Recent Results in K2K Experiment

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ICEPP Symposium 11

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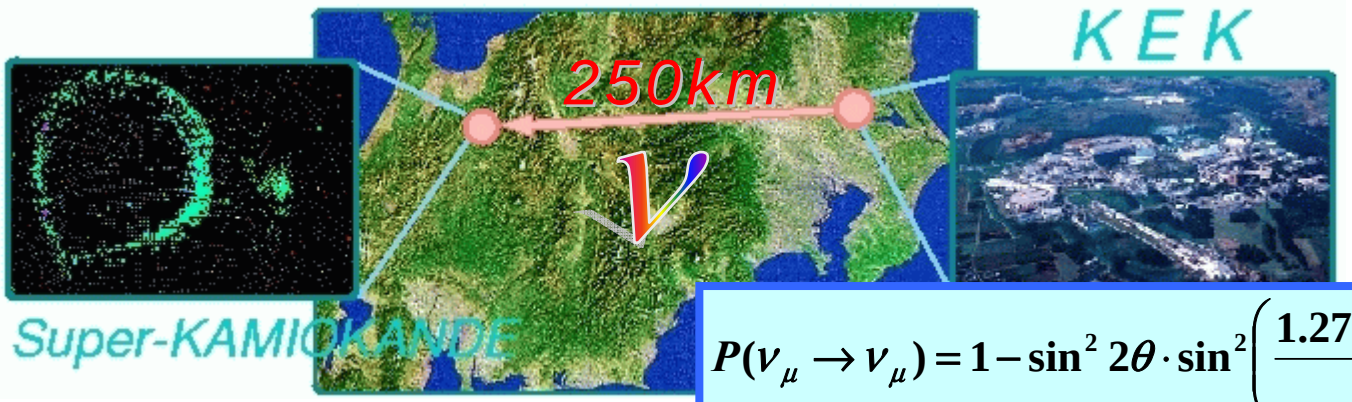
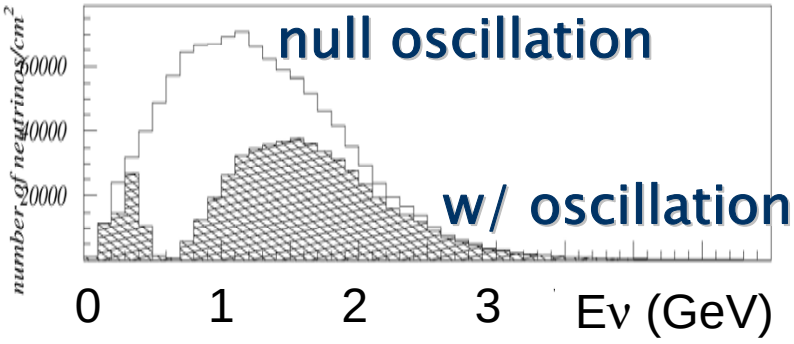
1. Introduction

K2K: KEK to Kamioka



$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \cdot \sin^2\left(\frac{1.27 \cdot \Delta m^2[\mathrm{eV}^2] \cdot L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}\right)$$

Expected spectrum at SK



Goals:

- Confirmation of ν_μ disappearance
- Discovery of ν_e appearance

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

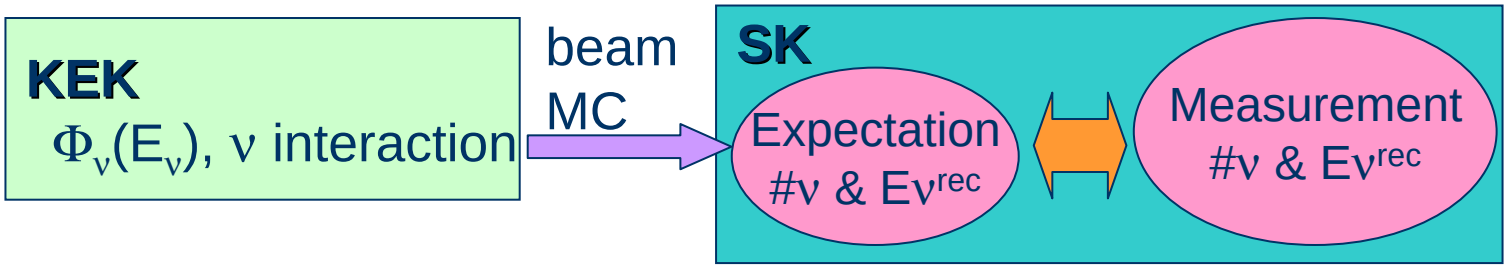
CANADA: TRIUMF / University of British Columbia

Italy: Rome Frace: Saclay Spain: Barcelona / Valencia Switzerland: Geneva

RUSSIA: INR-Moscow

2. K2K Experiment ~Overview~

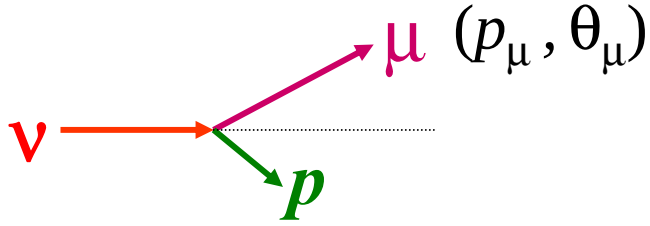
- Comparison between Far & Near measurements



- Neutrino energy reconstruction

Charged Current Quasi Elastic (CC-QE) interaction

$\nu_\mu + n \rightarrow \mu^- + p$

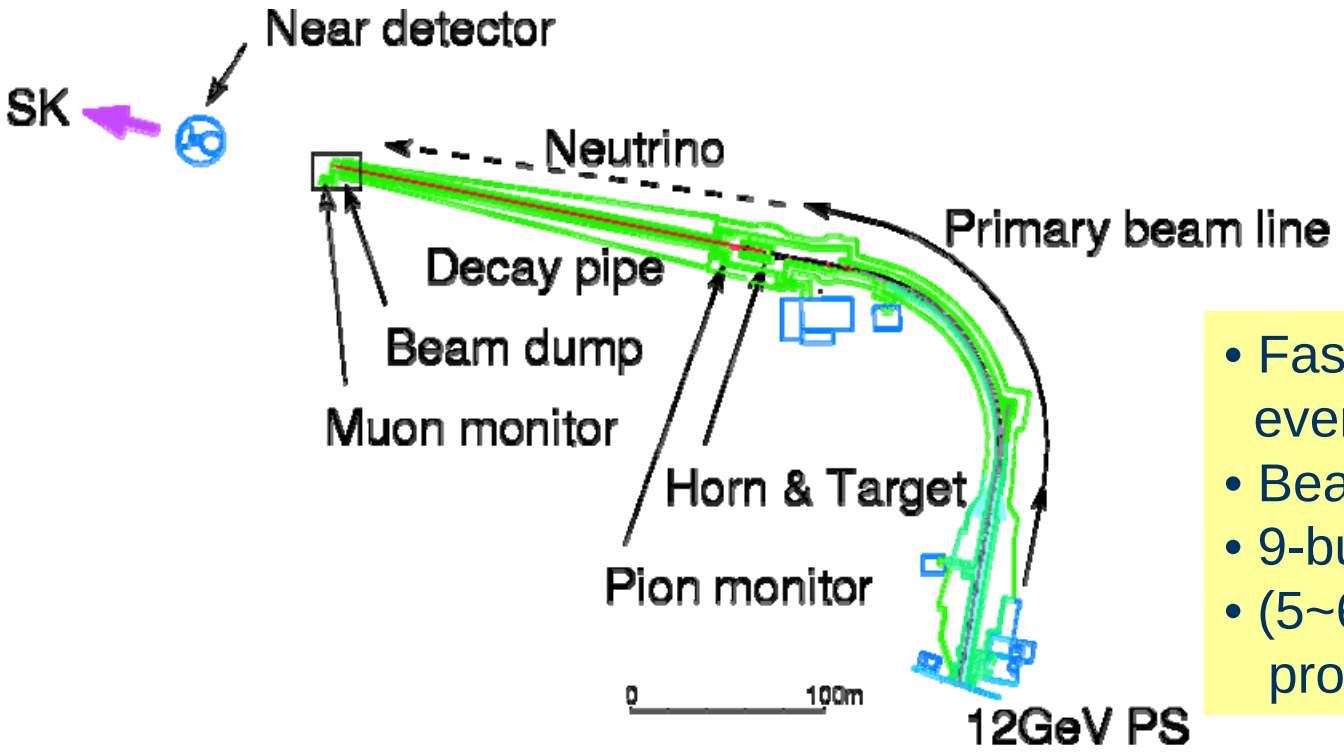


$$E_\nu^{rec} = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

2.1 Neutrino Beamline

$p + Al \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu$ (~98%)

$\hookrightarrow e^+ + \nu_e + \overline{\nu}_\mu$ (1.3%)

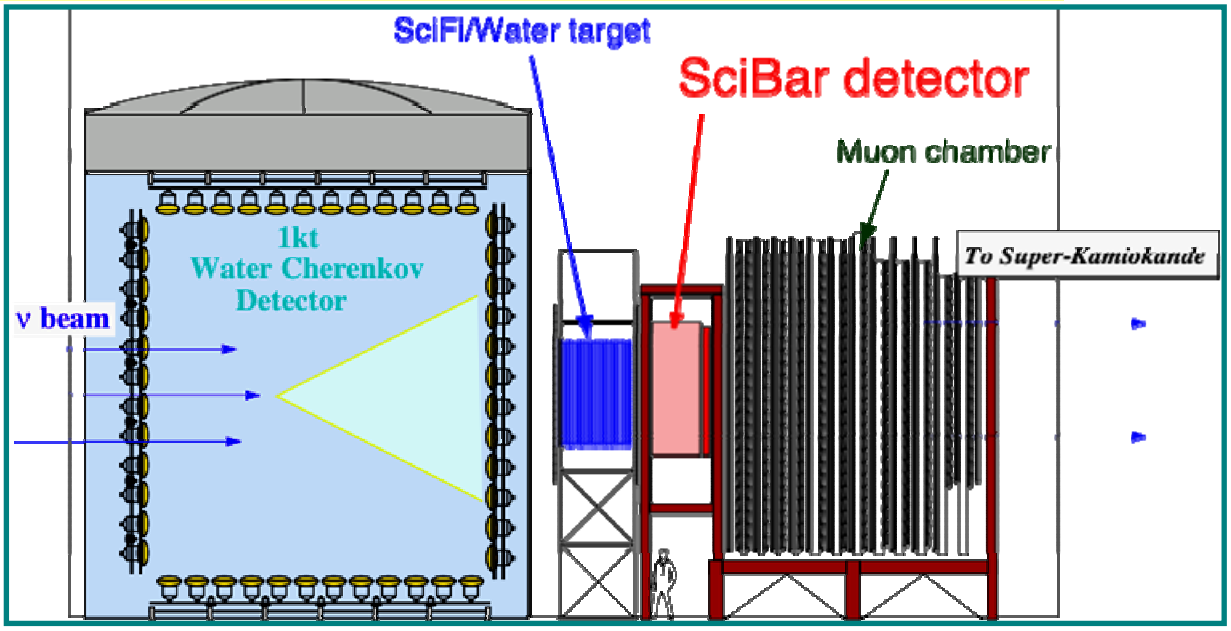


- Fast extraction every 2.2sec
- Beam spill 1.1μsec
- 9-bunch structure
- (5~6)x10^{12} protons per pulse

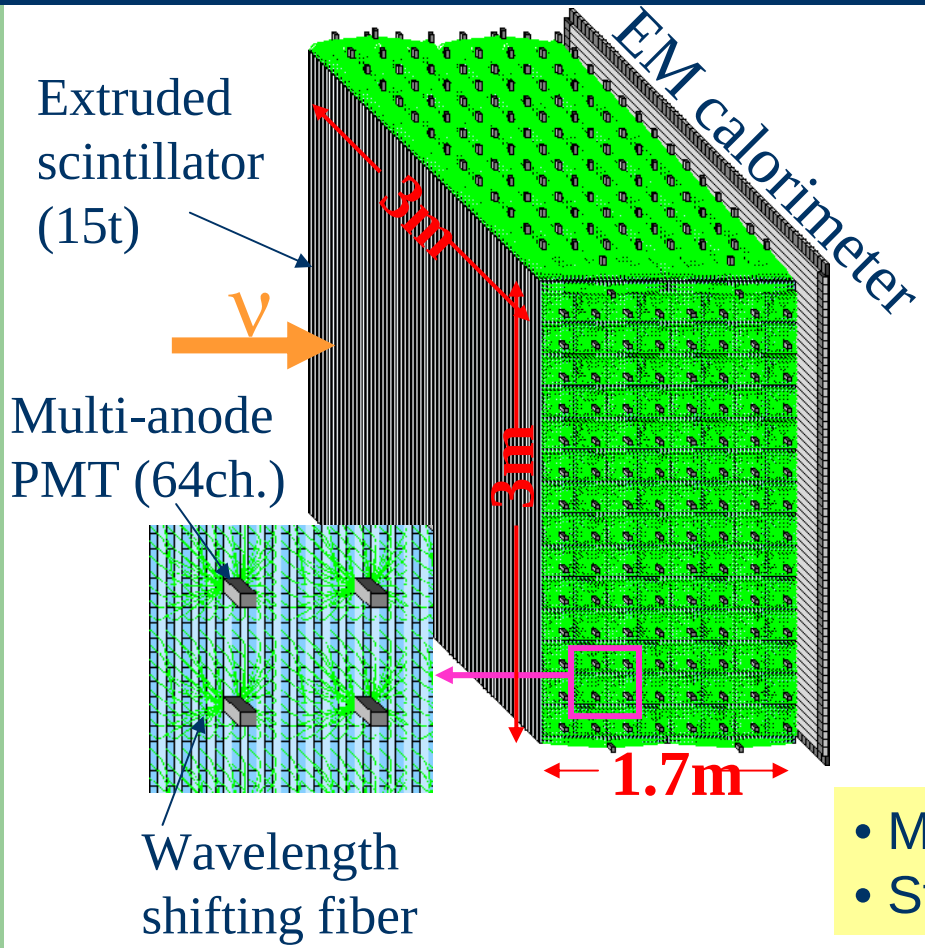
2.2 Near Detectors

- 1kt Water Cherenkov Detector (1KT)
- Scintillating-fiber/Water sandwich Detector (SciFi)
- Lead Glass calorimeter (LG) before 2002
- Scintillator Bar Detector (SciBar) after 2002
- Muon Range Detector (MRD)

→ similar to SK
→ measure nonQE/QE
→ measure ν_e/ν_μ ratio
→ study ν interaction



2.3 New Near Detector: SciBar!



Full active, fine segmented Scintillator tracker

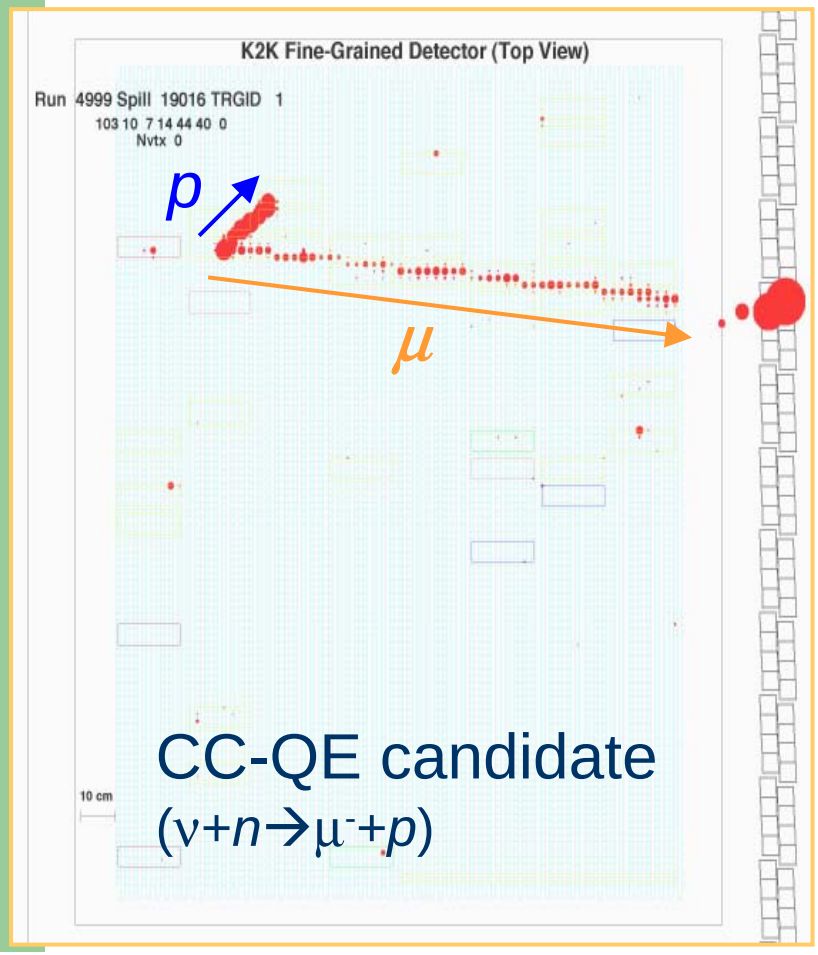
- strip size: 2.5x1.3x300 cm^3
- ~15,000 channels

Features

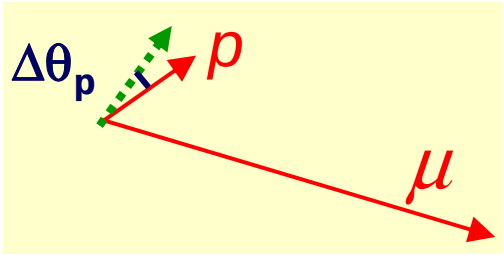
- Detection of short tracks
- *p* / π separation using dE/dx
- High efficiency for CC-QE

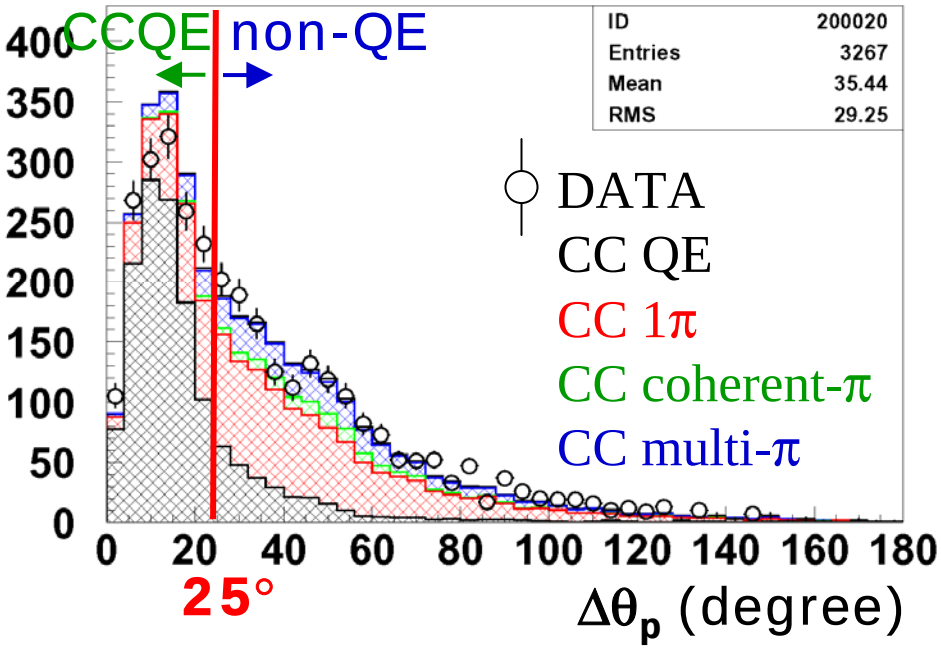
- Measure neutrino energy spectrum
- Study neutrino interaction

2.4 SciBar: spectrum measurement

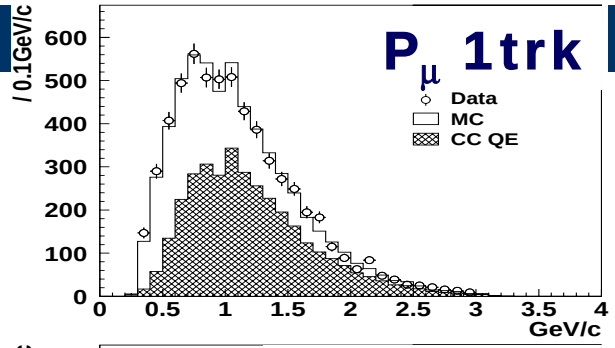


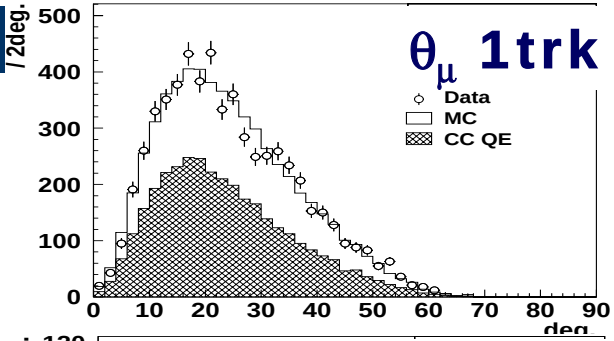
2 track events

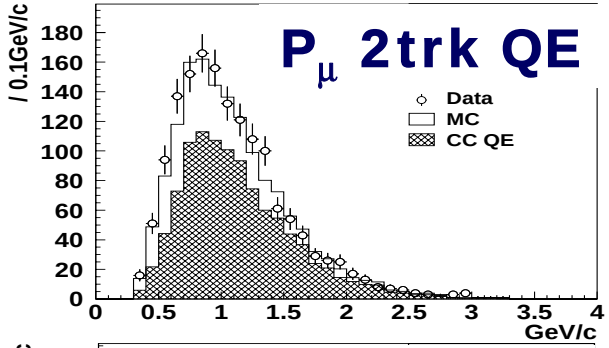


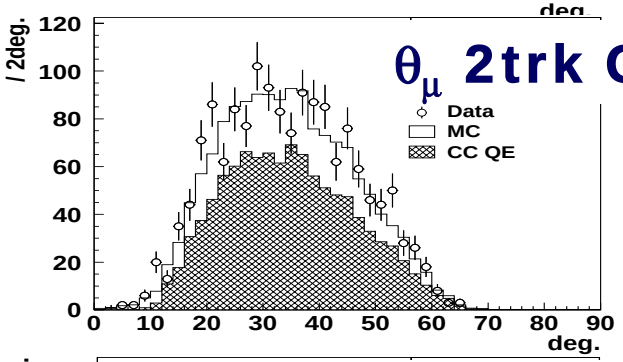


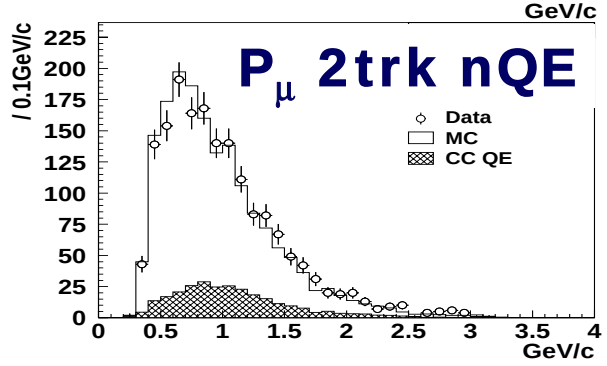
2.4 SciBar: spectrum measurement

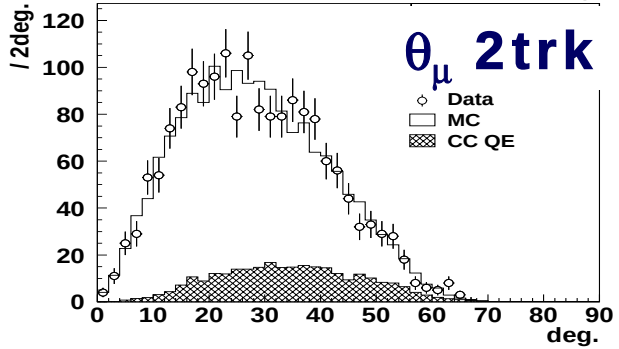












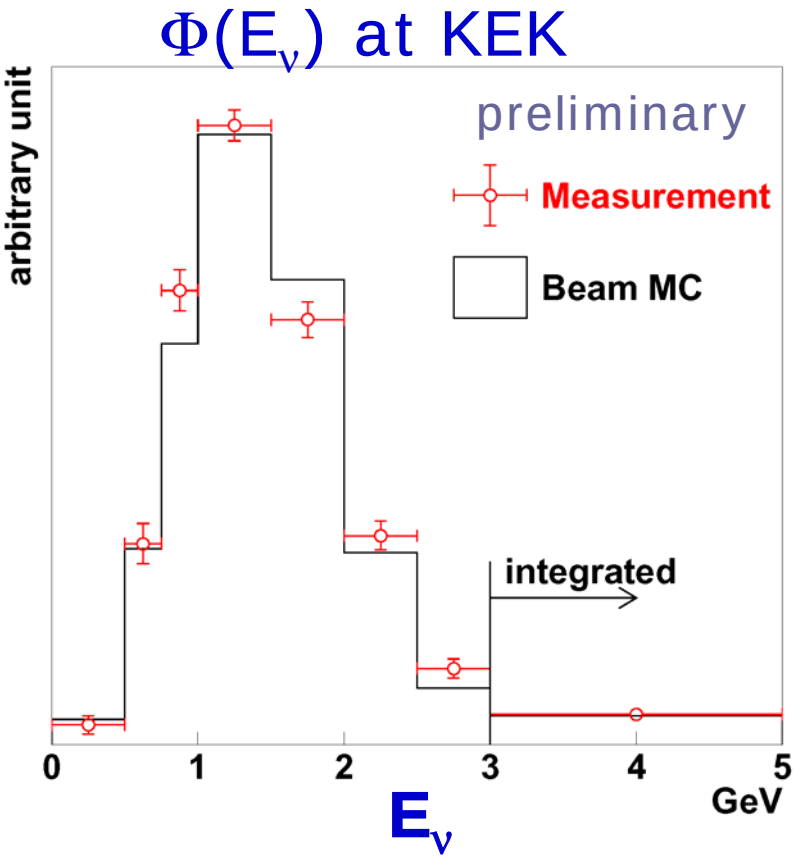
Flux measurements (using all ND)

χ^2=638.1 for 609 *d.o.f*

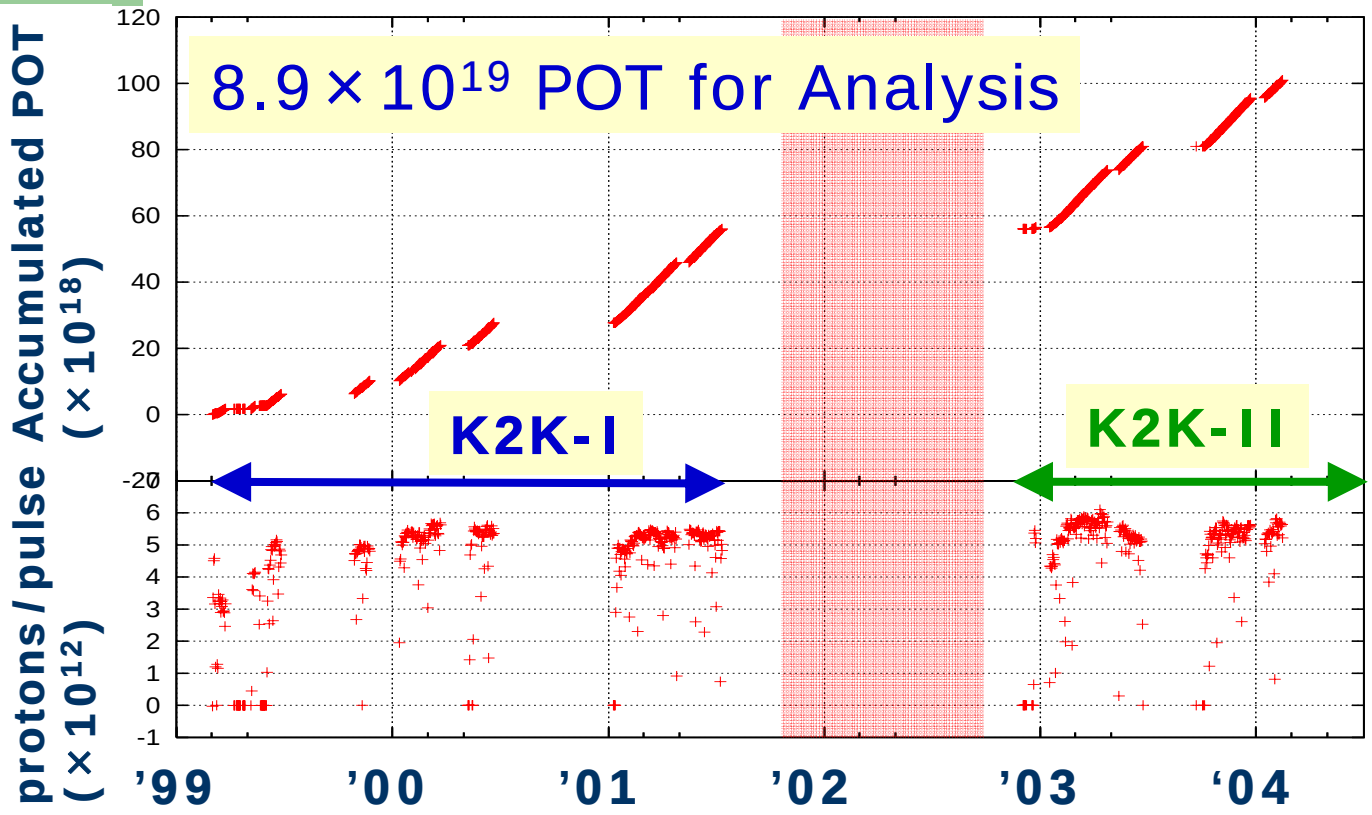
- Φ1 (Eν < 500) = 0.78 ± 0.36
- Φ2 (500≤ Eν < 750) = 1.01 ± 0.09
- Φ3 (750≤ Eν <1000) = 1.12 ± 0.07
- Φ4 (1500≤ Eν <2000) = 0.90 ± 0.04
- Φ5 (2000≤ Eν <2500) = 1.07 ± 0.06
- Φ5 (2500≤ Eν <3000) = 1.33 ± 0.17
- Φ6 (3000≤ Eν) = 1.04 ± 0.18
- nQE/QE = 1.02 ± 0.10

The nQE/QE error of 10% is assigned based on the variation by the fit condition.

- θ>10°(20 °) cut: nQE/QE=0.95 ±0.04
- standard(CC-1π low q^2 corr.): nQE/QE=1.02 ±0.03
- No coherent: π=nQE/QE=1.06 ±0.03



Accumulated POT (Protons On Target)



K2K-I

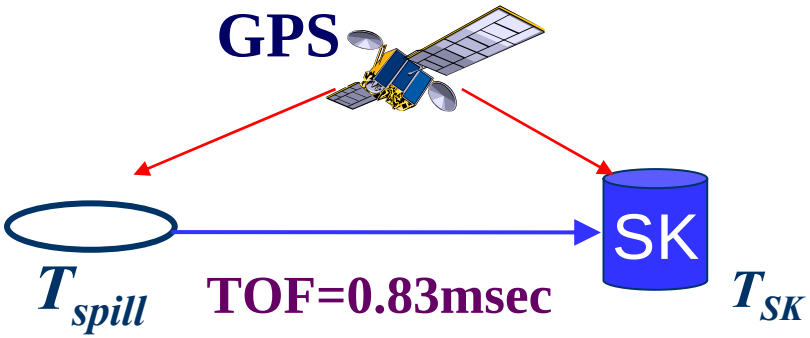
'99 Jun. ~ '01 Jul.
SK-I (11,146PMTs)

SK accident!

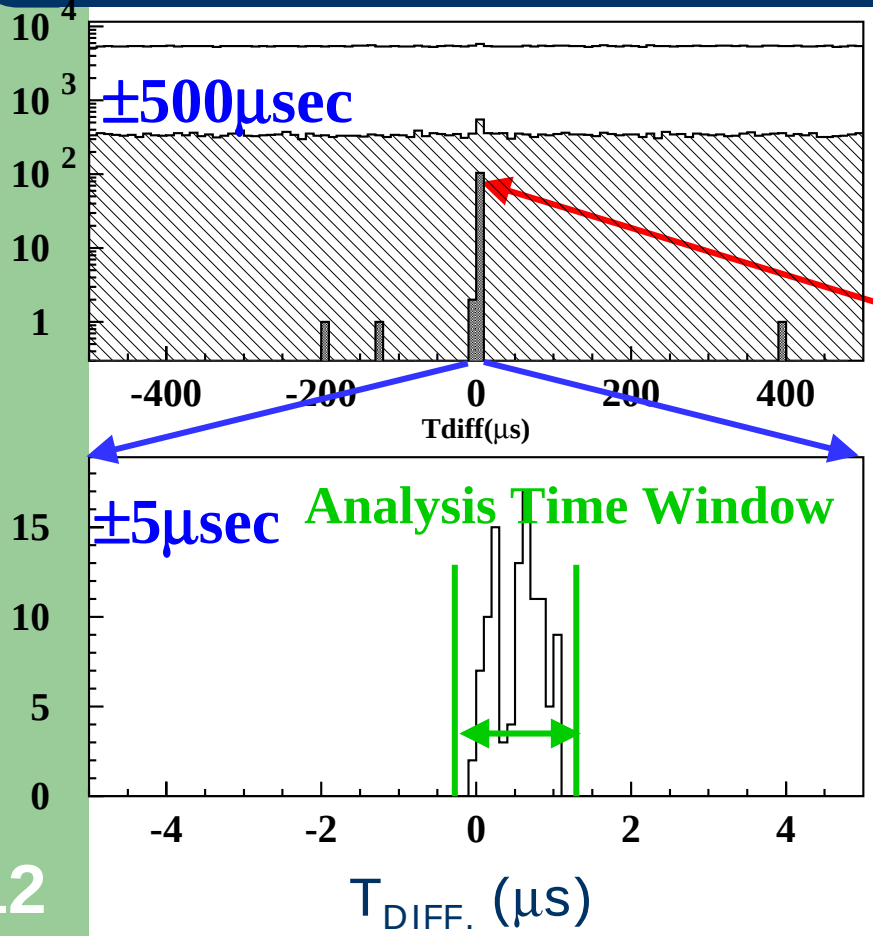
K2K-II

'02 Dec. ~
SK-II (5,182PMTs)
LG → SciBar

SK Event selection



K2K-1+2 Jun1999 - Feb2004



← Decay electron cut

← ≥20MeV Deposited Energy

Fully Contained (FC)
Vertex in Fiducial Volume (FV)
Evis>30MeV

107 events

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

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

3.1 Results ~ν_μ disappearance~

DATA set: K2K-I + K2K-II ('99 Jun.~'04 Feb.) 8.9x10^{19} POT

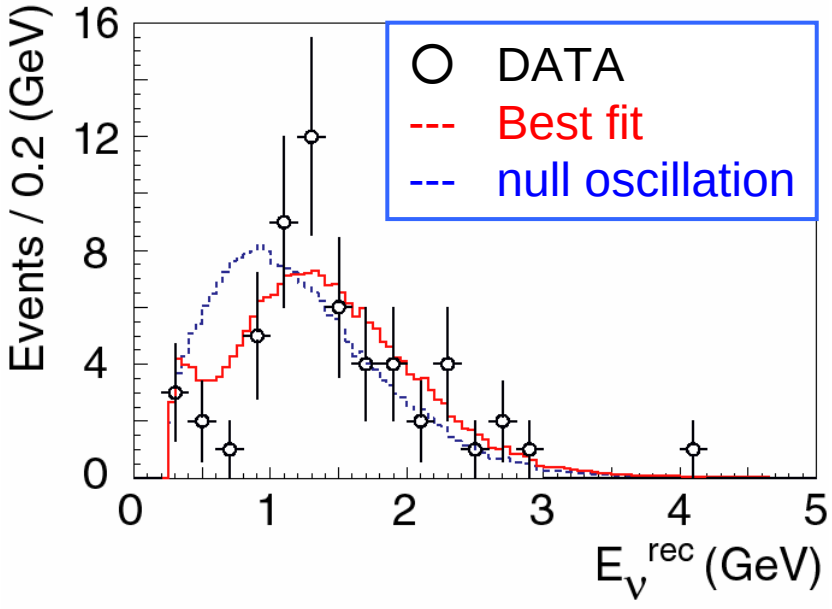
K2K-I+II	DATA	MC
FCFV,	107	150.9
1ring	67	94.0
μ-like	For $E\nu^{rec}$ 57	85.4
e-like	10	8.6
Multi Ring	40	56.9

3.1 Results ~ν_μ disappearance~

- Number of neutrino events

  107 events ⟺ Expected: 151^{+12}_{-10} events

- Neutrino energy distribution



Best fit within physical region

$\Delta m^2 = 2.8 \times 10^{-3}$ eV^2

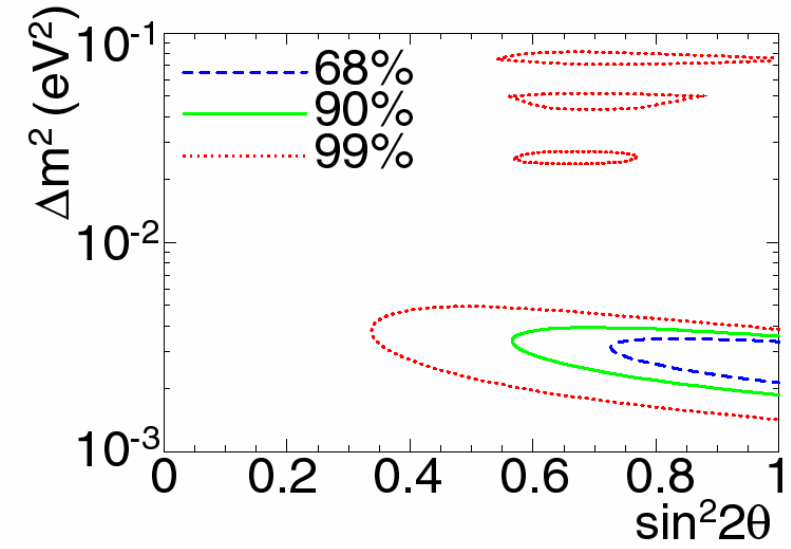
$\sin^2 2\theta = 1$

Confirm neutrino oscillation with

- ***a deficit of ν_μ events and***
- ***the distortion of the E_ν spectrum.***

3.1 Results ~ν_μ disappearance~

- Allowed region



90% C.L.

$\Delta m^2 = (1.9\sim3.6) \times 10^{-3}$ eV^2

$\sin^2 2\theta = 1$

Null oscillation probability
0.0050% (4.0σ)

arXiv:hep-ex/0411038
Accepted for publication in PRL

3.2 Results ~ν_e appearance~

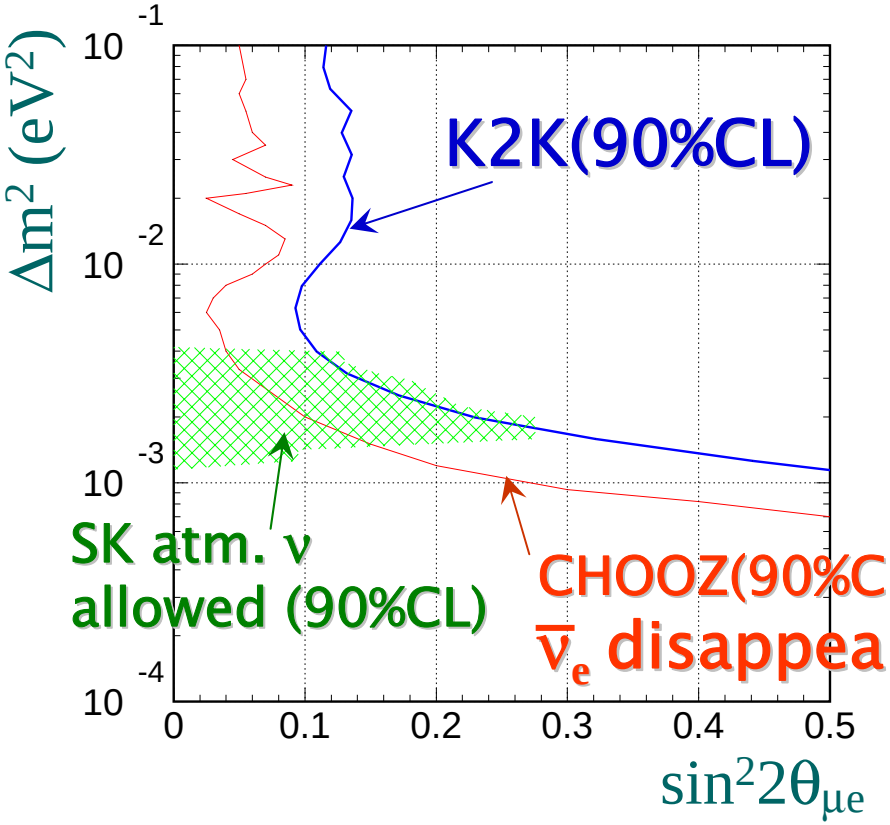
DATA set: K2K-I ('99 Jun. ~ '01 July) 4.8x10^{19} POT

	DATA	MC		
		ν_μ w/o osc.	Beam ν_e	ν_e from 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

1 electron candidate ⟺ Expected background 2.4±0.6 events

3.2 Results ~ν_e appearance~

- Exclude region ($\nu_\mu \rightarrow \nu_e$)



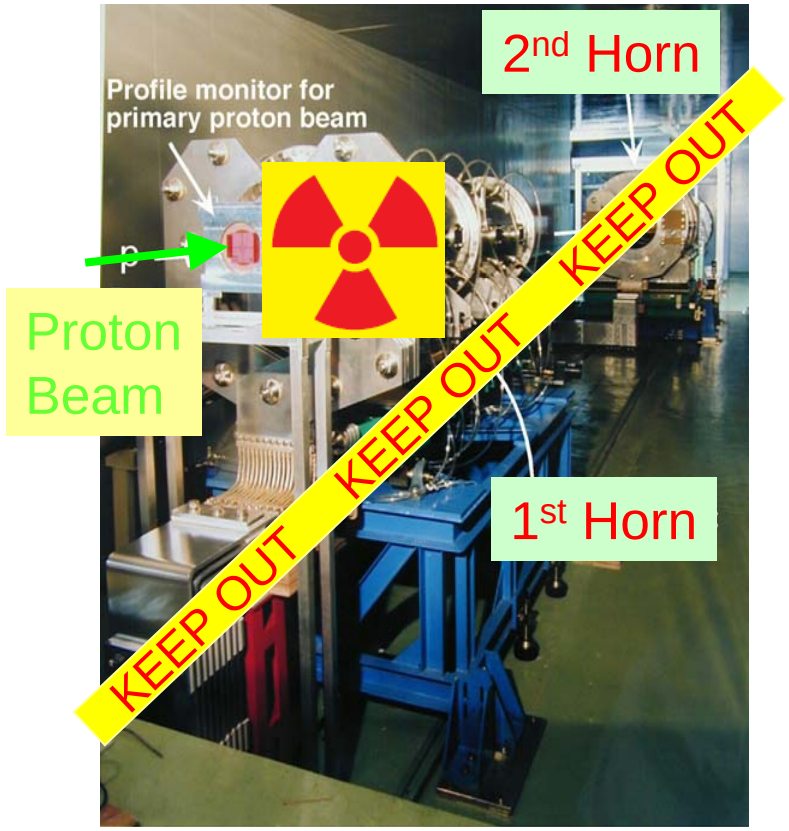
90%CL

$\sin^2 2\theta_{\mu e} < 0.15$

$@\Delta m^2 = 2.8 \times 10^{-3}$ eV^2

PRL **93,** 051801(2004)

4. Current Status



- ’04 Oct.

  K2K has resumed.

  However…
- ’04 Nov. 6th

  1st Horn broke down!
- ’04 Dec.

  K2K decided to finish the run.

5. Summary

- K2K has confirmed ν_μ disappearance at 4.0σ with
  - Deficit of ν_μ events and
  - Distortion of the Eν spectrum
- As for ν_e appearance mode, there is one candidate event, but consistent with background.

- K2K finished the run due to horn trouble.
- However, physics analyses are going on.

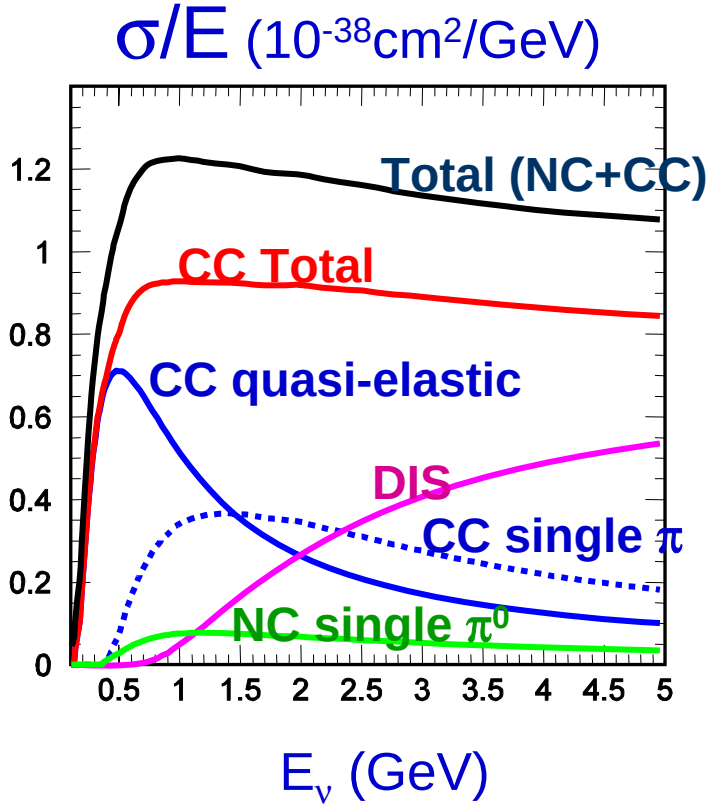
~ From K2K to T2K ~

Backup slides

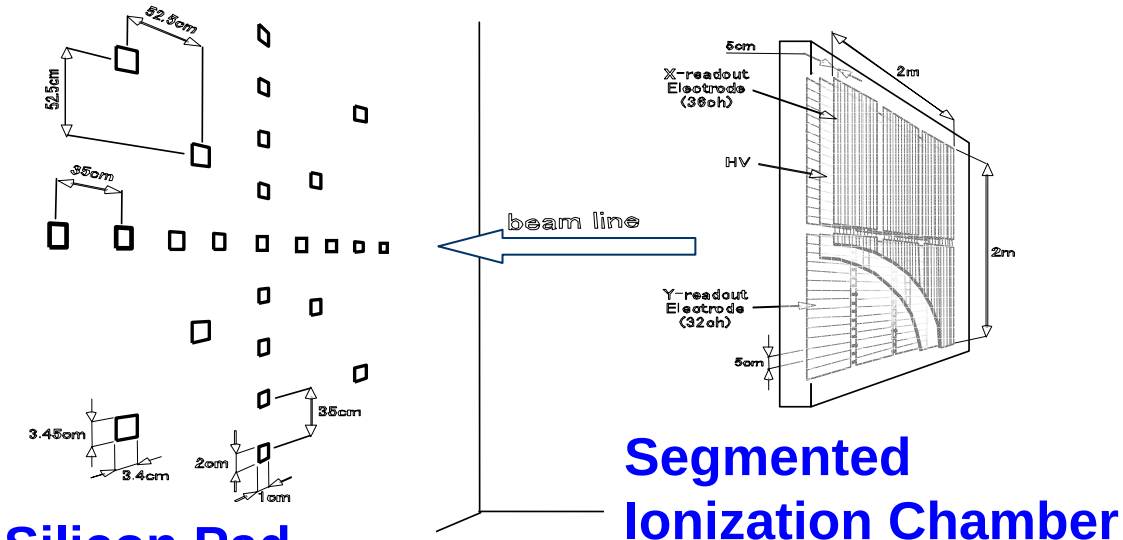
NEUT: K2K Neutrino interaction MC

- **CC quasi elastic (CCQE)**
  - Smith and Moniz with M_A=1.1GeV
- **CC (resonance) single π(CC-1π)**
  - Rein and Sehgal's with M_A=1.1GeV
- **DIS**
  - GRV94 + JETSET with Bodek and Yang correction.
- **CC coherent π**
  - Rein&Sehgal with the cross section rescale by J. Marteau
- **NC**

+ Nuclear Effects



Muon monitor



Silicon Pad Detector Array

Segmented Ionization Chamber

Monitoring **Intensity** and **Direction** on **spill-by-spill basis**

Behind beam dump

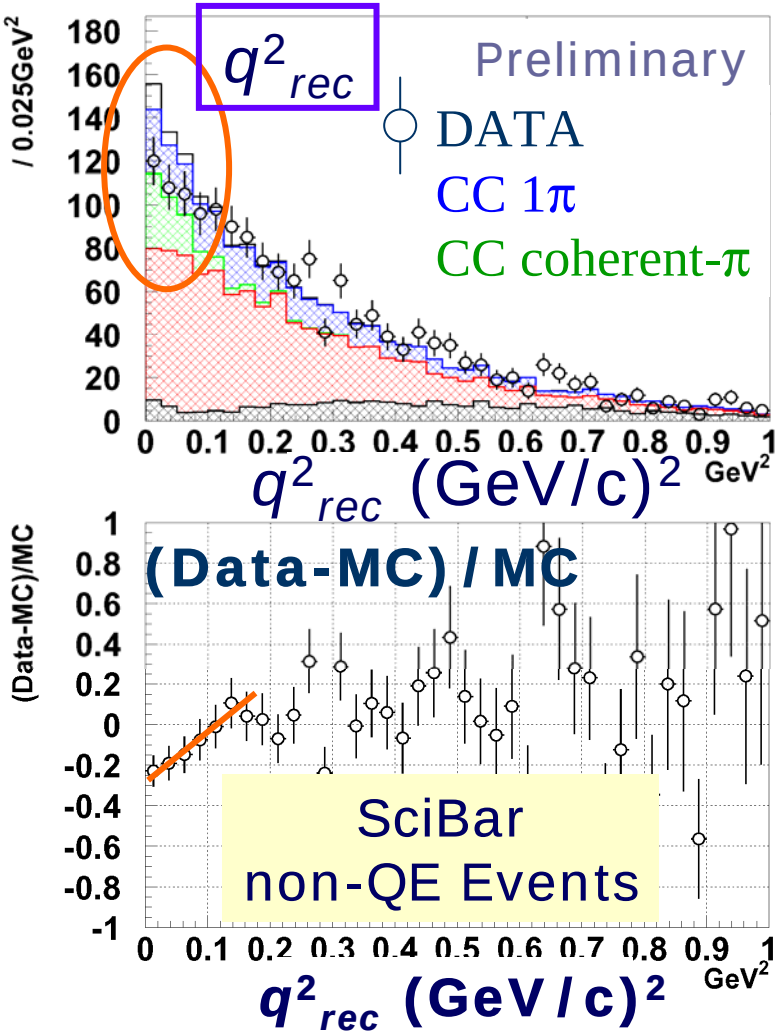
→sensitive to only high energy muons (>5.5GeV)

A hint of K2K forward μ deficit.

K2K observed forward μ deficit.

- A source is non-QE events.
- For CC-1π,
  - Suppression of ~q^2/0.1[GeV^2] at q^2<0.1[GeV^2] may exist.
- For CC-coherent π,
  - The coherent π may not exist.

Oscillation analysis is insensitive to the choice.



Near Detectors combined measurements

(p_μ, θ_μ) for 1track, 2trackQE and 2track nQE samples

$\rightarrow \Phi(E\nu)$, nQE/QE ratio

- Fitting parameters

  $\Phi(E_\nu)$, nQE/QE ratio

  – Detector uncertainties on the energy scale and the track counting efficiency.

  – The change of track counting efficiency by nuclear effect uncertainties; proton re-scattering and π interactions in a nucleus …

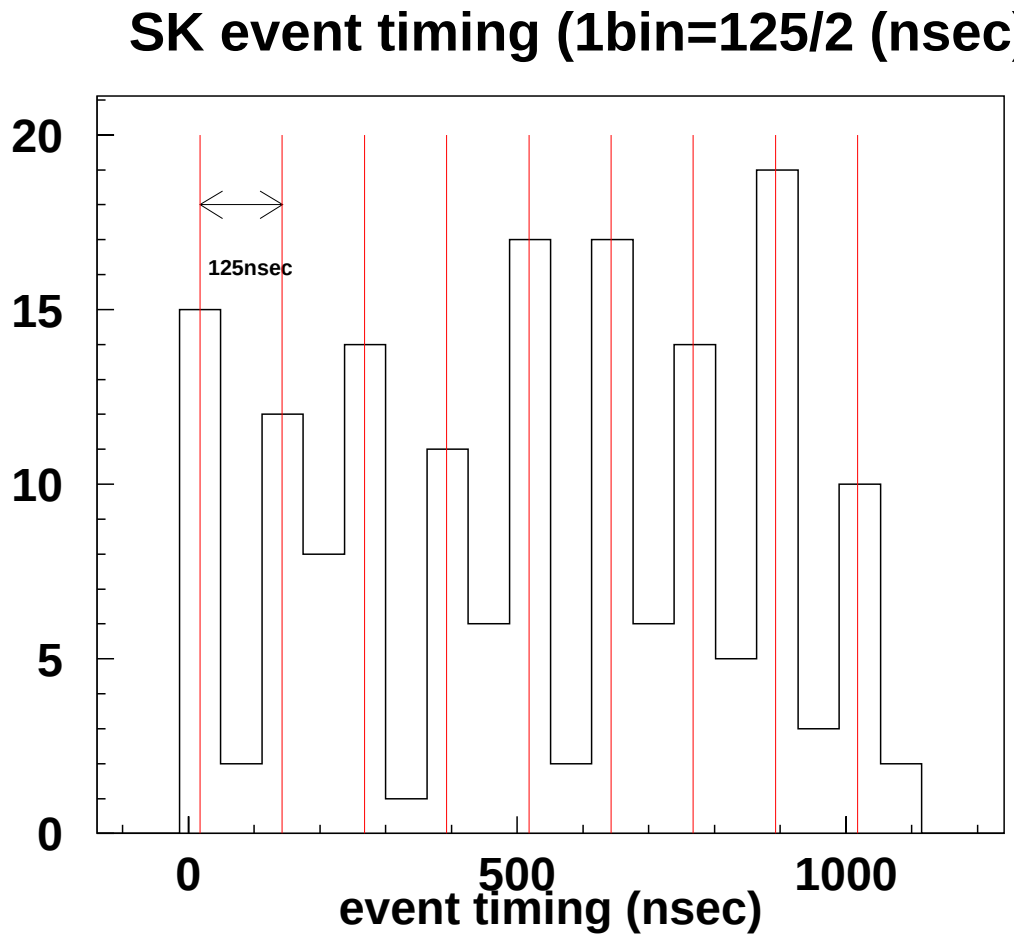
- Strategy

  ① Measure $\Phi(E_\nu)$ in the more relevant region of $\theta_\mu \geq 20°$ for 1KT and $\theta_\mu \geq 10°$ for SciFi and SciBar.

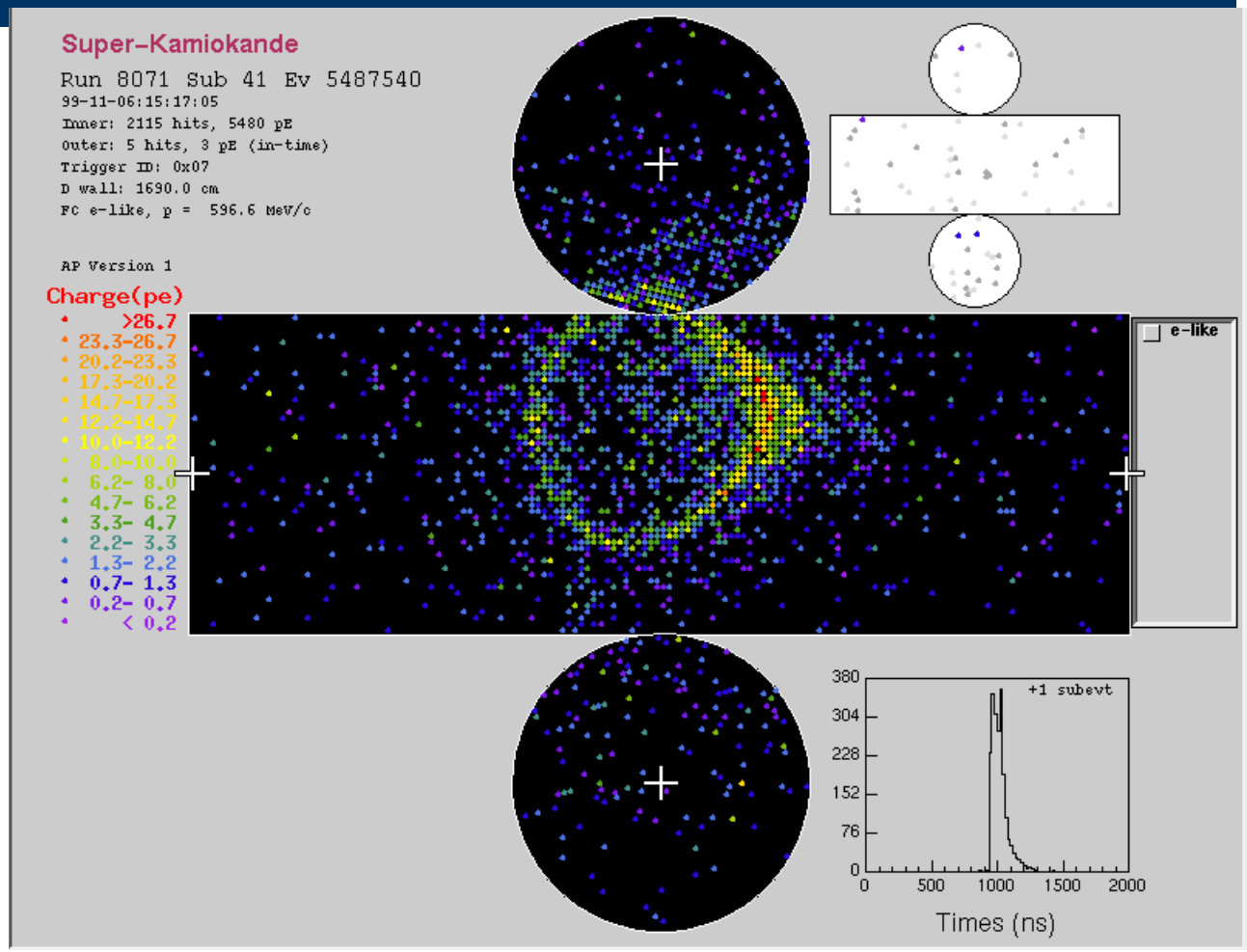
  ② Apply a low q^2 correction factor to the CC-1π model (or coherent π).

  ③ Measure nQE/QE ratio for the entire θ_μ range.

Bunch structure of SK events



ν_e candidate event



SciBar event gallery