Final Results of K2K

Takanobu Ishii (KEK)
for the K2K Collaboration

Honolulu Oct. 31,2006

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

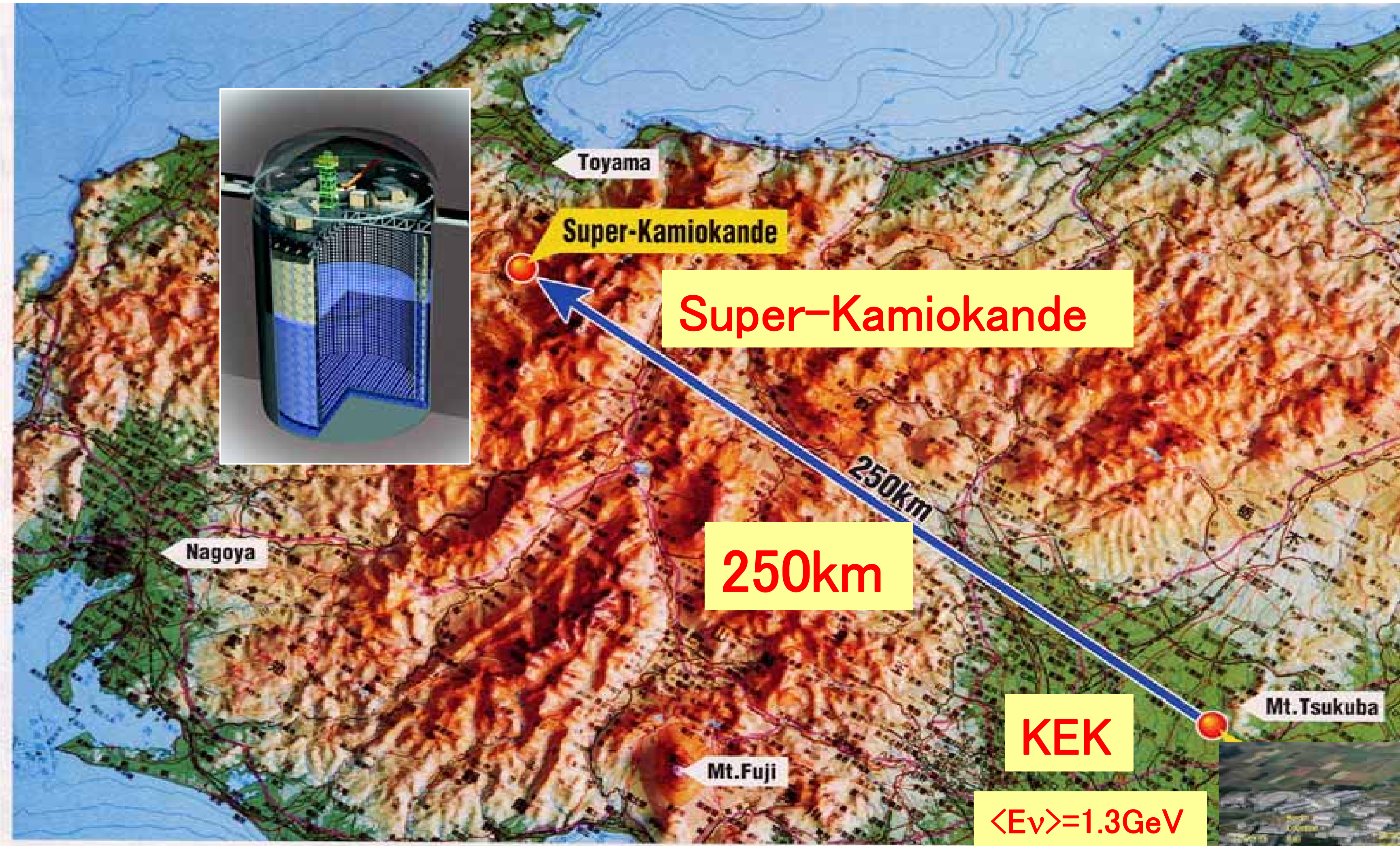
JAPAN: Hiroshima University / Osaka University U.S.A.: Duke University

CANADA: TRIUMF / University of British Columbia

ITALY: Rome FRANCE: Saclay SPAIN: Barcelona / Valencia SWITZERLAND: Geneva

RUSSIA: INR-Moscow

K2K experiment



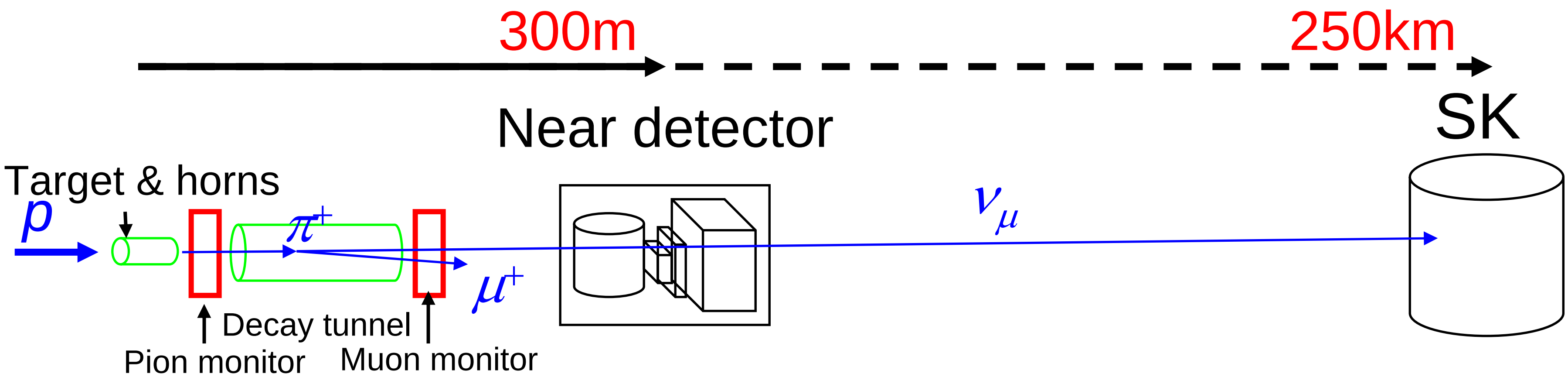
Study the atmospheric neutrino anomaly

Key Issues of K2K

K2K is the first long-baseline neutrino experiment

- Precise neutrino beam aiming
- Beam control and monitoring at the near site
- Extrapolation from the near to the far site
- Gigantic far detector (SK)
- Timing synchronization between near and far

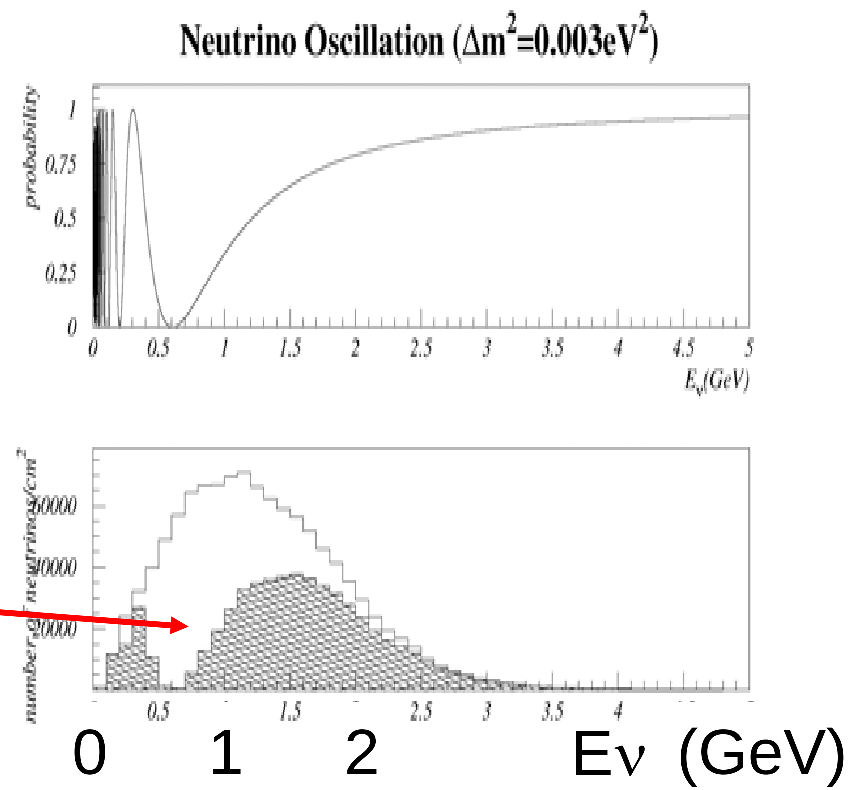
Overview of the K2K experiment



$$prob. = \sin^2 2\theta \cdot \sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

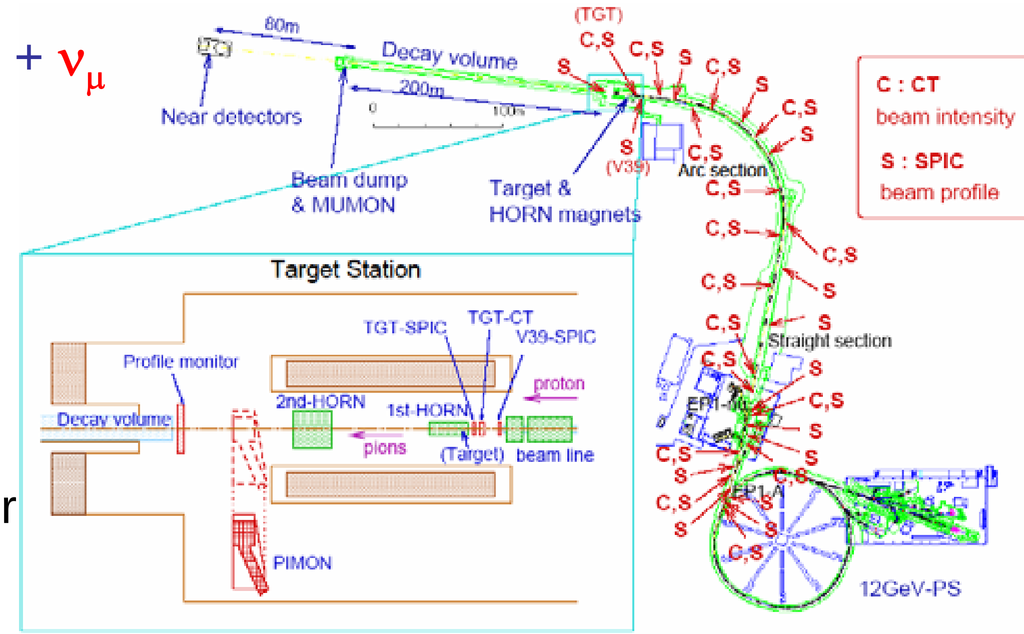
L =250km : fixed

⇨ reduction of events
spectrum distortion



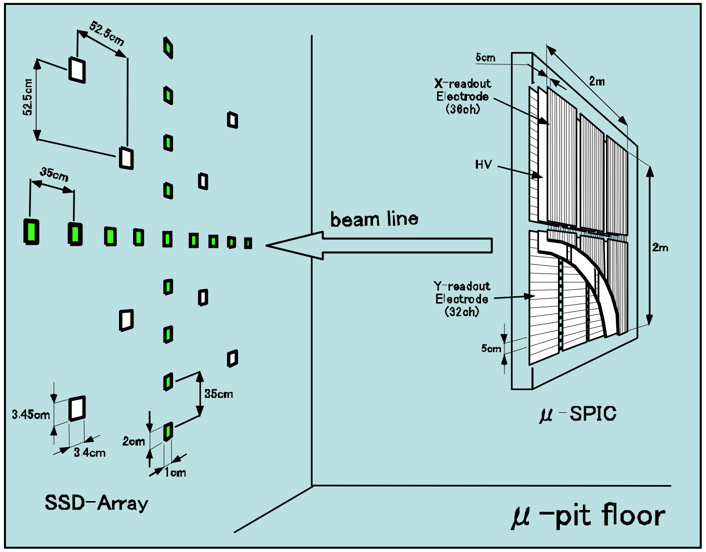
Beam Line and Beam Monitors

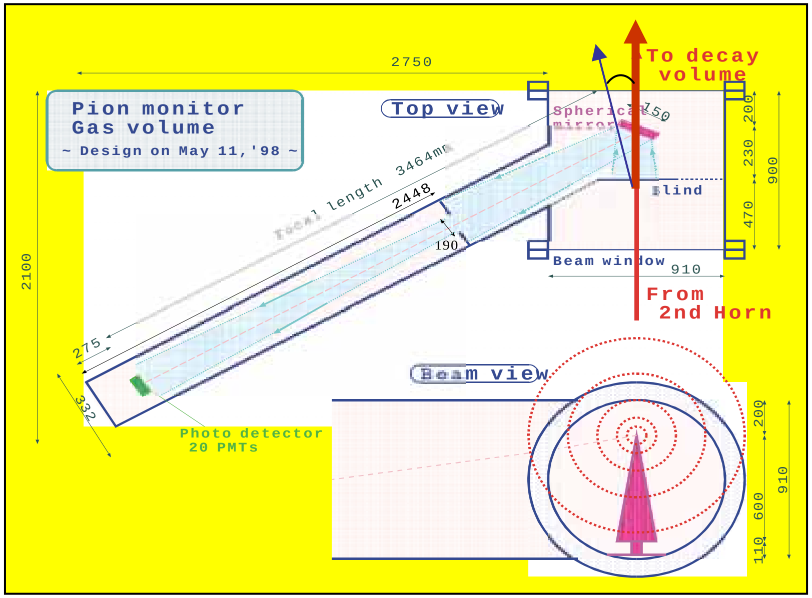
$p + \mathrm{Al} \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu$



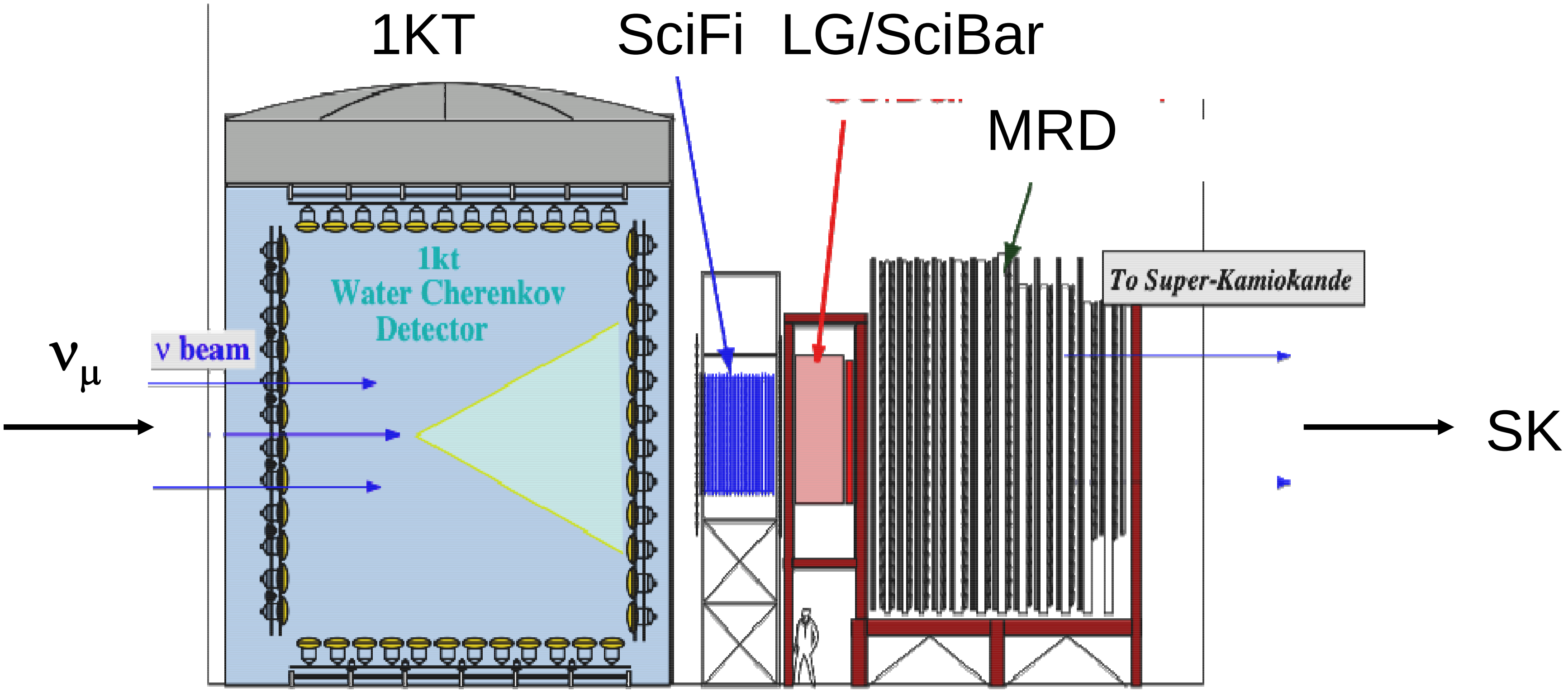
Muon Monitor
Segmented ionization chamber and Silicon-pad detector array

Pion Monitor
Gas Cherenkov detector with a spherical mirror and a PMT array



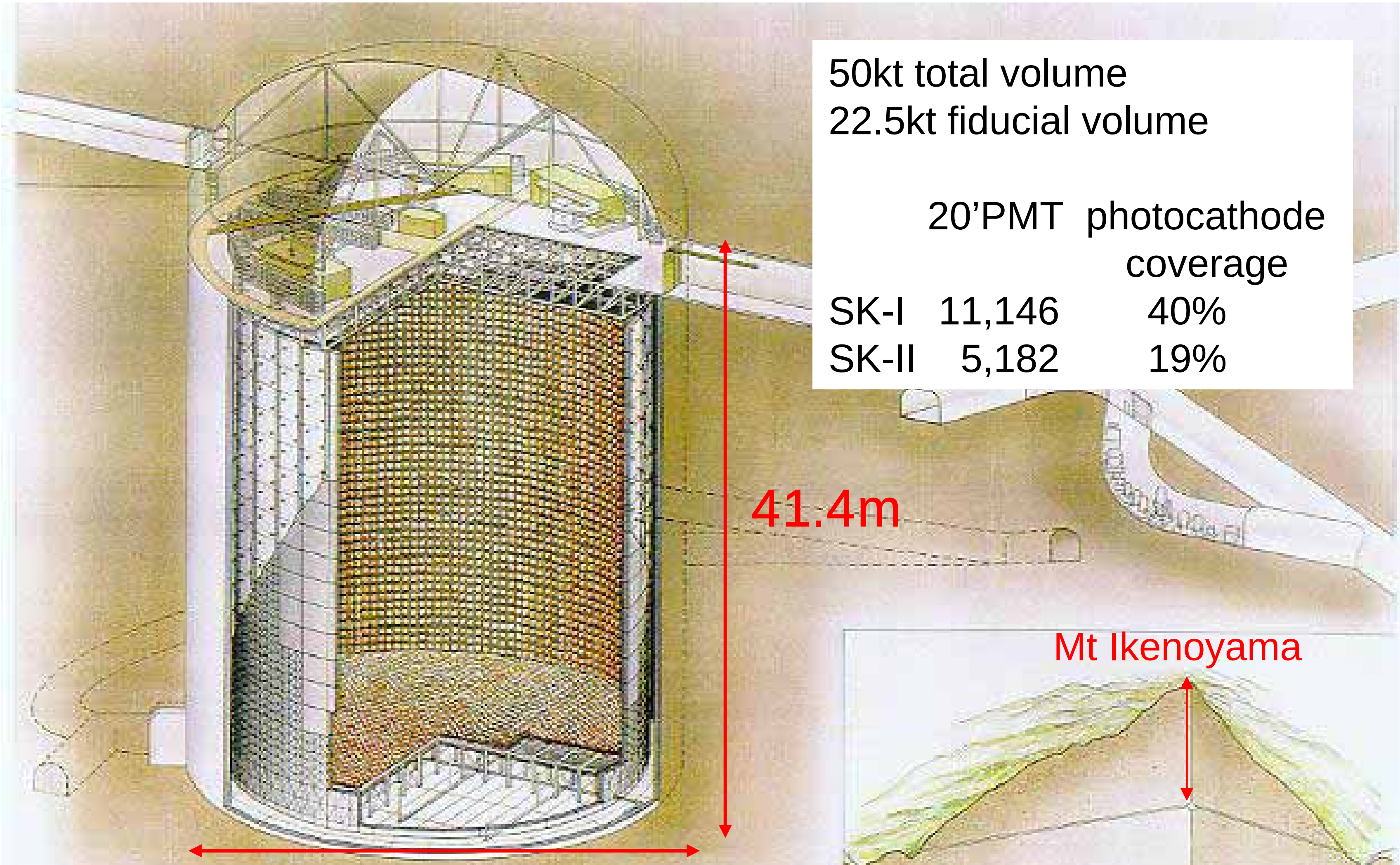


Near Detectors



- 1KT: water cherenkov detector
- SciFi: scintillating fiber and water target
- LG: Lead glass calorimeter (removed in 2002)
- SciBar: fully-active scintillator detector (installed in 2003)
- MRD: Iron absorbers and drift tubes

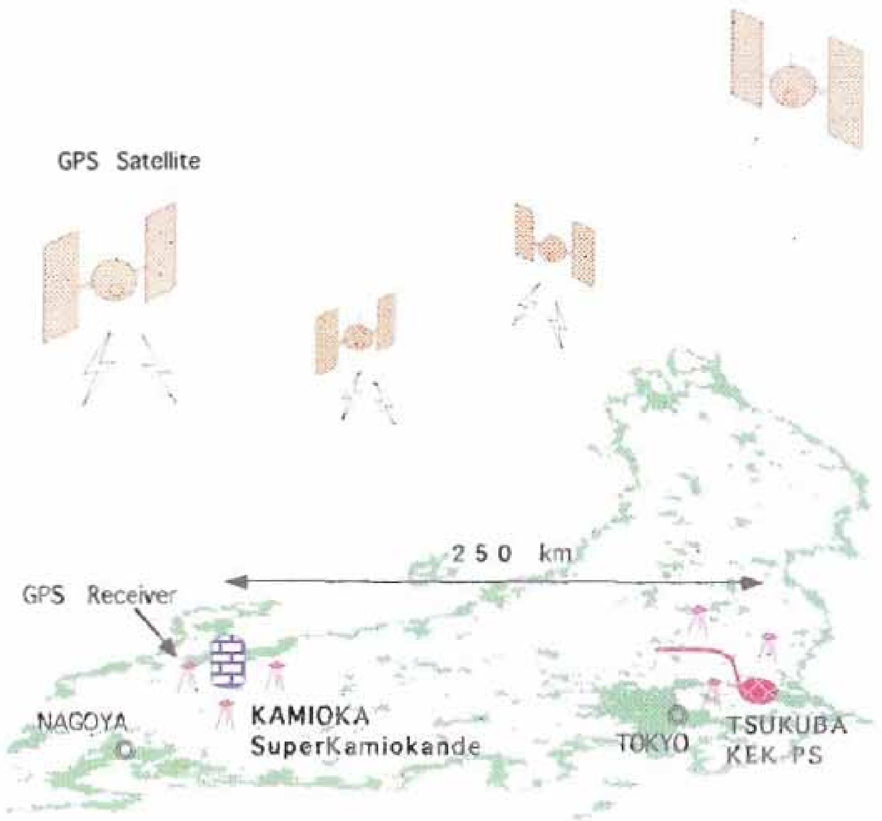
Super-Kamiokande (Far detector of K2K)



50kt total volume
22.5kt fiducial volume

	20'PMT	photocathode coverage
SK-I	11,146	40%
SK-II	5,182	19%

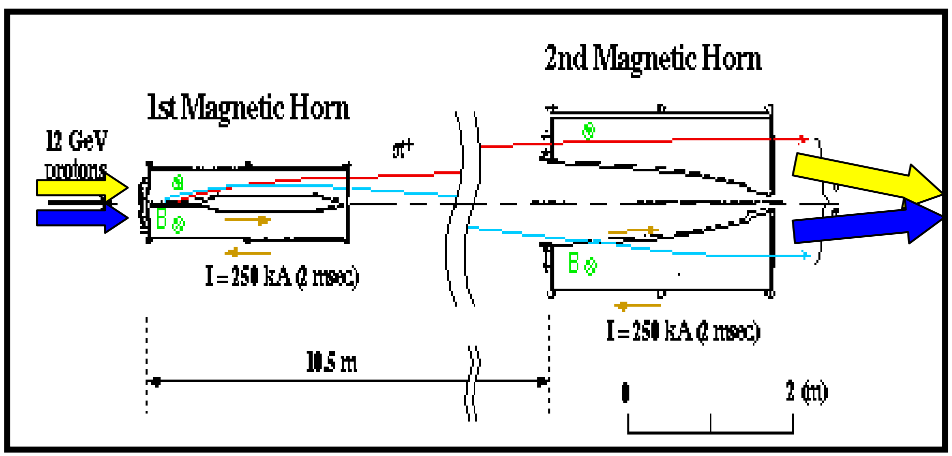
Beam Aiming



- **Beam line was aligned by a long-baseline GPS survey between KEK and Kamioka. (precision 0.01mrad)**
- **Construction precision at the near site is better than 0.1mrad.**
- **Beam direction is monitored by MUMON and controlled.**
- **Delivered neutrino beam direction is monitored and confirmed by MRD to be within 1mrad.**

Direction monitor by MUMON

At the start of every beam period, beam direction is controlled by tuning the beam-line magnets while looking at the muon-profile center by MUMON.

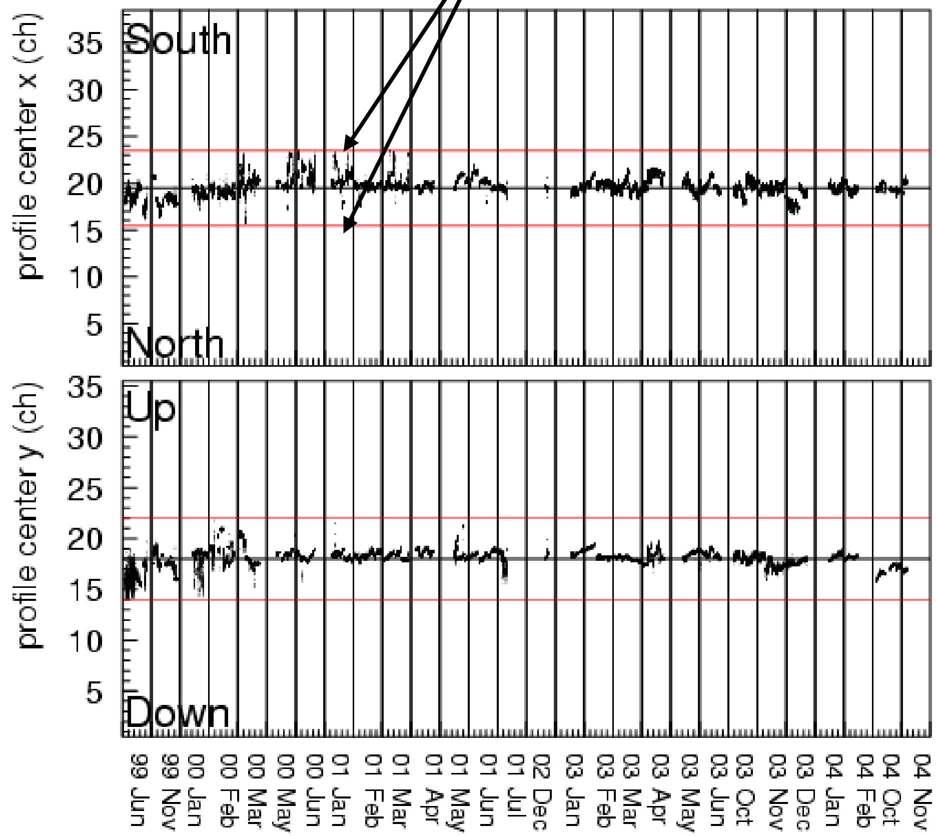


1mm shift of protons at the target causes about -0.5mrad deflection for muons

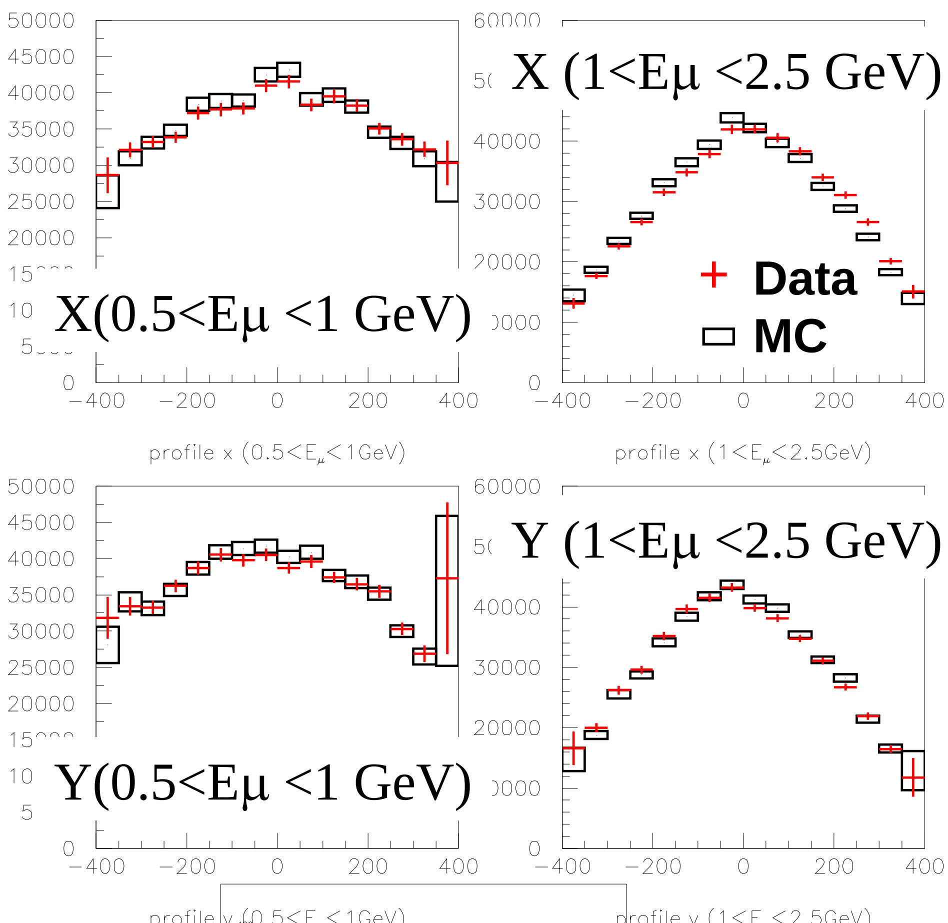
Throughout the whole experimental period, muon direction is monitored.

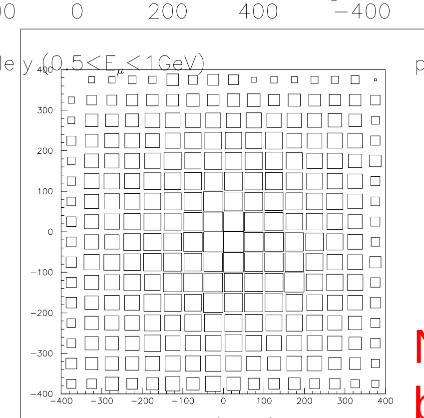
- **spill by spill.**
- **E_μ > 5 GeV**

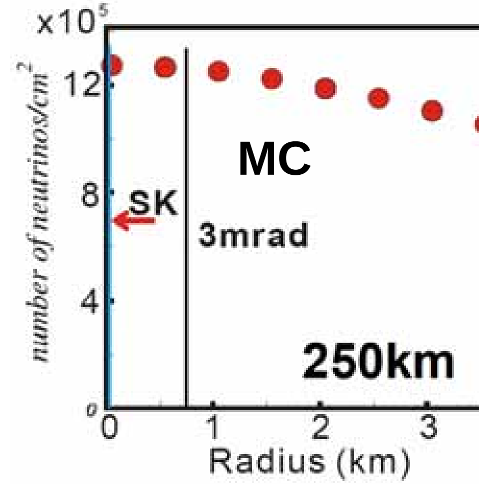
±1 mrad.

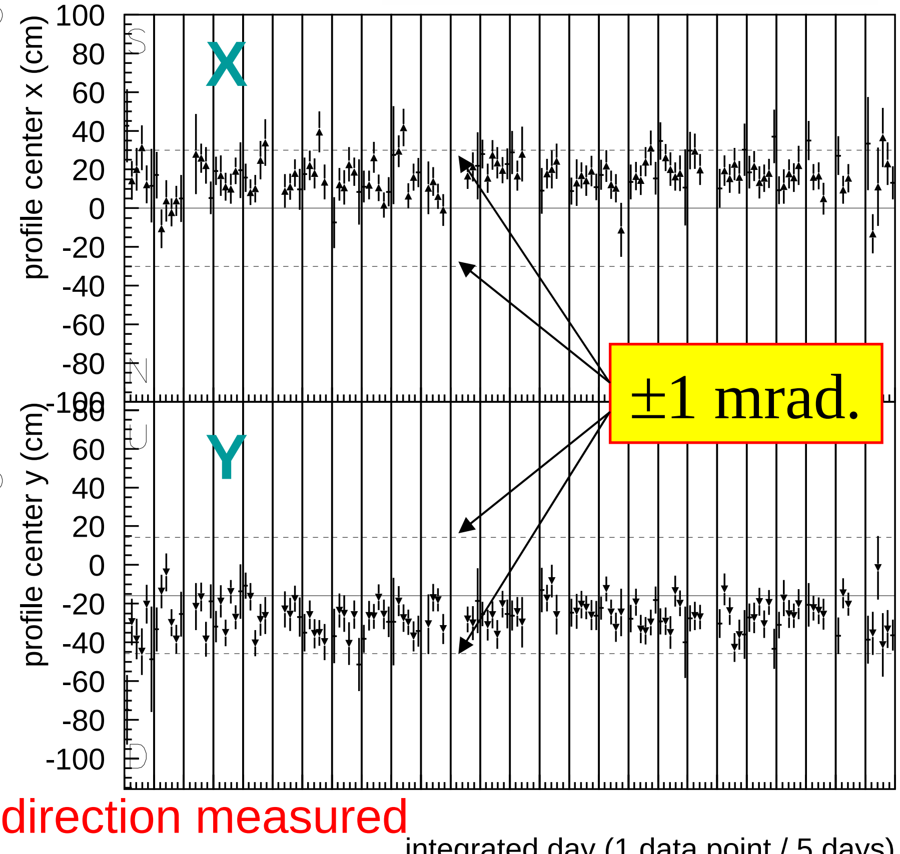


ν Profile and Direction Monitor by MRD





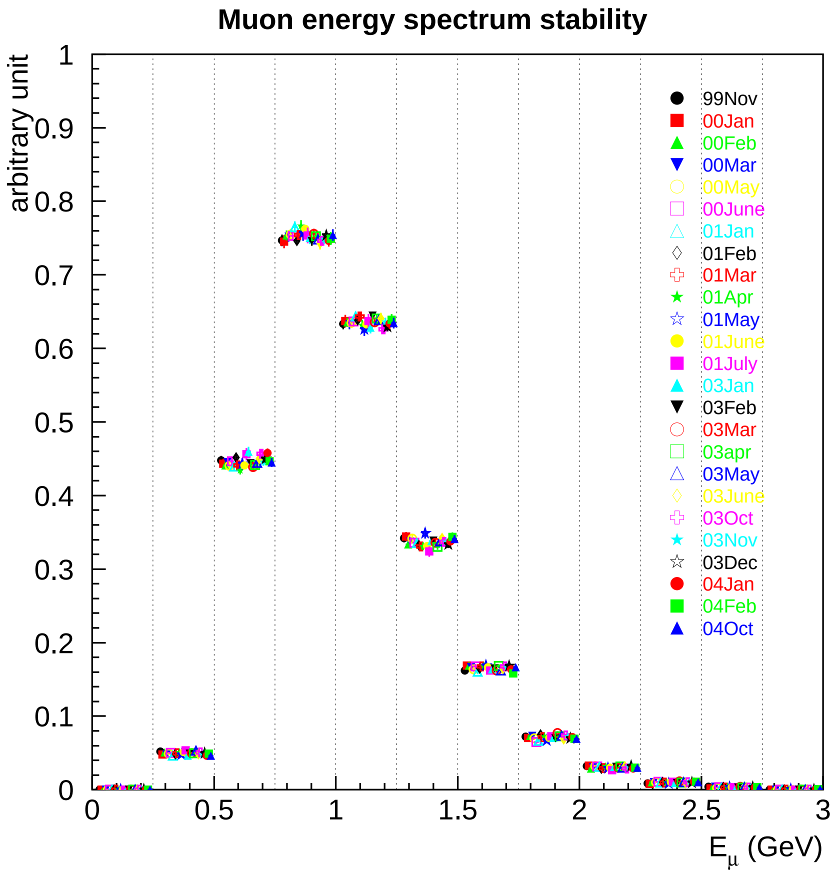




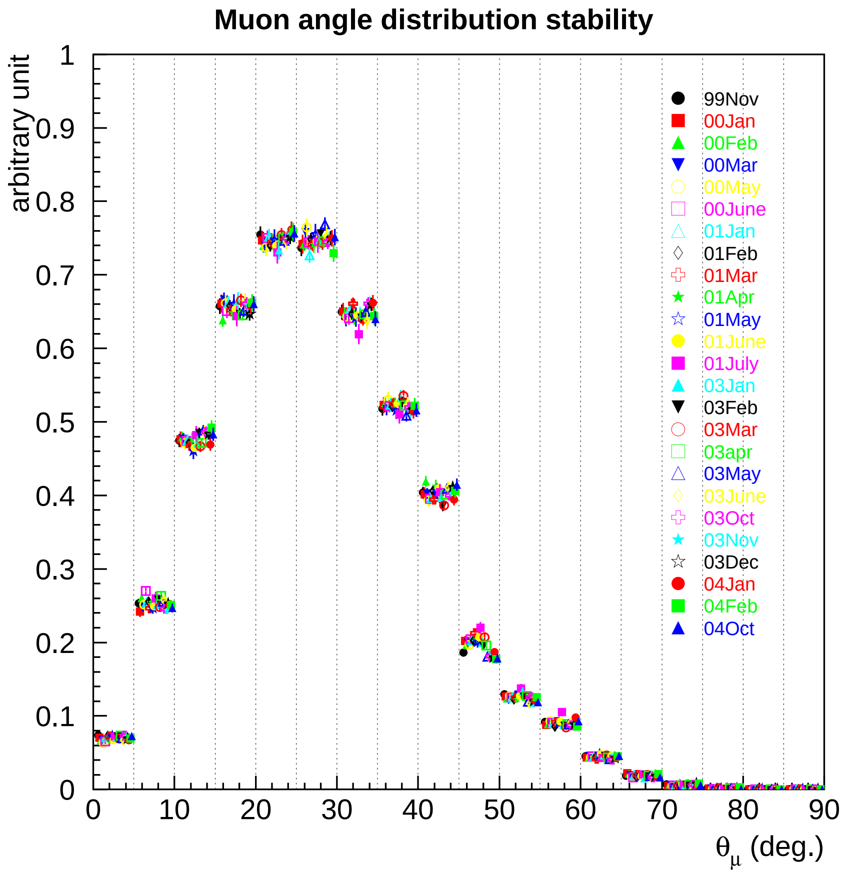
Neutrino beam direction measured by MRD is stable within ±1 mrad.

ν spectrum stability confirmed by MRD

Eμ (MRD)



θμ (MRD)

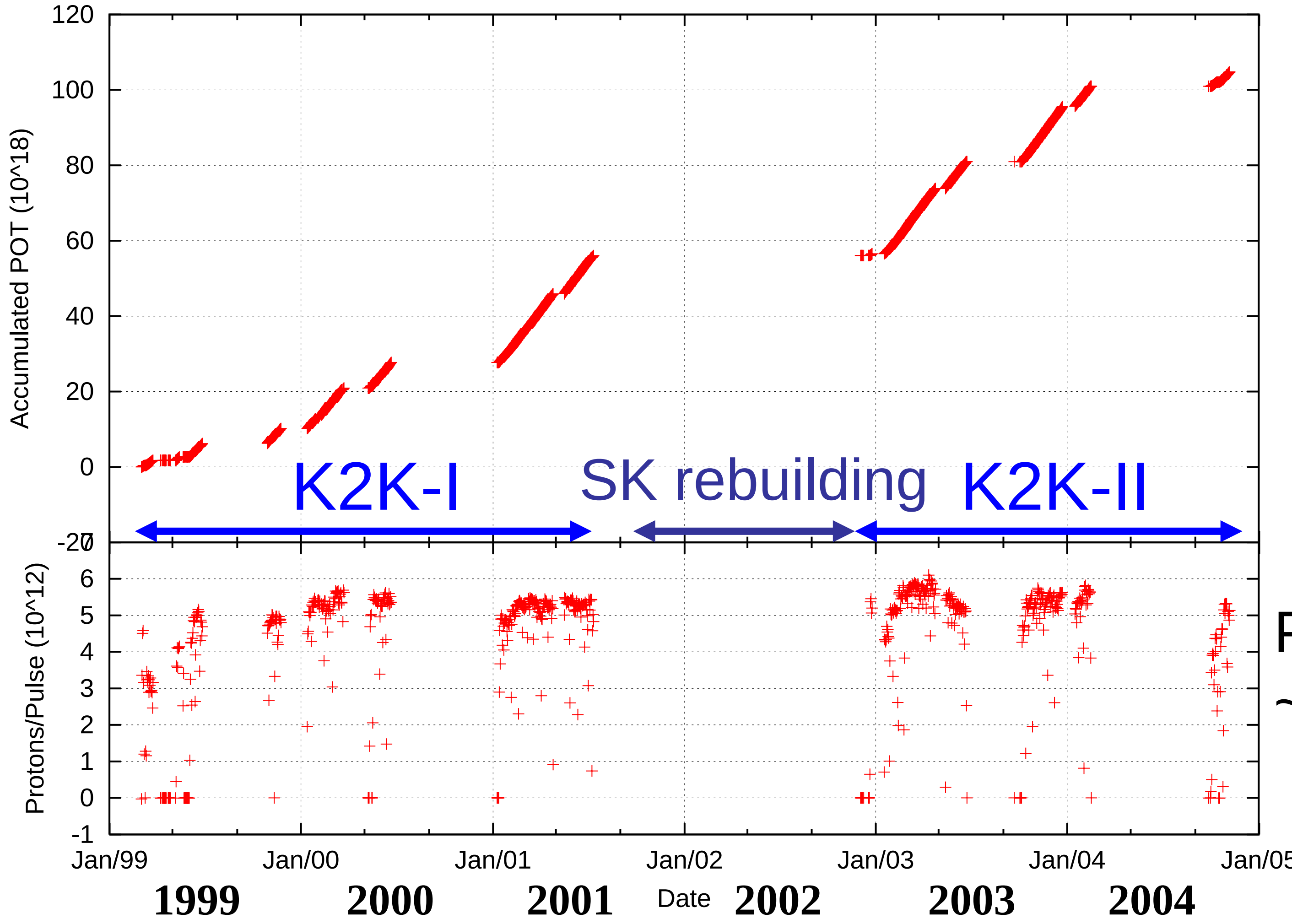


Muon energy and angle distribution measured by MRD is stable.

This confirms the ν spectrum stability.

Delivered Protons On Target

Jun. 1999 – Nov. 2004



POT/spill ~5.4×10^{12} protons

POT for analysis : 9.22×10^{19}POT

ND Measurements

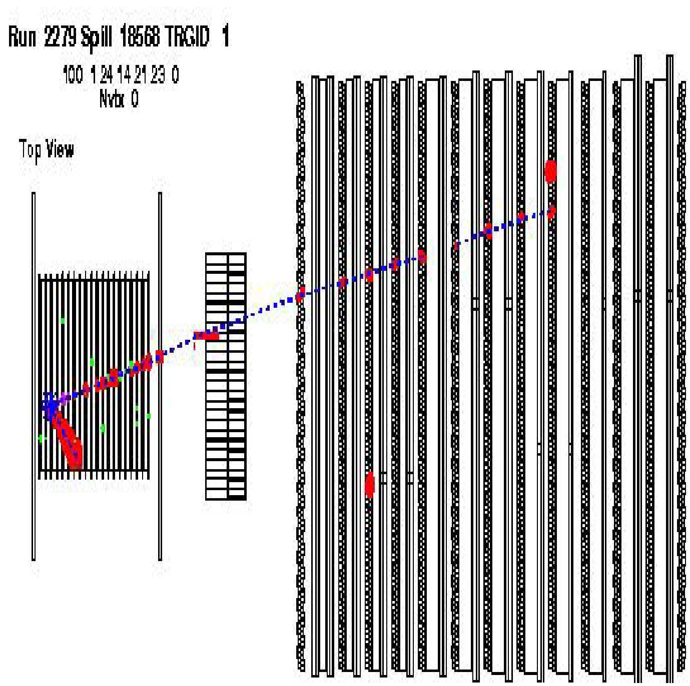
ND neutrino measurement

- Flux measurement
  - 1KT (same target and detection technique as SK)

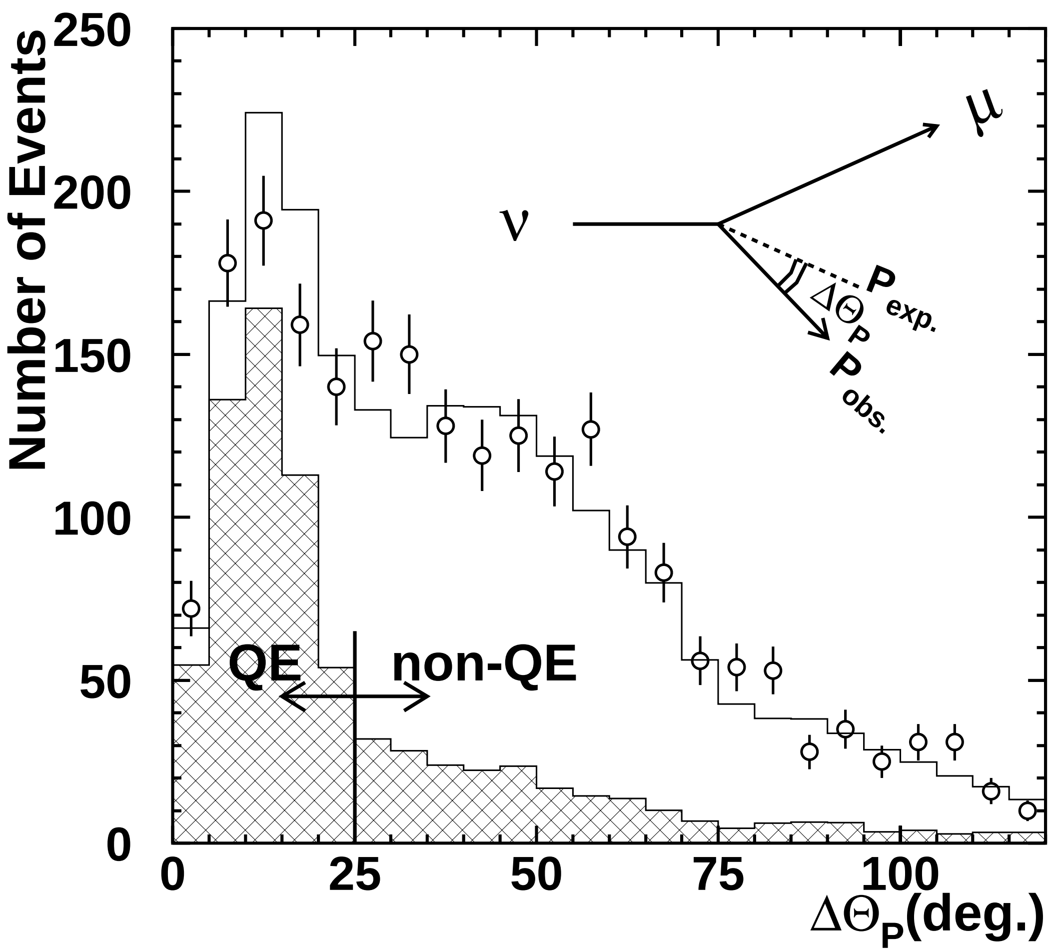
$$N_{SK}^{\exp} = N_{1KT}^{obs} \bullet \frac{\int \Phi_{SK}(E_\nu)\sigma(E_\nu)\varepsilon_{SK}(E_\nu)dE_\nu}{\int \Phi_{1KT}(E_\nu)\sigma(E_\nu)\varepsilon_{1KT}(E_\nu)dE_\nu} \bullet \frac{M_{SK}}{M_{1KT}}$$

- Spectrum measurement
  - 1KT (high efficiency at low Eν)
    - Fully contained 1-ring μ-like sample (QE enriched)
  - SciFi+MRD (high efficiency at high Eν)
    - 1track, 2track QE and 2track nonQE samples
  - SciBar+MRD (high efficiency at high Eν)
    - 1track, 2track QE and 2-track nonQE samples

QE and nQE separation in SciFi

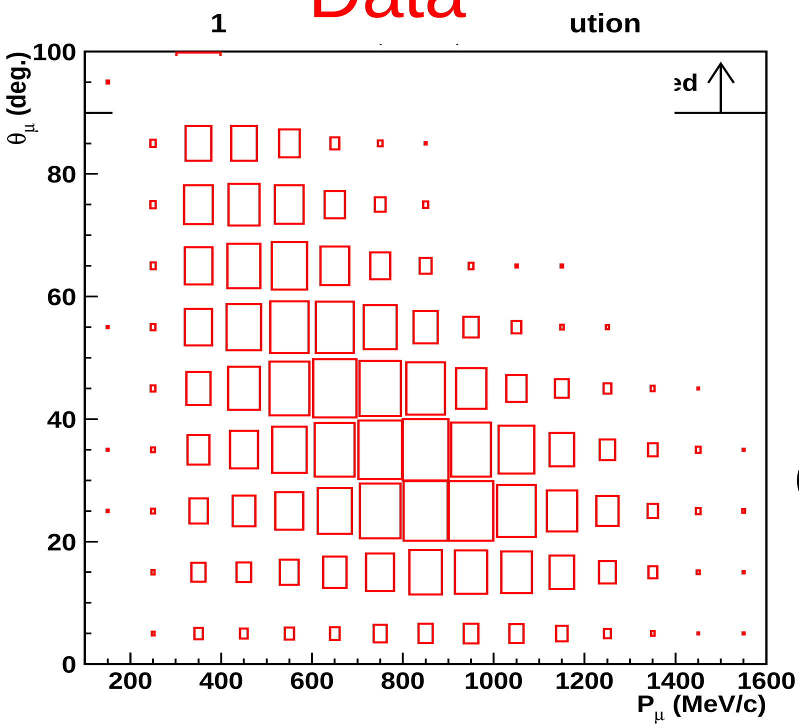


SciFi 2-track $\Delta\theta_p$ distribution



Neutrino spectrum fit at ND

Data



θ_μ (deg.)

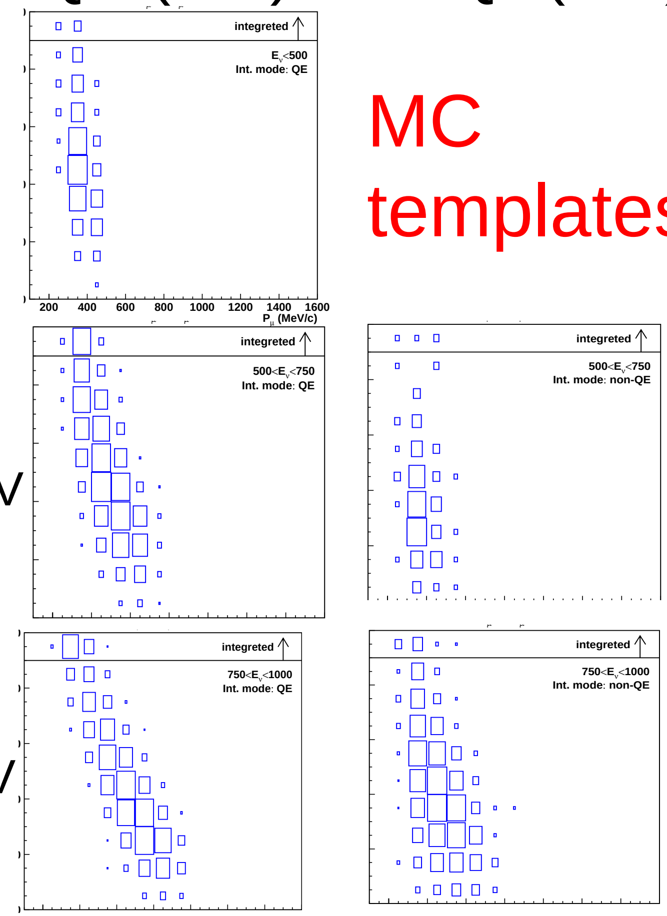
p_μ (MeV/c)

E_ν QE (MC) nonQE(MC)

0-0.5 GeV

0.5-0.75GeV

0.75-1.0GeV



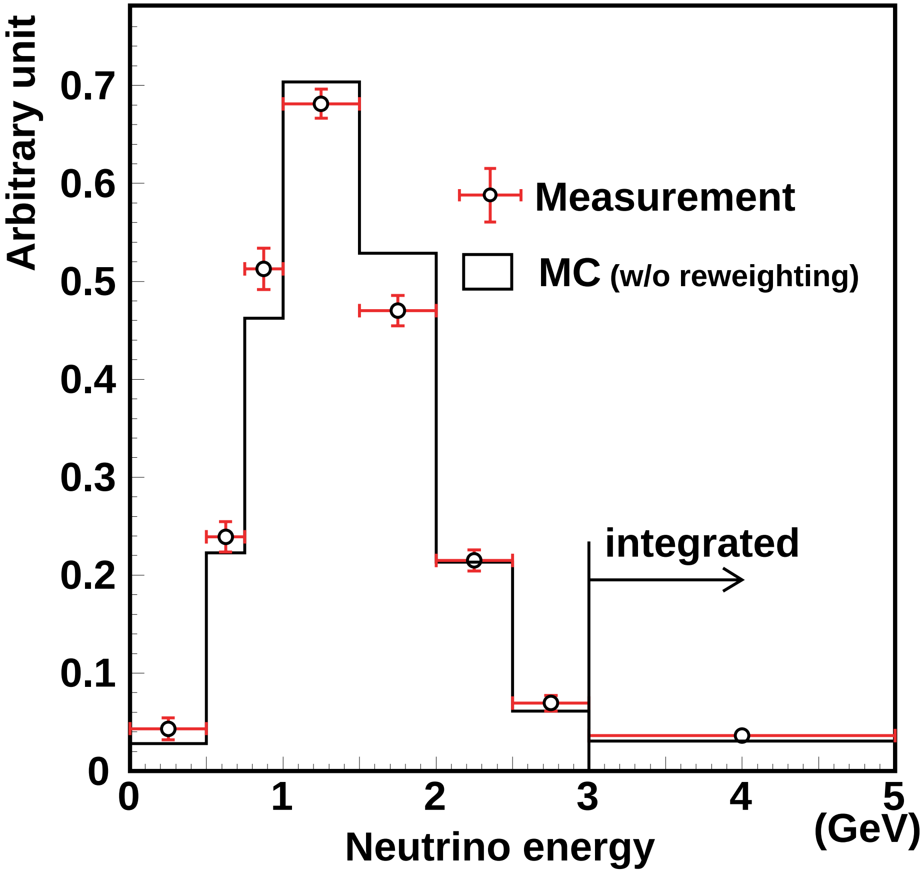
MC templates

($p\mu$, $\theta\mu$) for 1-ring μ-like sample (1KT), 1track, 2track QE and 2track nonQE sample (SciFi, SciBar)

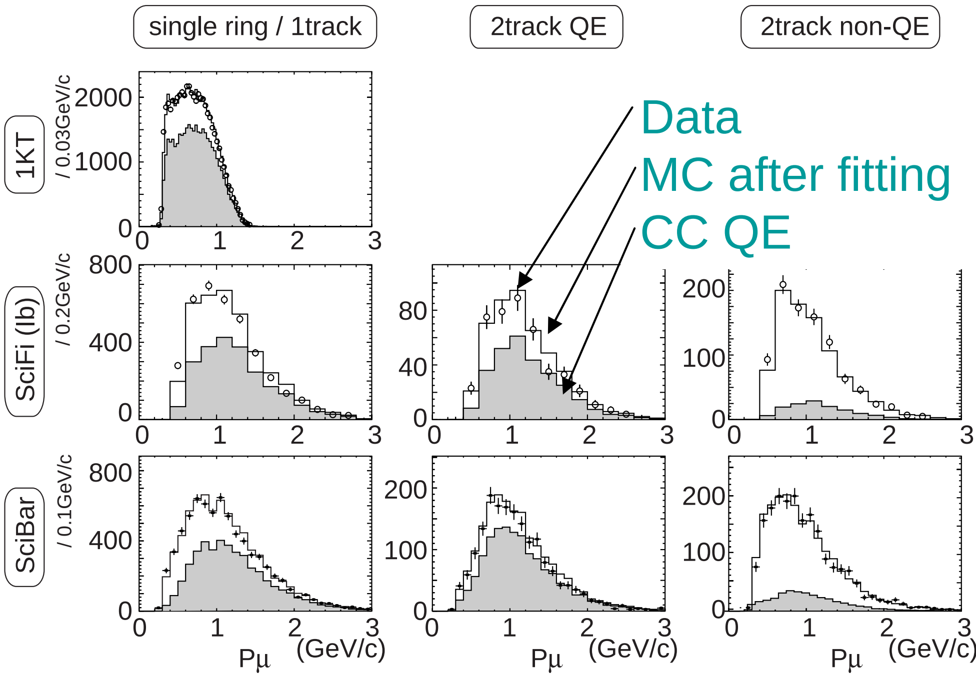
➡ $\Phi(E\nu)$, nonQE/QE ratio

Neutrino spectrum fit results at ND

Fit result of neutrino spectrum



Pμ distribution for each event sample after fit



MC reproduce all data well.

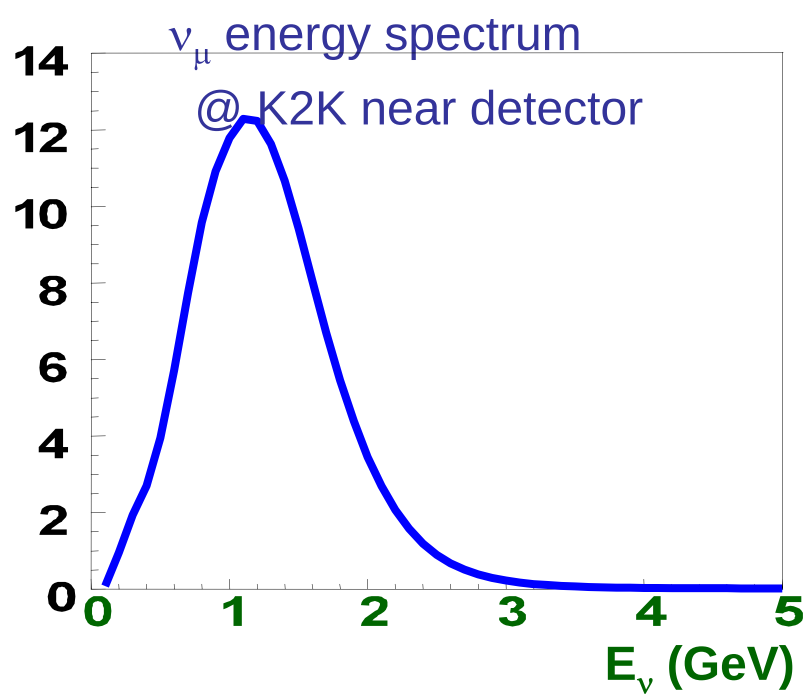
Far/Near Ratio

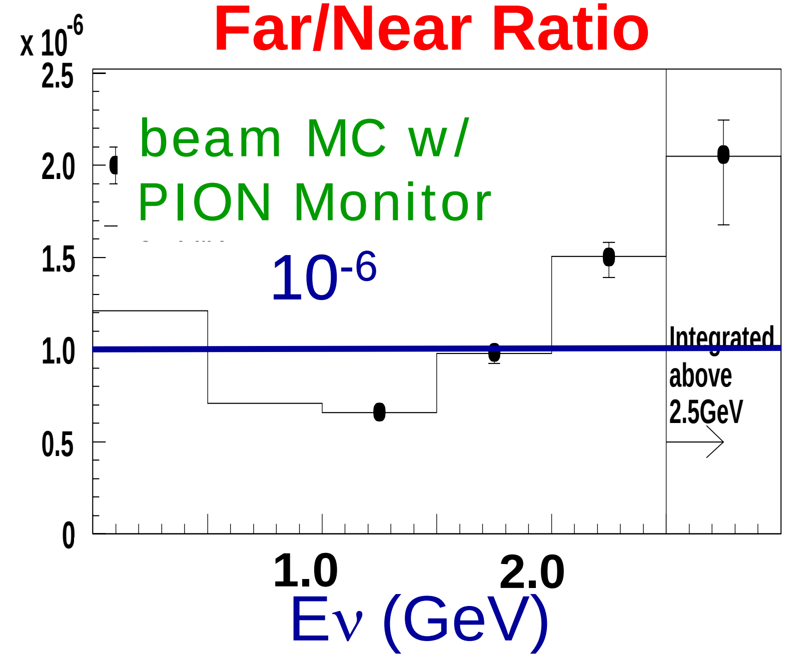
Neutrino spectrum and the far/near ratio

F/N ratio is not simply $1/r^2$, but depends on $E\nu$

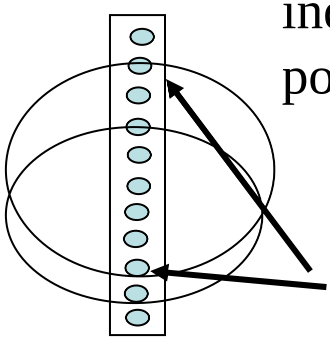
Angular acceptance

Finite decay volume length for near





PIMON Measurement of (P_π, θ_π)

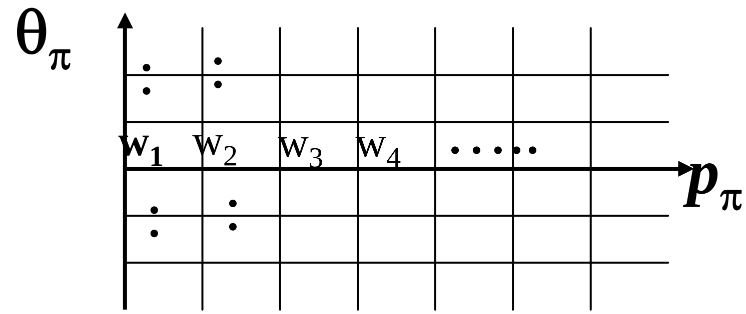


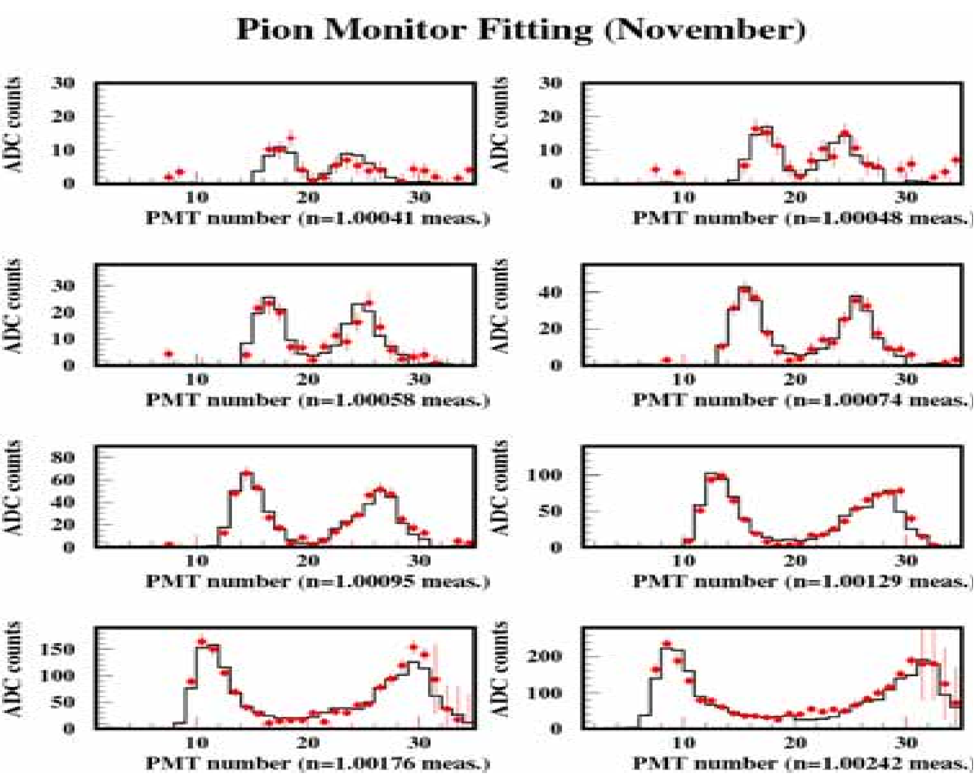
index of refraction : p_π threshold

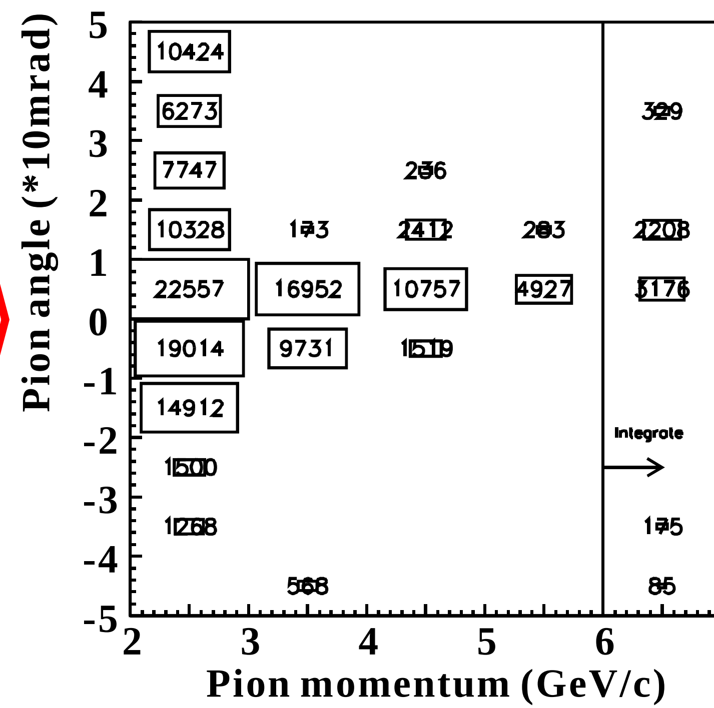
position of ring : θ_π

p_π, θ_π gives two C-light peaks

fit with Σ (w_i • C-light)

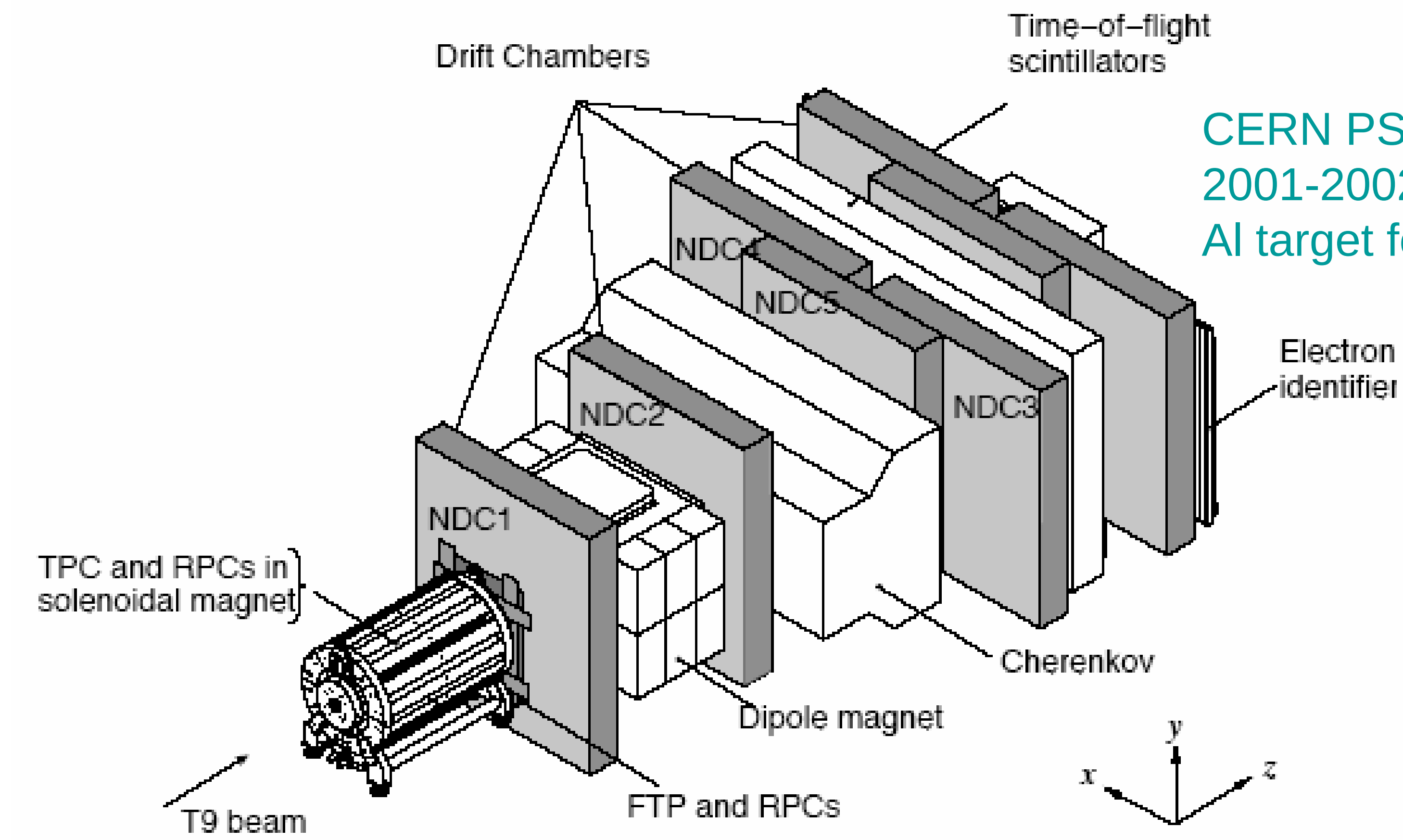






P_π>2GeV/c (E_ν>1GeV)

HARP experiment @ CERN

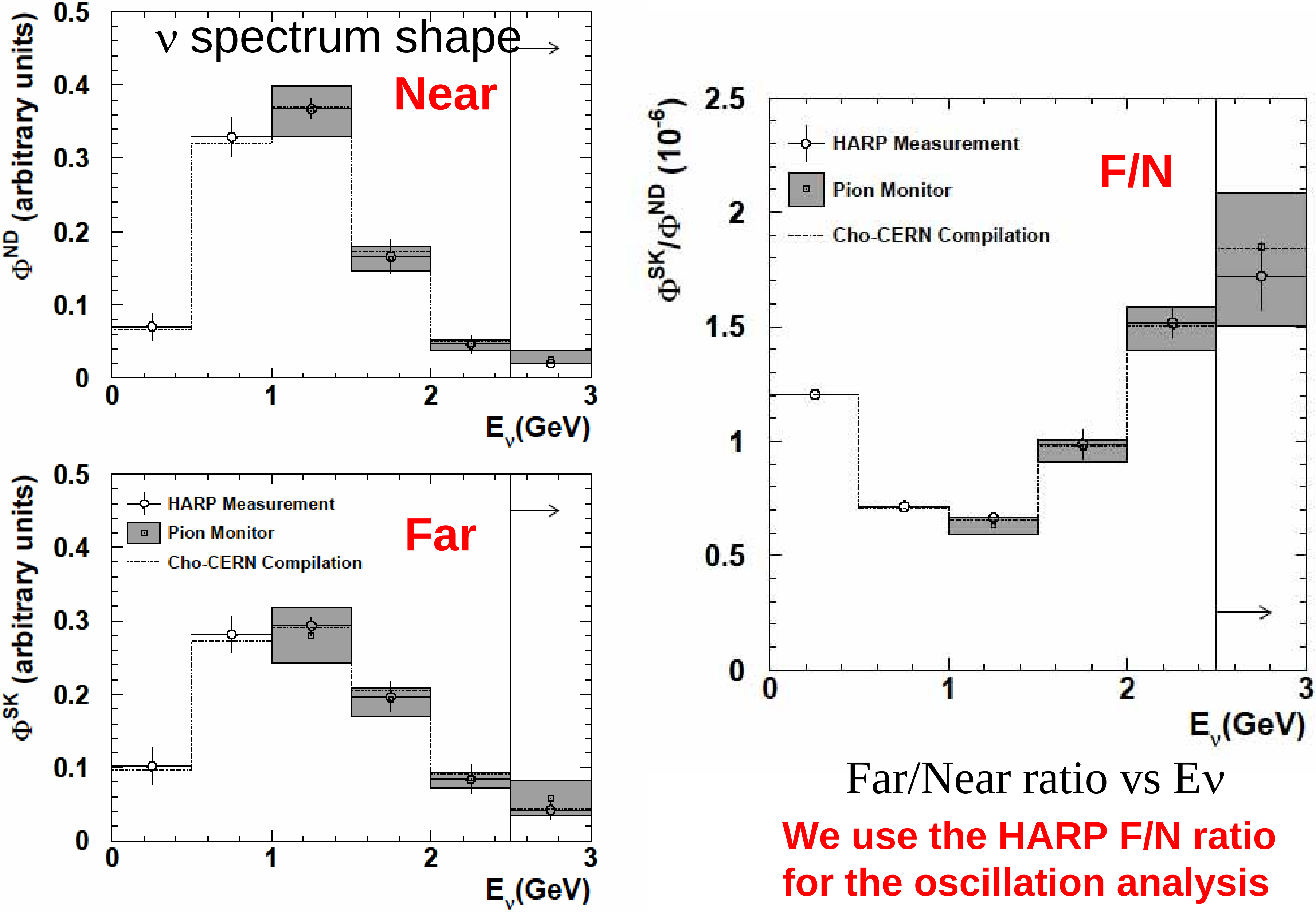


CERN PS T9 beam line
2001-2002
Al target for K2K

HARP pion production measurement
Same beam energy (12.9GeV/c) and same target (Al) as K2K

⇨ Reduce systematic uncertainty in Far/Near flux ratio.

HARP, Pion monitor and MC comparison



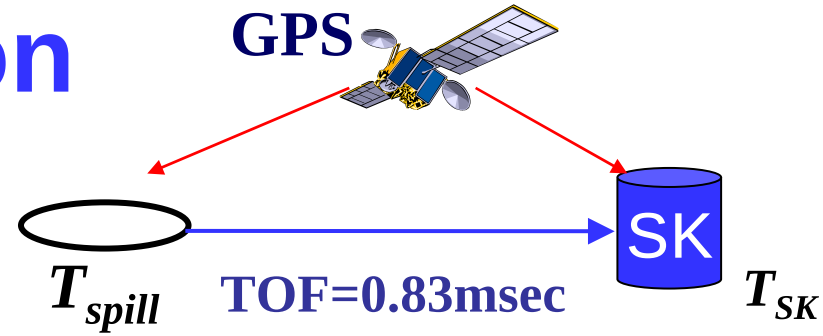
Far/Near ratio vs Eν

We use the HARP F/N ratio for the oscillation analysis

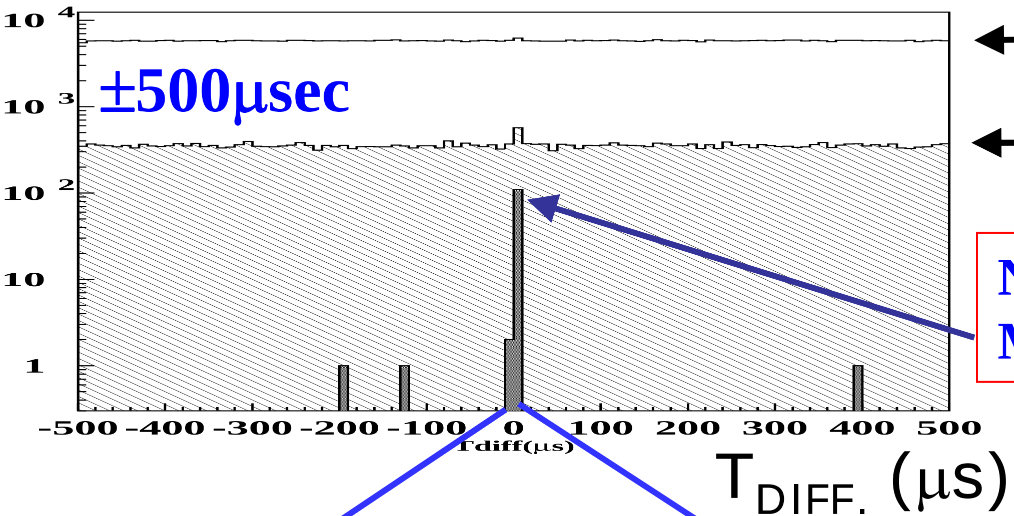
Measurement at the Far site

SK events selection

Atm-ν selection + Tdiff cut



Timing distribution using GPS

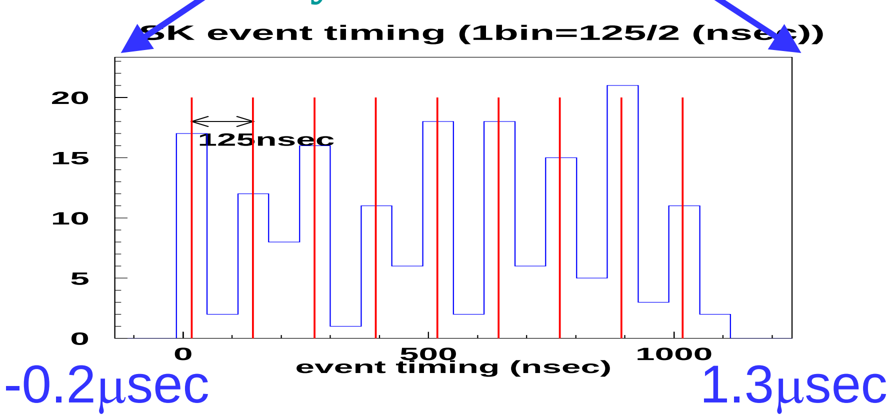


Decay electron cut.

≥20MeV Deposited Energy

No Activity in Outer Detector
More than 30MeV Deposited Energy

Analysis Time Window



112 events

$-0.2 < T_{SK} - T_{spill} - \mathrm{TOF} < 1.3\mu\mathrm{sec}$

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

Essentially BG free after Tdiff cut

SK event summary

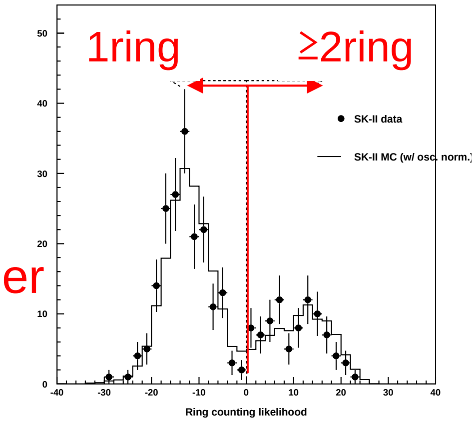
	K2K-I	K2K-II	K2K-I+II
FC	55	57	112
1ring	33	34	67
1ring μ	30	28	58
1ring e	3	6	9
multi ring	22	23	45

Number (FC: 112)

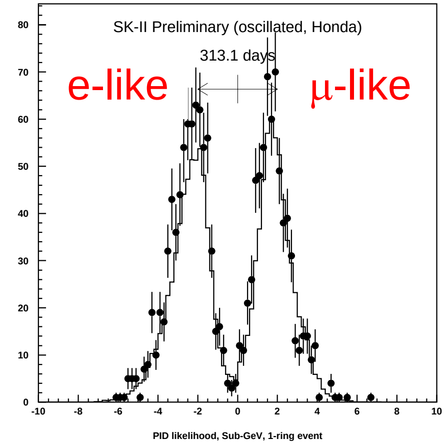
Spectrum (1ring μ: 58)

K2K-I(47.9×10^{18}POT), K2K-II(44.3×10^{18}POT)

ring counting likelihood dist. for SK-II atmospheric ν



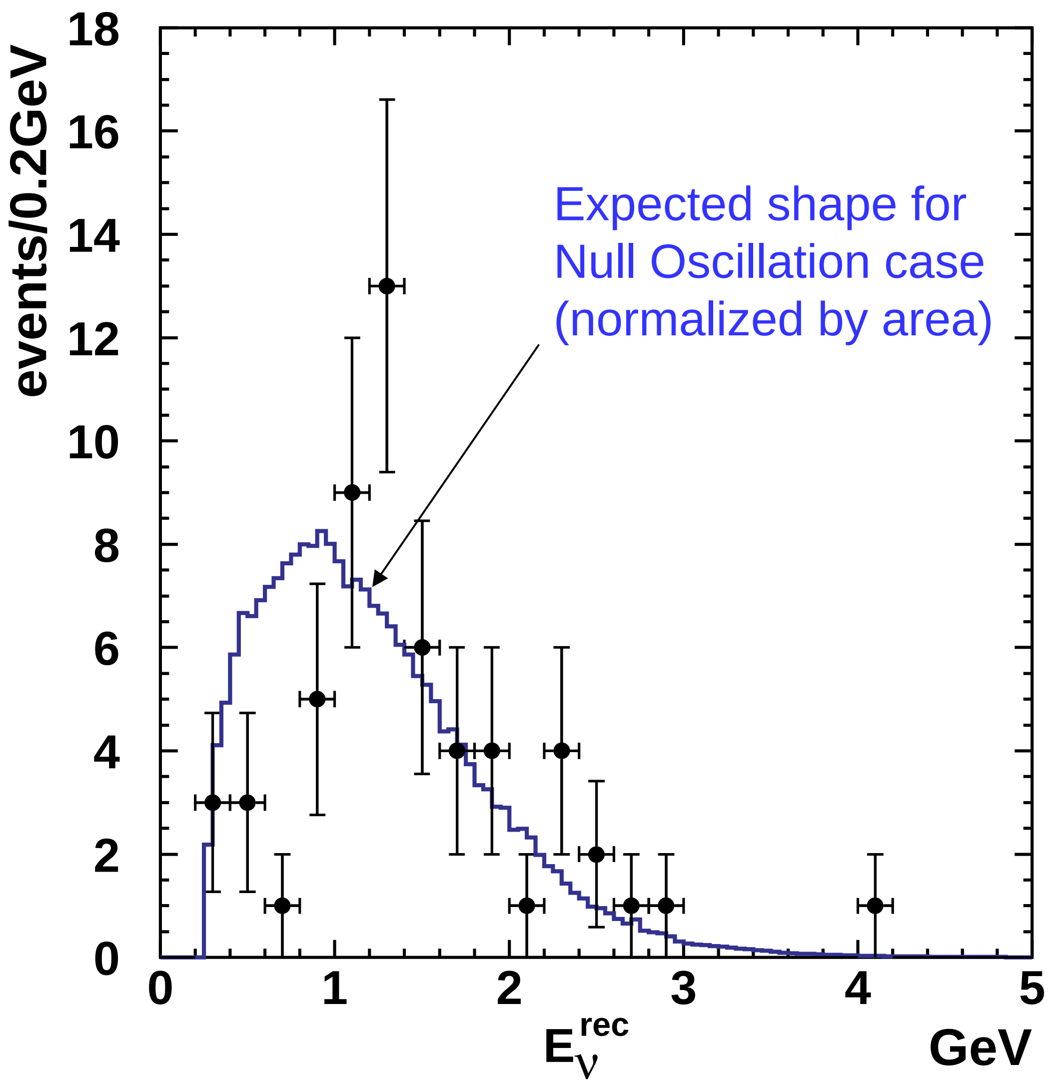
PID likelihood dist. for SK-II atmospheric ν



112 FC events are observed

158.1 +9.2 / - 8.6 events are expected (no osc.).

Reconstructed Eν for 1Rμ Events



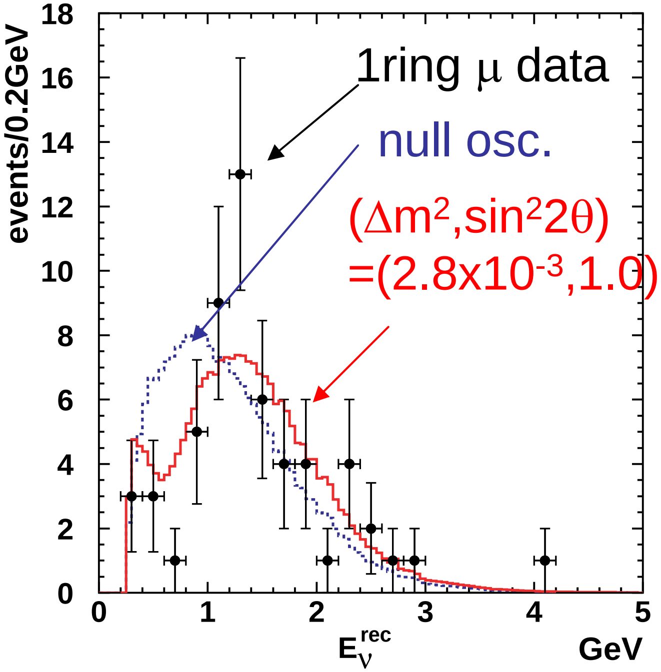
Neutrino energy is calculated assuming QE kinematics from the 58 one-ring mu-like events

Oscillation Analysis

ν_μ disappearance fit result

Fit was done by a maximum likelihood method for both number of events and spectrum shape

Reconstructed $E\nu$ spectrum



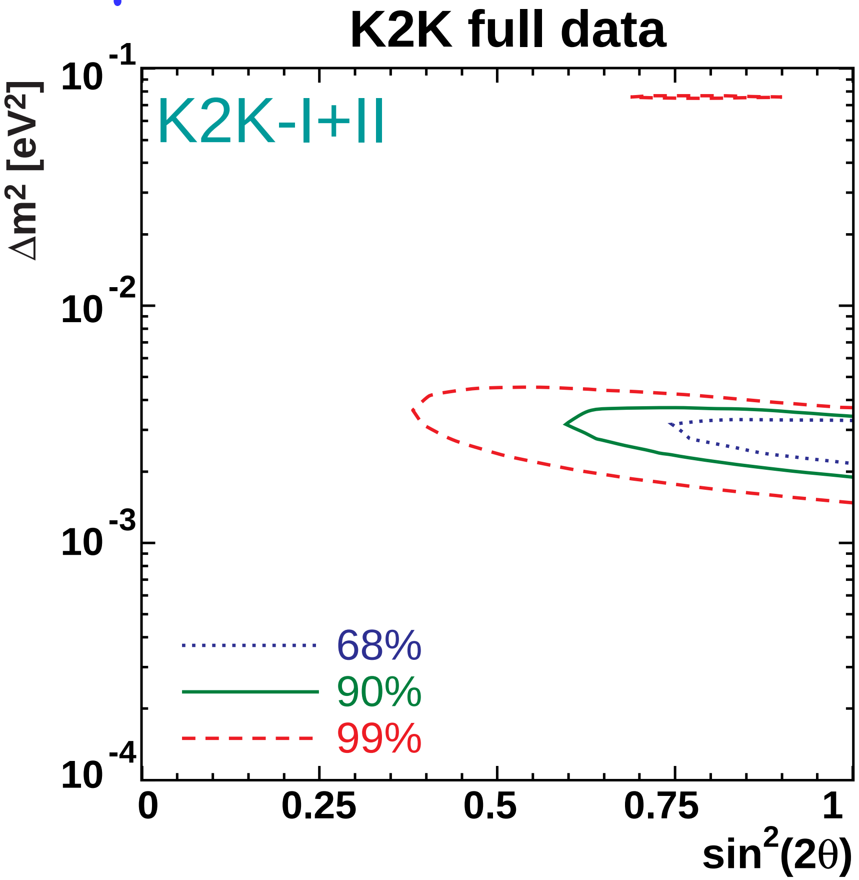
Number of FC events

Obs.	112
Expected.	$158.1^{+9.2}_{-8.6}$ (null osc.)
	107.2 $(\Delta m^2, \sin^2 2\theta) = (2.8\times10^{-3}, 1.0)$

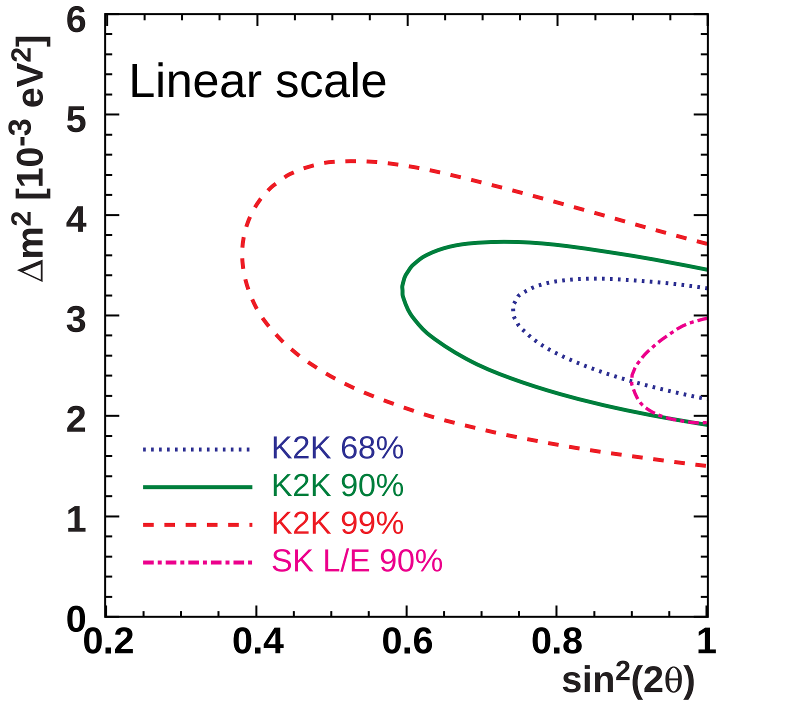
Best fit : $(\Delta m^2, \sin^2 2\theta) =$ (physical) $(2.75\times10^{-3}, 1.0)$ (all region) $(2.55\times10^{-3}, 1.19)$

Published in Phys. Rev. D 74, 072003 (2006)

ν_μ disappearance allowed region



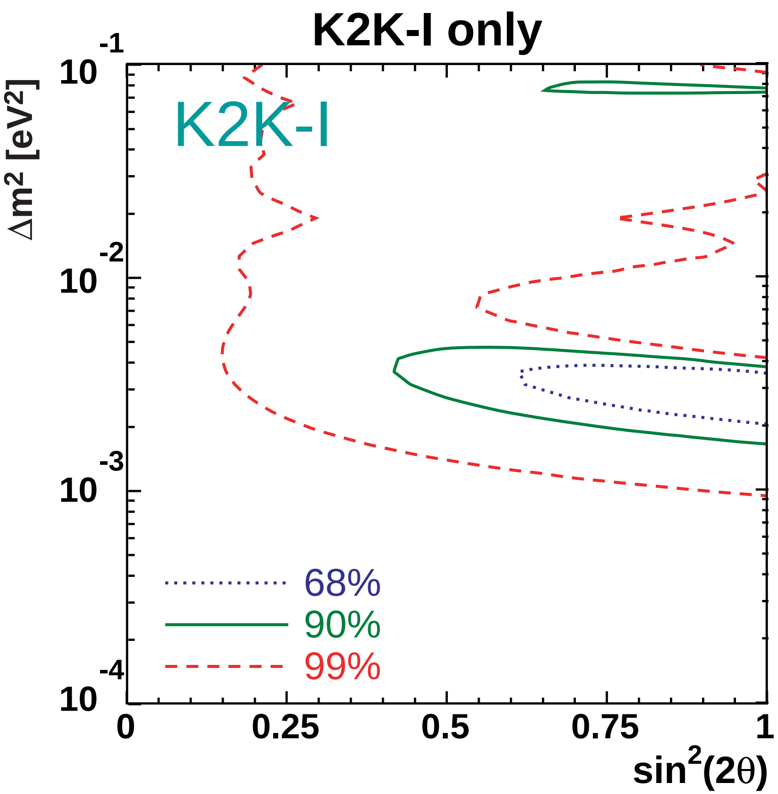
Comparison with the atm.ν data

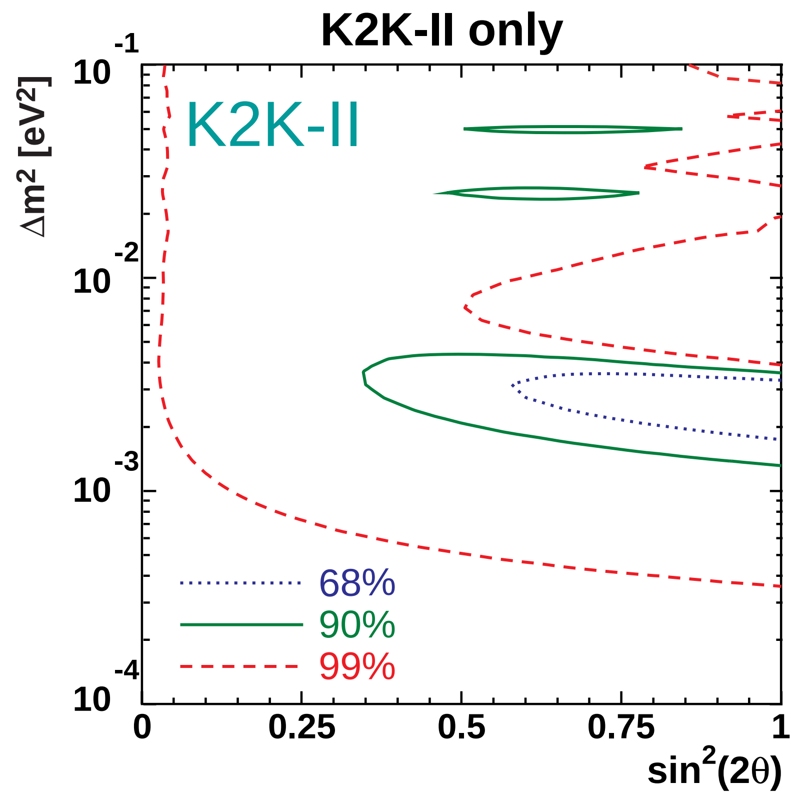


Null oscillation probability

	K2K-I+II		K2K-I / K2K-II
Norm.	0.06%	(3.4σ)	0.6% / 2.8%
Shape	0.42%	(2.9σ)	7.7% / 5.2%
Shape+Norm.	0.0015%	(4.3σ)	0.18% / 0.56%

Comparison of K2K-I and K2K-II Results



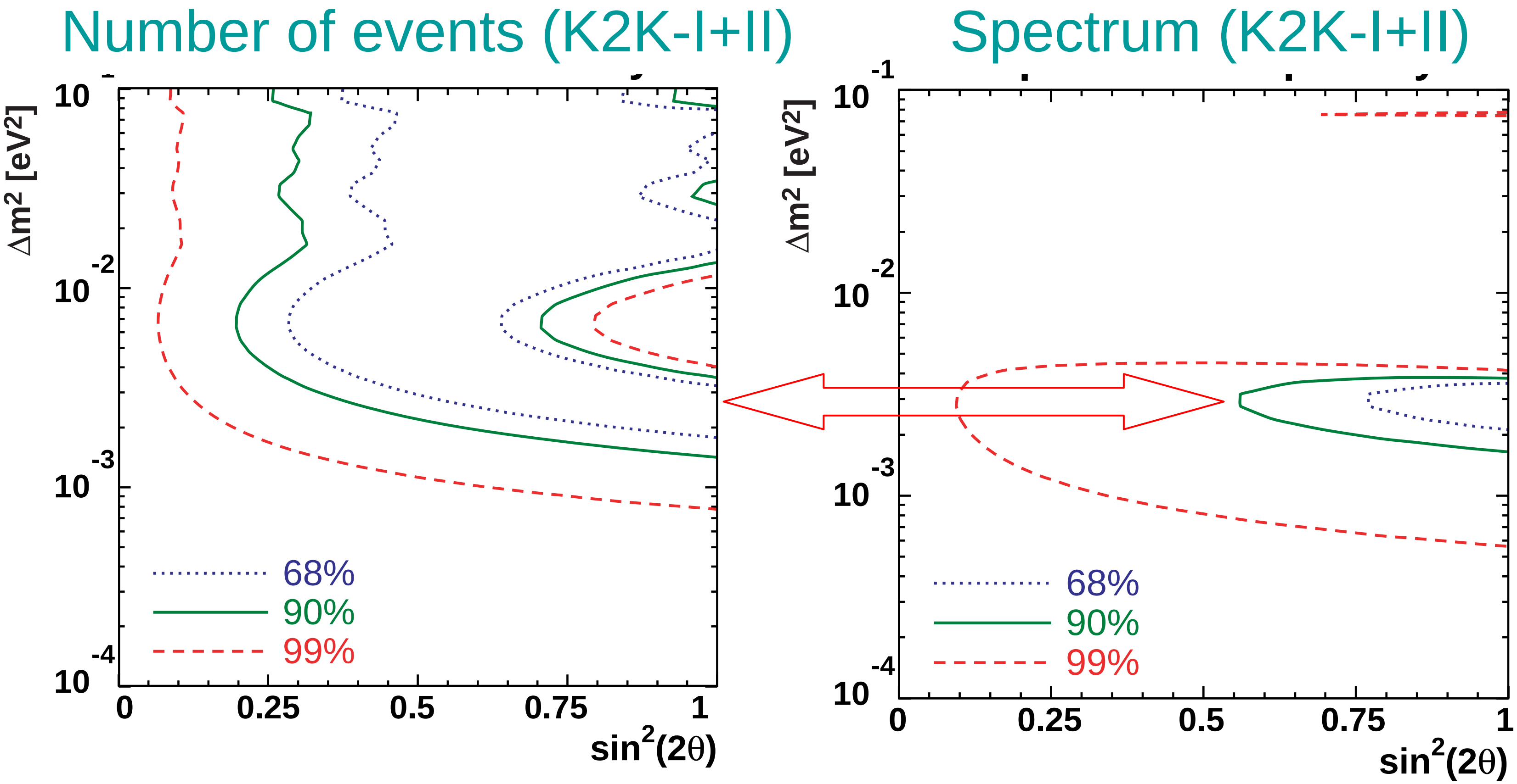


Best fit : (Δm^2, $\sin^2 2\theta$)

	(physical)	(all region)
K2K-I+II	(2.75×10^{-3}, 1.0)	(2.55×10^{-3}, 1.19)
K2K-I	(2.89×10^{-3}, 1.0)	(2.77×10^{-3}, 1.08)
K2K-II	(2.64×10^{-3}, 1.0)	(2.36×10^{-3}, 1.35)

K2K-I and K2K-II results agree well.

Comparison of Number and Spectrum Results



Both number of events and spectrum distortion indicate same oscillation parameters.

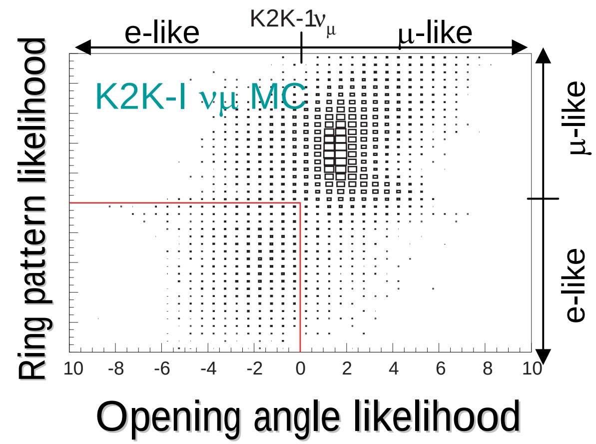
ν_e appearance analysis

Event selection for ν_e appearance search

—K2K-1—	νμ MC	beam νe	Data
FCFV	81.1	0.81	55
Single ring	50.92	0.47	33
Tight e-like cut	2.66	0.40	3
Evis > 100 MeV	2.47	0.40	2
No decay-e	1.90	0.35	1
Pi0 cut	0.58	0.17	0

—K2K-2—	νμ MC	beam νe	Data
FCFV	77.4	0.86	57
Single ring	49.41	0.52	34
Tight e-like cut	3.21	0.44	5
Evis > 100 MeV	2.93	0.44	5
No decay-e	2.17	0.39	4
Pi0 cut	0.74	0.21	1

Tight e-like cut



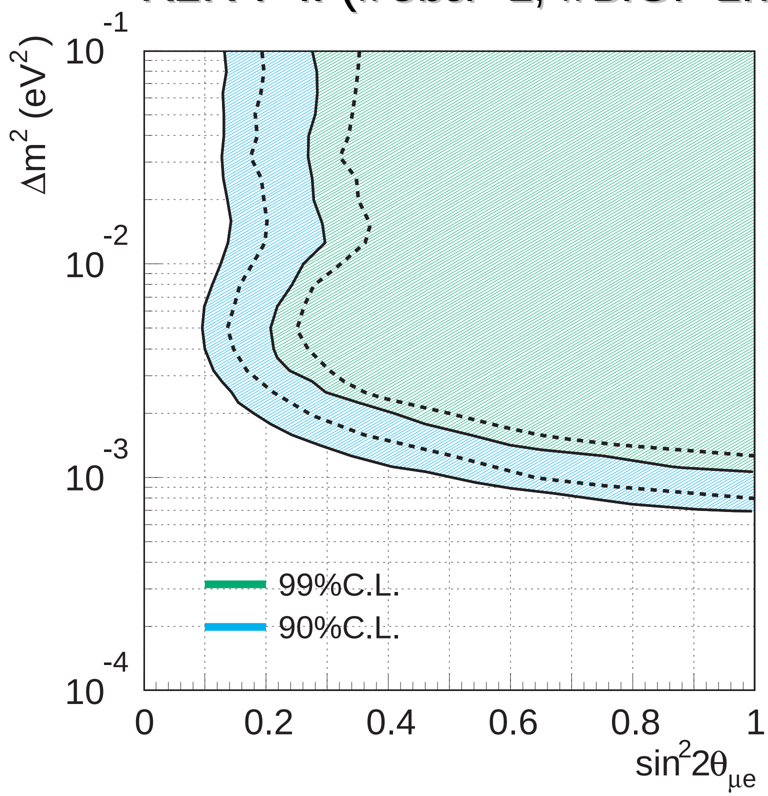
Both opening angle and ring pattern are required to be e-like.

In total,
#expected BG = 1.70
#observed = 1

Exclude region for ν_e appearance search

limit
sensitivity

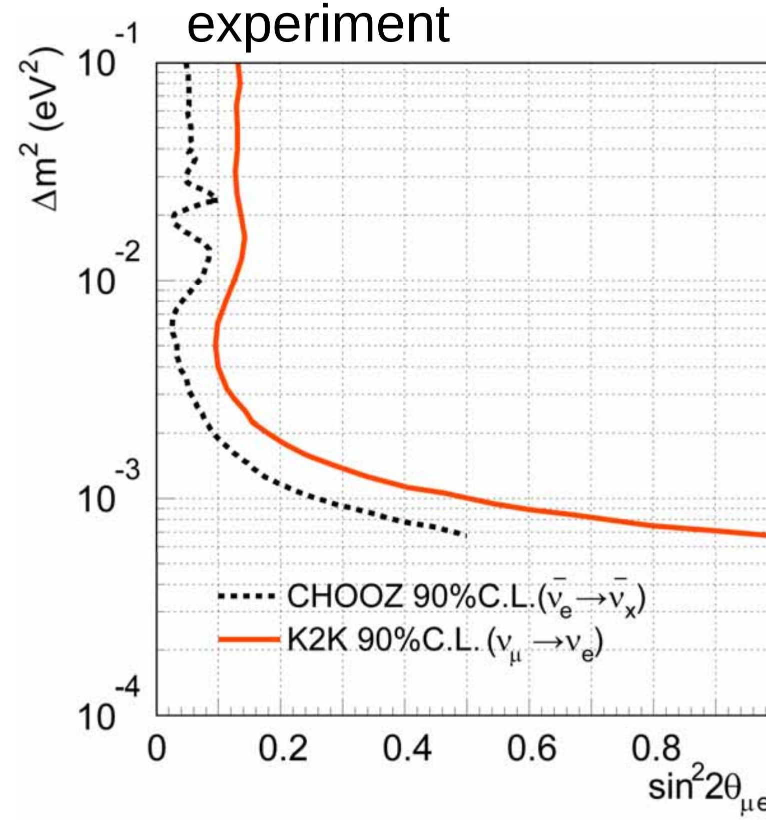
K2K-I+II (#obs.=1, #B.G.=1.70)



<u>upper limit (90% CL)</u>

$\sin^2 2\theta_{\mu e}=0.13$ @2.8×10^{-3} eV^2

Comparison with the reactor (disappearance) experiment



<u>Assumption: $2\sin^2 2\theta_{\mu e} = \sin^2 2\theta_{13}$</u>

Published in Phys. Rev. Lett. 96, 181801 (2006)

Conclusion

- K2K has proved the crucial principles of a long-baseline neutrino experiment to work
- Decrease and spectrum distortion of muon-neutrinos after traveling hundreds of kilometers is confirmed (4.3σ)
- Allowed region for Δm^2 ($1.9\text{-}3.5\times10^{-3}eV^2$) at $\sin^2 2\theta=1$ (90%C.L.) is consistent with the atm-ν result
- No evidence for ν_e appearance is found $\sin^2 2\theta_{\mu e}<0.13$ at $2.8\times10^{-3}eV^2$ (90%C.L.)