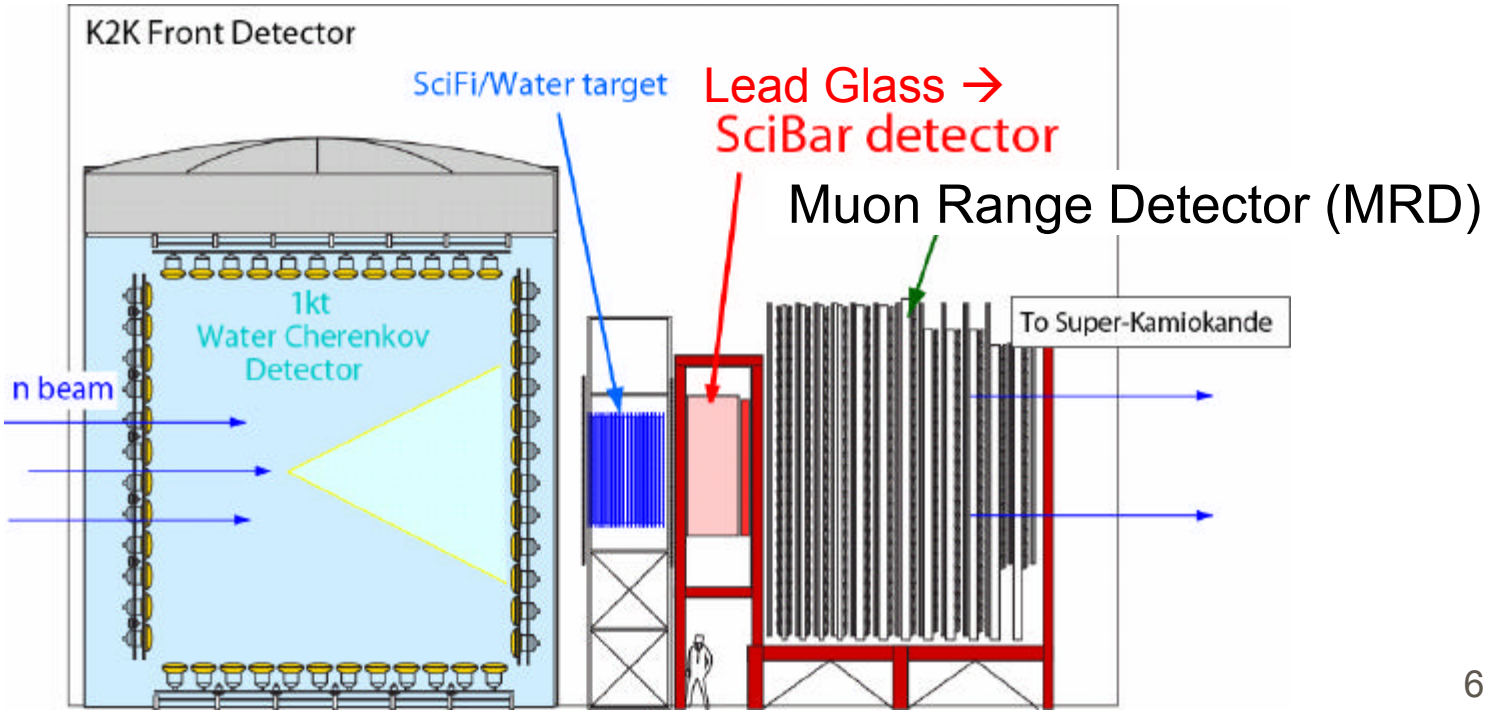


Near Detector

- 1KT: water Cerenkov detector [25t fiducial]
- SciFi: scintillating fiber and water target [6t fiducial]
- LG: Lead glass calorimeter (removed in 2002)

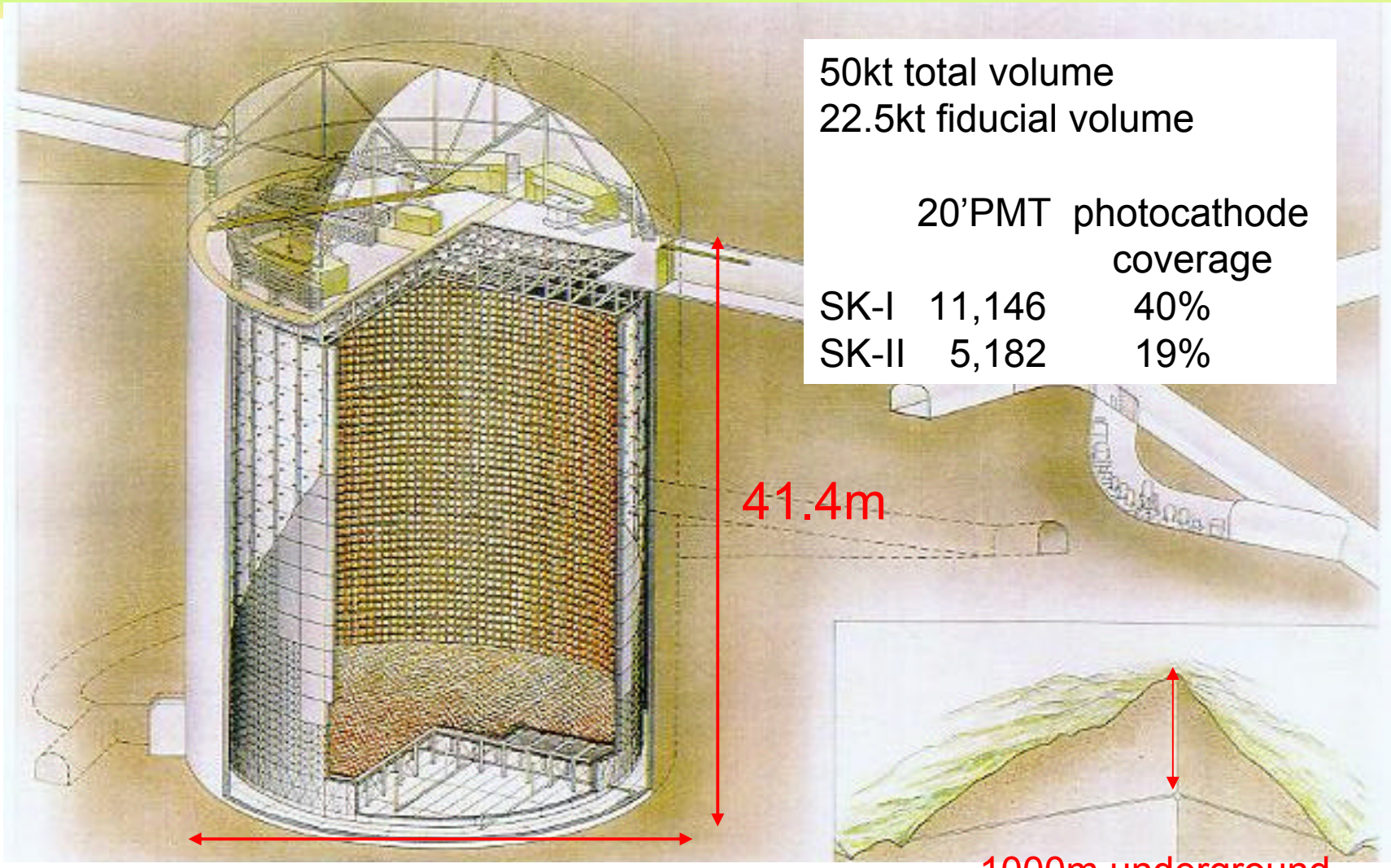
→ SciBar: fully-active scintillator detector [10t fiducial]
(installed in 2003)

- MRD: muon range detector

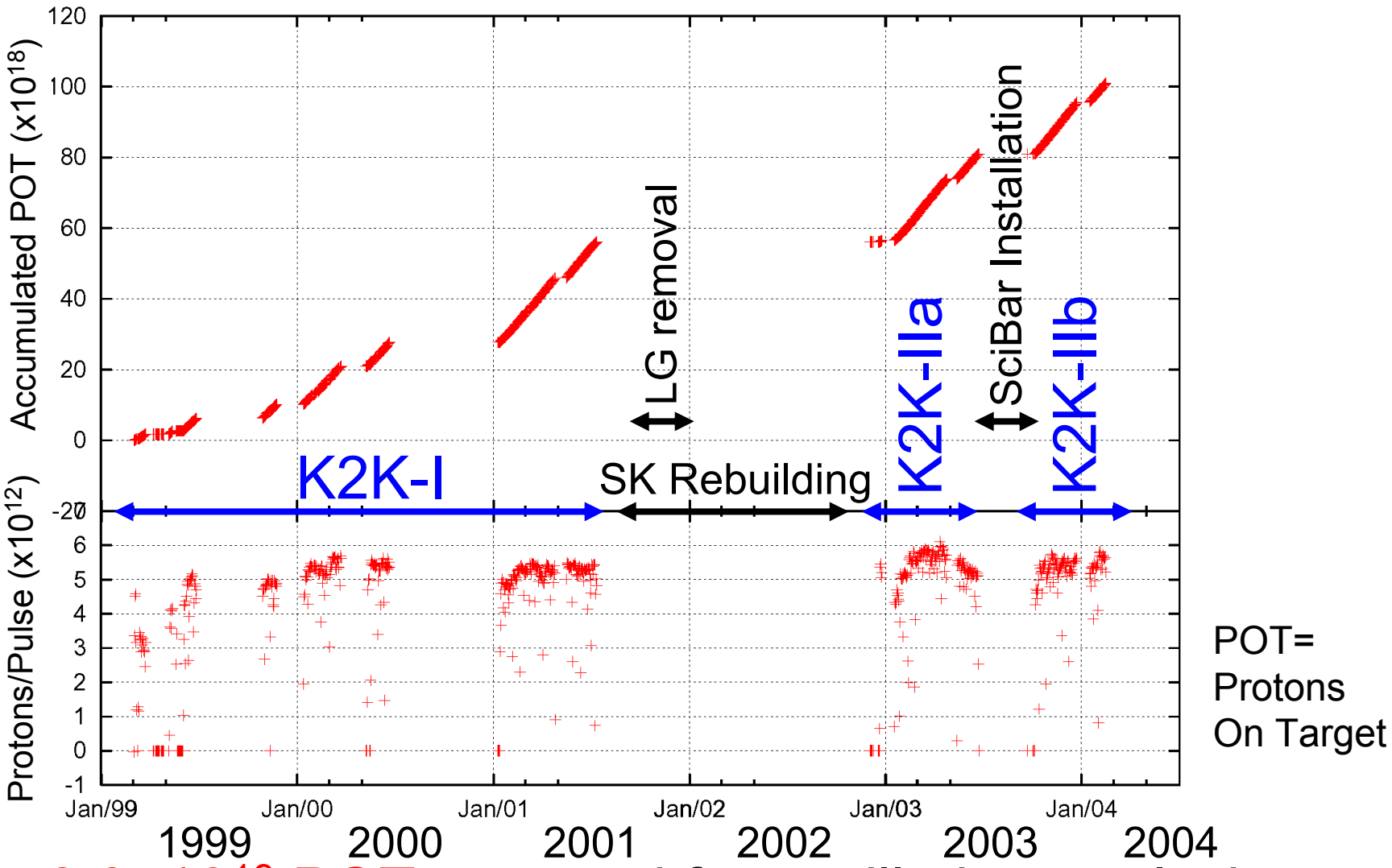


300m
from target

Super-Kamiokande (Far detector on K2K)



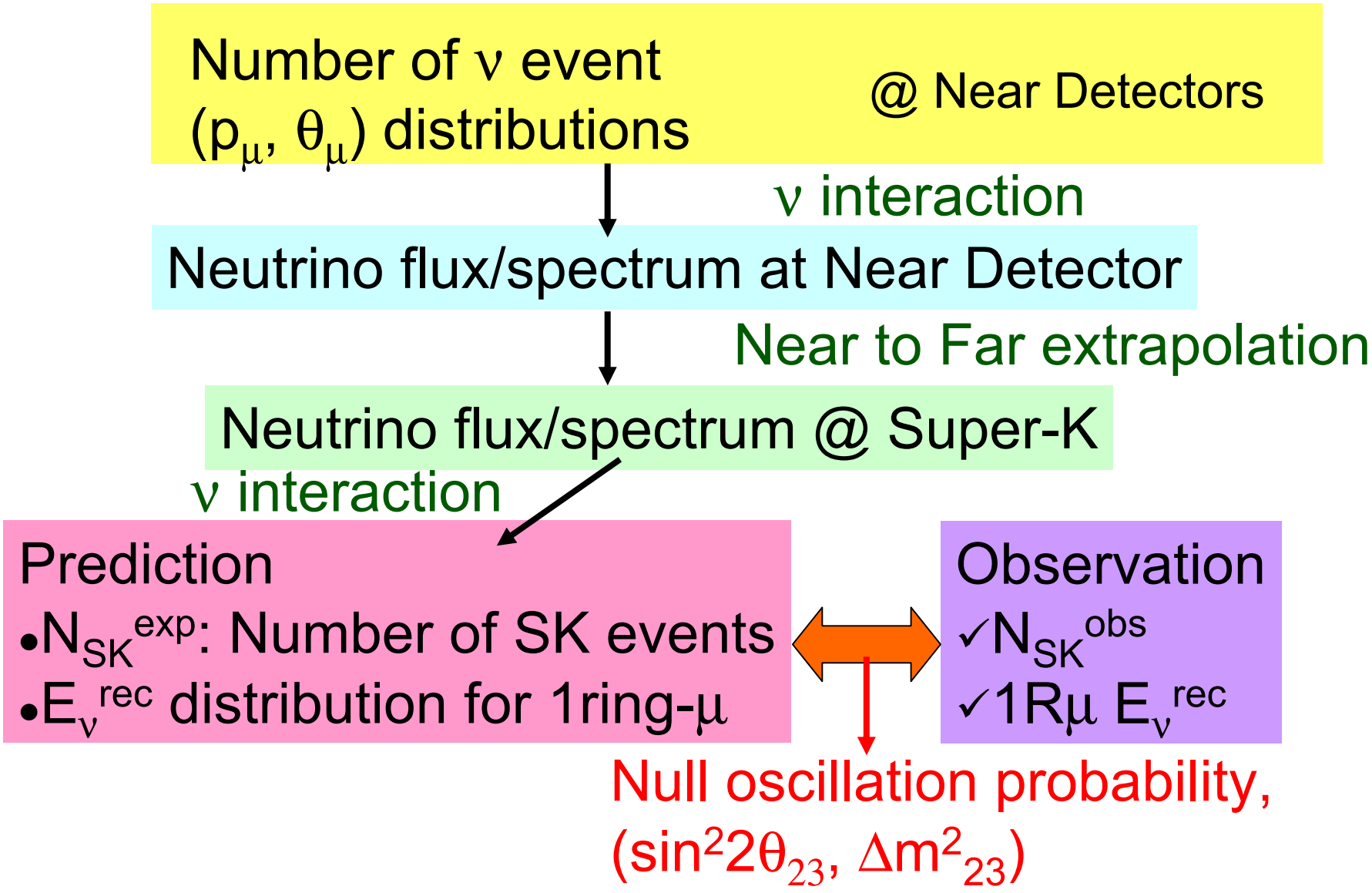
Delivered Protons On Target



POT=
Protons
On Target

$8.9 \acute{} 10^{19}$ POT are used for oscillation analysis

Analysis Flow



Near Detector Measurements

Event Rate Measurement @1KT

- Use total # of events in the fiducial volume (25t).

Φ_{KT} ´ Far/Near Ratio

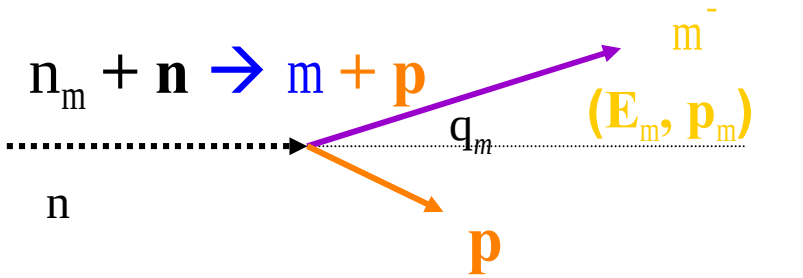
$$N_{SK}^{\exp} = N_{KT}^{obs} \bullet \frac{\int \Phi_{SK}(E_n)\, s(E_n)\, e_{SK}\, dE_n}{\int \Phi_{KT}(E_n)\, s(E_n)\, e_{KT}\, dE_n} \bullet \frac{M_{SK}}{M_{KT}}$$

measured spectrum

M: Fiducial mass M_{SK}=22,500ton, M_{KT}=25ton
e: efficiency $\varepsilon_{SK\text{-}I(II)}$=77.1(78.2)%, ε_{KT}=74.5%

$$N_{SK}^{expect} = 150.9^{+11.6}_{-10.0}$$ (w/o oscillation)

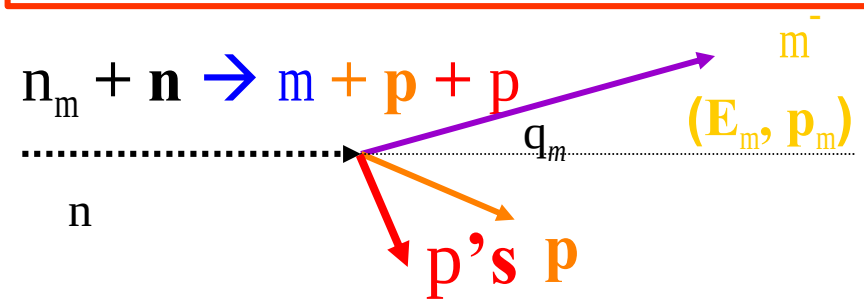
Eν Reconstruction



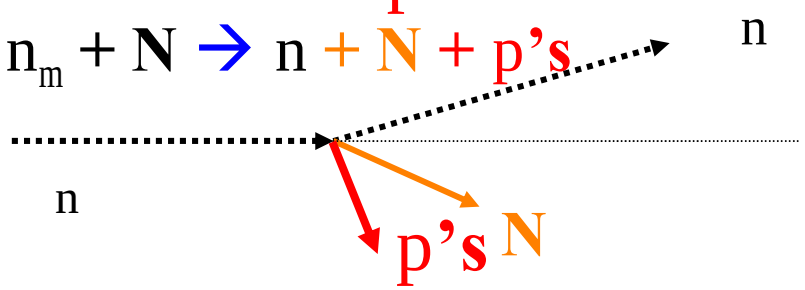
- CC Quasi Elastic (CC-QE)
  - 1Rμ in W-Cherenkov
  - can reconstruct Eν ←(θ_μ, p_μ)

$$E_n^{rec} = \frac{(m_N - V)E_m - m_m^2/2 + m_N V - V^2/2}{(m_N - V) - E_m + p_m \cos q_m}$$

V: nuclear potential energy



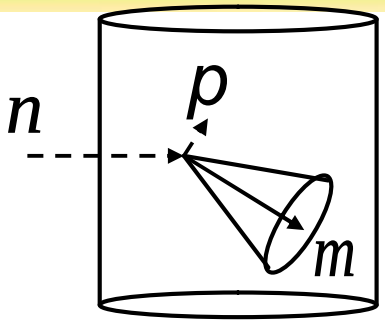
- CC nQE
  - Background for Eν meas.

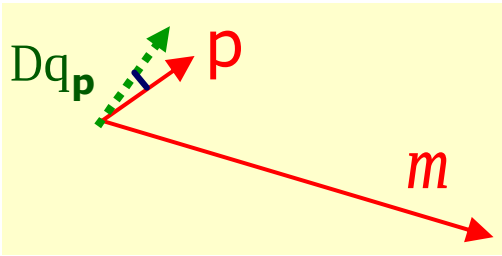


- NC

Used Data for Spectrum Meas.

1KT
(1) Fully Contained
1 ring μ-like events





SciFi
(2) 1-track μ events
(3) 2-track QE-like
(4) 2-track nonQE-like

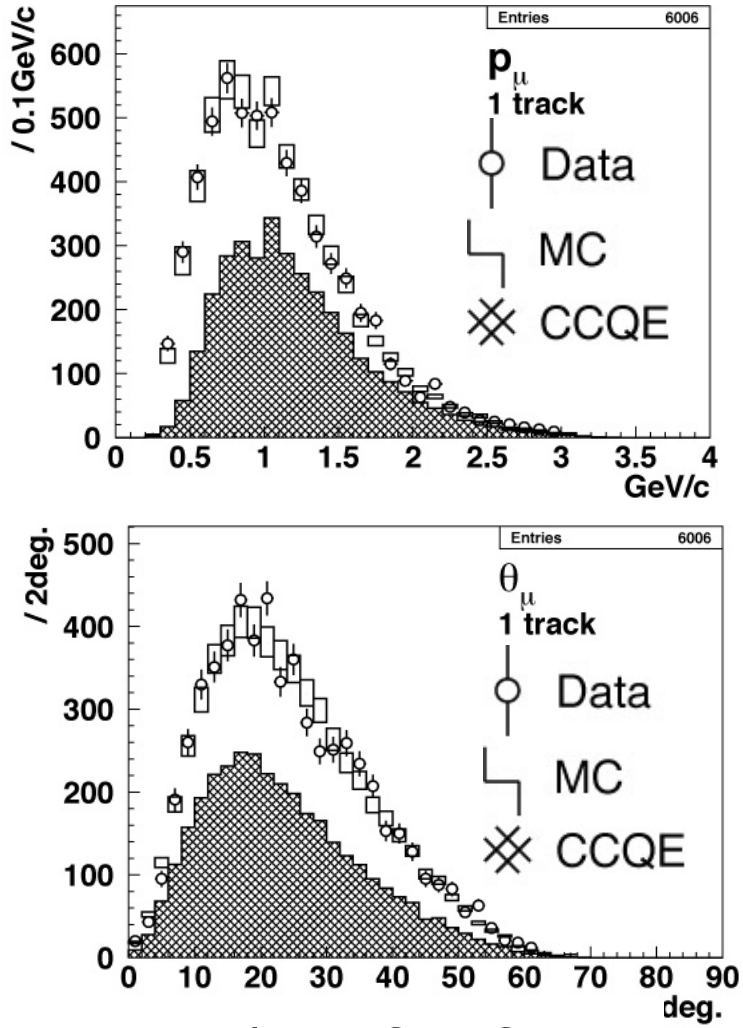
SciBar
(5) 1-track μ events
(6) 2-track QE-like
(7) 2-track nonQE-like

7 sets of (pμ,θμ) distributions

simultaneously fit

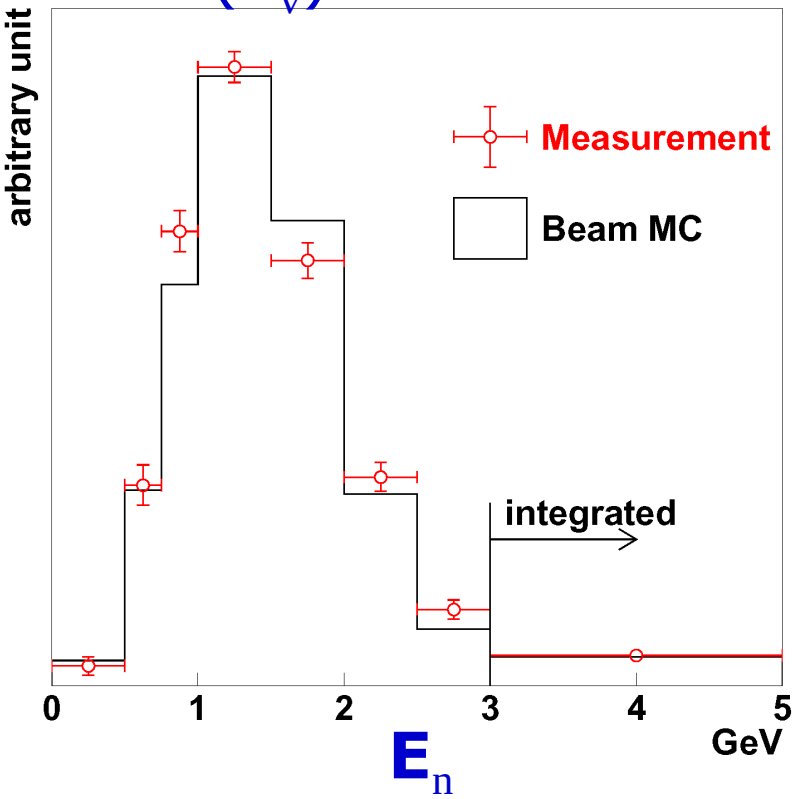
- n **spectrum** $F_{Near}(E_n)$ **(8 bins)**
- n **interaction model (nQE/QE)**

Measured Spectrum



pμ/θμ after fitting
(SciBar 1track)

$\Phi(E_\nu)$ at ND



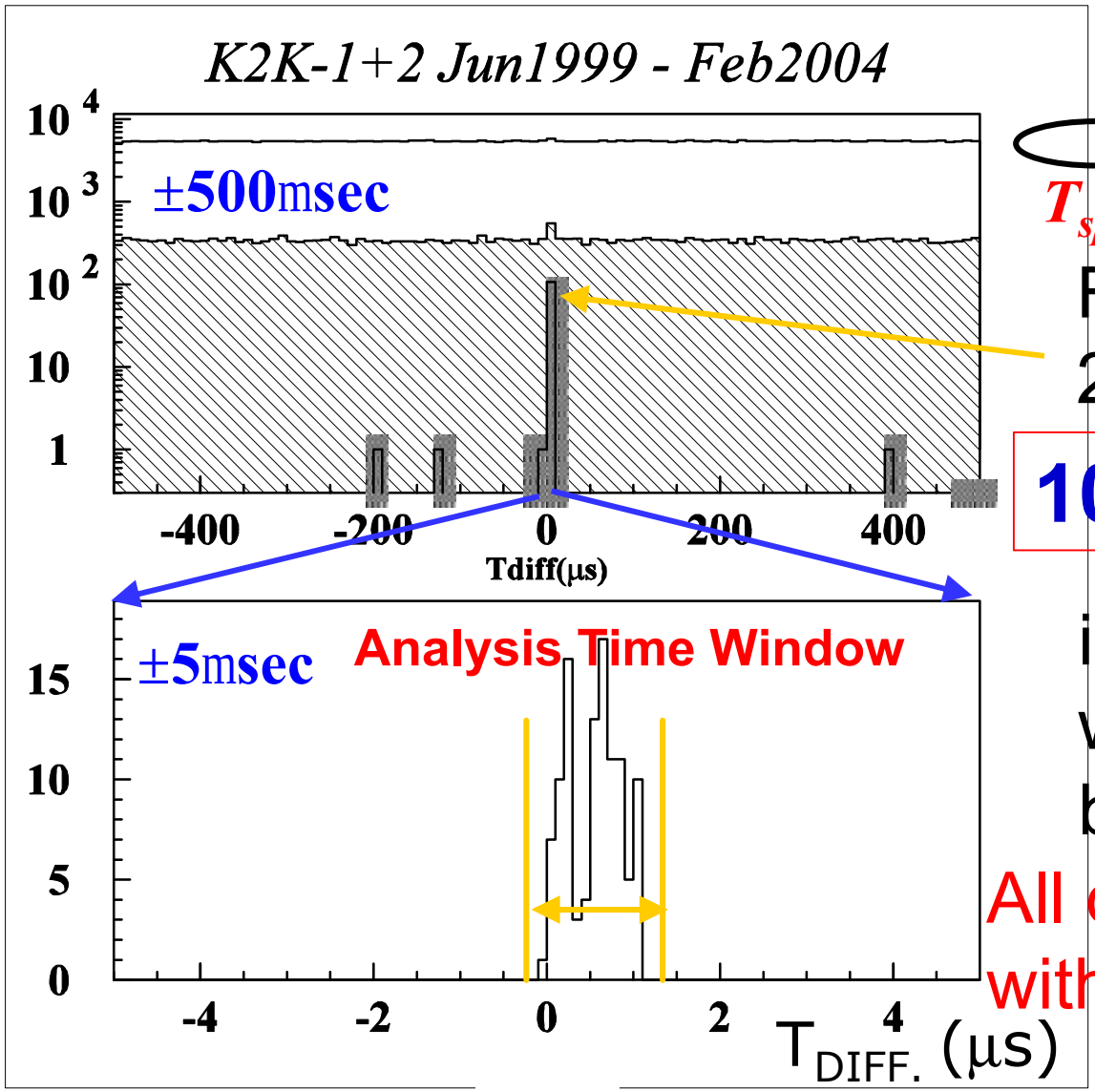
χ^2=638.1 for 609 *d.o.f*

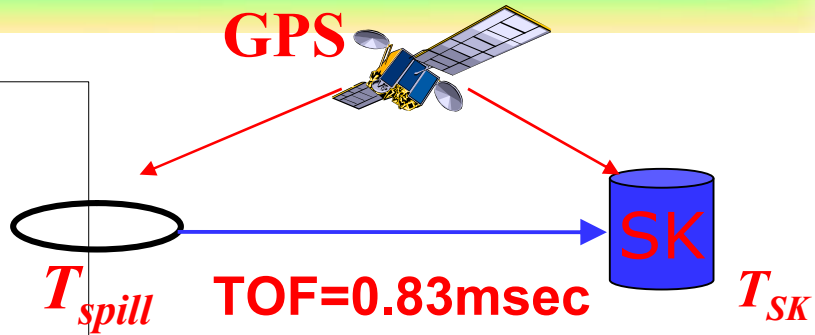
nQE/QE = 1.02 ± 0.10

Assigned based on the variation by the fit condition.

Super-K Observation and Oscillation Analysis

Super-K Event Selection





Fully contained in 22.5kt fiducial volume

107 events

in 1.5 μsec window w/ negligible (2×10^{-3}) background

All data are (re-)processed with consistent software.

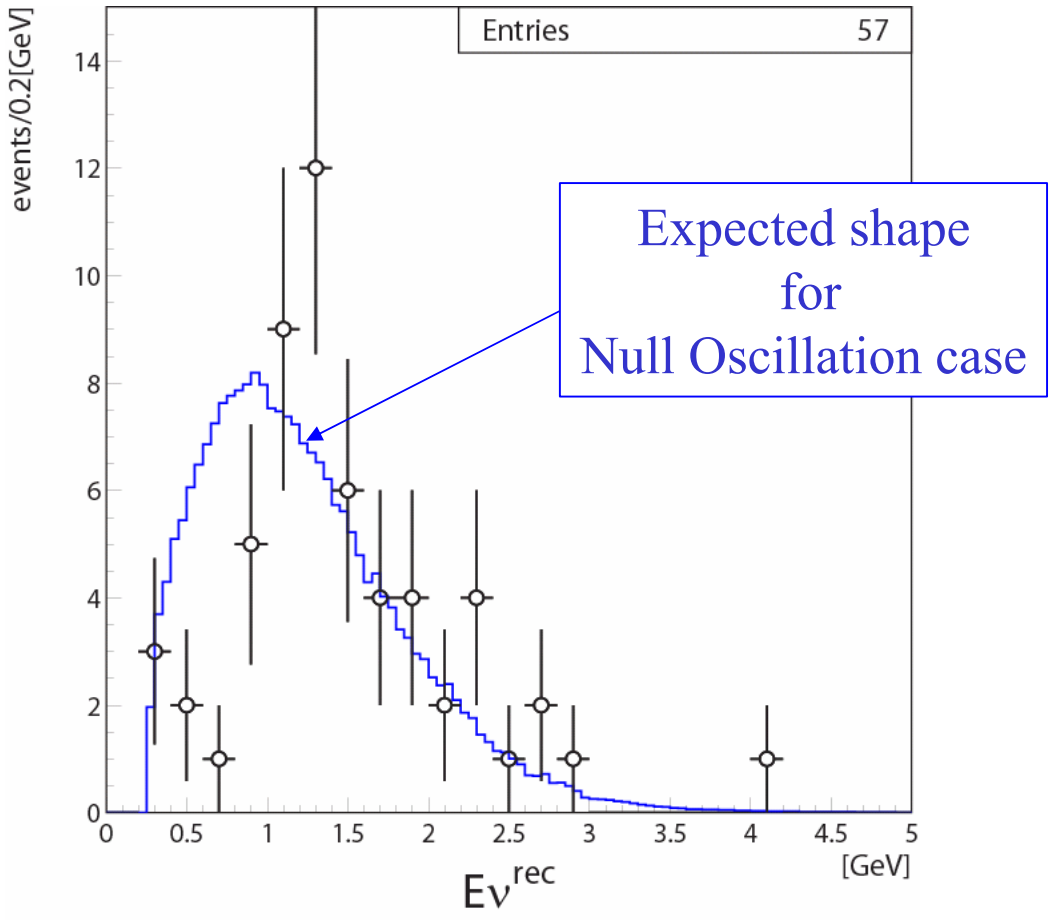
Super-K Event Summary

K2K-all (K2K-I, K2K-II)	DATA (K2K-I, K2K-II)	MC (K2K-I, K2K-II)
FC 22.5kt	**107** (55, 52)	**150.9** (79.1, 71.8)
1ring	**67** (33, 34)	**94.0** (48.9, 45.1)
μ-like for E_ν^{rec}	**57** (30, 27)	**85.4** (44.9, 40.5)
e-like	**10** (3, 7)	**8.6** (4.0, 4.5)
Multi Ring	**40** (22, 18)	**56.9** (30.2, 26.7)

Ref; K2K-I(47.9×10^{18}POT), K2K-II(41.2×10^{18}POT)

Reconstructed Eν for 1Rμ events

K2K-I + K2K-II ... 57 events



Maximum likelihood fit

- Total Number of events
- E_ν^{rec} spectrum shape of FC-1ring-μ events
- Systematic error term

$$L(\Delta m^2, \sin 2q, f^x)$$

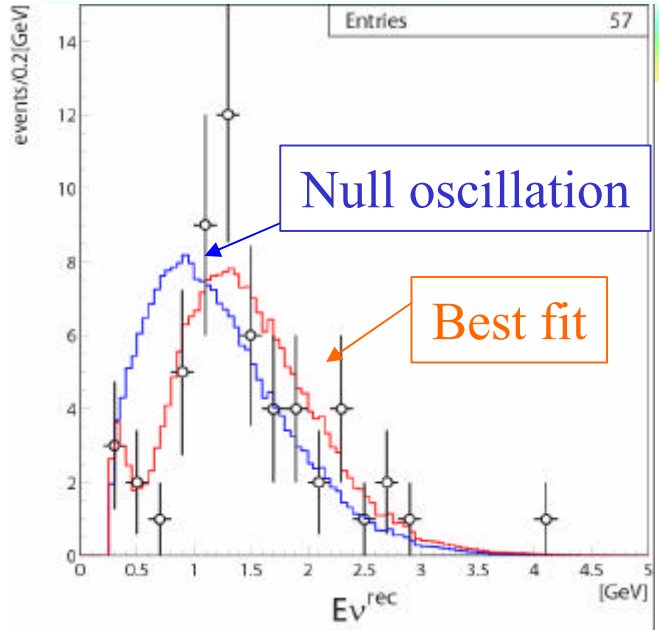
$$= L_{norm}(\Delta m^2, \sin 2q, f^x) \cdot L_{shape}(\Delta m^2, \sin 2q, f^x) \cdot L_{syst}(f^x)$$

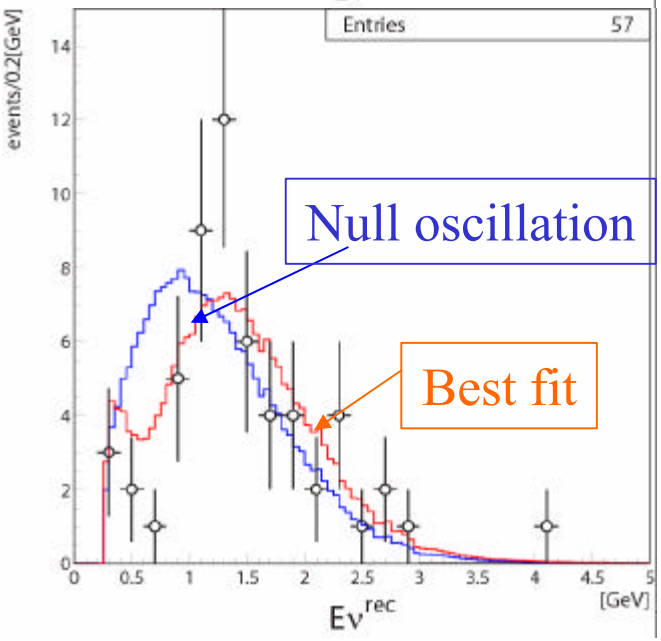
f^x : Systematic error parameters

Normalization, Flux, and nQE/QE ratio are in f^x

Near Detector measurements, Pion Monitor constraint, beam MC estimation, and Super-K systematic uncertainties.

Fit results of ν oscillation parameters



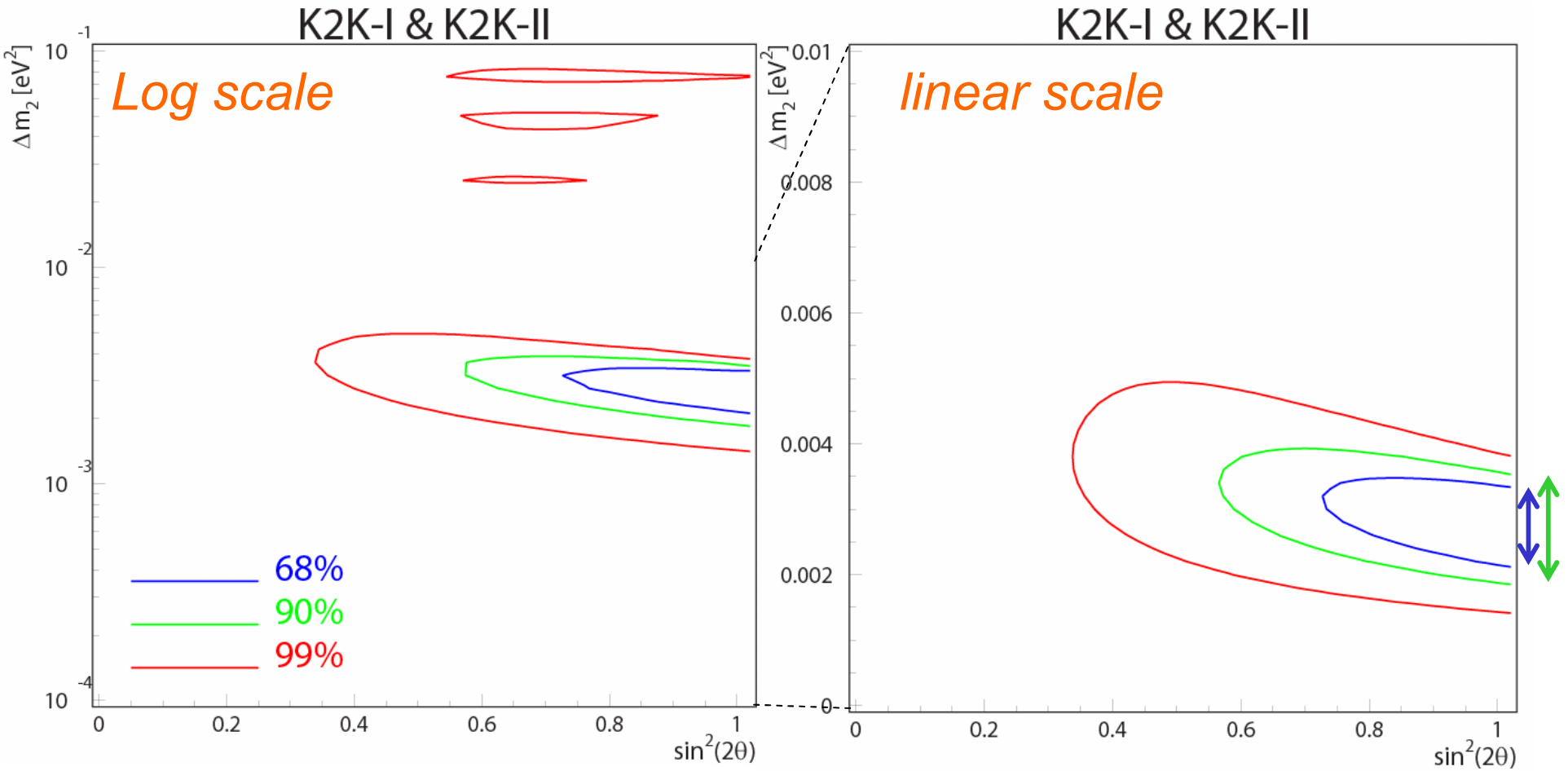


- Best fit in all parameter region
  - $\sin^2 2\theta = 1.51$
  - $\Delta m^2\,[eV^2] = 2.19 \times 10^{-3}$
- # of FC events
  - Nexp = 101.5 ←→ Nobs=107
- Goodness of fit (KS test)
  - KS prob.(Data & fit): 63%
  - KS prob.(Data & Null osci.): 0.08%

$\Delta \ln L = 0.75$ (within 1σ)

- Best fit in physical region
  - $\sin^2 2\theta = 1.00$
  - $\Delta m^2\,[eV^2] = 2.79 \times 10^{-3}$
- # of FC events
  - Nexp = 103.8 ←→ Nobs=107
- Goodness of fit
  - KS prob. (data & fit) : 36%

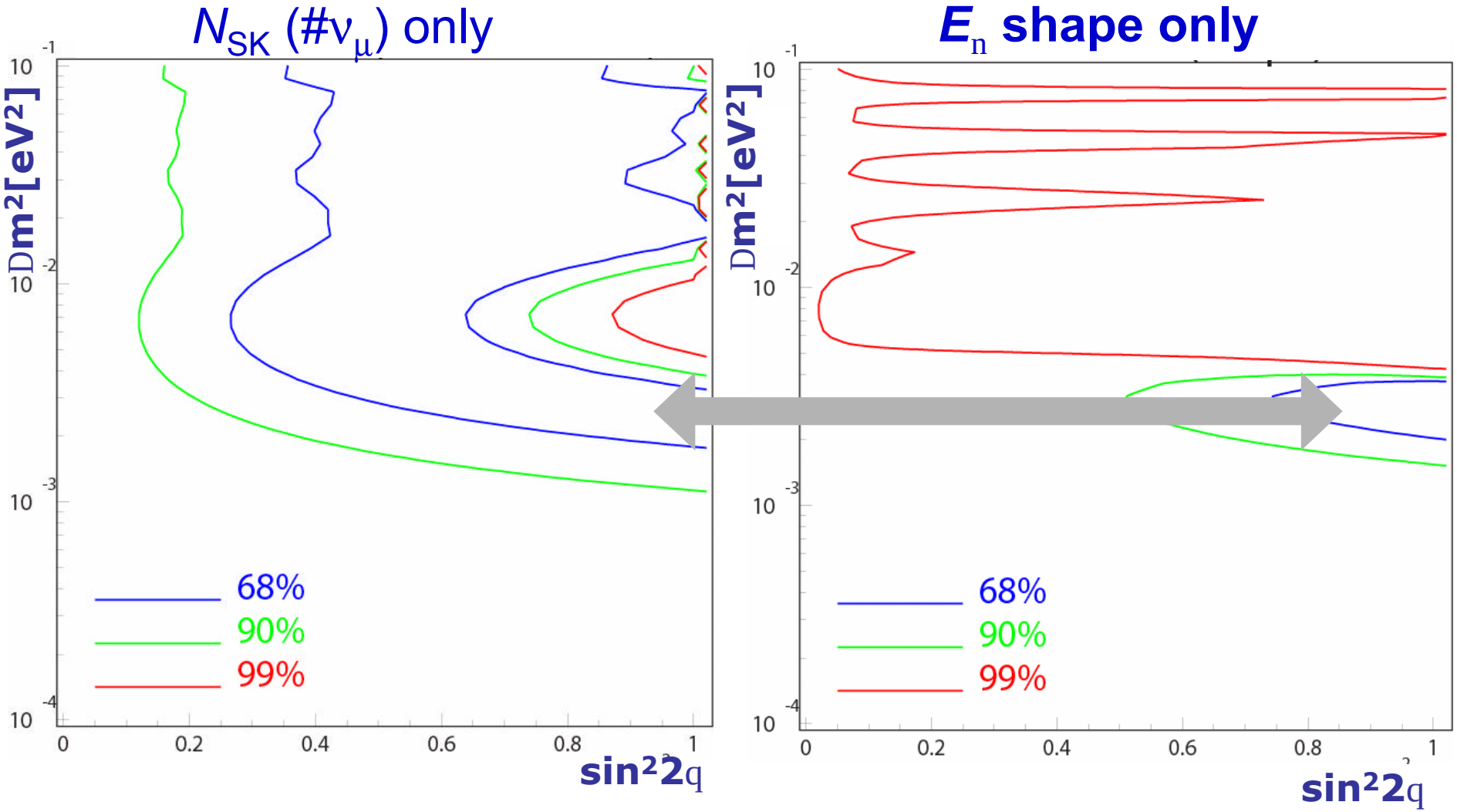
Allowed region (Contour of $\Delta \ln L$)



Δm^2 @ $\sin^2 2\theta = 1$: 68% … $2.14 \times 10^{-3} \leq \Delta m^2 \leq 3.37 \times 10^{-3}$ [eV^2]

90% … $1.87 \times 10^{-3} \leq \Delta m^2 \leq 3.58 \times 10^{-3}$ [eV^2]

Event Rate vs. Spectrum



Consistent answer.

Null Oscillation Probability

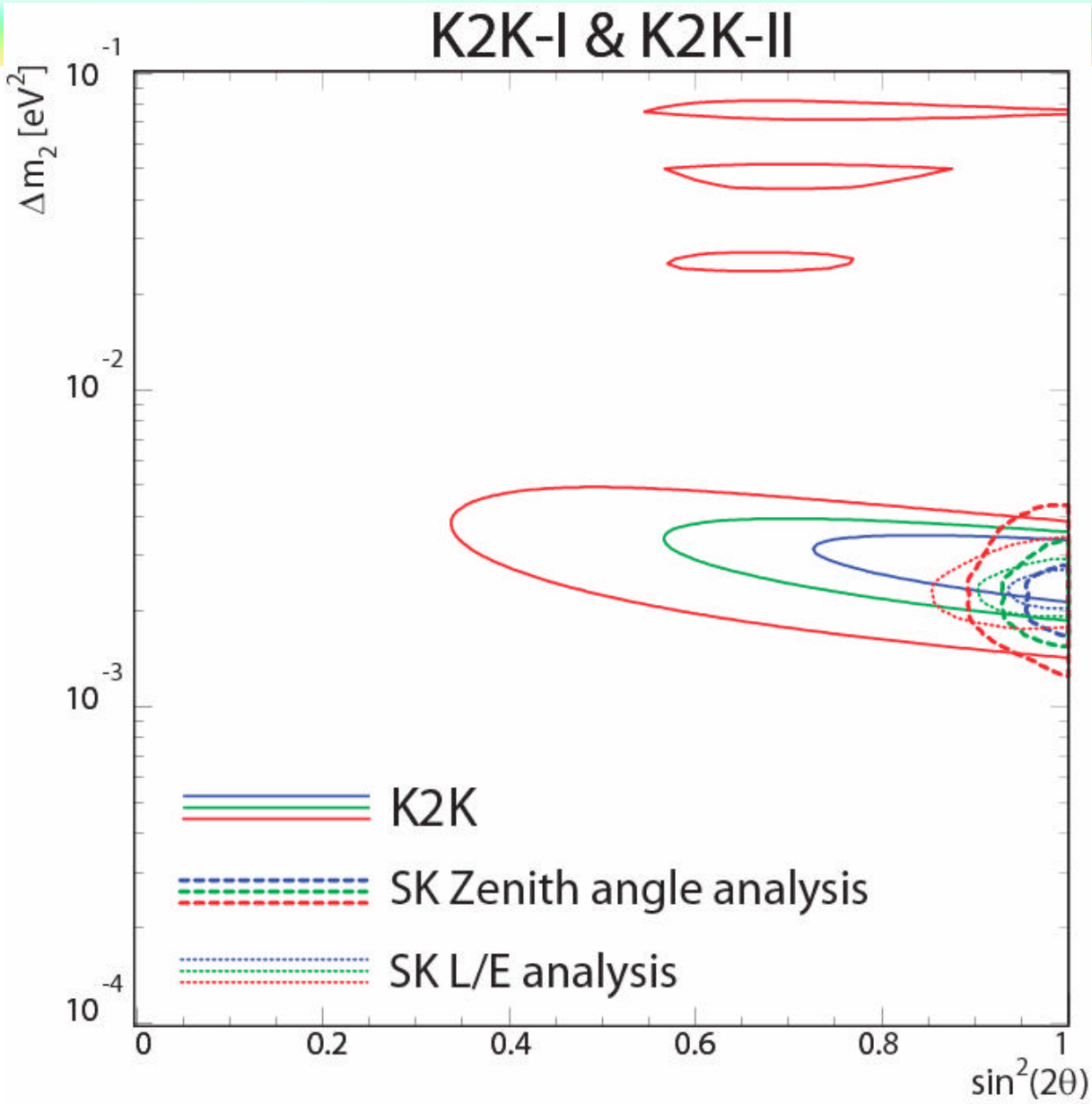
The null oscillation probabilities calculated based on $\Delta \ln L$.

	K2K-I	K2K-II	K2K-I+II
number of events	1.4%	3.7%	0.26%(3.0σ)
E_ν spectrum distortion	12.0%	5.8%	0.74% (2.6σ)
Combined	0.58% (2.7σ)	0.56% (2.7σ)	**0.005%** (4.0σ)

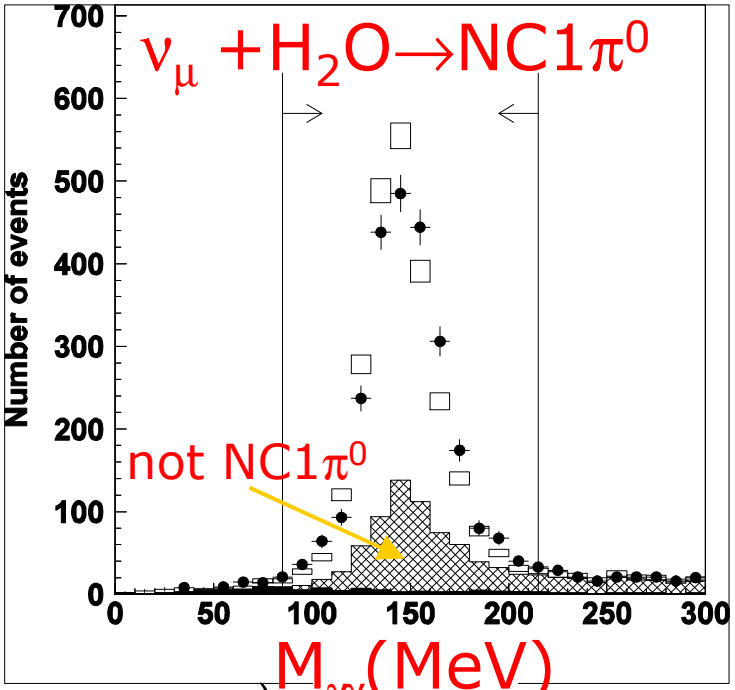
Disappearance of ν_μ and distortion of the energy spectrum as expected in neutrino oscillation.

K2K confirmed ***neutrino oscillation*** *discovered in Super-K atmospheric neutrinos.*

K2K & SK Atmospheric results



Other Physics in K2K **(based on K2K-I data)**



$$\frac{s\left(\nu_m \rightarrow NC1p^0\right)}{s\left(\nu_m \rightarrow CCall\right)}$$

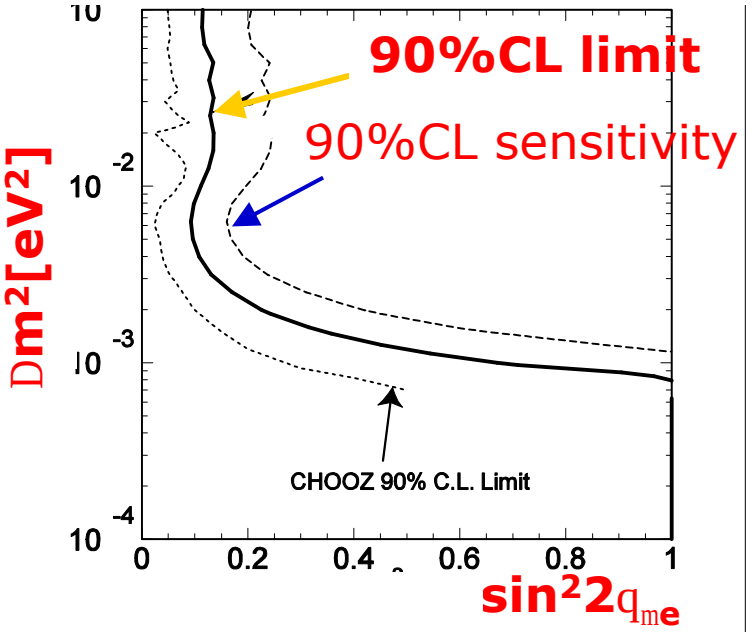
=0.064±0.001±0.007

=0.065 (prediction)

hep-ex/0408134

Submitted to PLB

$\nu_m \to \nu_e$ **search**



PRL 93, 051801 (2004)

Summary and Prospects

- K2K confirmed neutrino oscillation at 4.0σ with 8.9x10^{19}POT.
  - Both number of events and Eν spectrum distortion are consistent with neutrino oscillation
  - Allowed region for ν_μ dis-appearance is
    $1.9 \times 10^{-3} \leq \Delta m^2 \leq 3.6 \times 10^{-3}$ (90%C.L.) @ $\sin^2 2\theta = 1.0$
    ← Consistent with SK atm. results.
  - This result will be published soon.
    hep-ex/0411038 (Accepted by PRL)
- K2K physics run resumed in Oct. 2004, but …
  - The horn was broken in Nov. 2004.
    It is hard to recover because we can not access the horn area due to high radiation.
    → K2K physics run is finished.
- Next long-baseline ν experiment in Japan (T2K) will starts in 2009.
  - ´100 intense ν beam using 0.75MW 50GeV PS (JPARC).