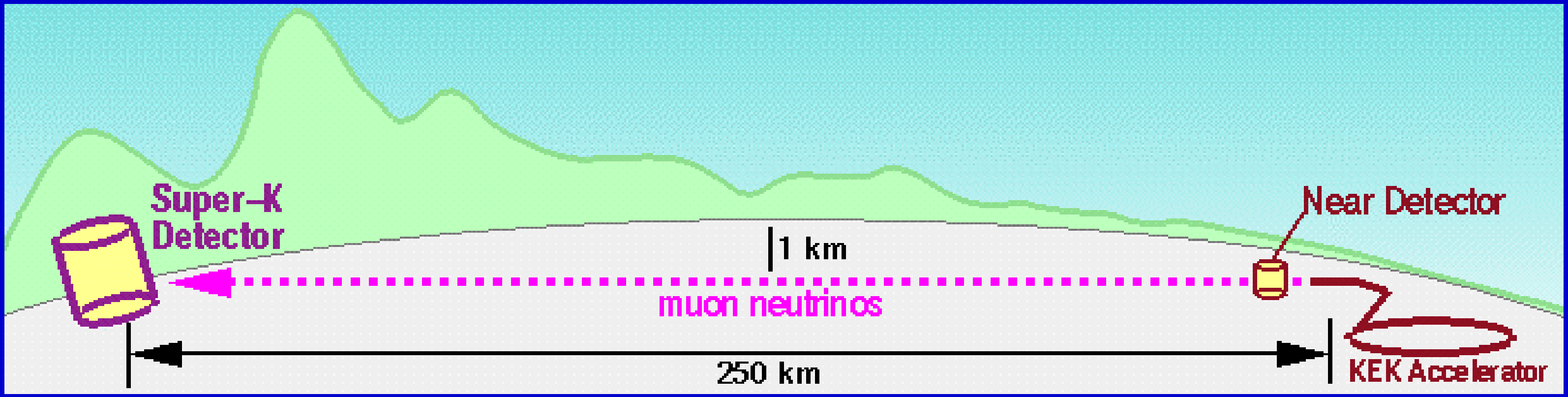
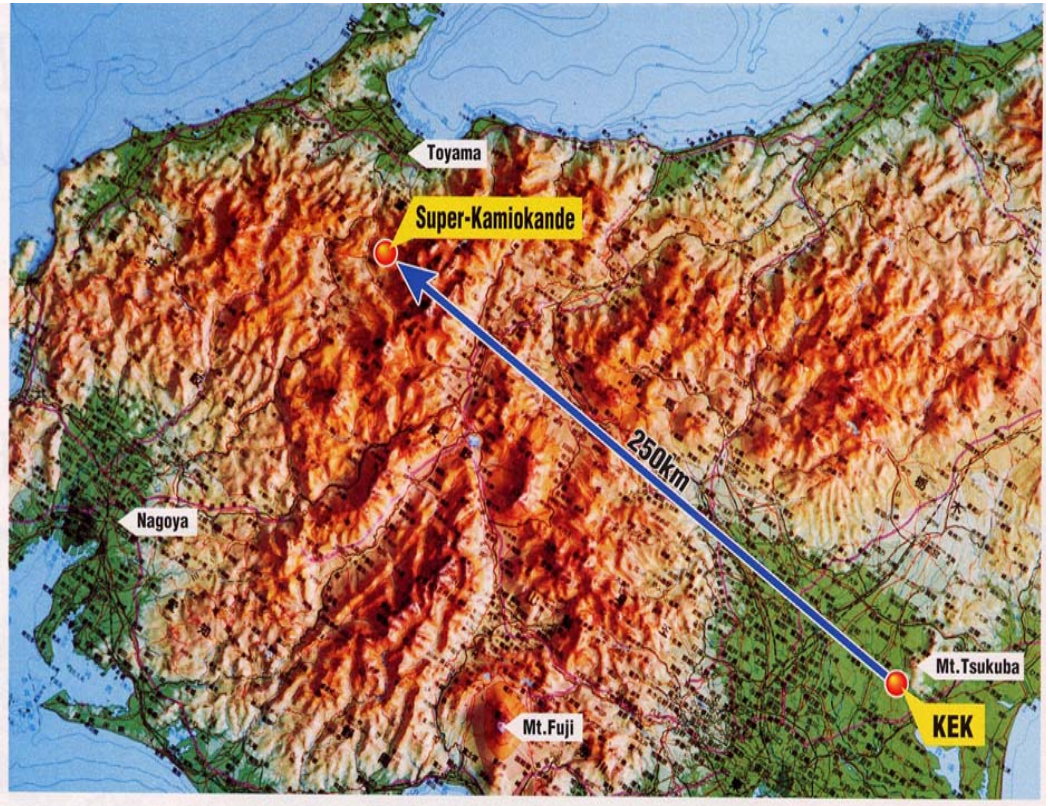
Results from the K2K Experiment

KK Joo (Seoul National Univ)
for the K2K collaboration



K2K (KEK to Kamioka) long-baseline neutrino experiment is the first accelerator-based experiment to investigate the neutrino oscillation observed in atmospheric neutrinos



- **Neutrino beam**:

  almost pure ν_μ (99%)

- **$<E_\nu>$** ~ **1.3GeV**

Contents

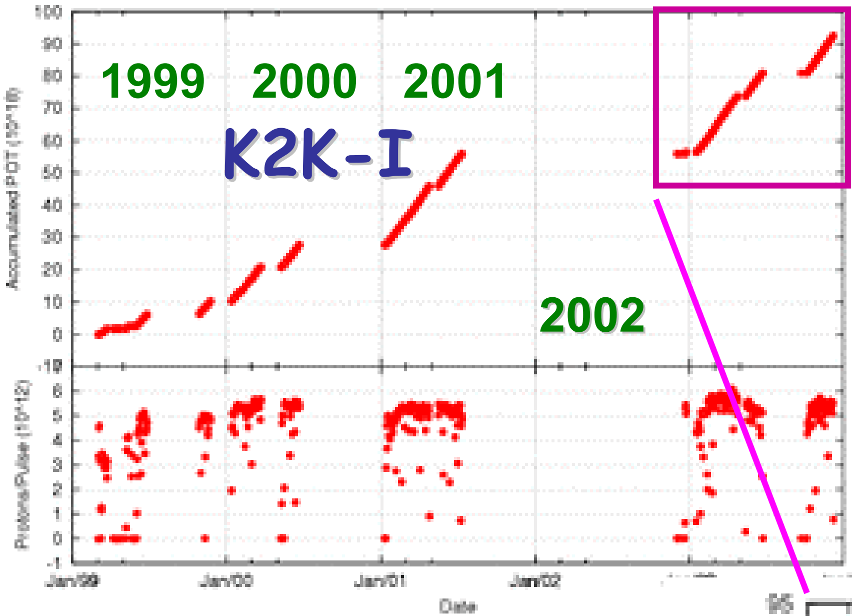
- **Data Accumulation (K2K-I, K2K-II)**
- **Brief Introduction of K2K, SK Detector**
- **Result of Oscillation Analysis (K2K-I)**
- **Search for ν_e Appearance (K2K-I)**
- **New SciBar Detector @Near Detector**
- **Summary**

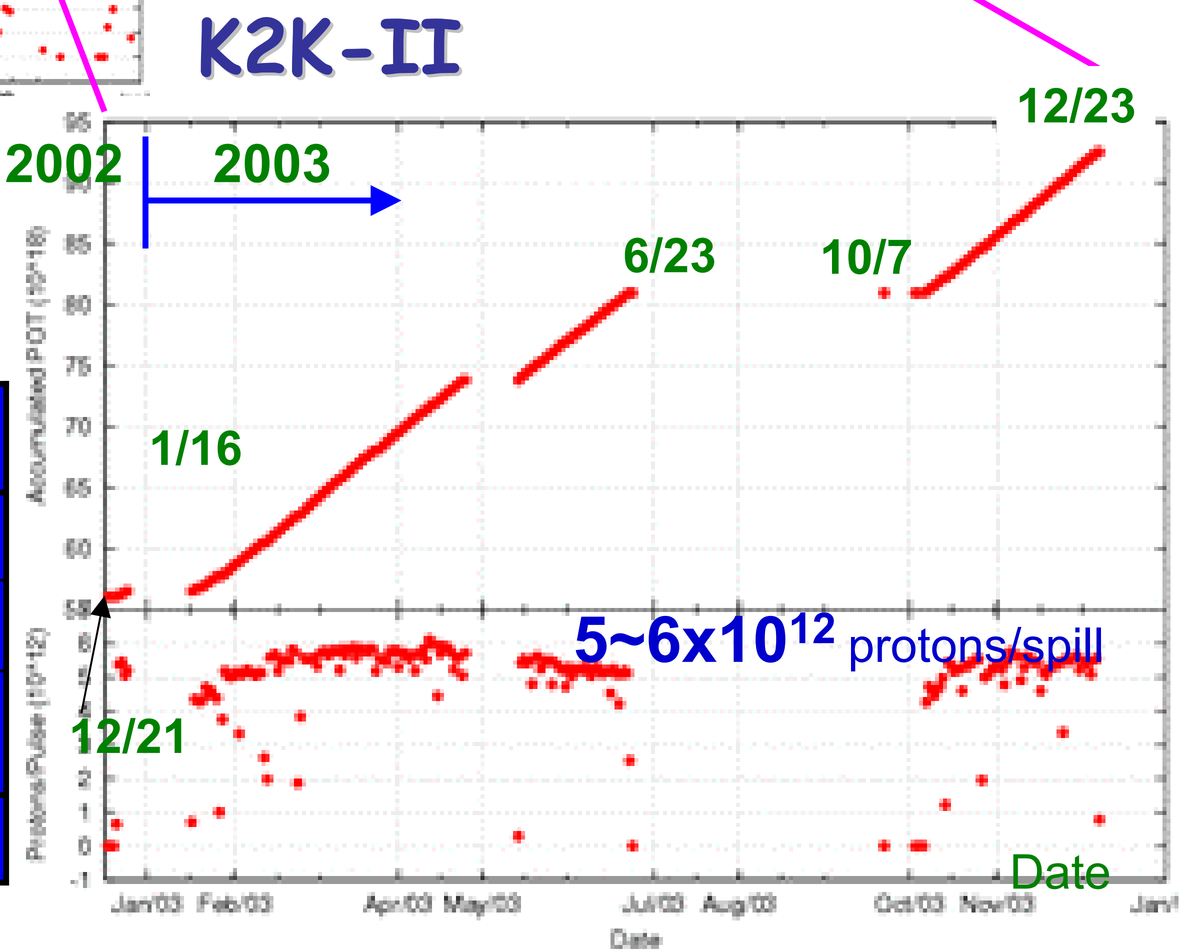
❑ K2K (KEK to Kamioka) Experiment Period:

- K2K-I: 1999.3 – 2001.7
- **Experiment resumed successfully**
- K2K-II: 2002.12 – Present
  + K2K-IIa: 2002.12.21 ~
  + K2K-IIb: 2003.10.03 ~
  + K2K-IIb period (with SciBar detector)
- K2K-I: USA, Japan, Korea
- K2K-II: EU, Canada group joined
  + EU: Barcelona/Geneva/INR/Rome/Saclay/Valencia/
    Warsaw/Solton
  + Canada: TRIUMF/UBC

Delivered P.O.T.

(since March 1999)





	Delivered	Analysis
K2K-I	5.6×10^{19}	4.8×10^{19}
K2K-IIa	2.4×10^{19}	2.3×10^{19}
K2K-IIb (-Dec03)	1.5×10^{19}	1.3×10^{19}
Total	9.5×10^{19}	8.4×10^{19}


K2K-II
January 9th, 2004

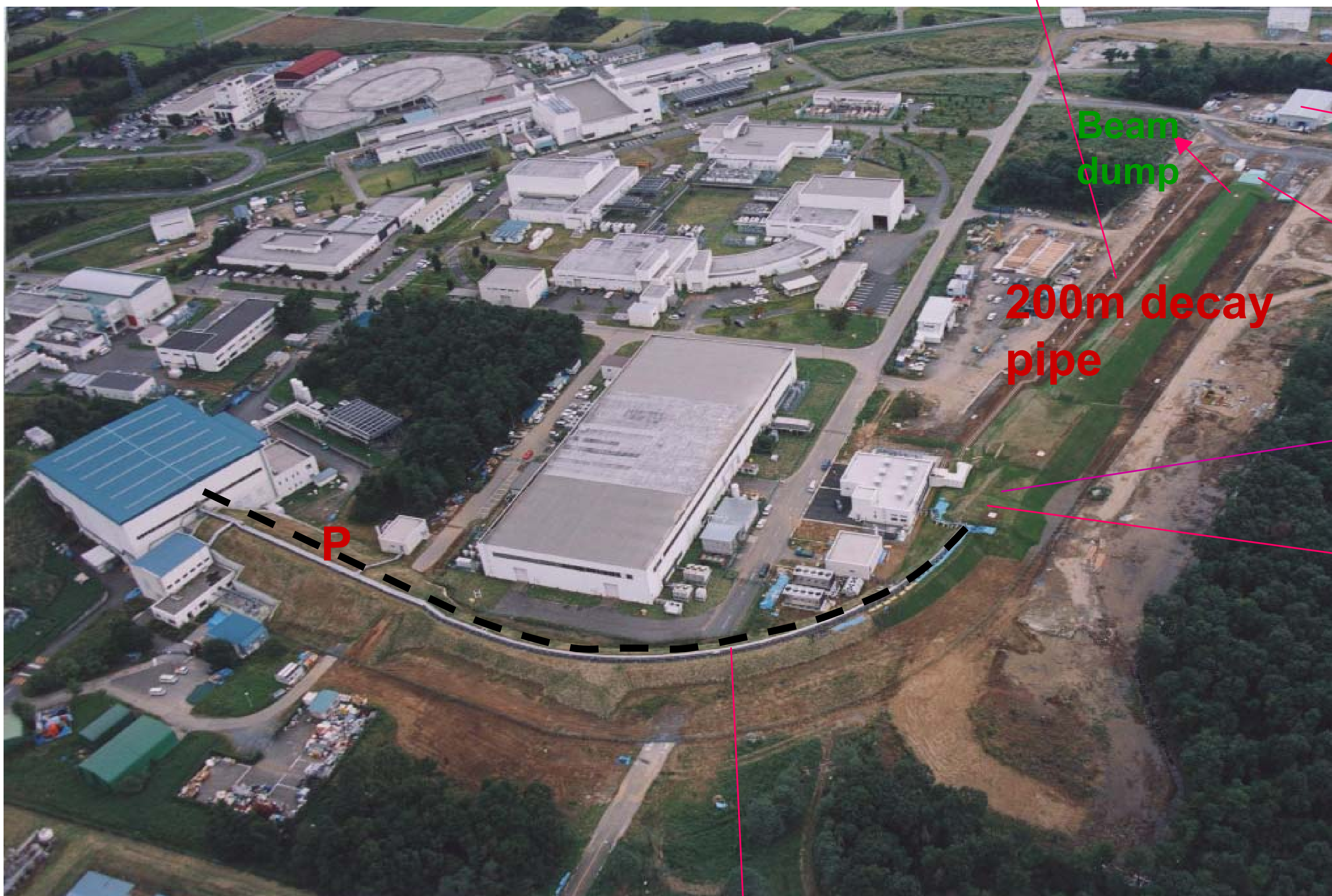
K2K Collaboration

- **JAPAN**: High Energy Accelerator Research Organization (KEK)
  Institute for Cosmic Ray Research (ICRR), University 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
- **EUROPE**: Rome / Saclay / Barcelona / Valencia / Geneva
- **RUSSIA**: INR

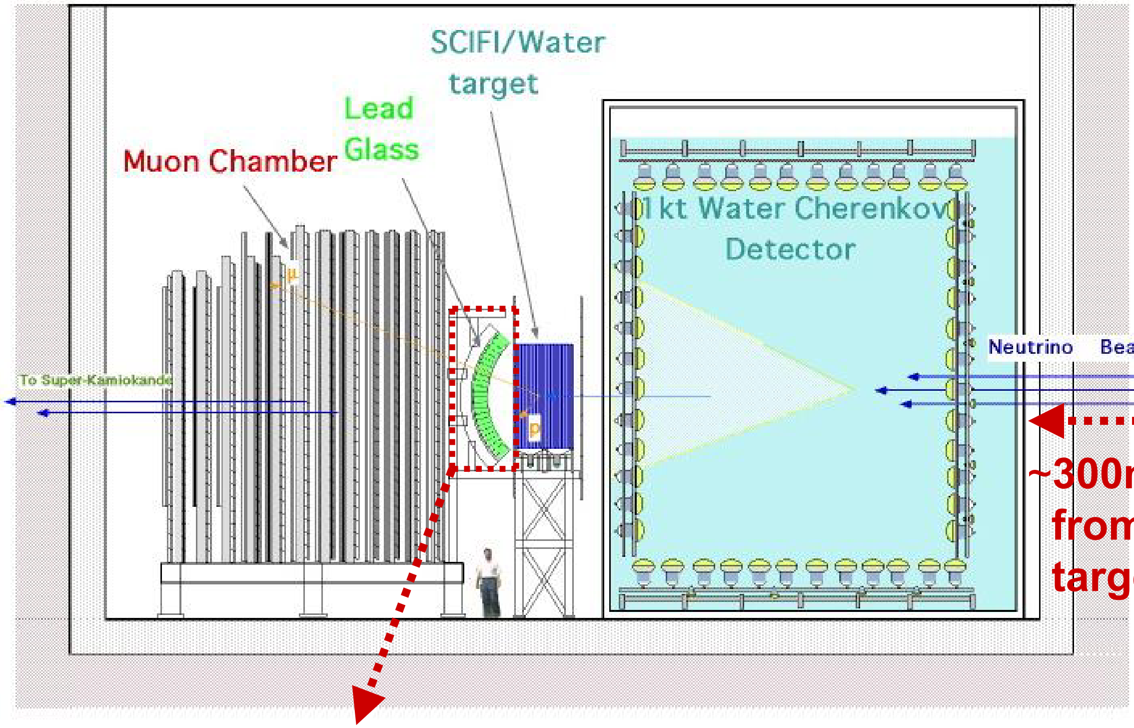
Neutrino Beam Line @KEK



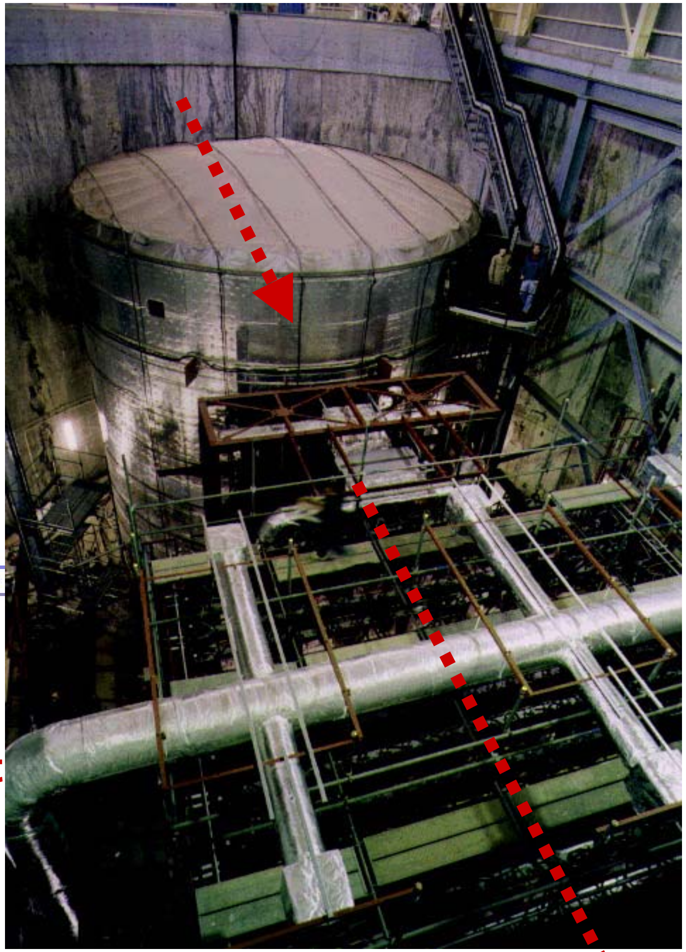
PS: 12GeV proton
1.1μsec spill/2.2sec
~6x10^{12} protons/spill

Near Detector
(1kton water, Scintillating Fiber, Muon)

- Remove Lead Glass(LG) detector to explore low energy region

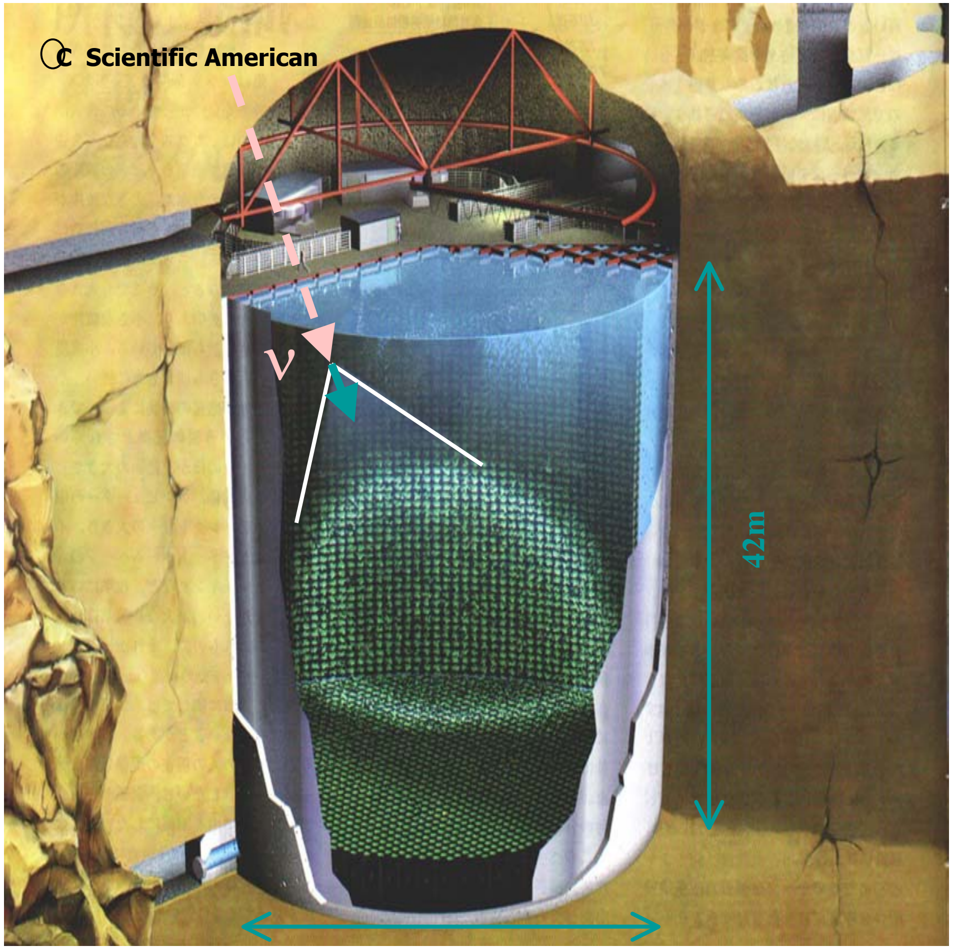


Replaced by SciBar detector during summer of 2003



ν
SK direction

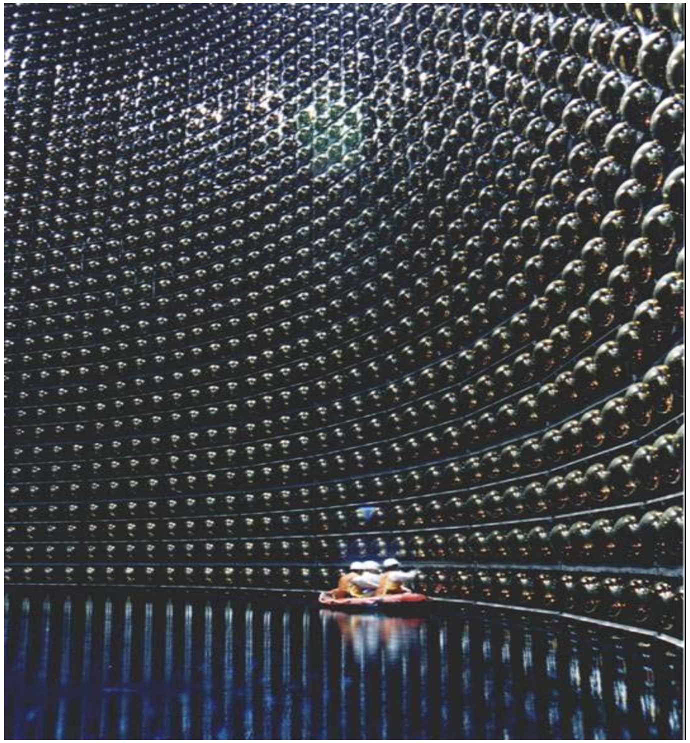
Far Detector (Super- Kamiokande)



39m

Water Cherenkov detector

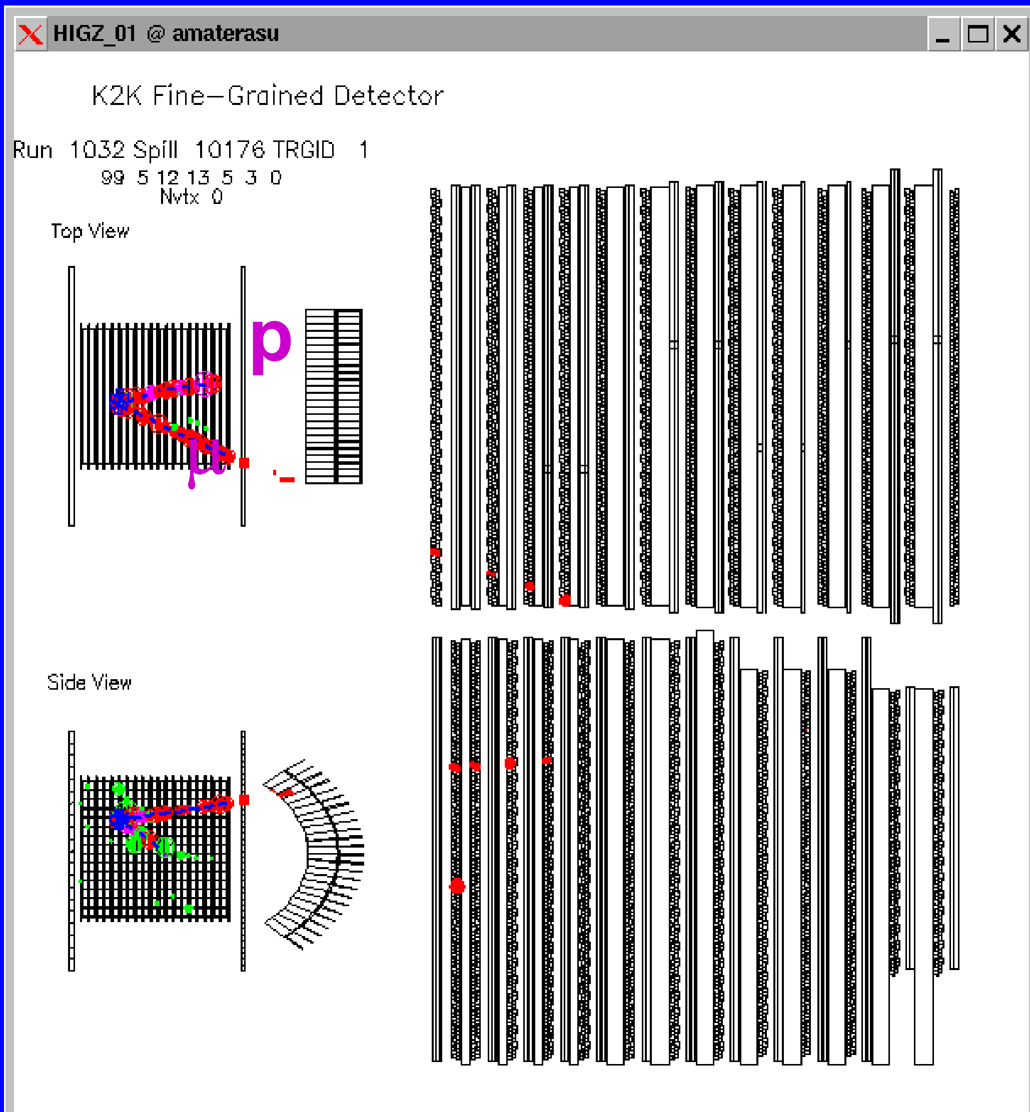
- 1000 m underground
- 50,000 ton
- 11,146 20 inch PMTs



SK-I: Mar 1996 – Jul 2001
SK-II: Dec 2002 - Present

Typical Event @ Near Detector

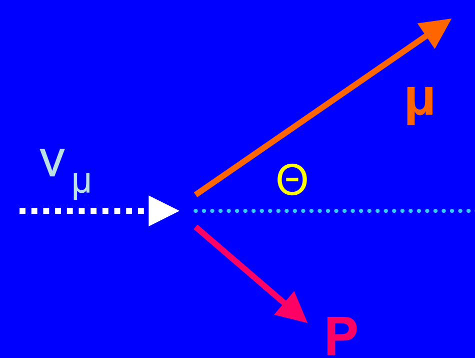
(K2K-I)



Quasi-elastic scattering event @ SciFi detector

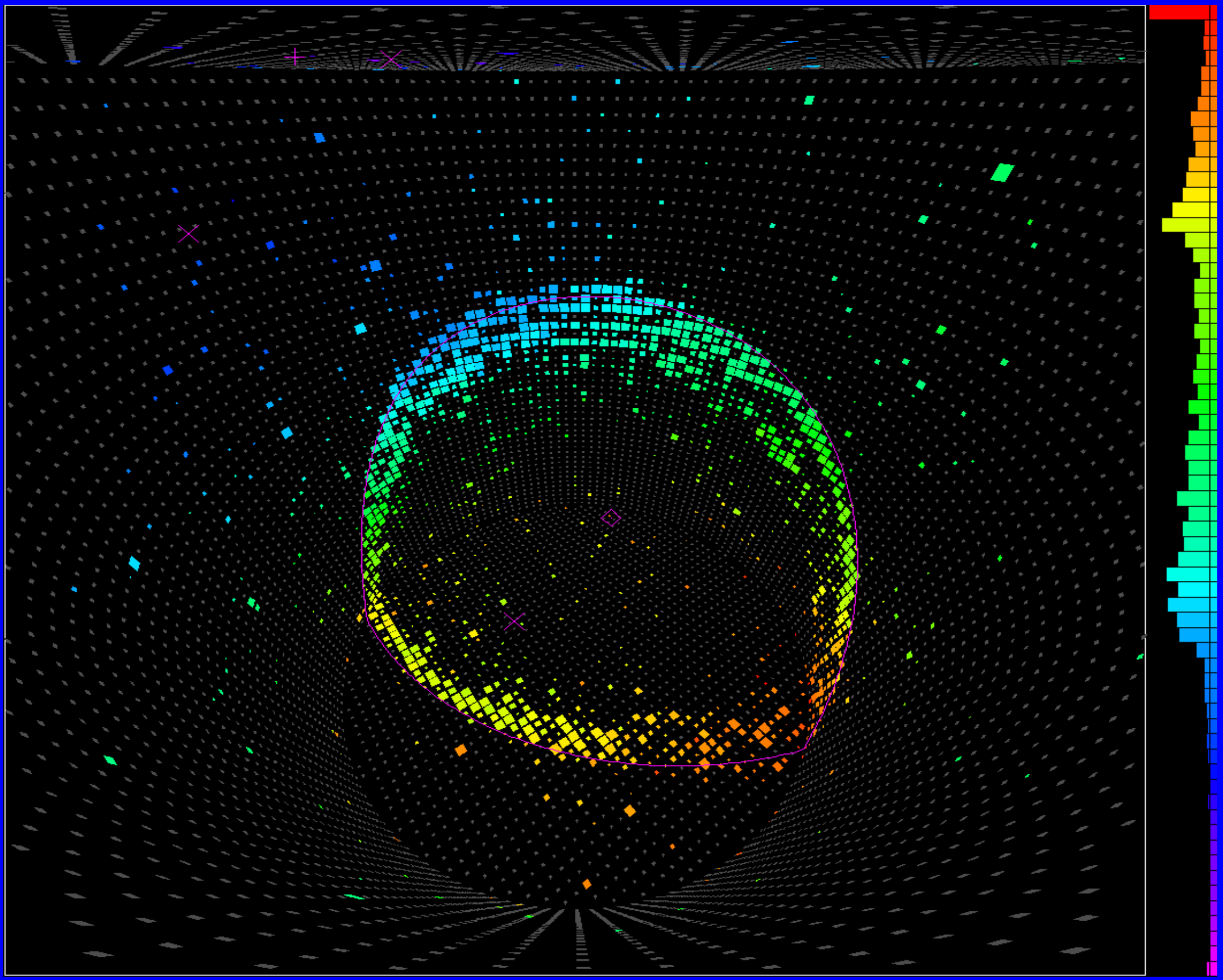
Quasi-elastic scattering

$$(\nu_\mu + n \rightarrow p + \mu)$$



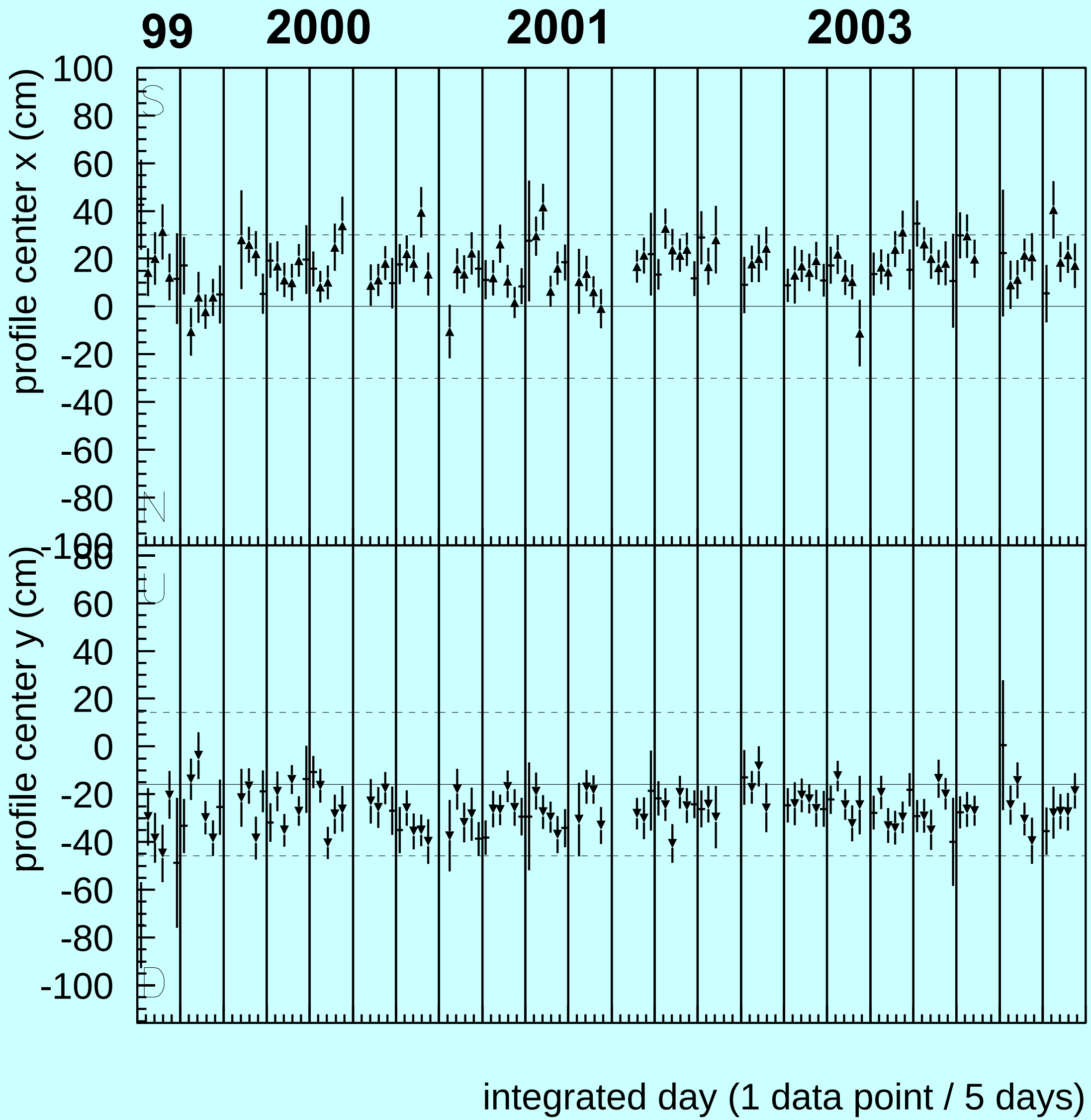
- From muon energy and angle, neutrino energy can be calculated

Event Display @ SK



Muon Neutrino Candidate Event, 692MeV

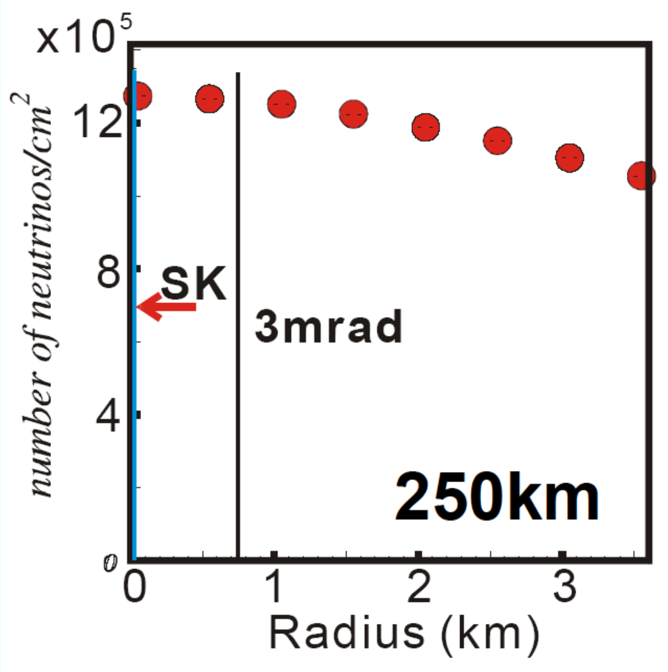
Neutrino Direction Measured by MRD



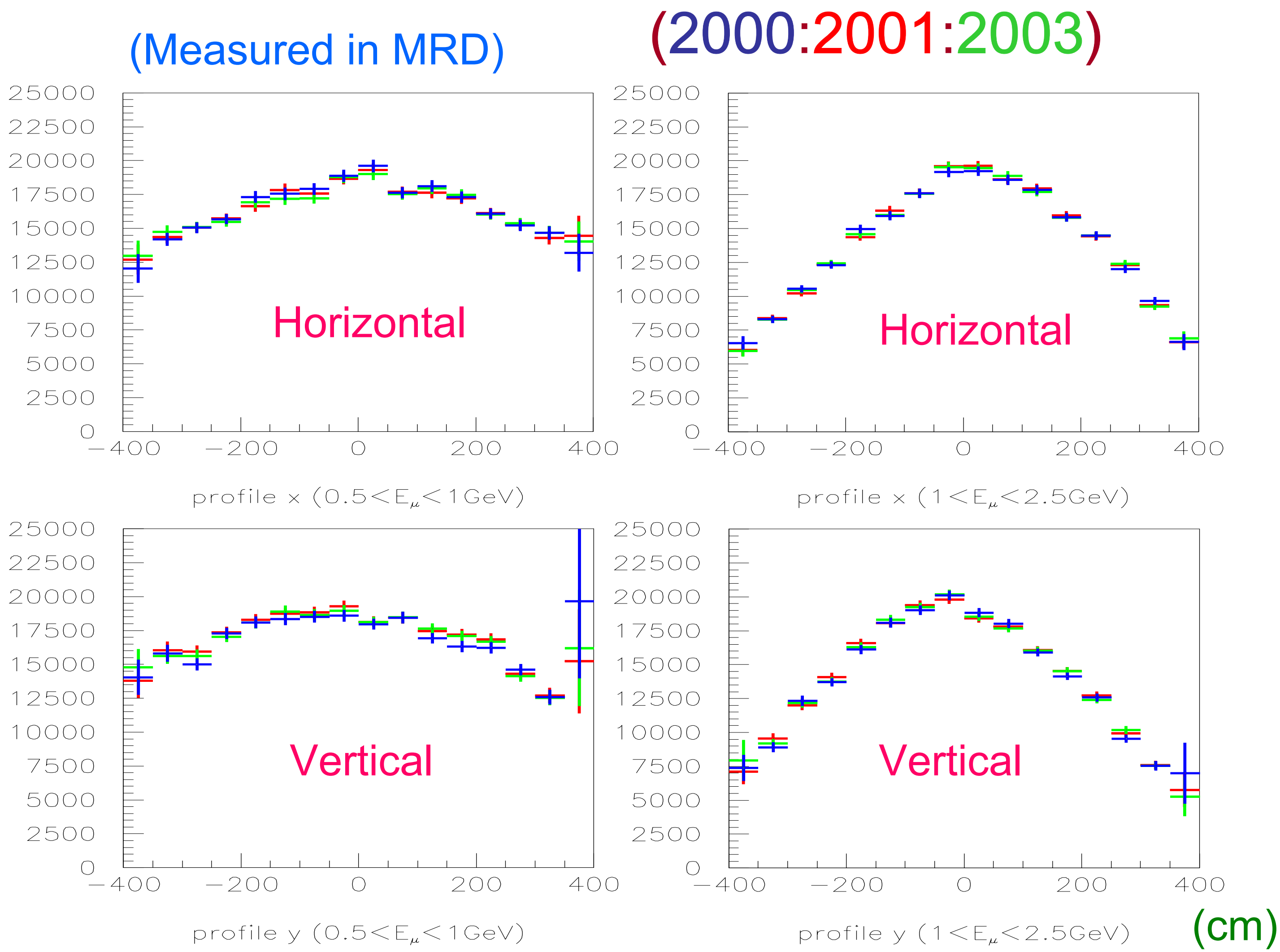
Neutrino direction is stable within 1 mrad.

+- 1 mrad.

Neutrino flux MC

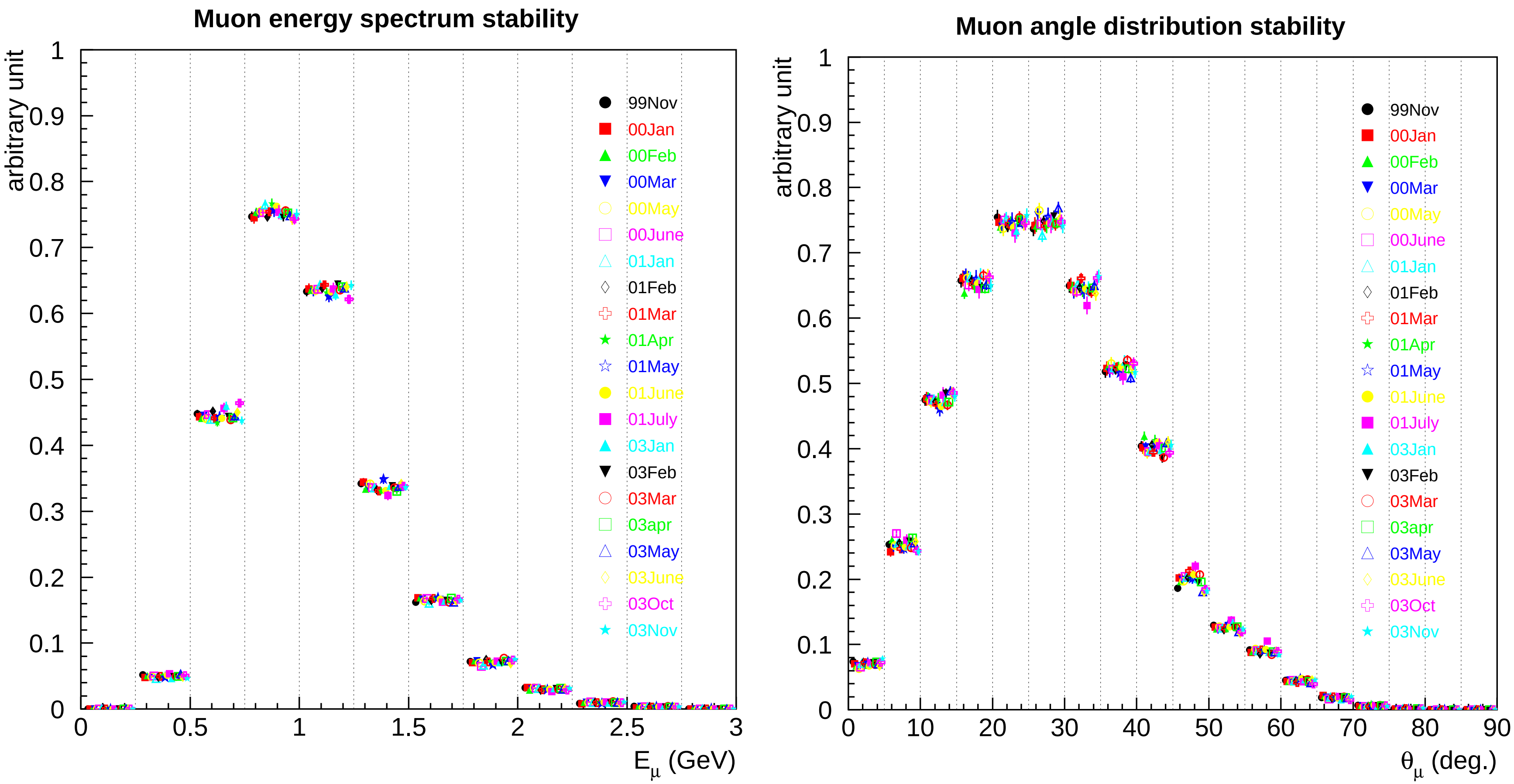


Beam Profile Comparsion



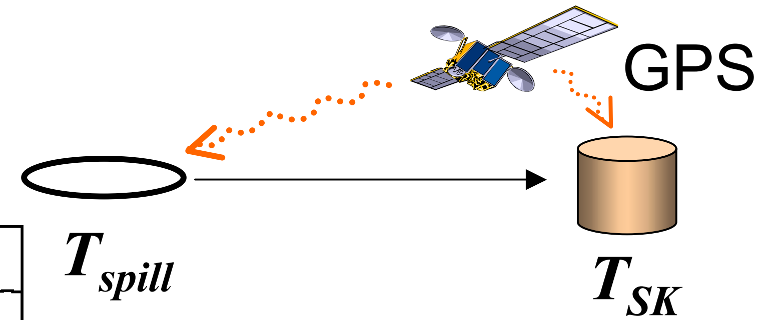
Spectrum Stability

Spectrum stability is confirmed by the measurements of energy and angle of muons produced in the CC interactions by MRD.

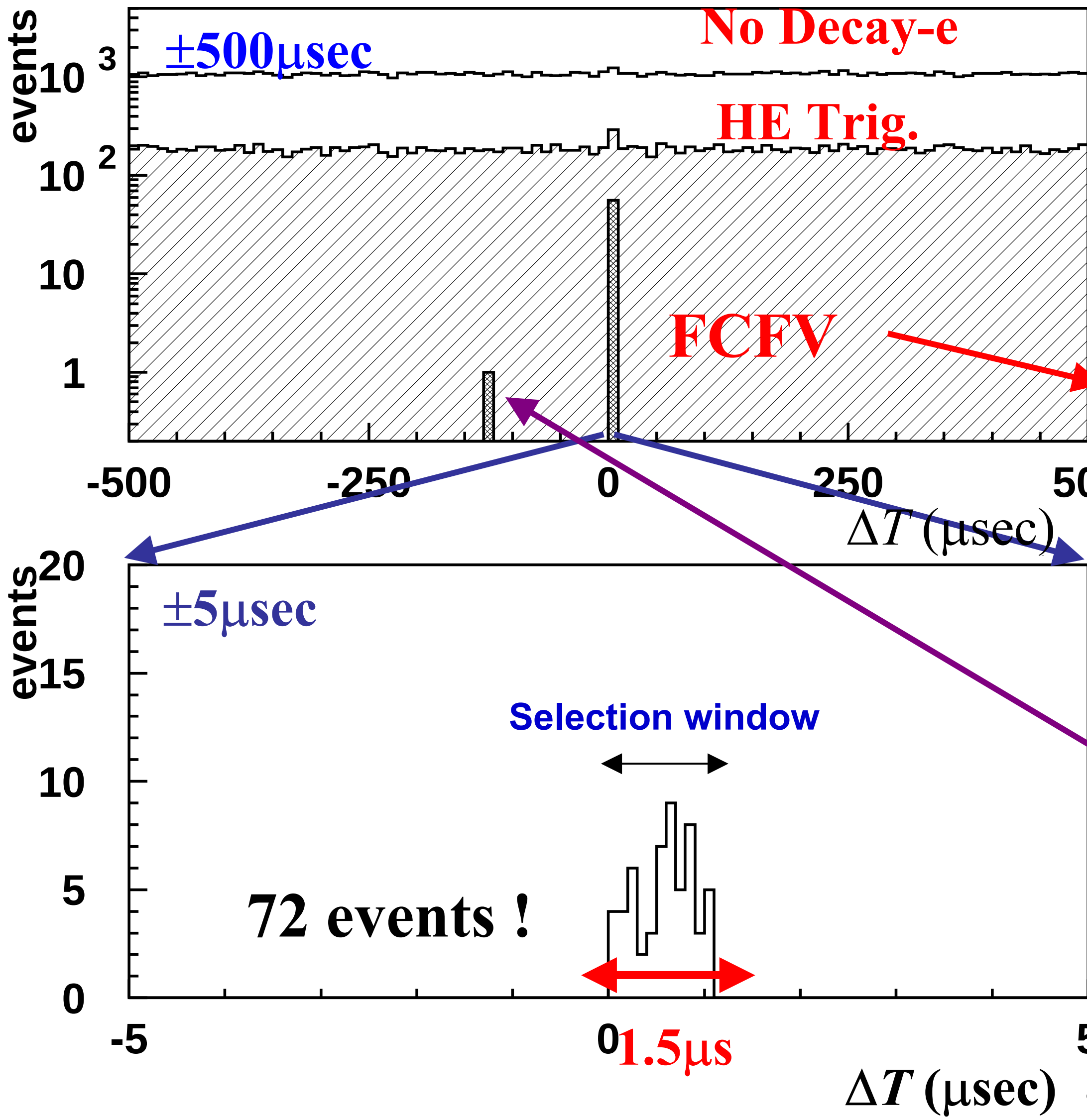


Super-K Event Selection

$$-0.2 \leq \Delta T \equiv T_{SK} - T_{Spill} - \mathrm{TOF} \leq 1.3\mu\sec$$



T_{Spill}: Abs. time of spill start
T_{SK}: Abs. time of SK event
TOF: 0.83ms (KEK to Kamioka)



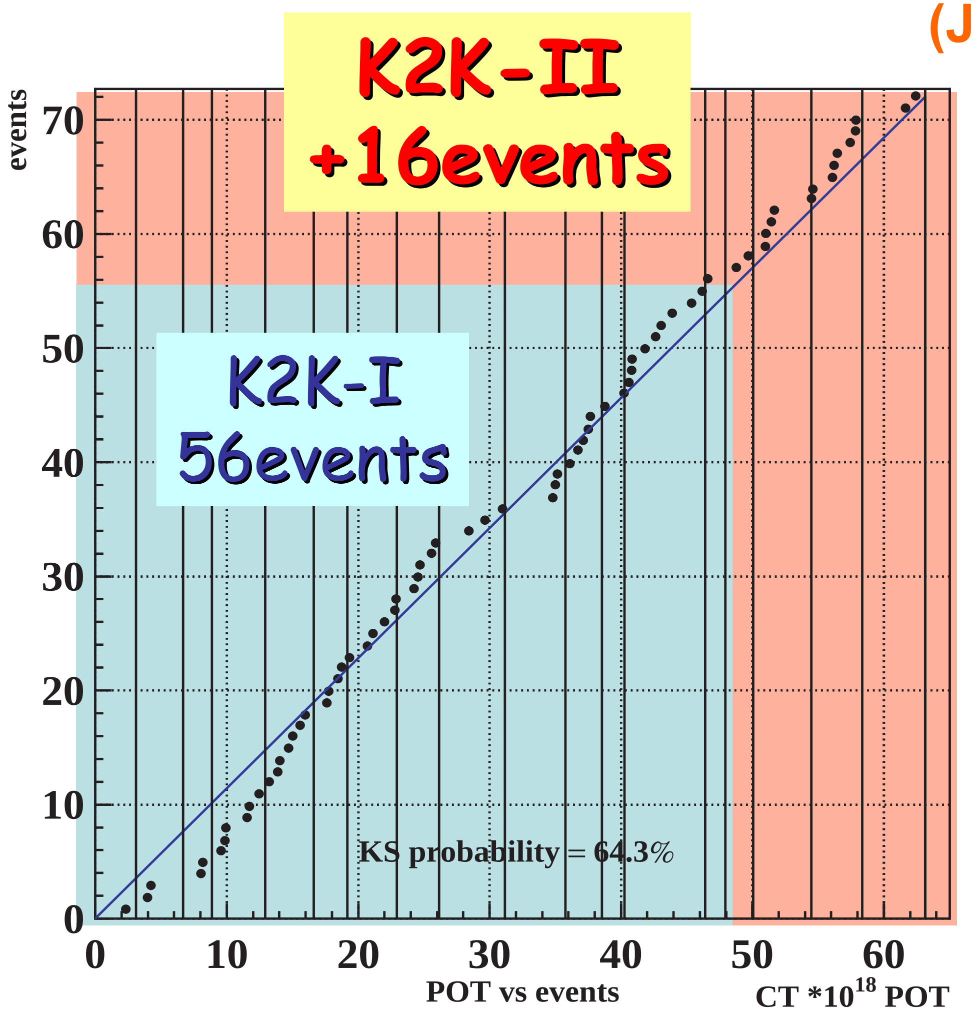
FC: fully contained
(No activity in Outer Detector)
FV: 22.5kt Fiducial Volume

Jun.'99 – Apr.'03
6.4 x 10^{19} proton on target

Expected Atm. ν BG
$<10^{-3}$ within 1.5μs.

Arrival Time of Super-Kamiokande Events

(Jun99-Apr03)

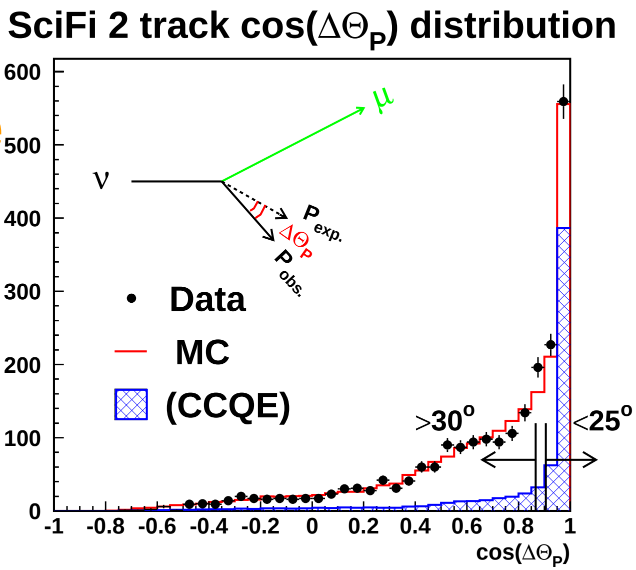


Oscillation Analysis (K2K-I)

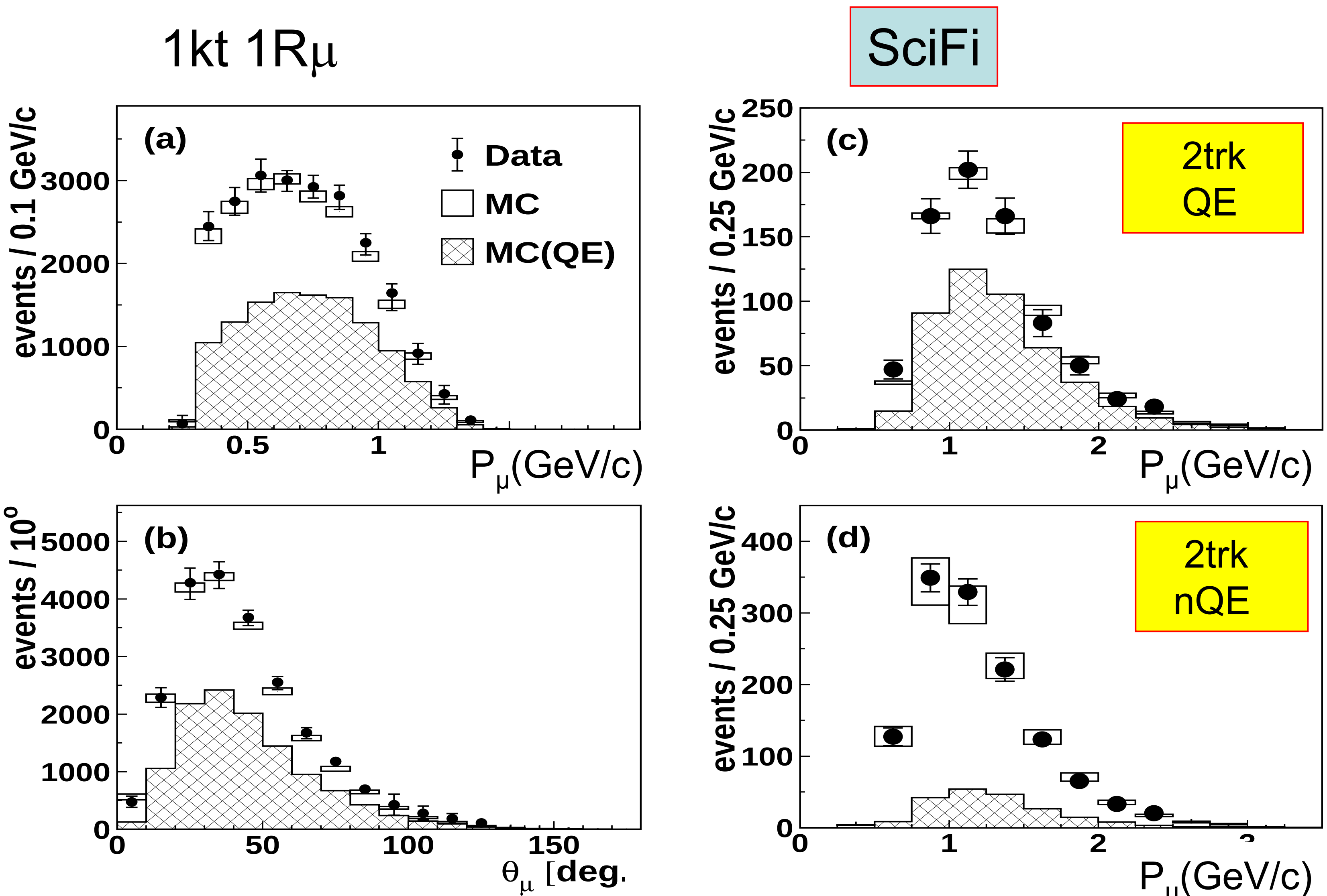
Published in PRL 90 (2003) 041801-1

Spectrum Measurements @ ND

- 1KT : P_μ<1.5GeV/c, 4π acceptance
  - 1-ring μ-like(1Rμ) fully contained in Fid.25ton(FC) : 22,476ev.
- SciFi : P_μ>1GeV/c, θ_μ<60deg.
  - 1-track μ-like : 5963ev.
  - 2-track QE-like ($\Delta\theta_p$<25deg.) : 764ev.
  - 2-track nonQE-like ($\Delta\theta_p$>30deg.) : 1288ev.
- PIMON
  - π (p,θ) distribution $\Rightarrow$ Neutrino Spectrum (>1GeV)



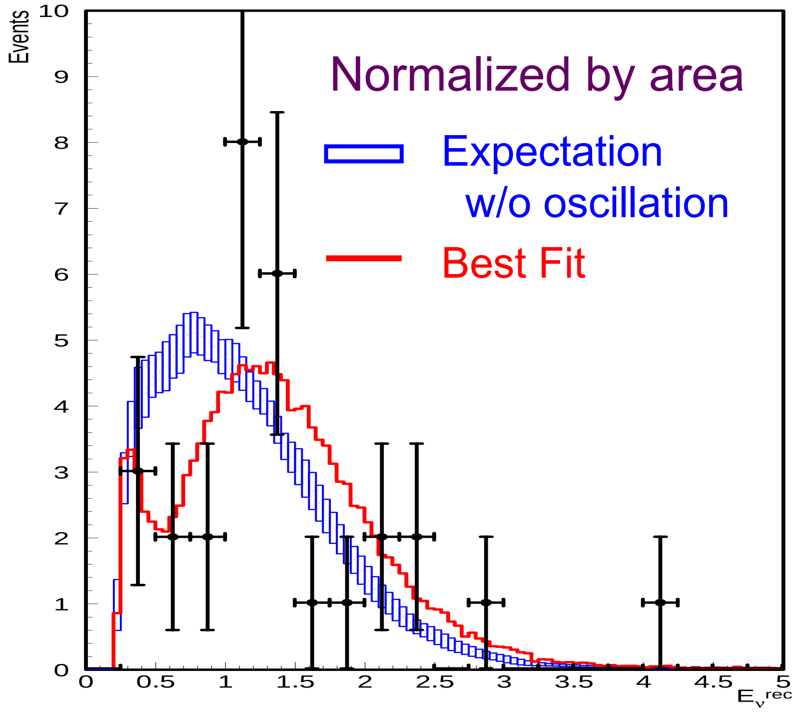
Measured Spectrum @ Near Detector



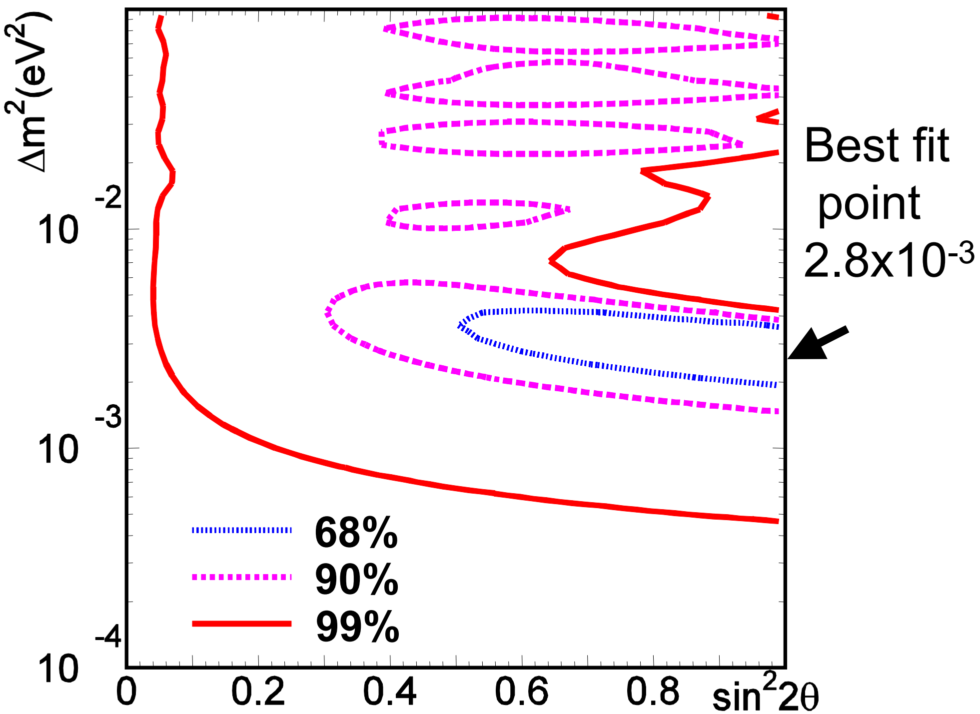
- Good agreement for all samples

Result of Oscillation Analysis (K2K-I)

Reconstructed E_ν



K2K allowed region



- The best fit spectrum shape agrees with the observation

❑ Result of K2K-I:

- (June 1999 ~ July 2001)
- Use # of event + Spectrum shape analysis
- Total 5.6×10^{19} POT ν **beam are delivered**
- Based on ~200.000 events @K2K,

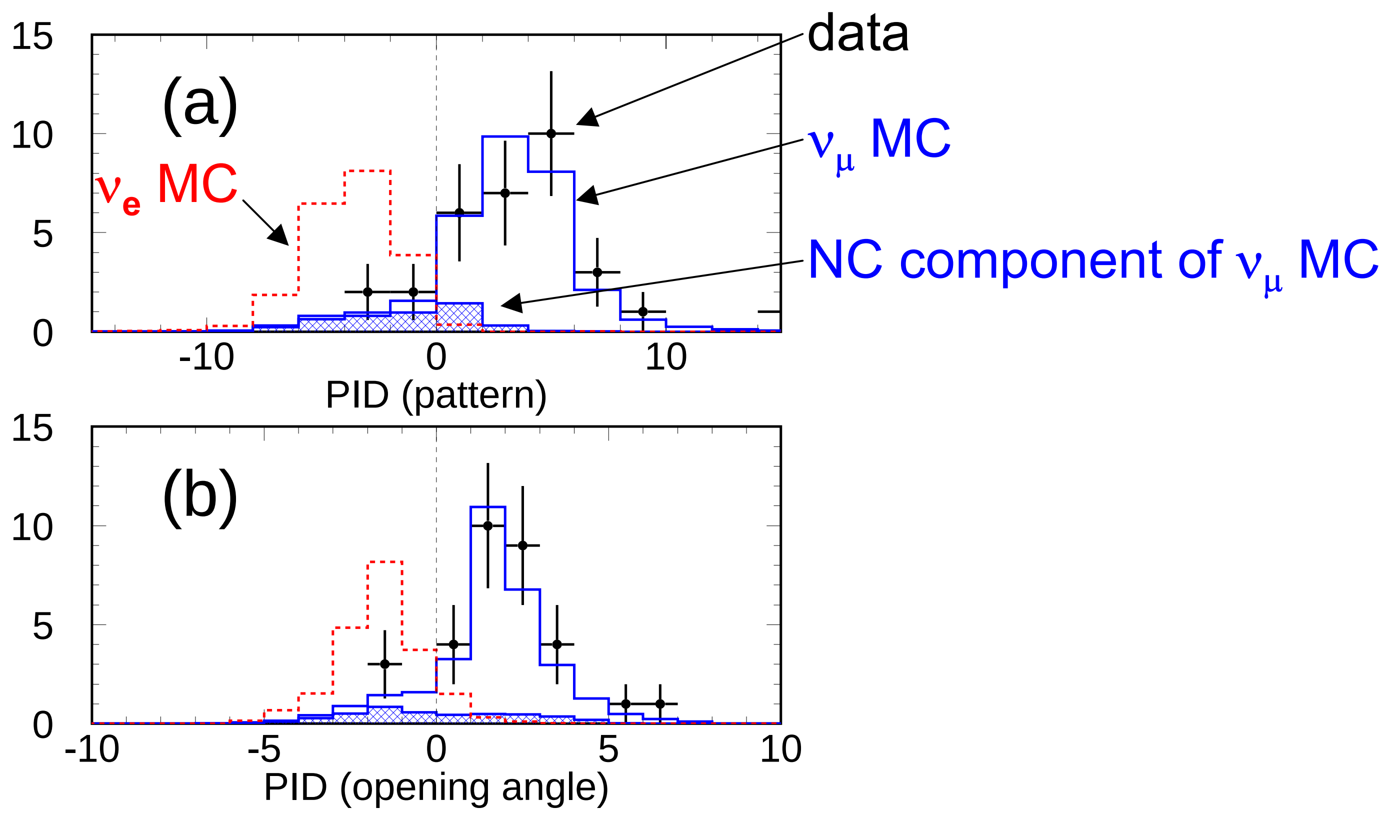
  $N_{expected}$ @SK is $80.1(^{+6.2}_{-5.4})$ events
- $N_{observed}$ @SK is 56 events
- $\Delta m^2 \sim 1.5 \sim 3.9 \times 10^{-3}\ eV^2$ @$\sin^2 2\Theta = 1$ (90%CL)

Search for ν_e Appearance in K2K-I

- One single e-like Cherenkov ring is the signature of ν_e appearance
- Both the Cherenkov ring pattern & opening angle are required to select an electron event
- $E_{visible}$ > 100 Mev : to reject low momentum charged π & e from μ decay

Chrenkov Ring pattern

Cherenkov Opening angle

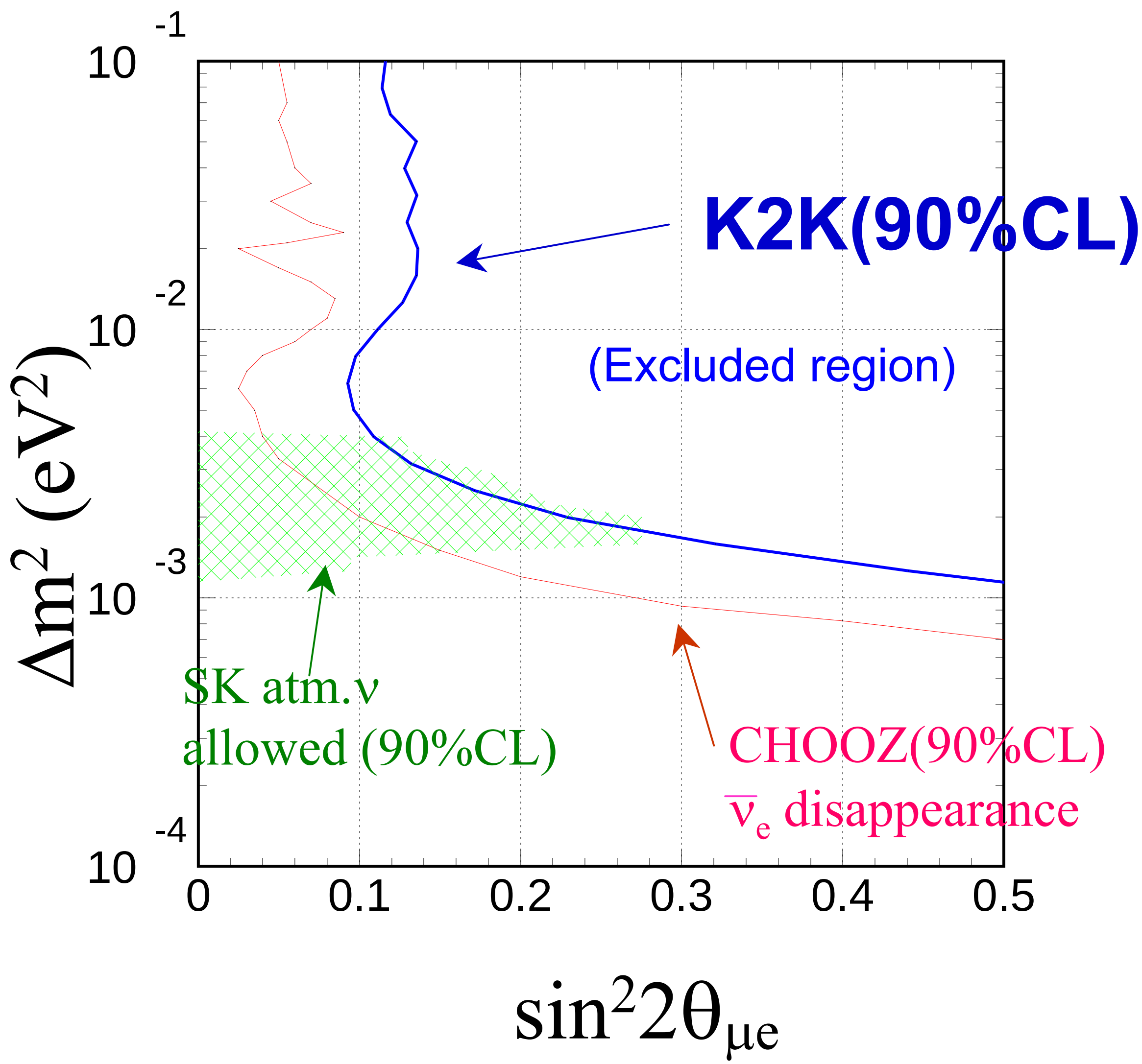


Summary of Event Reduction ($\nu_\mu \rightarrow \nu_e$)

DATA set: June 99 – July 01 (4.8×10^{19} POT)

	DATA	ν_μ MC (w/o osc)	beam ν_e MC	ν_e from ν_μ $\sin^2 2\theta_{\mu e}=1$, $\Delta m^2=2.8\times10^{-3}eV^2$
FCFV	**56**	80	0.82	28
Single ring	**32**	50	0.48	20
PID (e-like)	**1**	2.9	0.42	18
E_{vis}>100MeV	**1**	2.6	0.41	18
w/o decay-e	**1**	2.0	0.35	16

Comparison to Other Experiments ($\nu_\mu \rightarrow \nu_e$)



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

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(Dated: February 11, 2004)

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 $\sin^2 2\theta_{\mu e} > 0.15$ 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 $\Delta m^2_{\mu e} = 6 \times 10^{-3}\text{eV}^2$.

PACS numbers: PACS numbers: 14.60.Pq, 13.15.+g, 23.40.Bw, 95.55.Vj

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 sug-

Submitted to PRL (Feb 11, 2004)

From K2K-I result,

Mass² difference (eV²) Flight length (km)

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

Mixing angle

Neutrino energy (GeV)

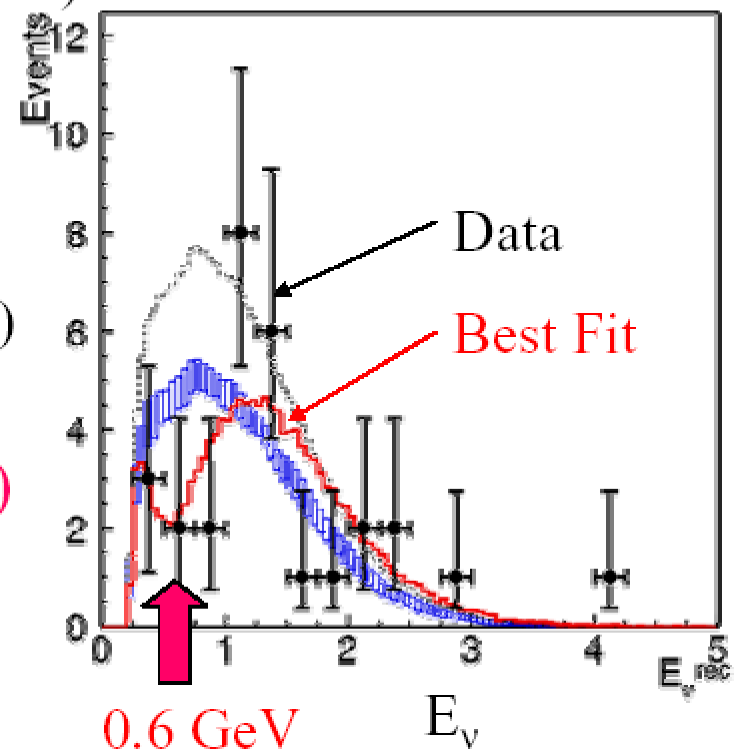
- Best fit:

  $(\Delta m^2, \sin^2 2\theta) = (2.8\times10^{-3}, 1.0)$

  for $\nu_\mu \leftrightarrow \nu_x$ Oscillation

- $E_\nu = 0.6\,\mathrm{GeV}$

  is oscillation maximum.



⇨ Need to study low energy neutrino interactions

Need for New Detector

- Detect low energy ν interactions below 1GeV to maximize the sensitivity

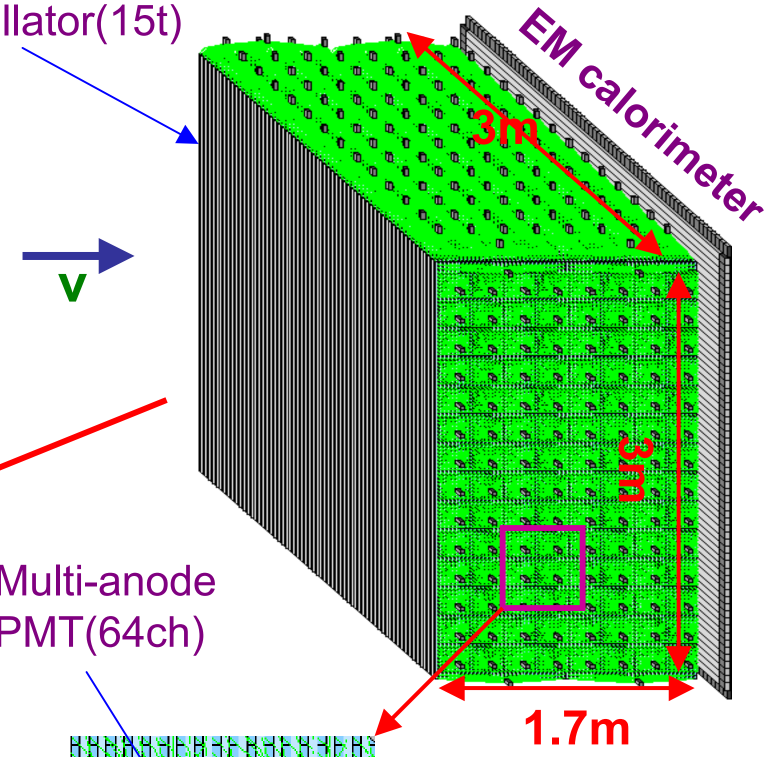
Requirements:
- Tracking detector
- Can detect low momentum protons
- P/π/μ separation
- Fairly large fiducial volume
- e-ID and energy measurement

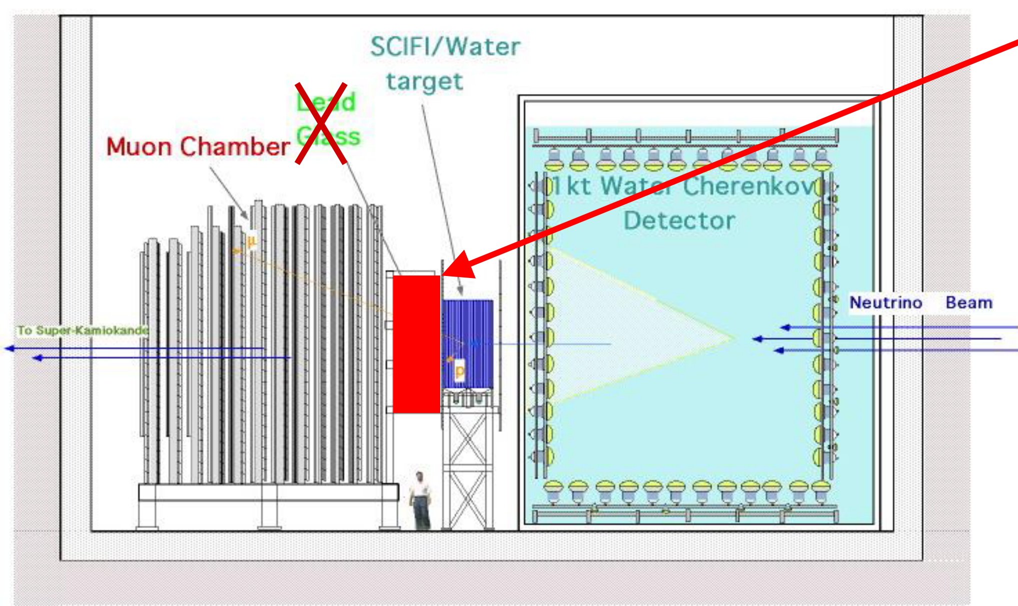
→ Need for a new detector to replace Lead Glass(LG) detector

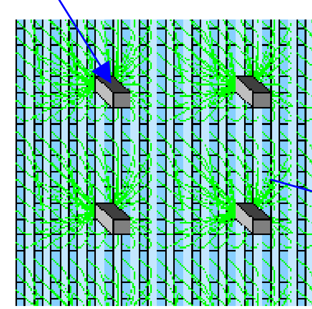
K2K Upgrade (SciBar Detector)

- Scintillator + WLS fiber

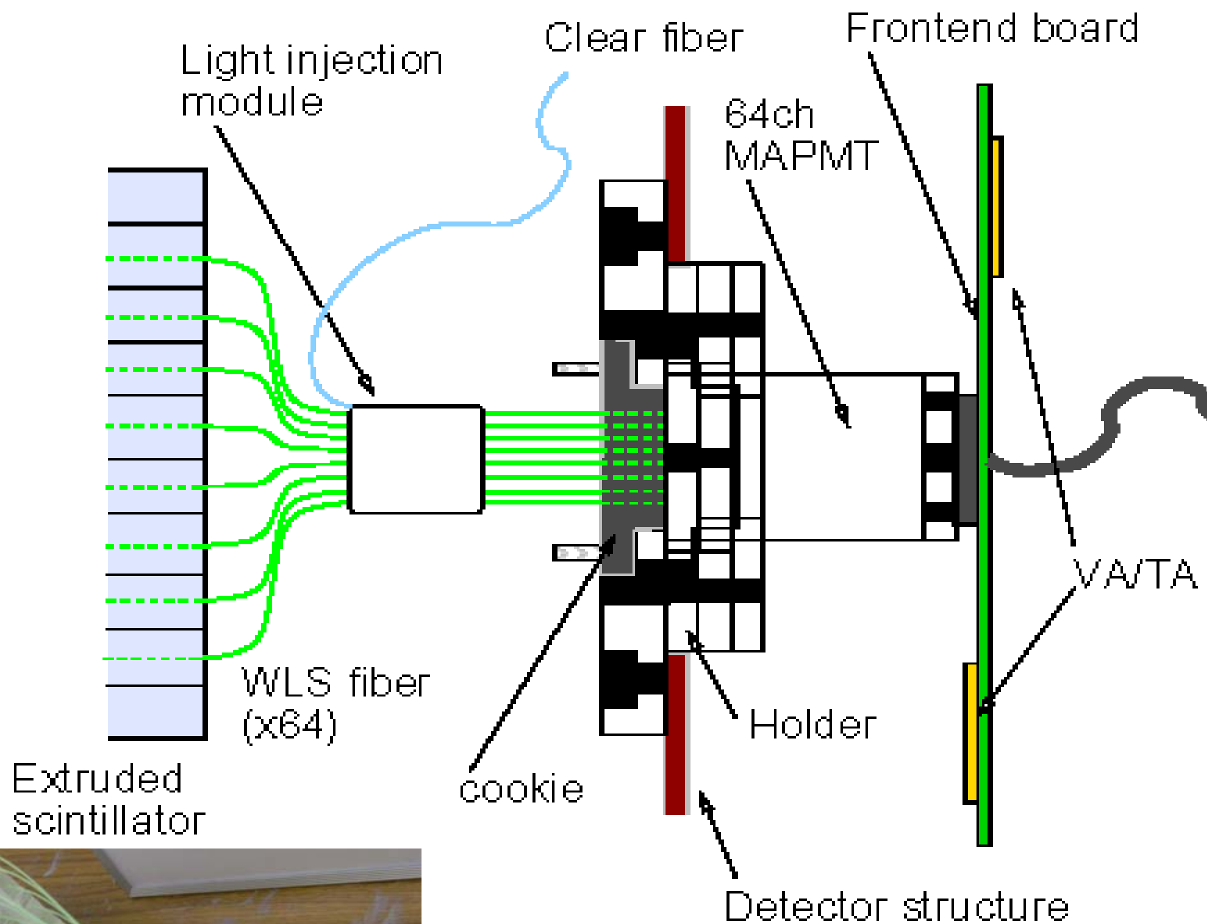
- Scintillator:
  Fine segments (2.5×1.3×300cm^3 cell)
- Neutrino target is scintillator itself
- WLS fiber (1.5mmΦ x 360 cm)
- ~15,000 channels

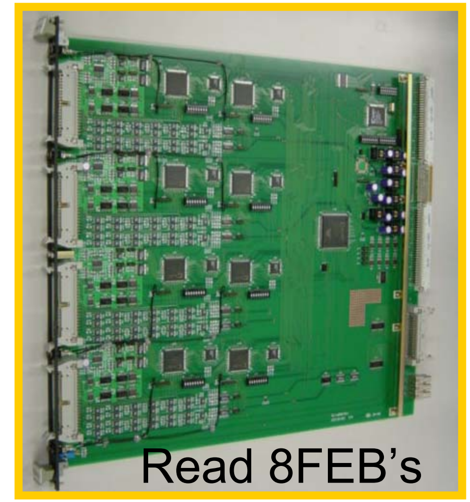




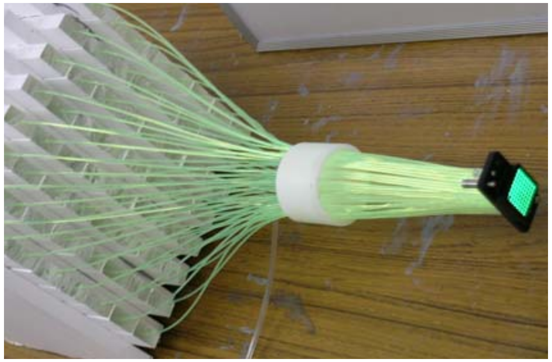


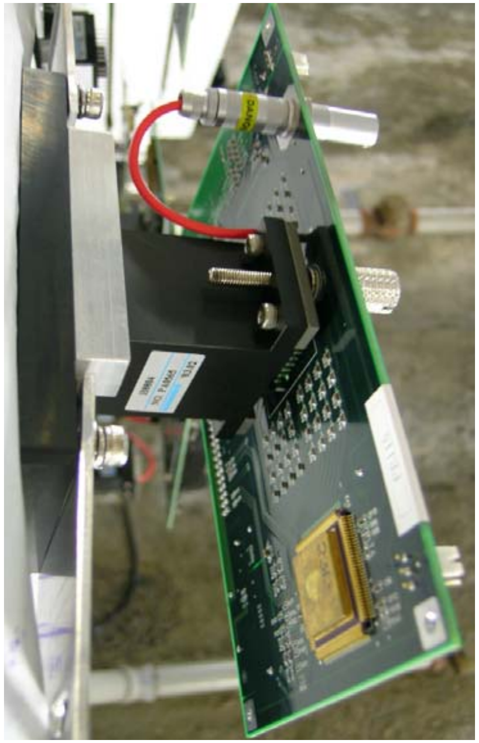
SciBar Detector Components





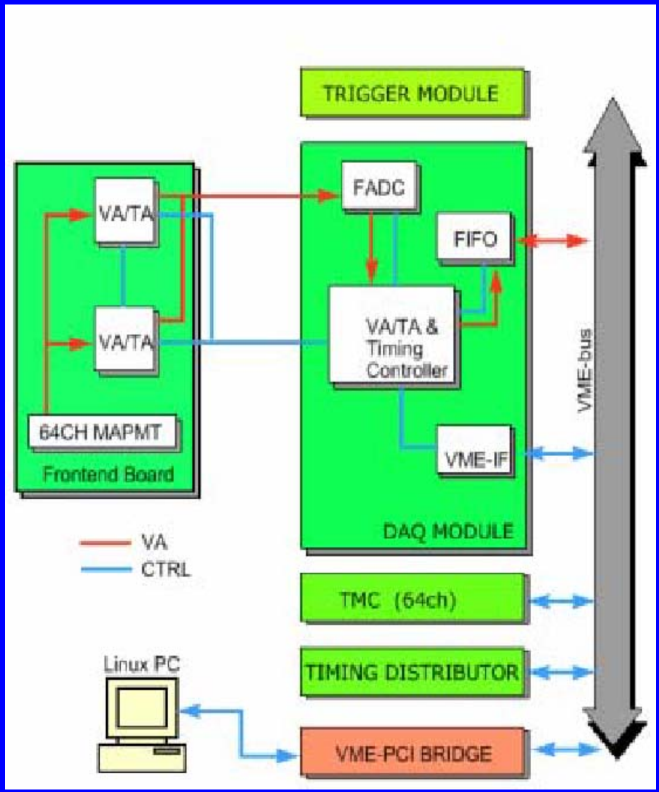
→VME board



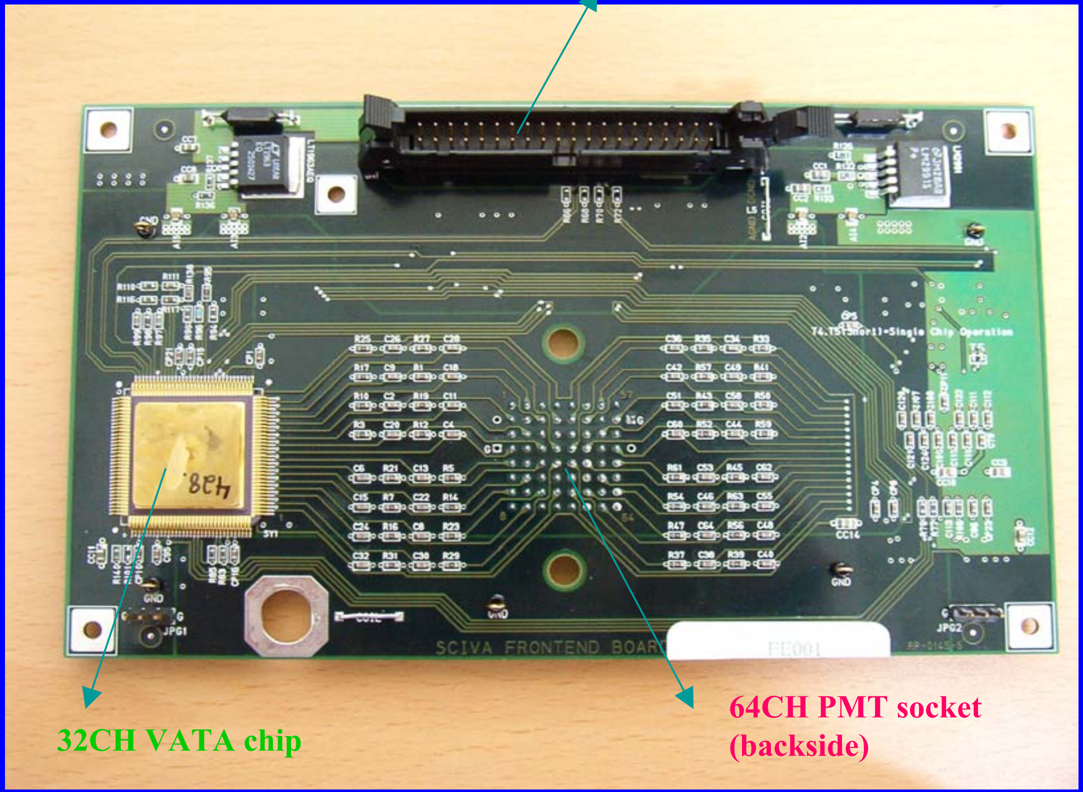


Read-out electronics supported strongly by KEK electronics group

Front End Board (FEB)



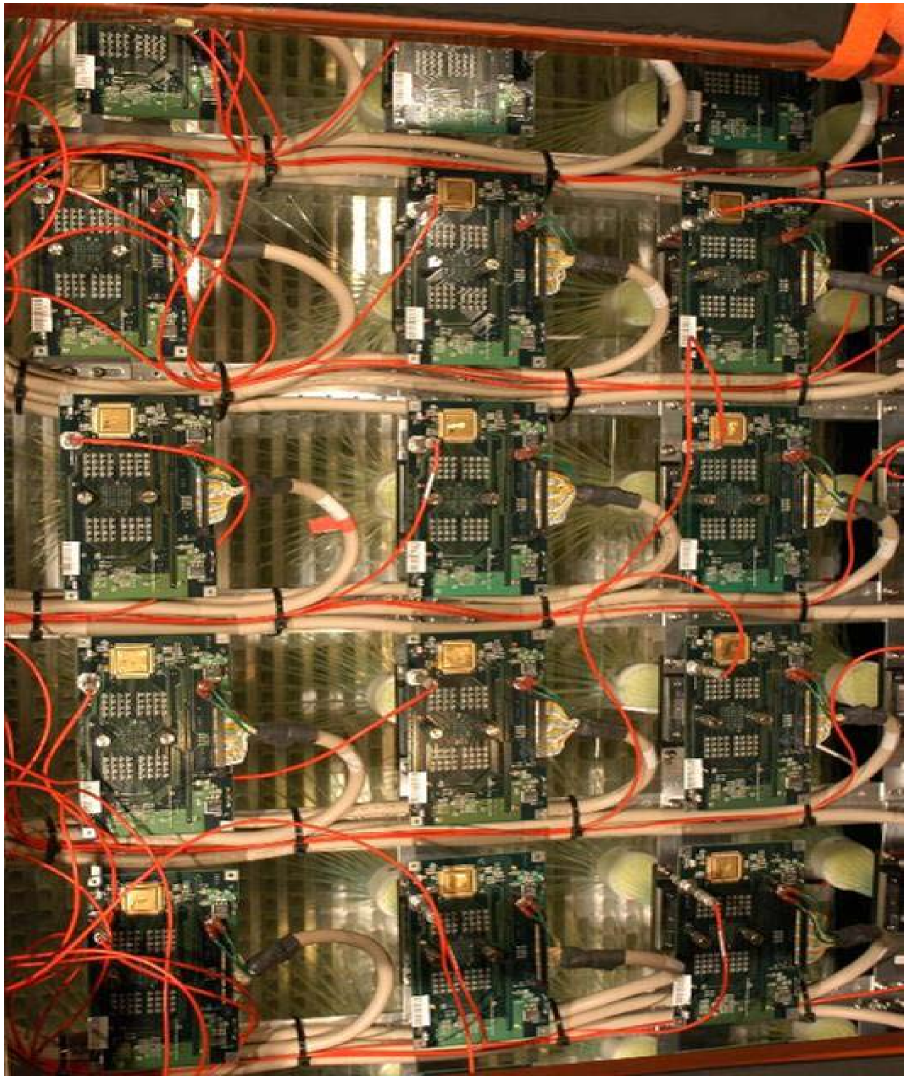
Size: 10 x 17cm



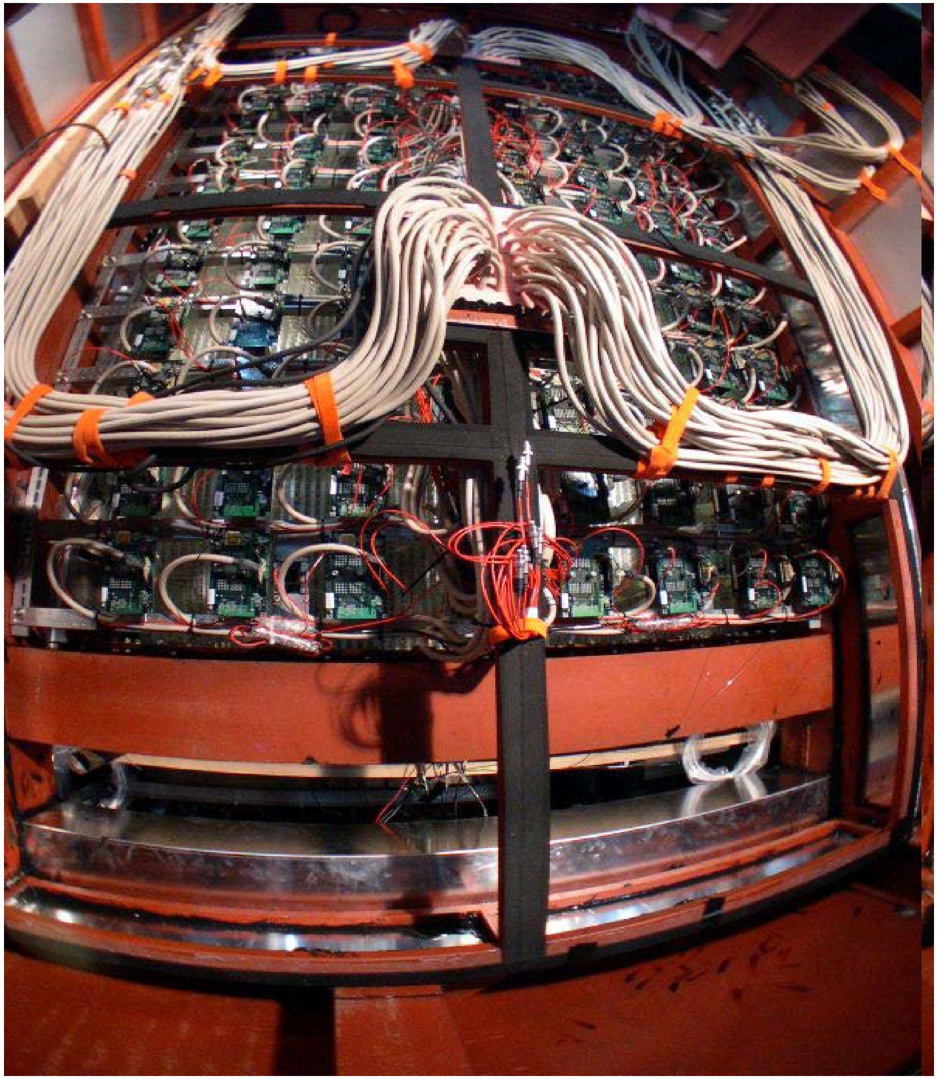
- ~300 FEBs have been made & tested at SNU
- Installed at K2K site during the summer of 2003

Installation Completed

Side View



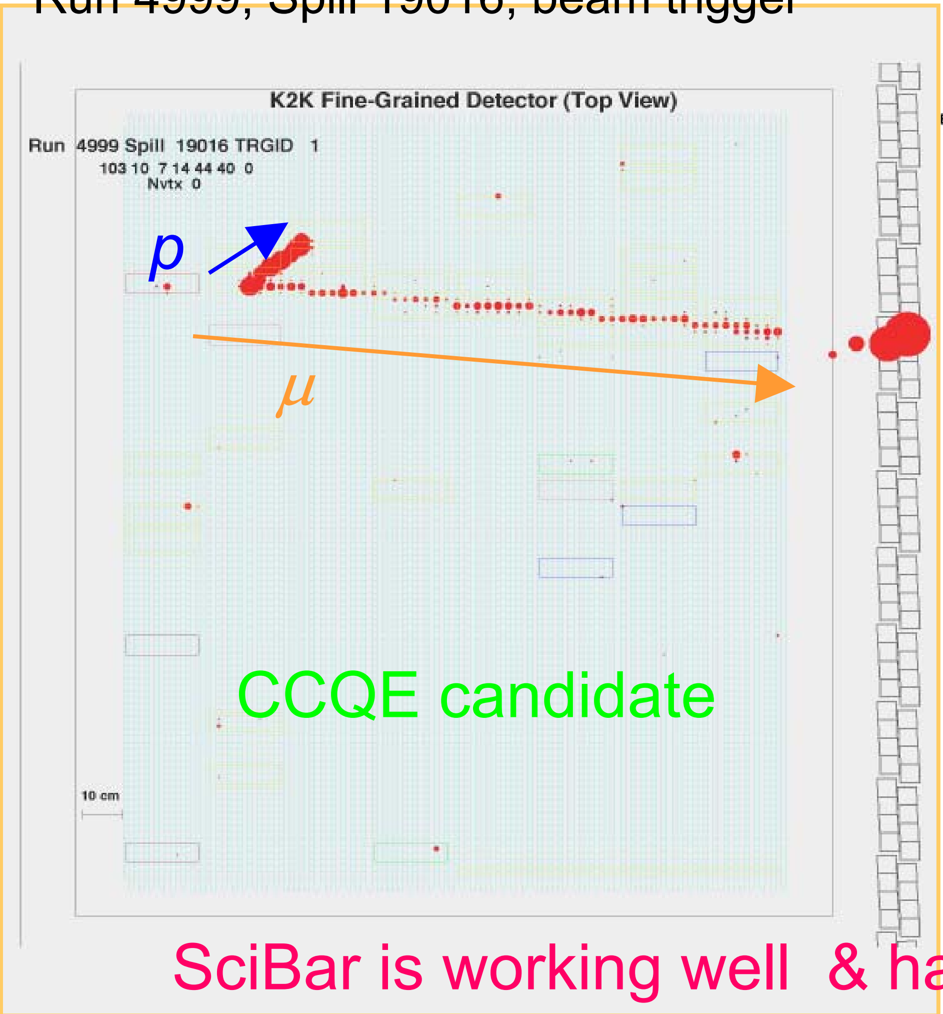
Top View

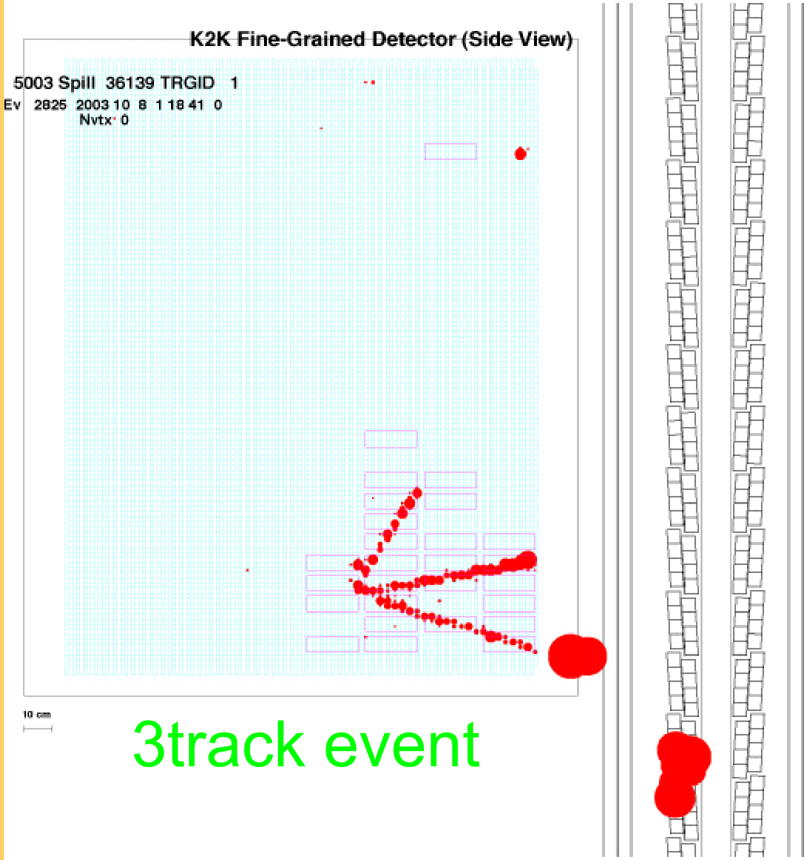


- Signal cable, HV cable are connected & well arranged

SciBar Event Display

Run 4999, Spill 19016, beam trigger

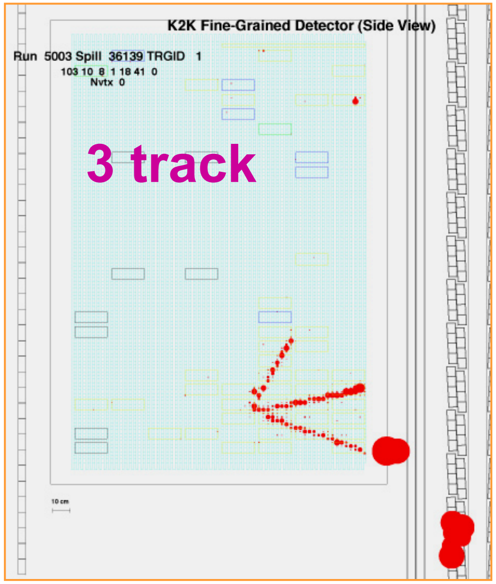


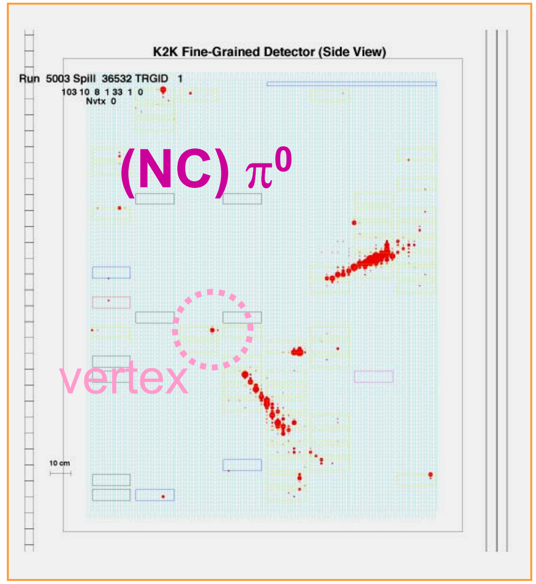


3track event

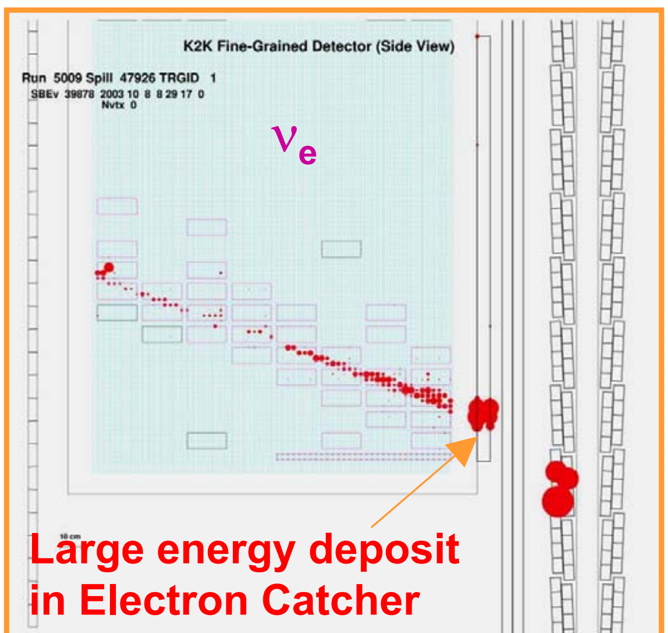
SciBar is working well & has collected nice ν events since October 2003

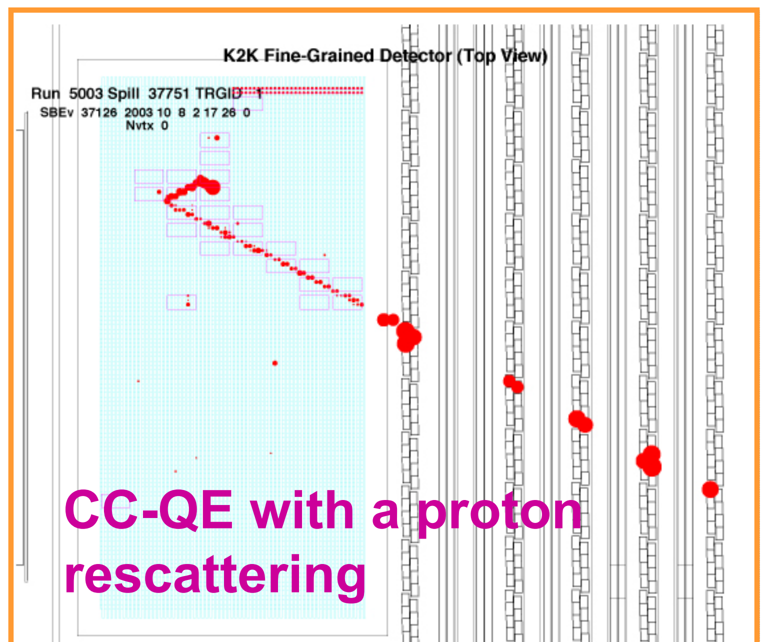
Event Gallery





- ❑ Many different kinds of ν events are observed
  - 3 track events
  - π^0 events
  - ν_e events
  - μ track + hadronic interaction
  - Single track events

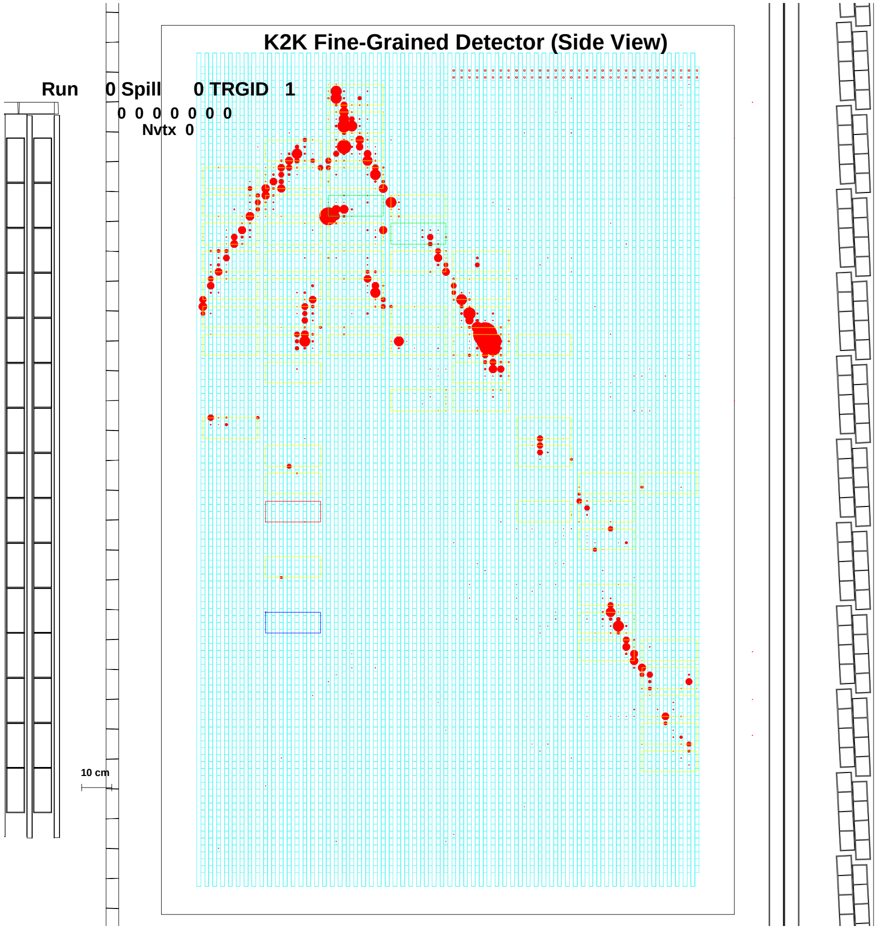




Interesting Cosmic-ray Event

Side View

Top View



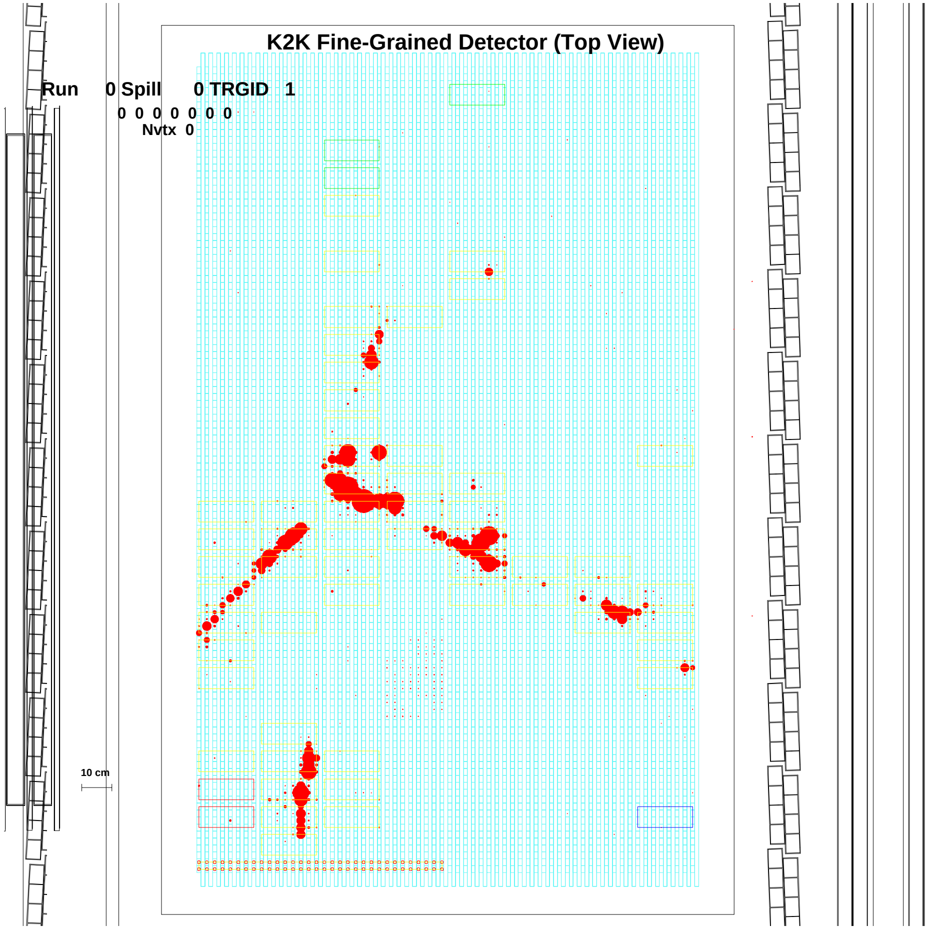
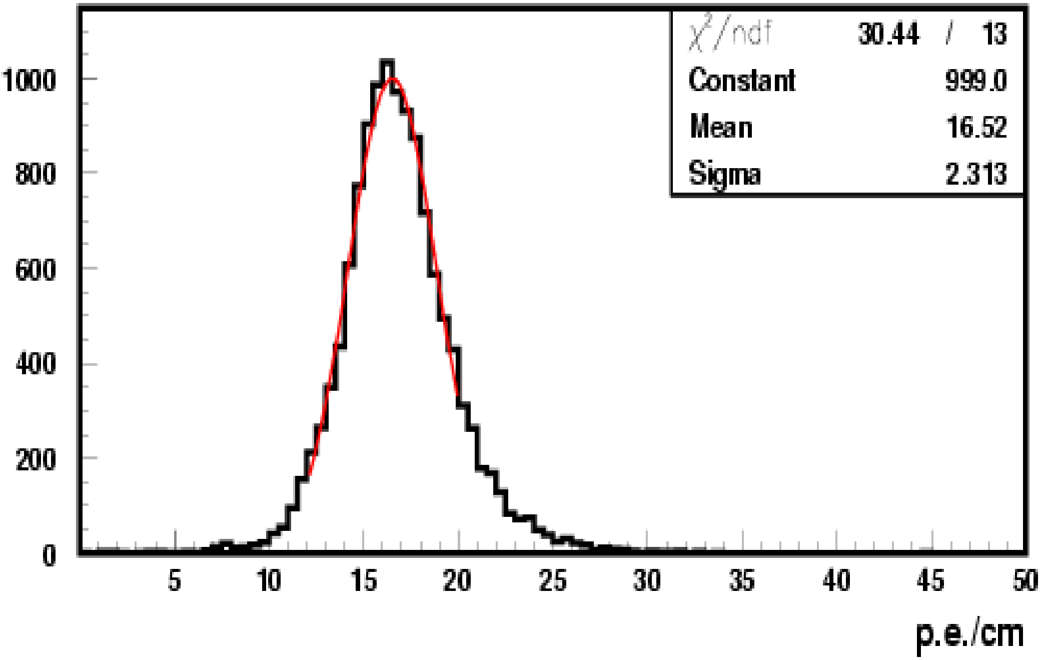
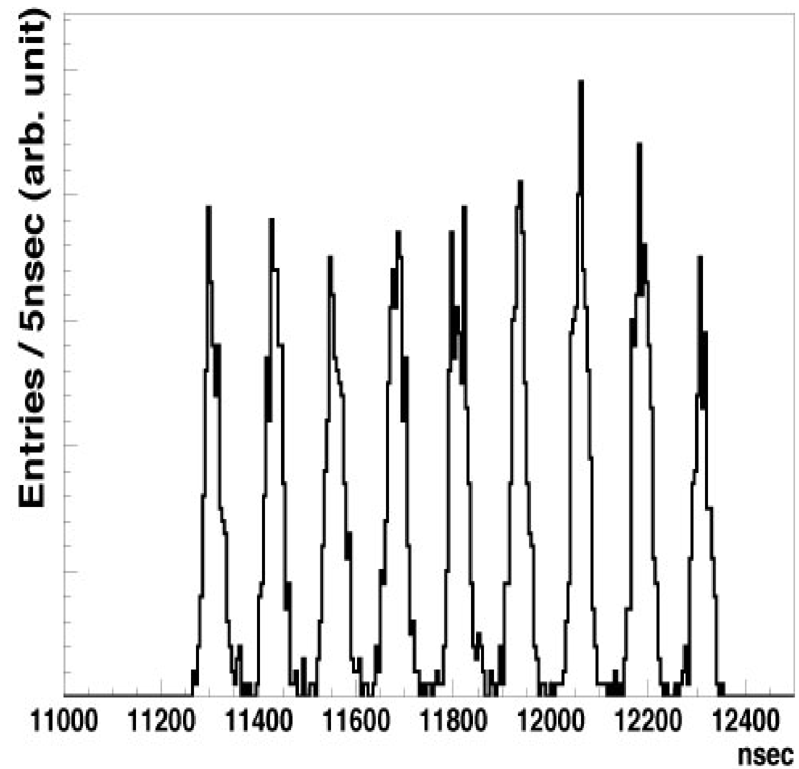


Photo-electrons of SciBar scintillators



Light Yield = 16.52±2.31 p.e./MIP/cm
@ 40cm from PMT

(SciBar + MRD) Track Timing Distribution



9 bunch structure is observed

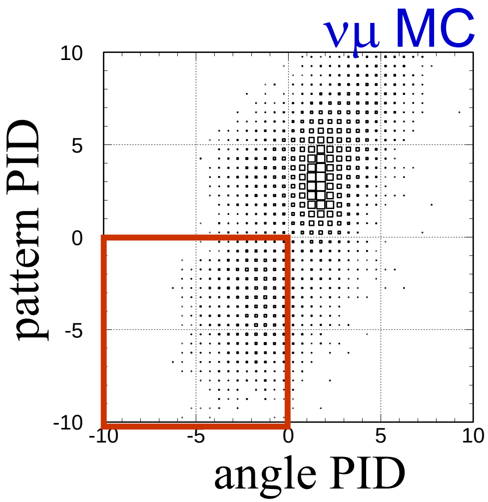
- ❑ Extensive analysis is under way
- ❑ Expected to have many good results from SciBar detector soon

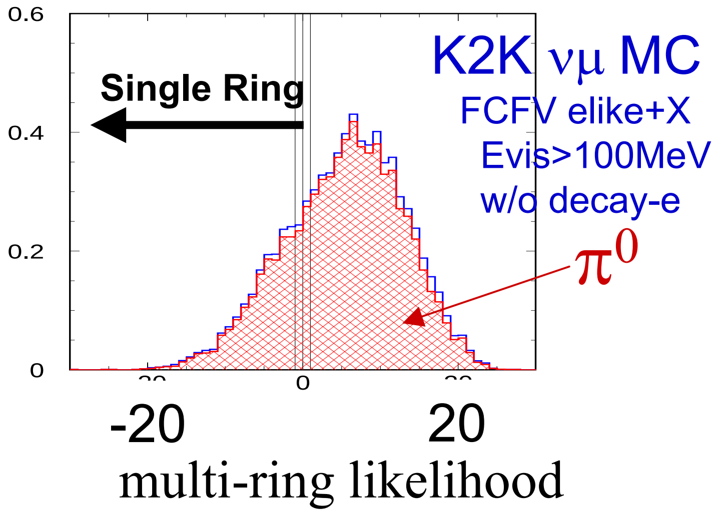
Summary

- With K2K-I data, oscillation analysis has been done
- Search for ν_e appearance has been made
- Excluded region is set for the $\nu_\mu \to \nu_e$ oscillation
- K2K-II data taking is under way & going very smoothly
- New detector SciBar has been constructed & working well
- Expected to a good results from a new detector
- All results will be updated by May, 2004

Systematic Errors ($\nu_\mu \rightarrow \nu_e$)

- Particle ID
  - shift likelihood distributions in MC
    - +11%–11% in νμ BG
    - +7%–12% in νe appearance signal
- Ring Counting
  - shift likelihood distributions in MC
    - +15%–13% in νμ BG
  - compare likelihood of atm.ν DATA and MC
    - ±6% in νe appearance signal
- NC Cross Section
  - change NC cross section within 30%
    - +20%–25% in νμ BG



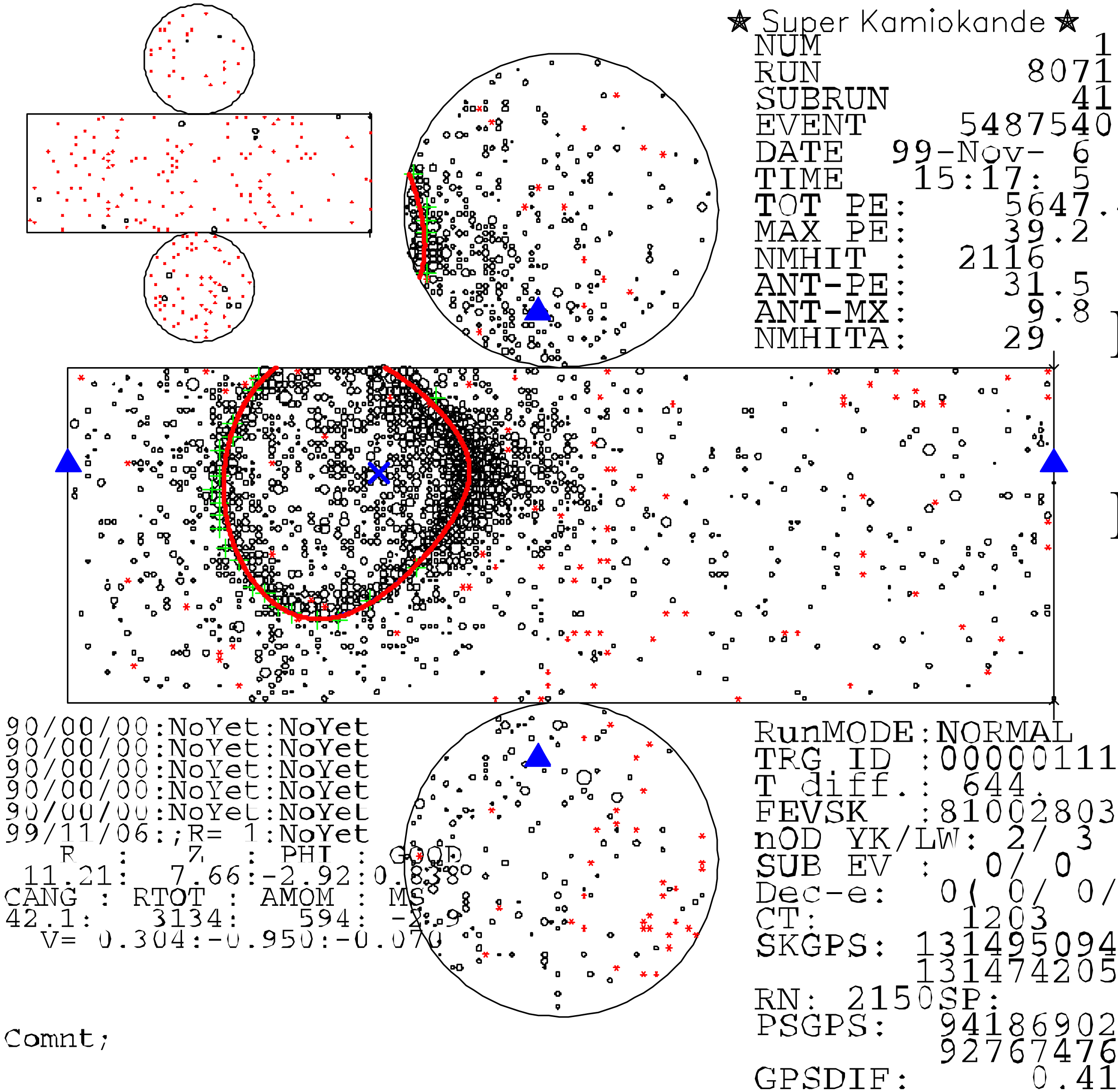


Systematic errors in the expected number of ν_μ BG in SK

- Horn current & target diameter were different in June 99 from the other period

	Jun.'99	Nov.'99~
(FV) ε_{1KT}	$\pm$4%	$\pm$4%
(FV) ε_{SK}	$\pm$3%	$\pm$3%
Ring count	+15% –13%	+15% –13%
PID	$\pm$ 11%	$\pm$ 11%
Far/Near ratio	+15% –11%	$\pm$ 6%
Spectrum	$\pm$14%	$\pm$ 1%
NC cross section	+22% –27%	+20% –25%
CC –nQE cross section	$\pm$ 1%	$\pm$ 0.4%
POT normalization	$\pm$ 0.9%	$\pm$ 0.6%
Total	$\pm$36%	+33% -31%

Electron Candidate



Reconst. momentum
597 MeV/c

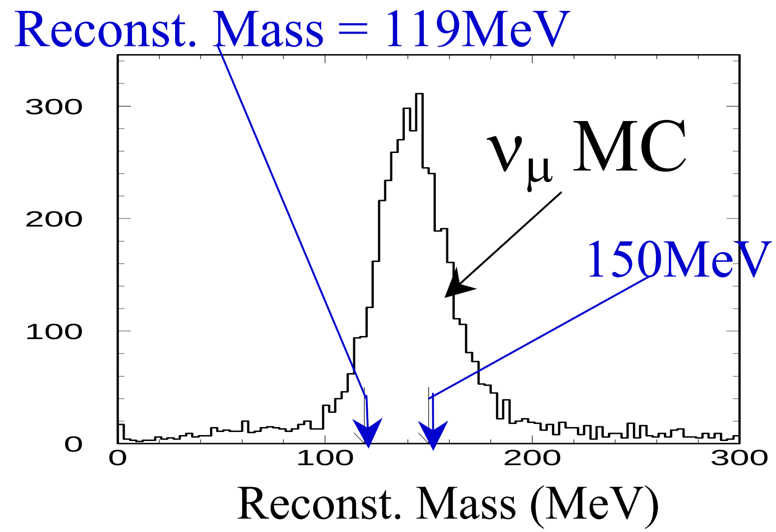
Reconst. E_ν
assuming ν_e CCQE
612 MeV

π^0 in K2K-SK

check for amount of π^0 production

π0 : FCFV & 2 e-like ring & 90<mass<190MeV & Evis>100MeV w/o decay-e
νe : FCFV & 1 e-like(tight) ring & Evis>100MeV w/o decay-e

	DATA	$\nu\mu$ MC (NC w/ π^0)
FCFV	56	80.1 (7.7)
π0	2	2.6 (2.4)
νe	1	2.0 (1.7)



Expectation by $\nu\mu$ MC is consistent with observed 2 events

K2K-I에서 관측한 중성미자

Detector	P.O.T.	Observed Events	SK Expected (w/o oscillation)
1kt (25t, H_2O)	4.24×10^{19}	~80K	**80.6** ±0.3(stat) +7.3(sys)-8.0(sys)
SciFi (5.9t, H_2O+Al)	4.20×10^{19}	7,240	**87.6** ±1.03(stat) +10.6(sys)-11.9(sys)
MRD (73t, Fe)	4.19×10^{19}	~125K	**87.4** ±0.24(stat) +12.7(sys)-13.9(sys)