June 24th, 2004
@ ICRR
ニュートリノ研究会

K2K実験の最新結果

M. Yokoyama (Kyoto University)
for K2K collaboration

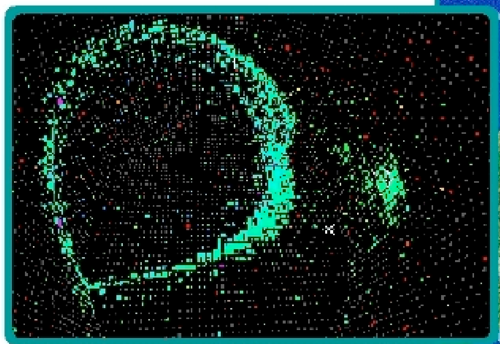
Introduction

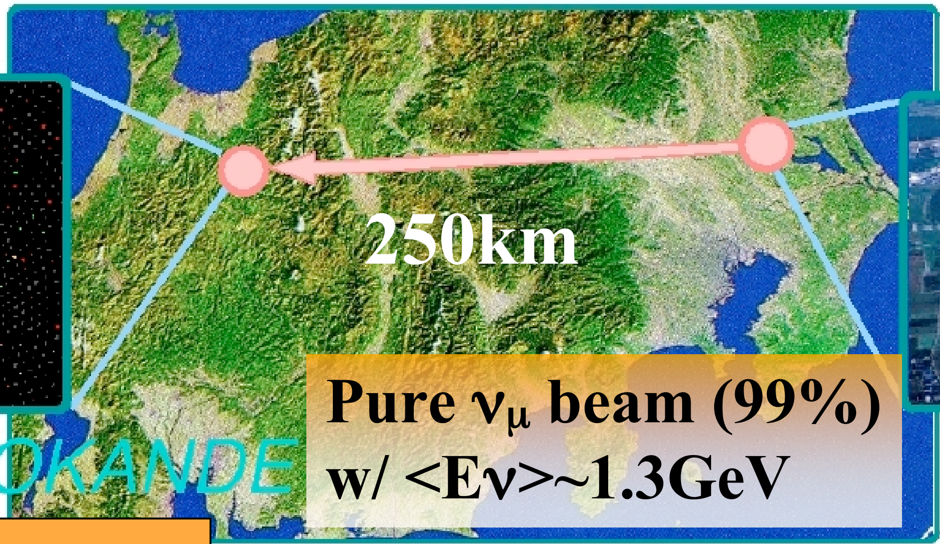
1. Introduction
K2K experiment since 1999

First accelerator-based long baseline (***250km***) neutrino experiment.

Search for **ν_μ disappearance** and ν_e appearance

KEK





Super-KAMIOKANDE

Pure ν_μ beam (99%)
w/ <Eν>~1.3GeV

50 kton Water Cherenkov detector

12GeV PS
- **ν_μ beamline**
- **Beam monitor**
- **Near detector**

Brief history of K2K

- 1995
  - Proposed to study neutrino oscillation for atmospheric neutrinos anomaly.
- 1999
  - Started taking data.
- 2000
  - Detected the less number of neutrinos than the expectation at a distance of 250 km. Disfavored null oscillation at the 2σ level.
- 2002
  - Observed indications of neutrino oscillation. The probability of null oscillation is less than 1%.
- 2004
  - This result!

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

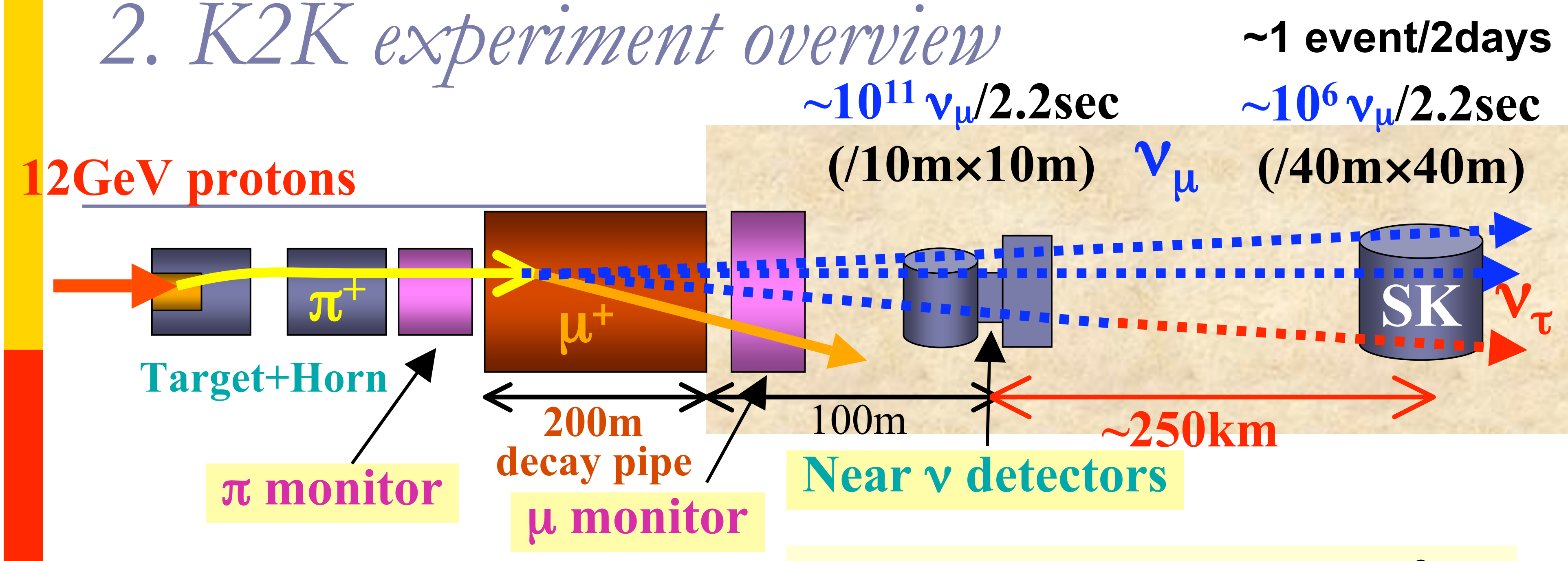
CANADA: TRIUMF / University of British Columbia

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

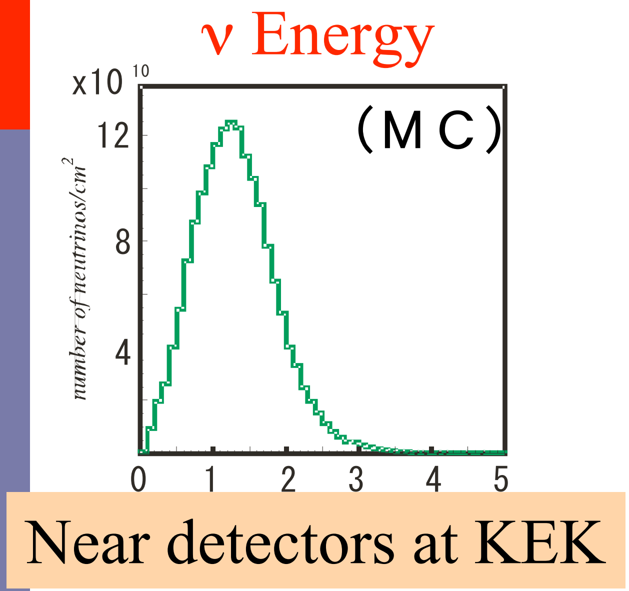
RUSSIA: INR-Moscow

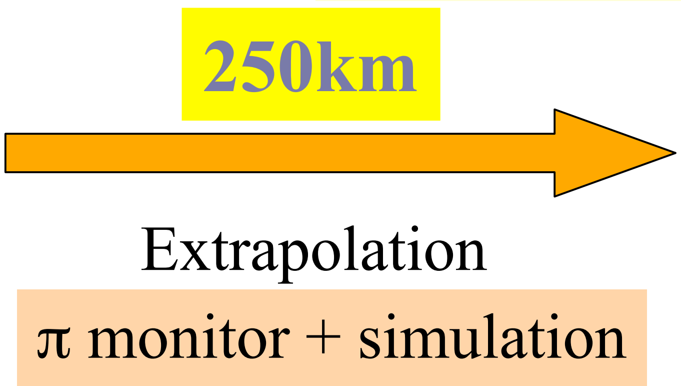
Overview

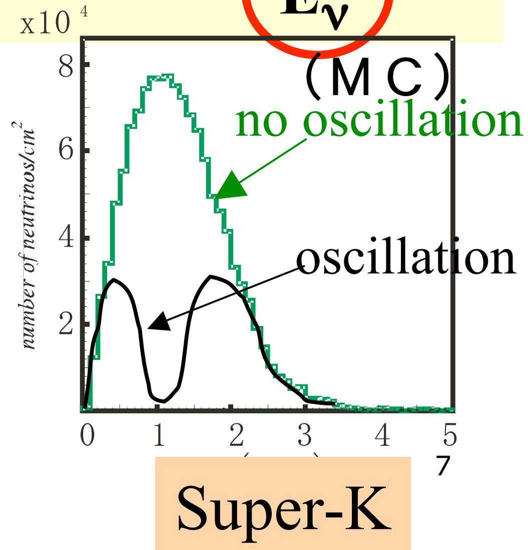
2. K2K experiment overview



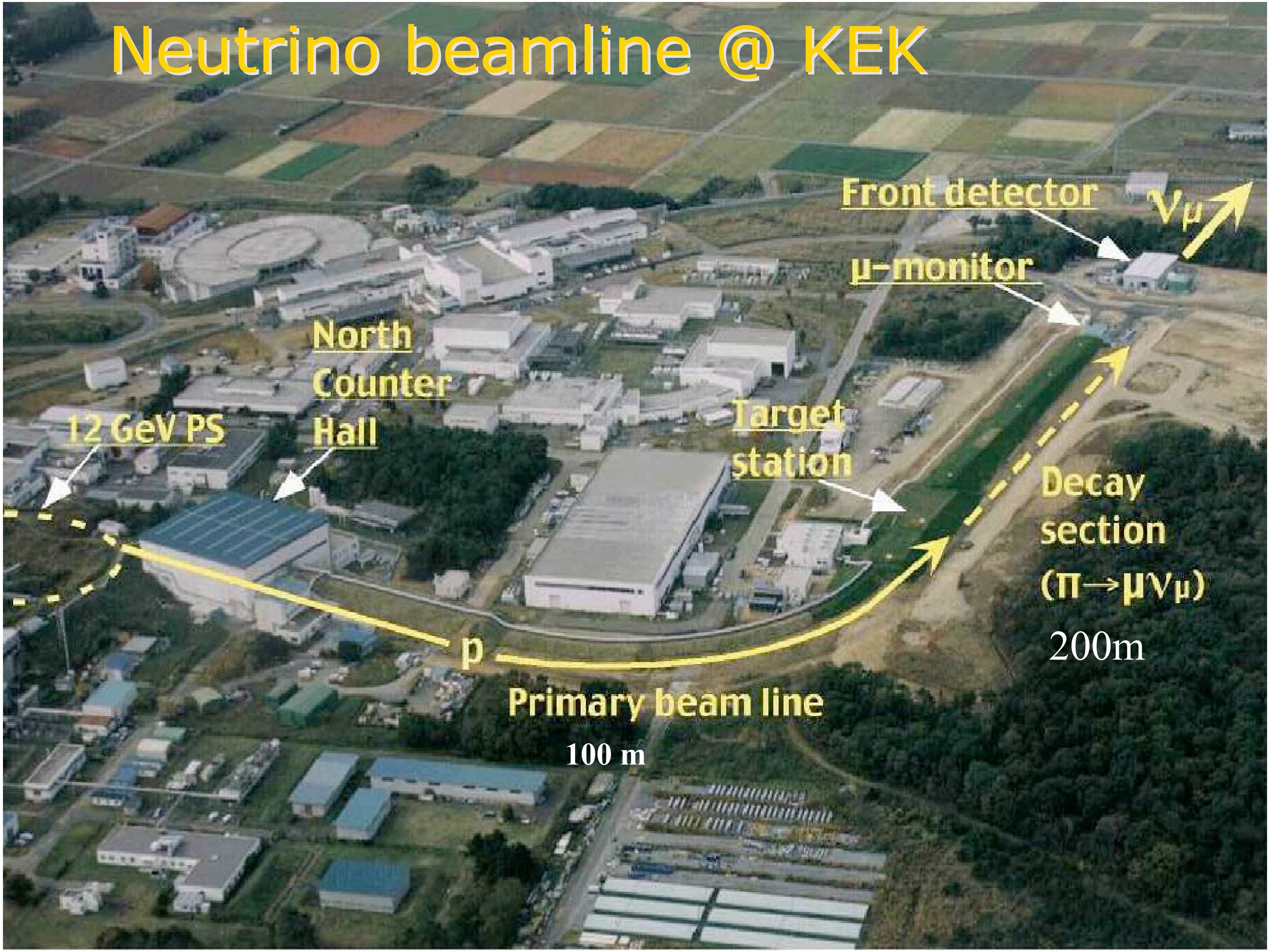
$$\text{prob.} = \sin^2 2\theta \cdot \sin^2\left(\frac{1.27\Delta m^2\ L}{E_\nu}\right)$$





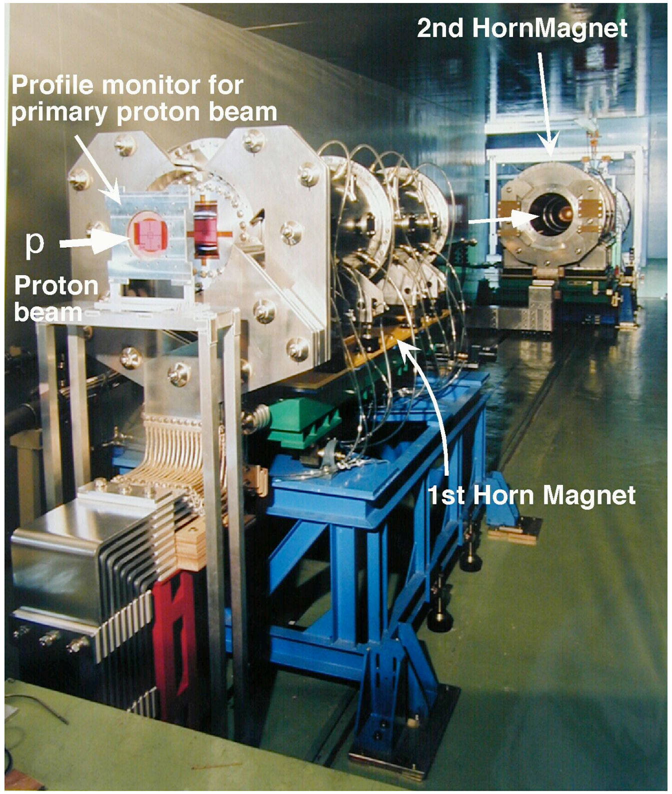


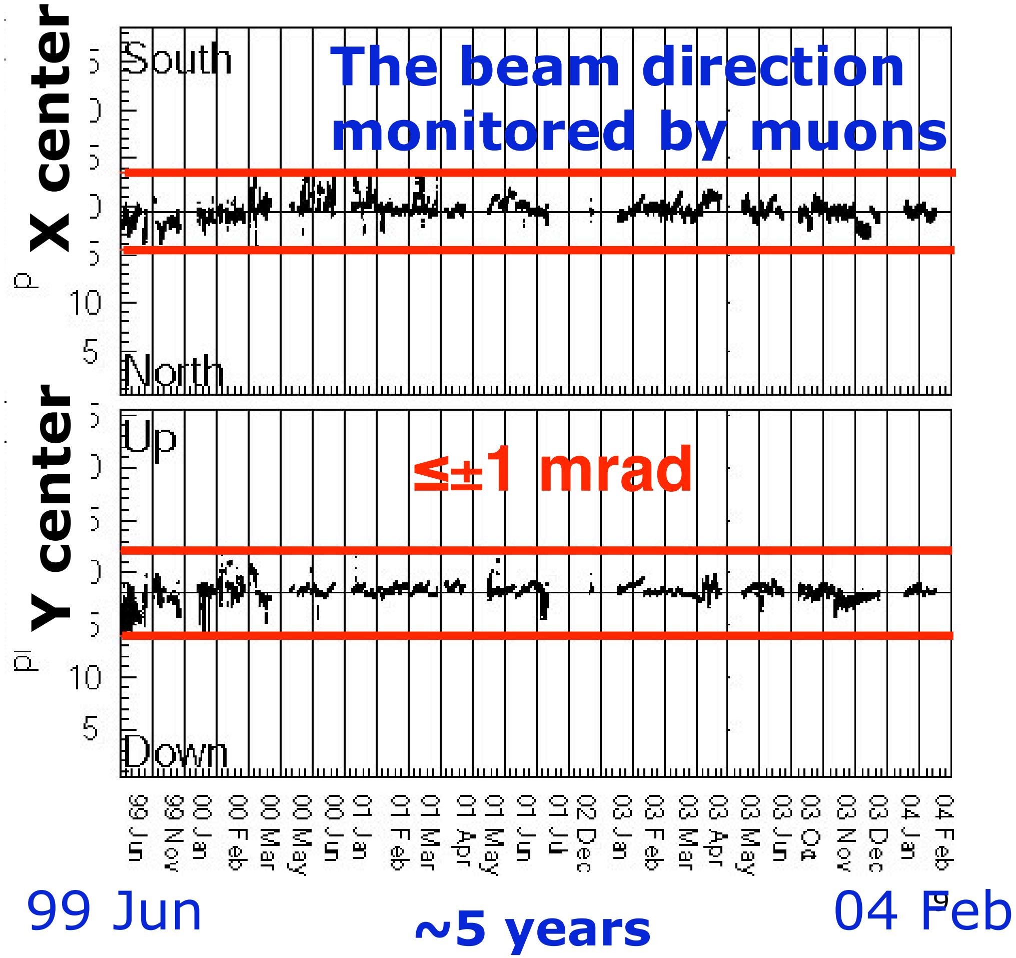
Neutrino beamline @ KEK



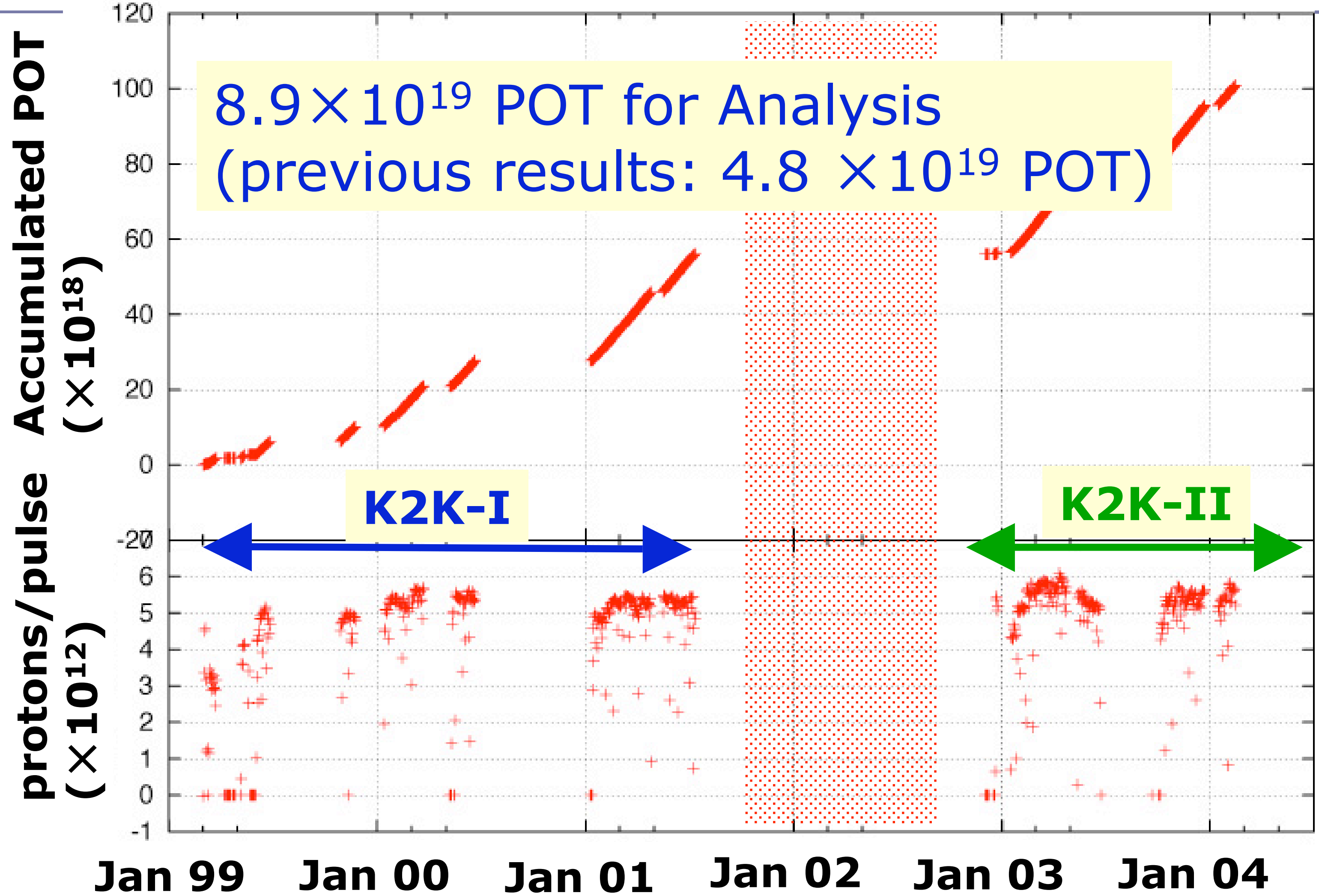
Neutrino beam and the directional control

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



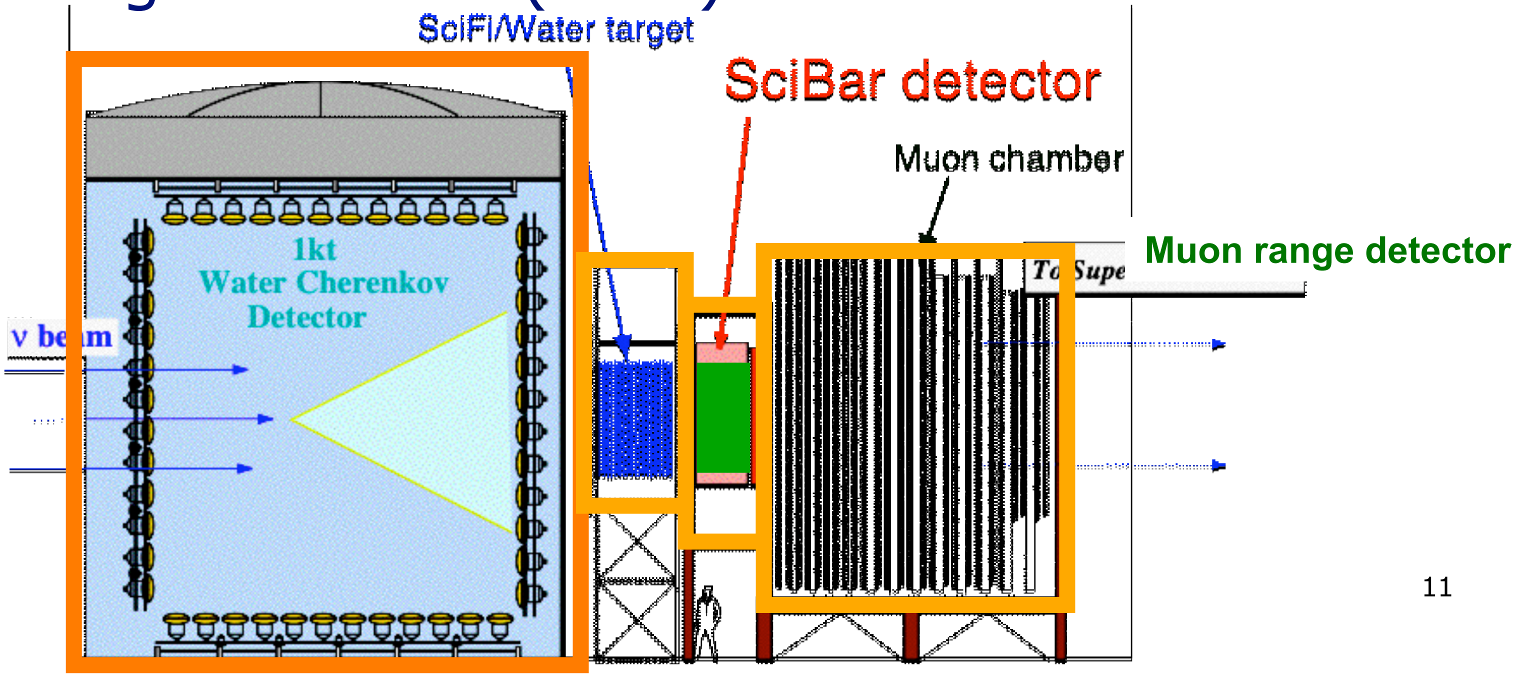


Accumulated POT (Protons On Target)



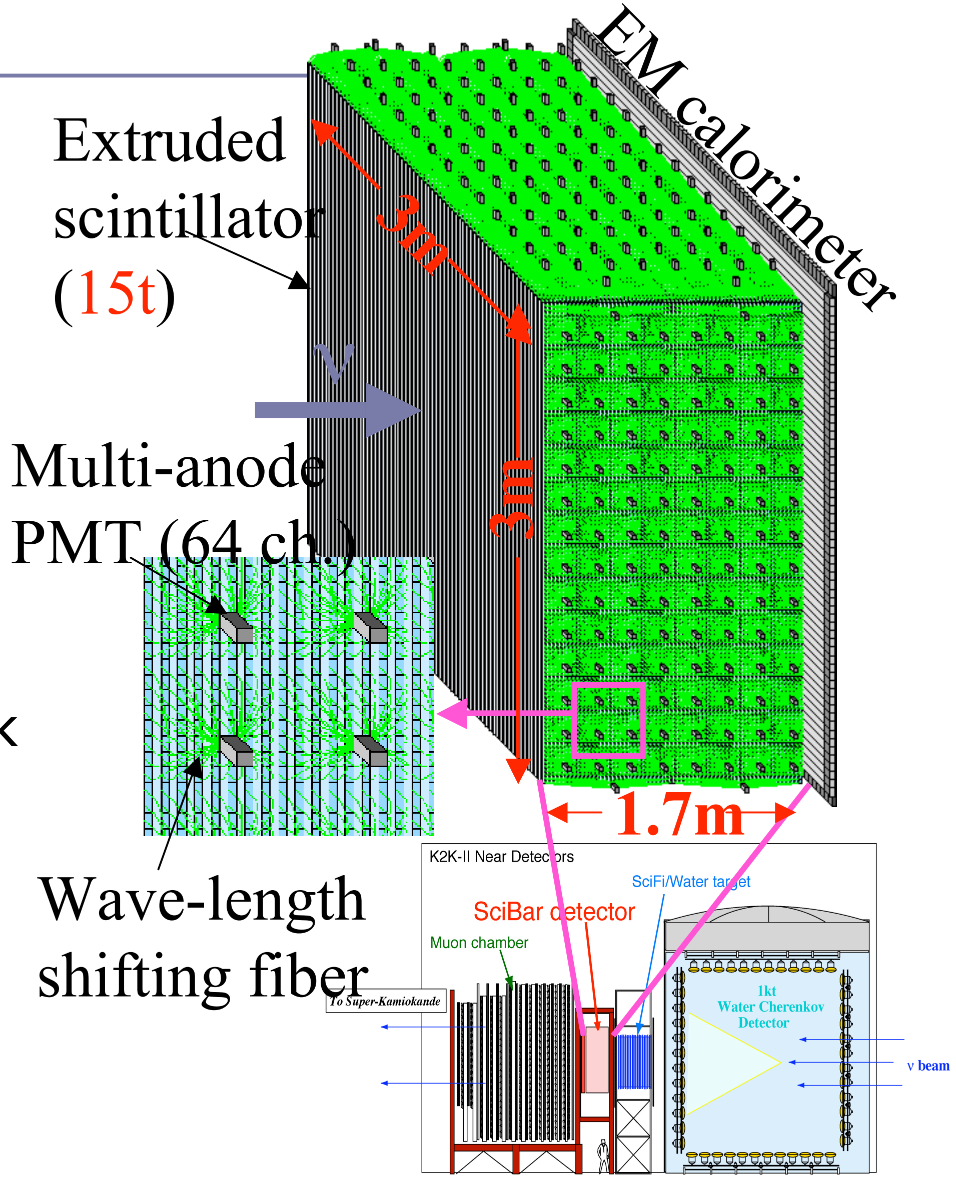
Near detector system at KEK

- 1KT Water Cherenkov Detector (1KT)
- Scintillating-fiber/Water sandwich Detector (SciFi)
- Lead Glass calorimeter (LG) before 2002 (K2K-I)
- Scintillator Bar Detector (SciBar) from 2003 (K2K-II)
- Muon Range Detector (MRD)

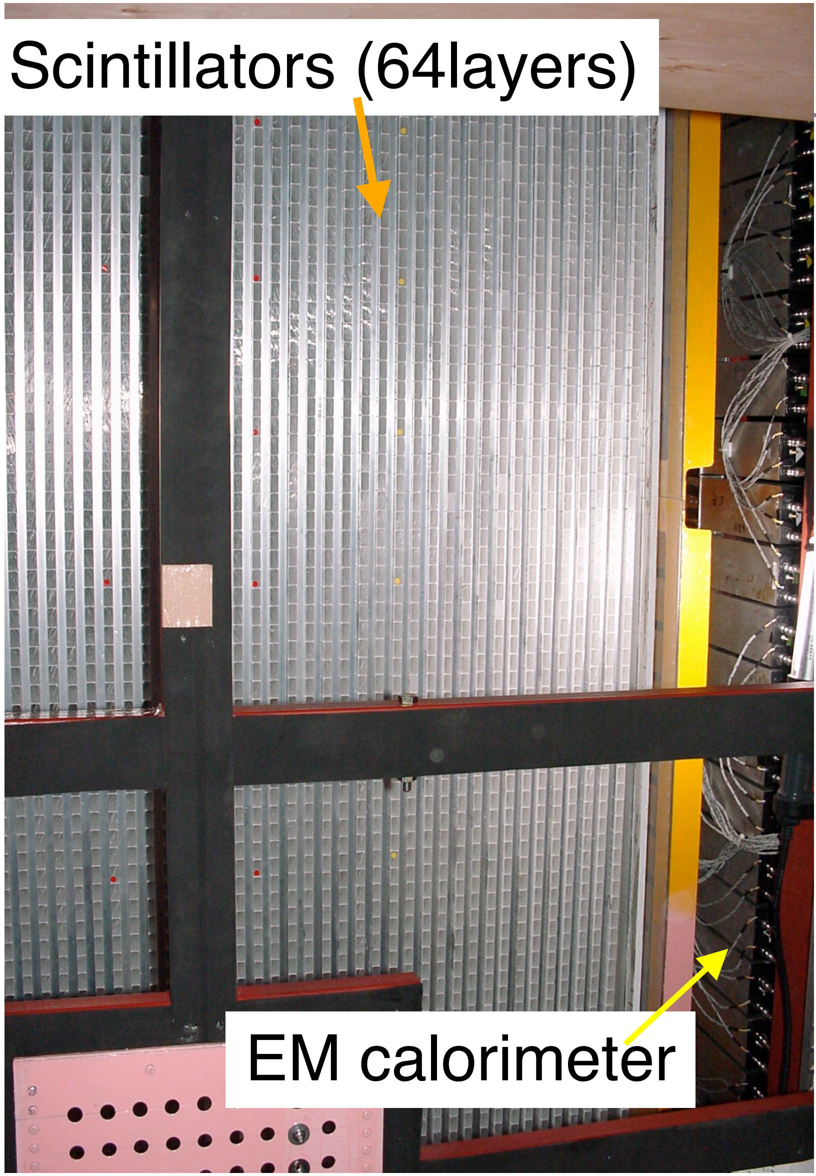


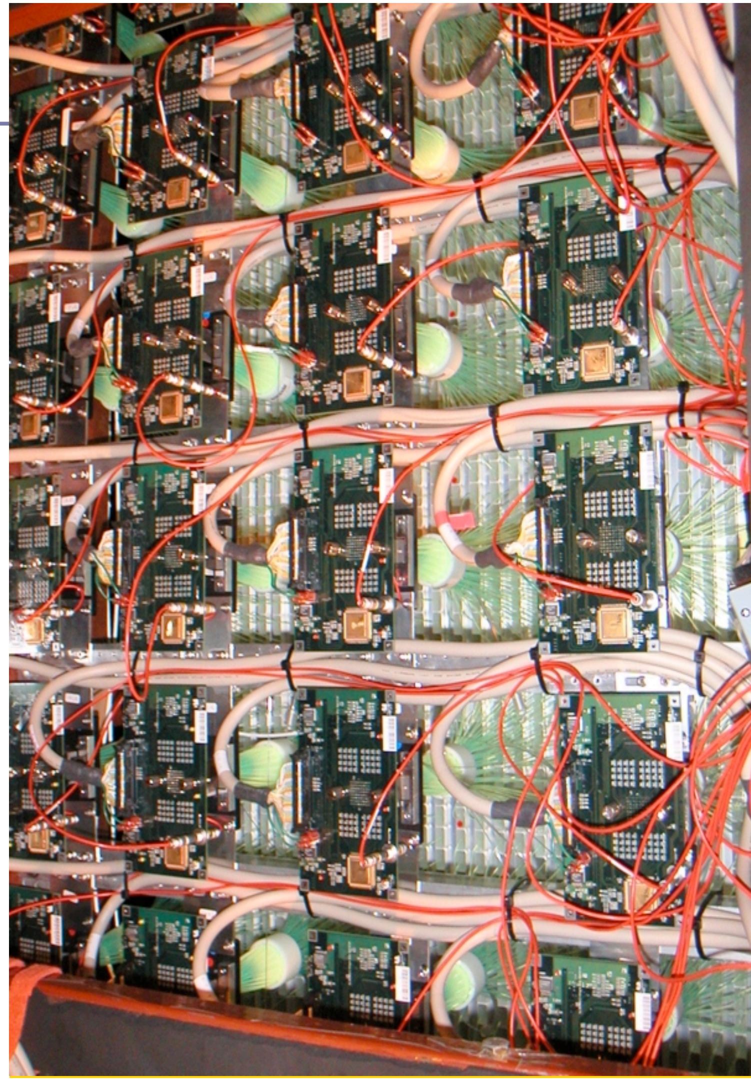
SciBar Detector

- Full-active, fine-segment detector made of Scintillator Bars
  - 2.5x1.3x300cm³ cell
  - ~15000 channels (dead-ch:<10)
  - WLS fiber+MAPMT readout
  - Detect short (~10cm) track
  - p/π separation using dE/dx
- Precise ν spectrum measurement
- ν interaction study



Detector Photos





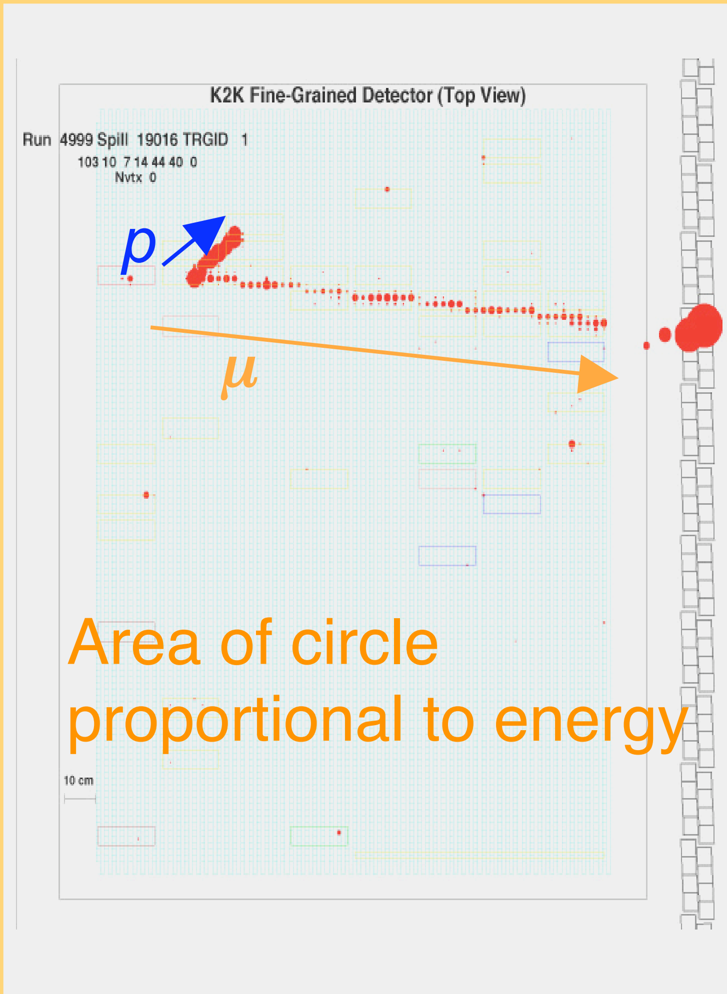
Fibers and front-end elec.

Just Completed!

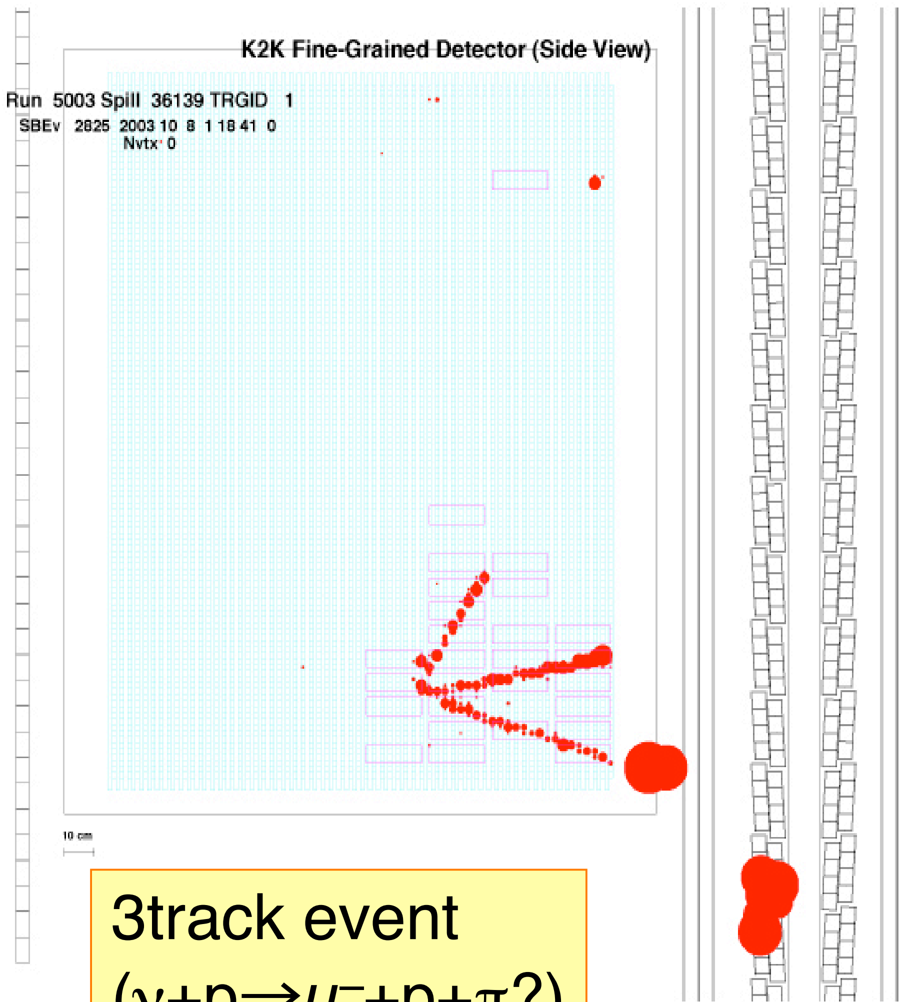
Aug. 22, 2003

Event Display

Area of red circles
Proportional to energy



CCQE (ν+n→μ^-+p) candidate

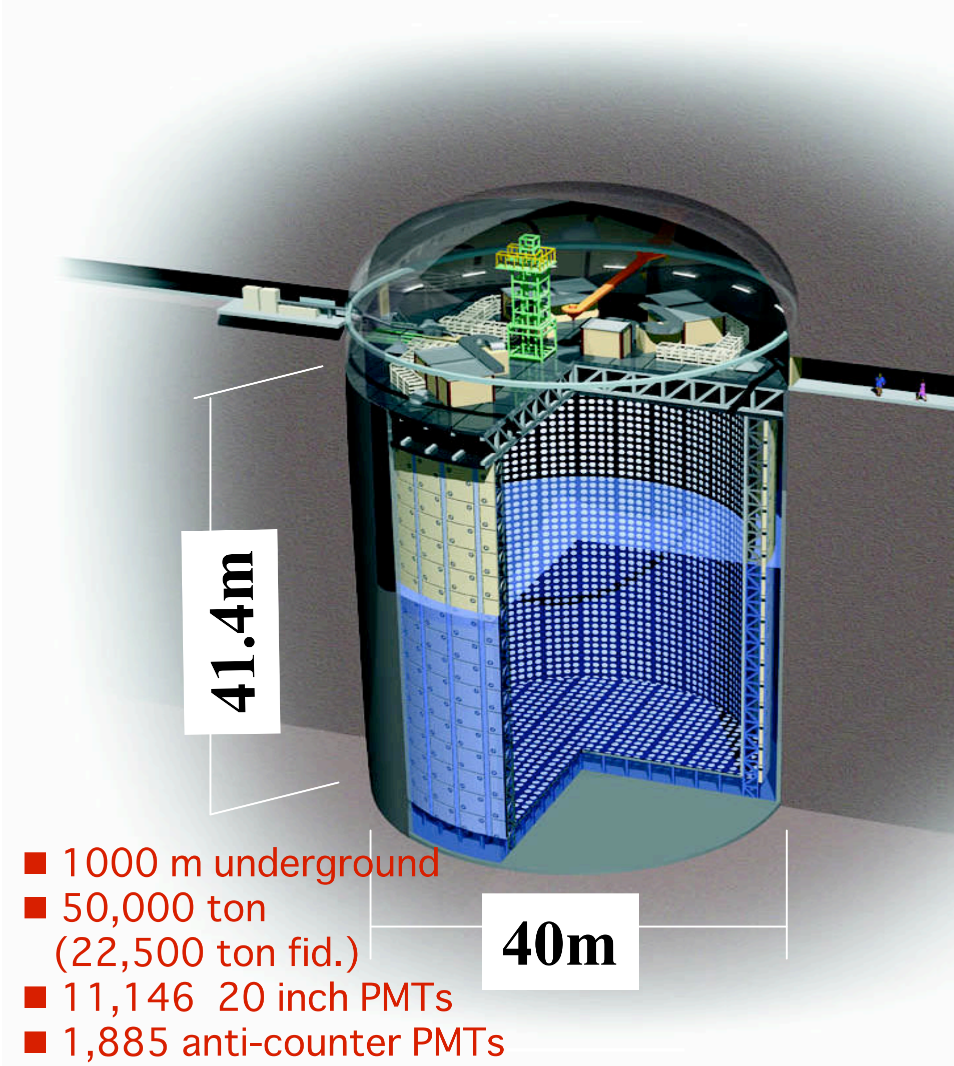


3track event
(ν+p→μ^-+p+π?)

Far Detector -Super-Kamiokande-

50,000 ton water Cherenkov detector (22.5 kton fiducial volume)

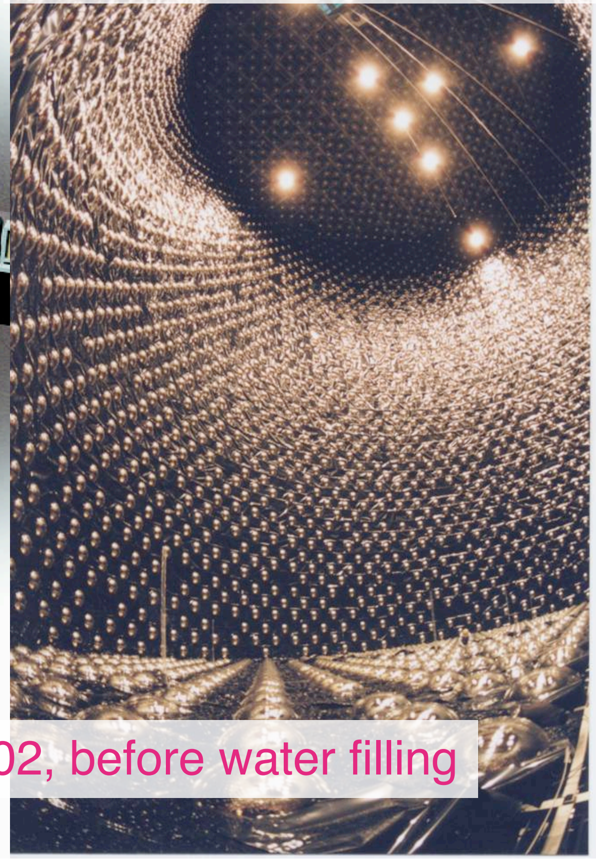
Optically separated INNER and OUTER detector



- 1000 m underground
- 50,000 ton (22,500 ton fid.)
- 11,146 20 inch PMTs
- 1,885 anti-counter PMTs

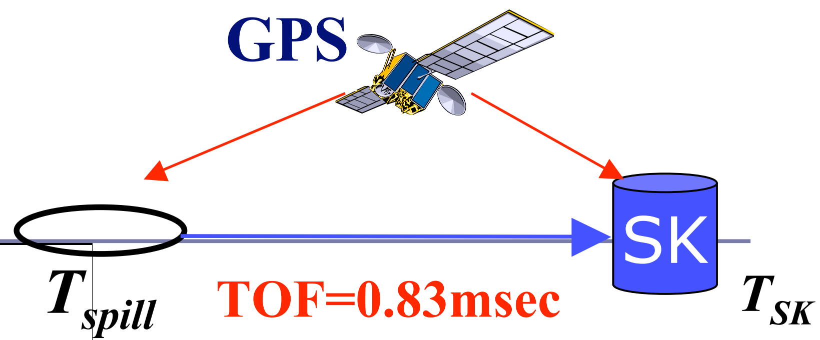
SK is back!

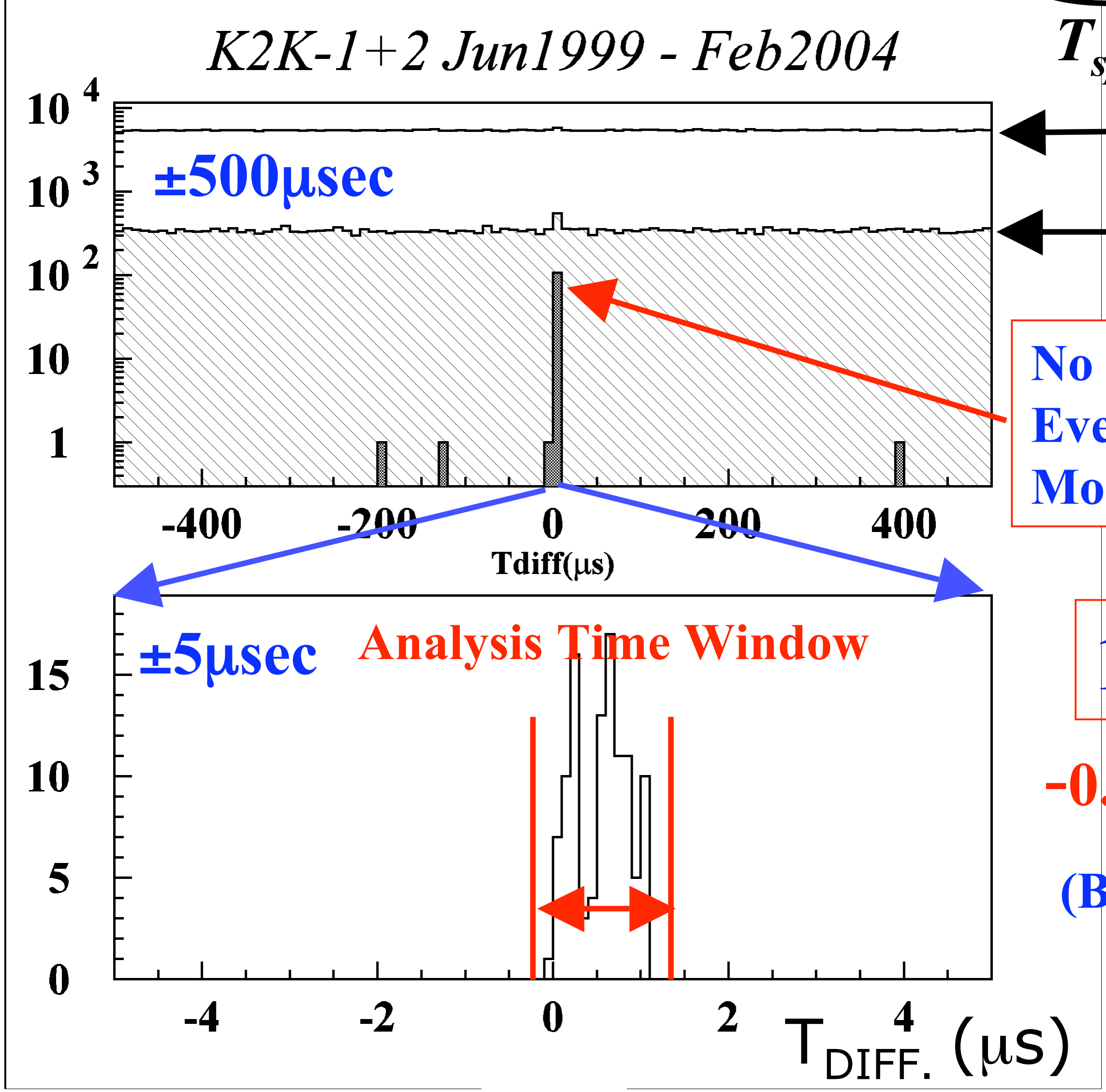
w/ half PMT density



Sep.-2002, before water filling

SK Events





Decay electron cut.

≥20MeV Deposited Energy

No Activity in Outer Detector
Event Vertex in Fiducial Volume
More than 30MeV Deposited Energy

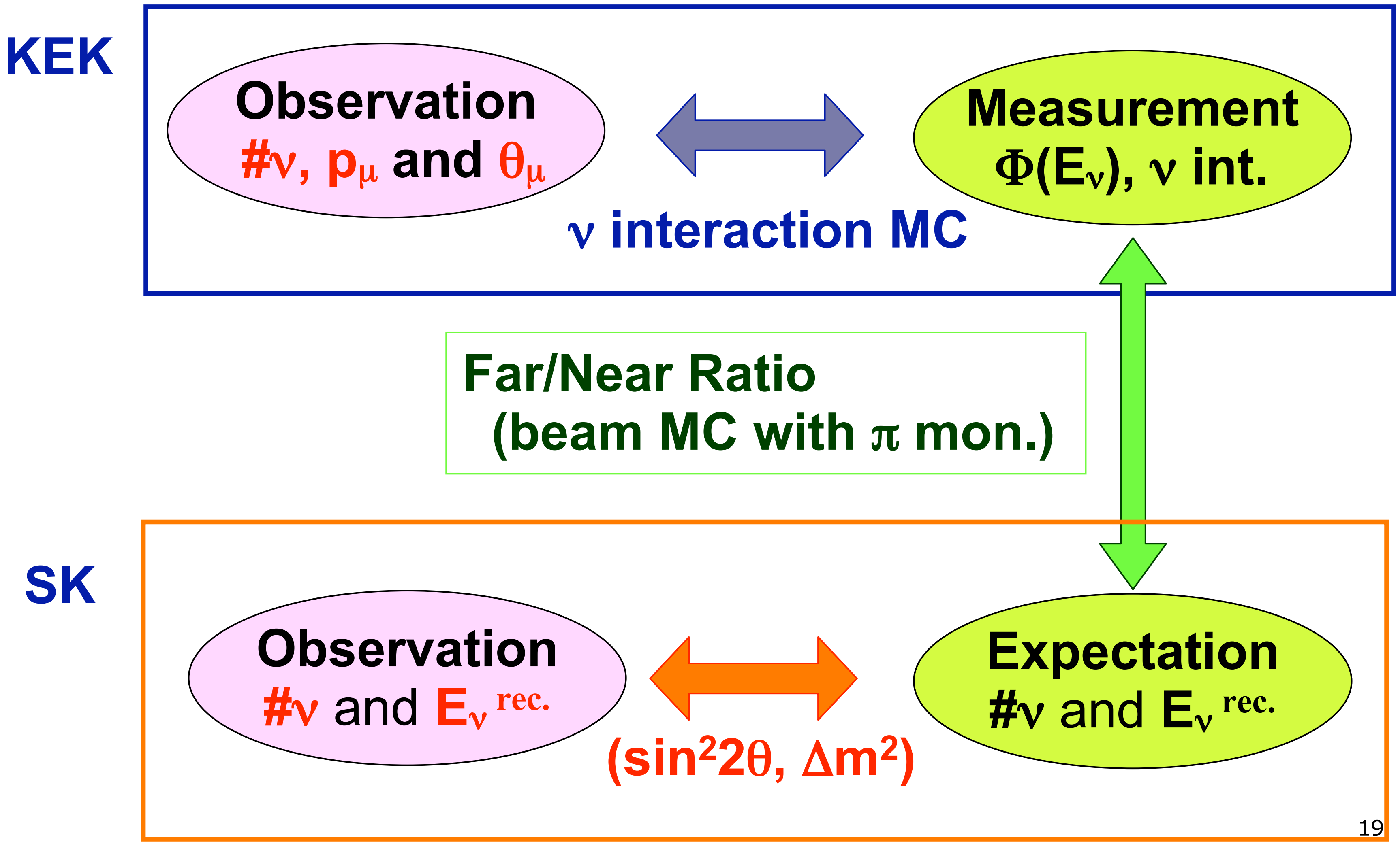
108 events (K2K-1:56)

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

(BG: 1.6 events within ±500μs
2.4×10⁻³ events in 1.5μs)

Near Detector Measurements

3. Analysis Overview



4. Near Detector measurements

- Event rate measurement (#of ν int.)
  - Measurement w/ 1KT
  - Cross-checked by other detectors
- Spectrum shape measurement
  - 1KT, SciFi, SciBar (p_μ, θ_μ)
  - Measure spectrum and nQE/QE (ν interaction model)

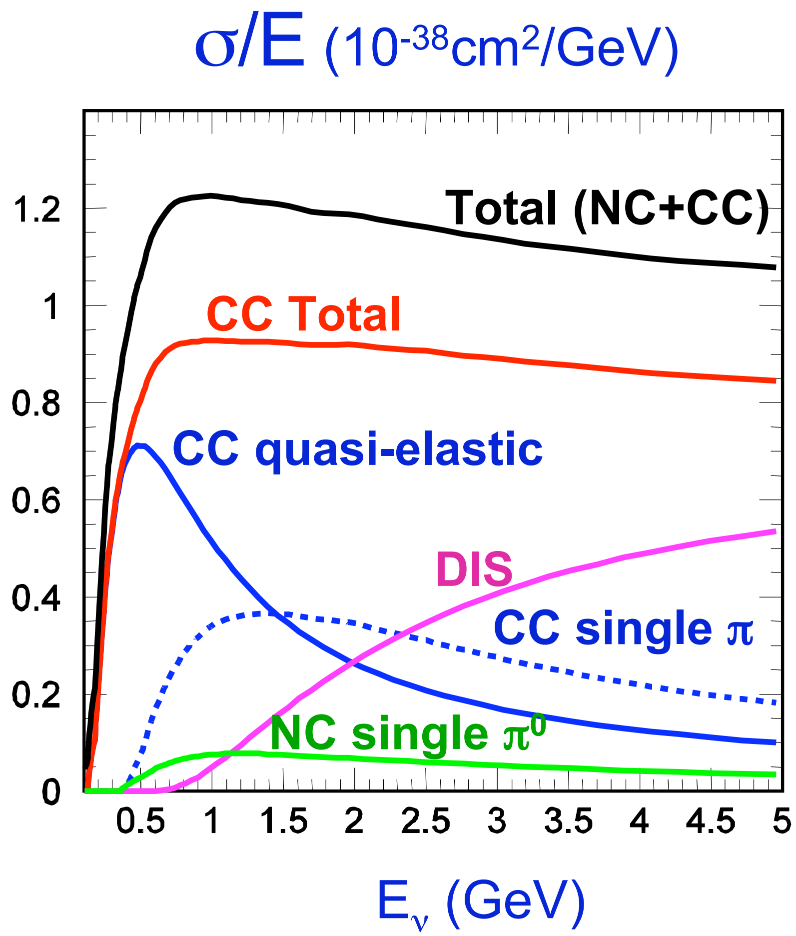
↓

Predict number of event and spectrum shape at SK

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



4.1 Event rate measurement @1KT

- The same detector technology as Super-K.
- Sensitive to low energy neutrinos.

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

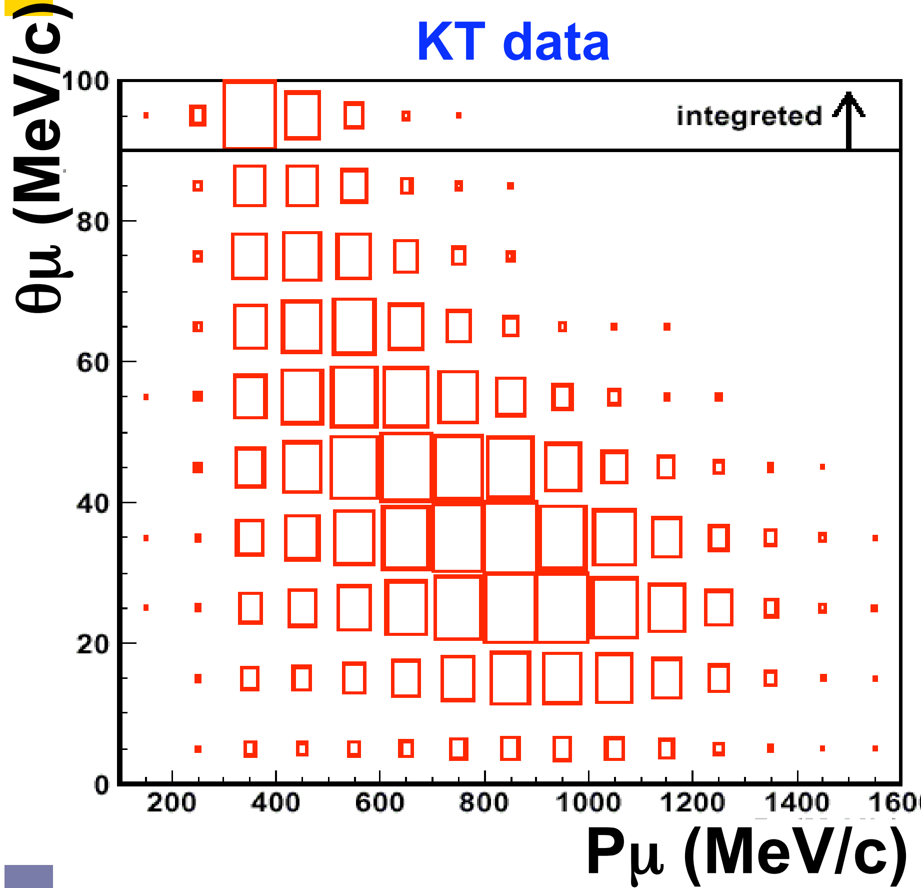
≡Far/Near Ratio (by MC)~1×10^{-6}

M: Fiducial mass M_{SK}=22,500ton, M_{KT}=25ton
ε: efficiency $\varepsilon_{SK\text{-}I(II)}$=77.0(78.2)%, ε_{KT}=74.5%

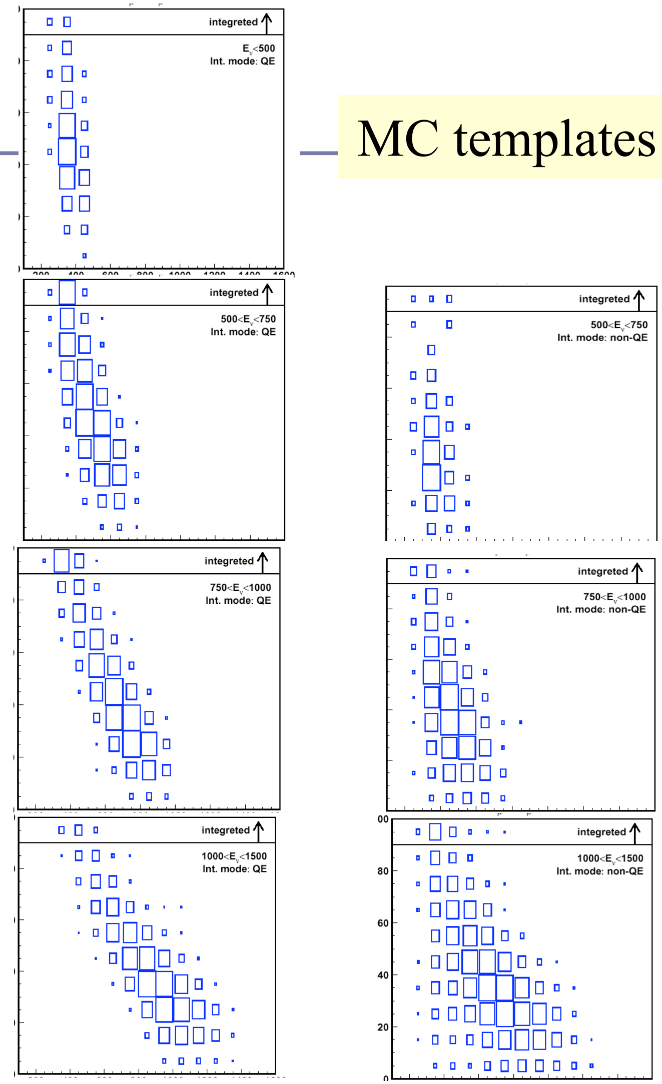
$N_{SK}^{exp}=150.9^{+11.6}_{-10.0}$ ⟷ $N_{SK}^{obs}=108$

4.2 Near Detector Spectrum Measurements

KT data



Eν	QE (MC)	nQE(MC)
0-0.5 GeV		
0.5-0.75GeV		
0.75-1.0GeV		
1.0-1.5GeV		



MC templates

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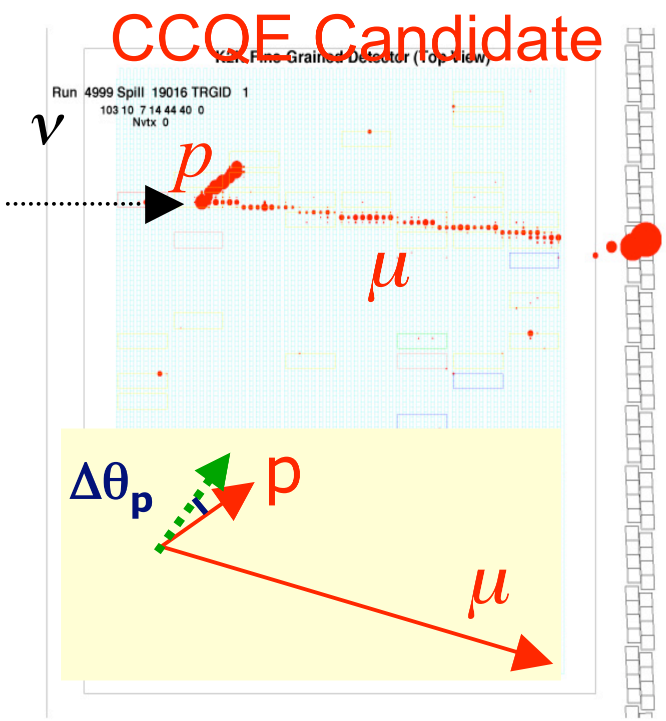
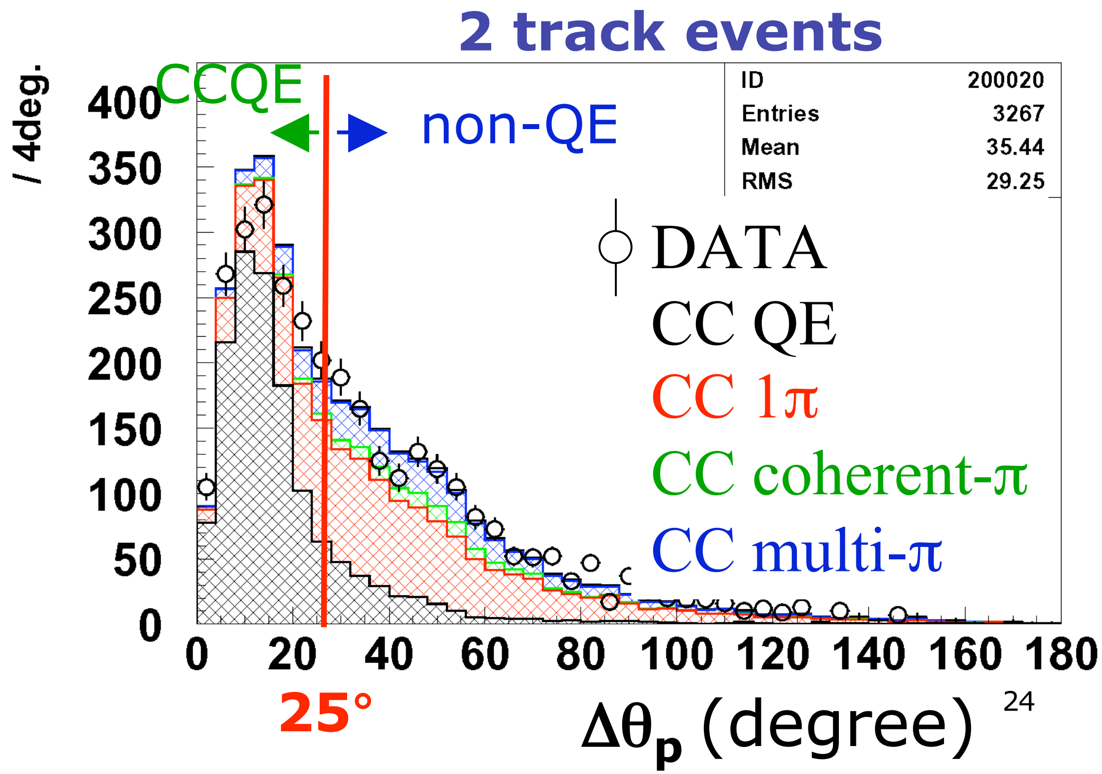
- ν flux $\Phi_{KEK}(E_\nu)$ (8 bins)
- ν interaction (nQE/QE)

Measurement with SciBar

- Full Active Fine-Grained detector (target: CH).
  - Sensitive to a low momentum track.
  - Identify CCQE events and other interactions (non-QE) separately.





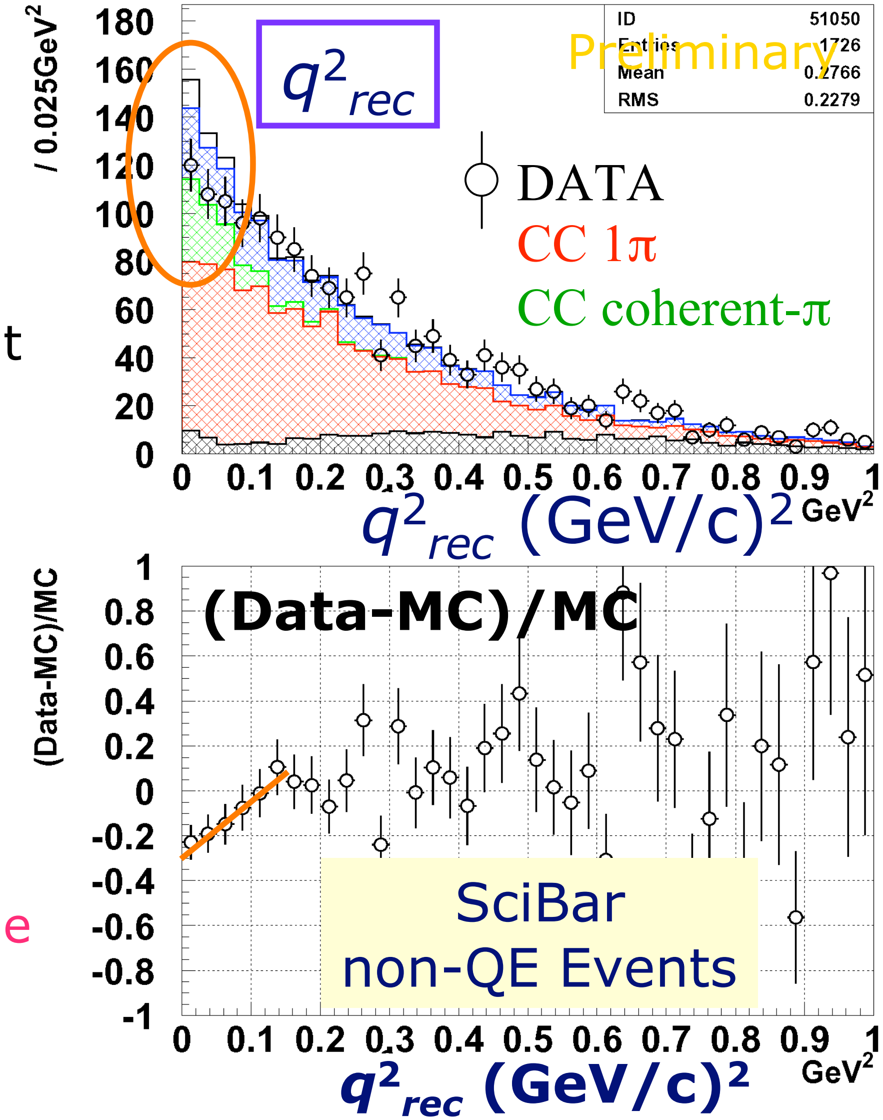
A hint of K2K forward μ deficit.

K2K observed forward μ deficit in all ND (KT, SciFi and SciBar).

- 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.

We do not identify which process causes the effect. The MC CC-1π (coherent π) model is corrected to be consistent with data.

Oscillation analysis is insensitive to the choice.



Near Detector Data

- 1KT
  - Fully Contained 1 ring μ (FC1Rμ) sample.
- SciBar
  - 1 track, 2 track QE ($\Delta\theta_p \leq 25°$), 2 track nQE ($\Delta\theta_p > 25°$) where one track is μ.
- SciFi
  - 1 track, 2 track QE ($\Delta\theta_p \leq 25°$), 2 track nQE ($\Delta\theta_p > 30°$) where one track is μ.

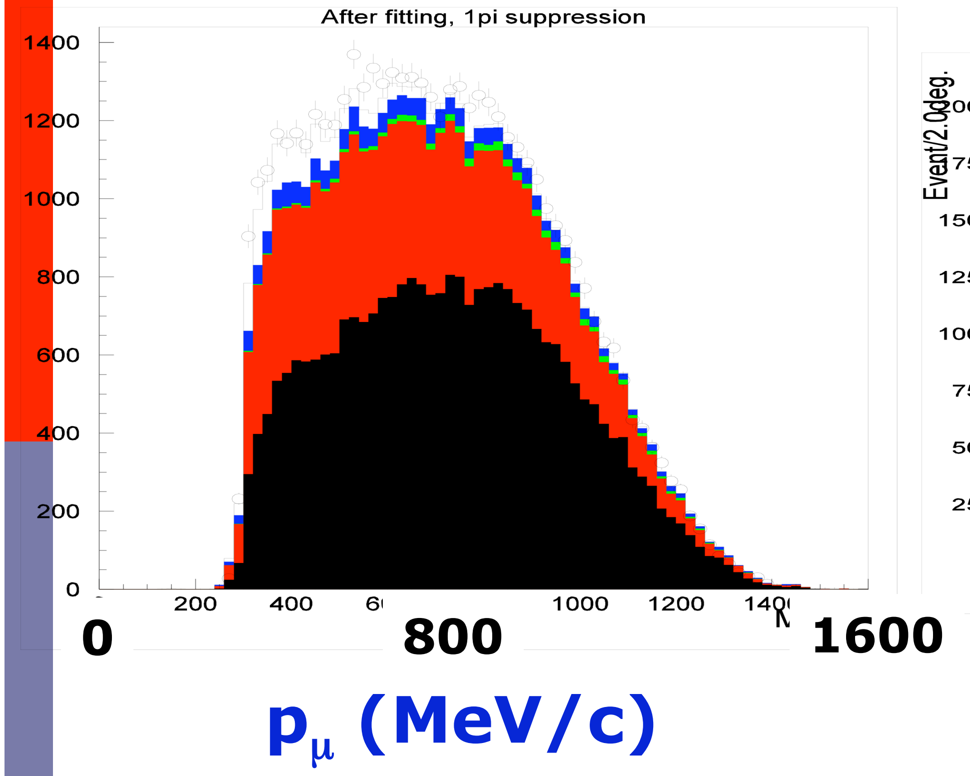
With the low q^2 suppression of nQE in SciBar, angular distributions of **all other samples** are reasonably reproducible with the correction.

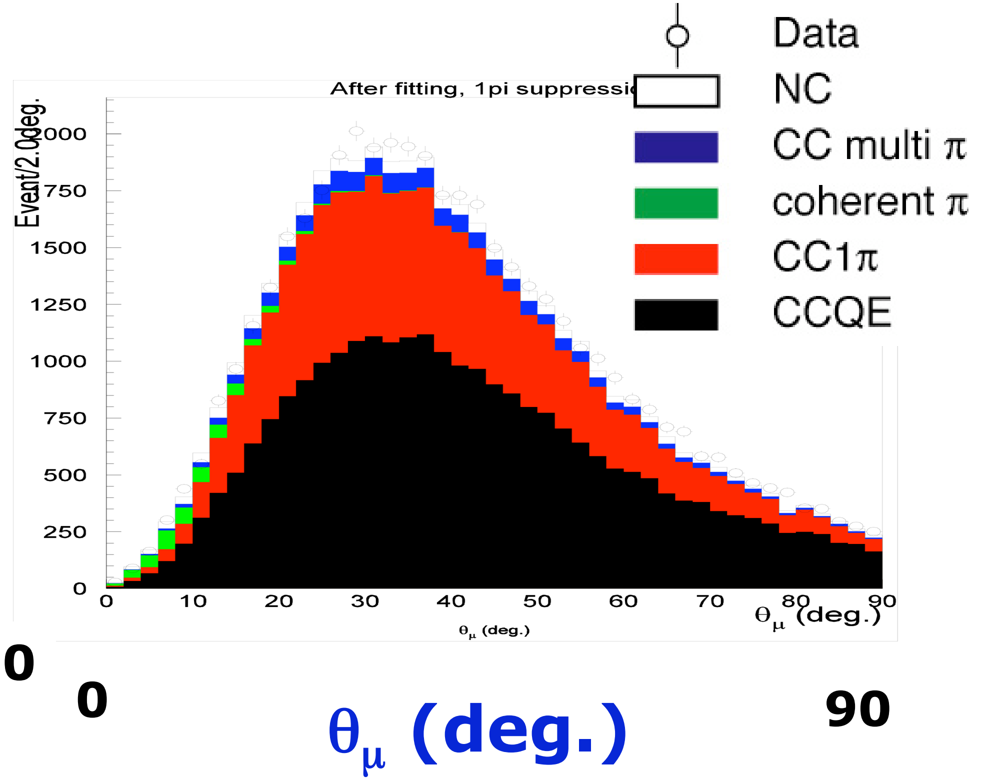
Near Detectors combined measurements

(p_μ,θ_μ) for 1track (1Rμ), 2trackQE and 2track nQE samples
→ Φ(Eν), nQE/QE

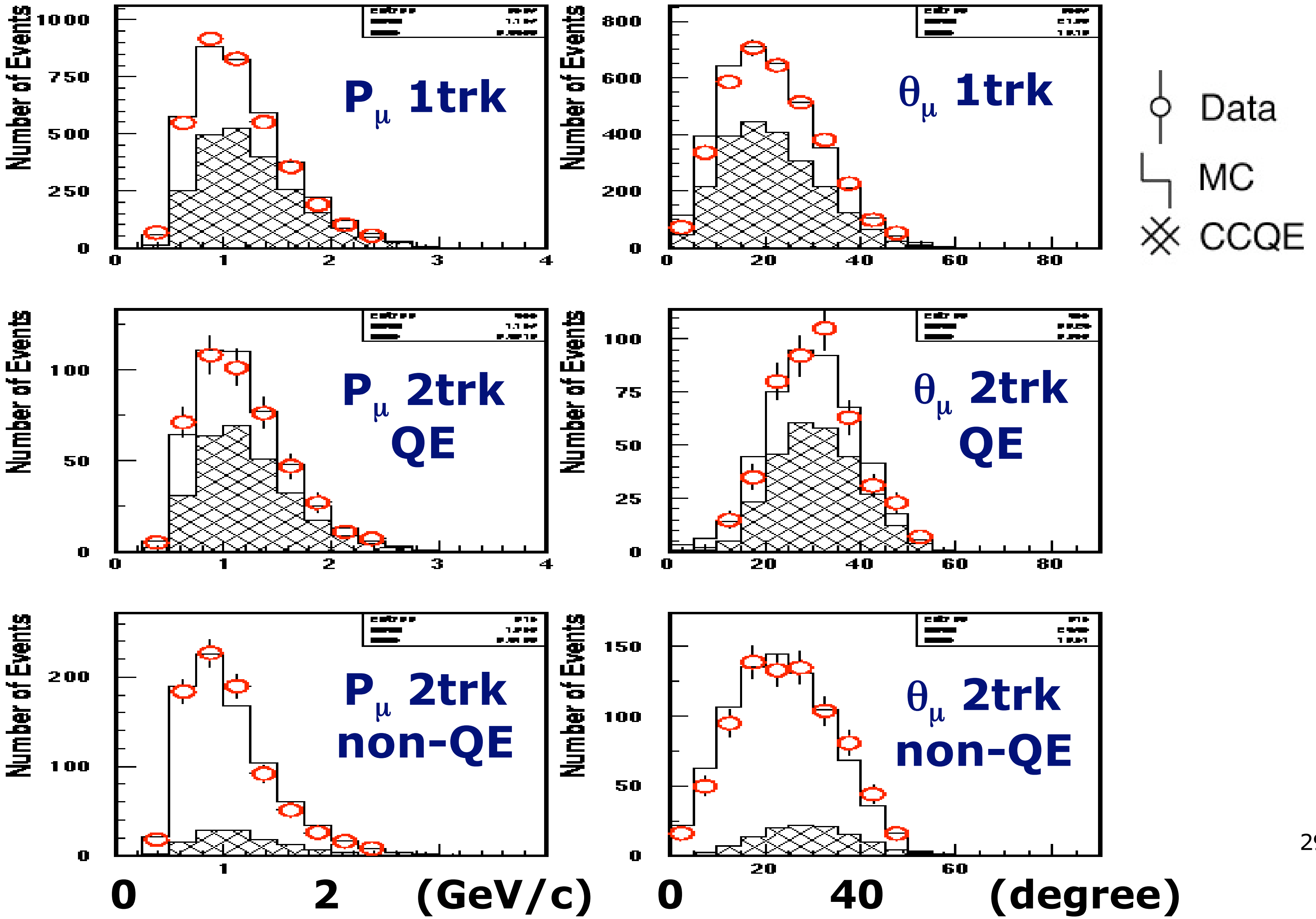
- Fitting parameters
  - $\Phi(E_\nu)$, nQE/QE ratio
  - Detector uncertainties on the energy scale and the track counting efficiency.
  - The change of track counting efficiency by nuclear effect uncertainties; proton re-scattering and π interactions in a nucleus …
- Strategy
  ① Measure $\Phi(E_\nu)$ 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) in MC.
  ③ Measure nQE/QE ratio for the entire θ_μ range.

1KT: μ momentum and angular distributions with measured spectrum

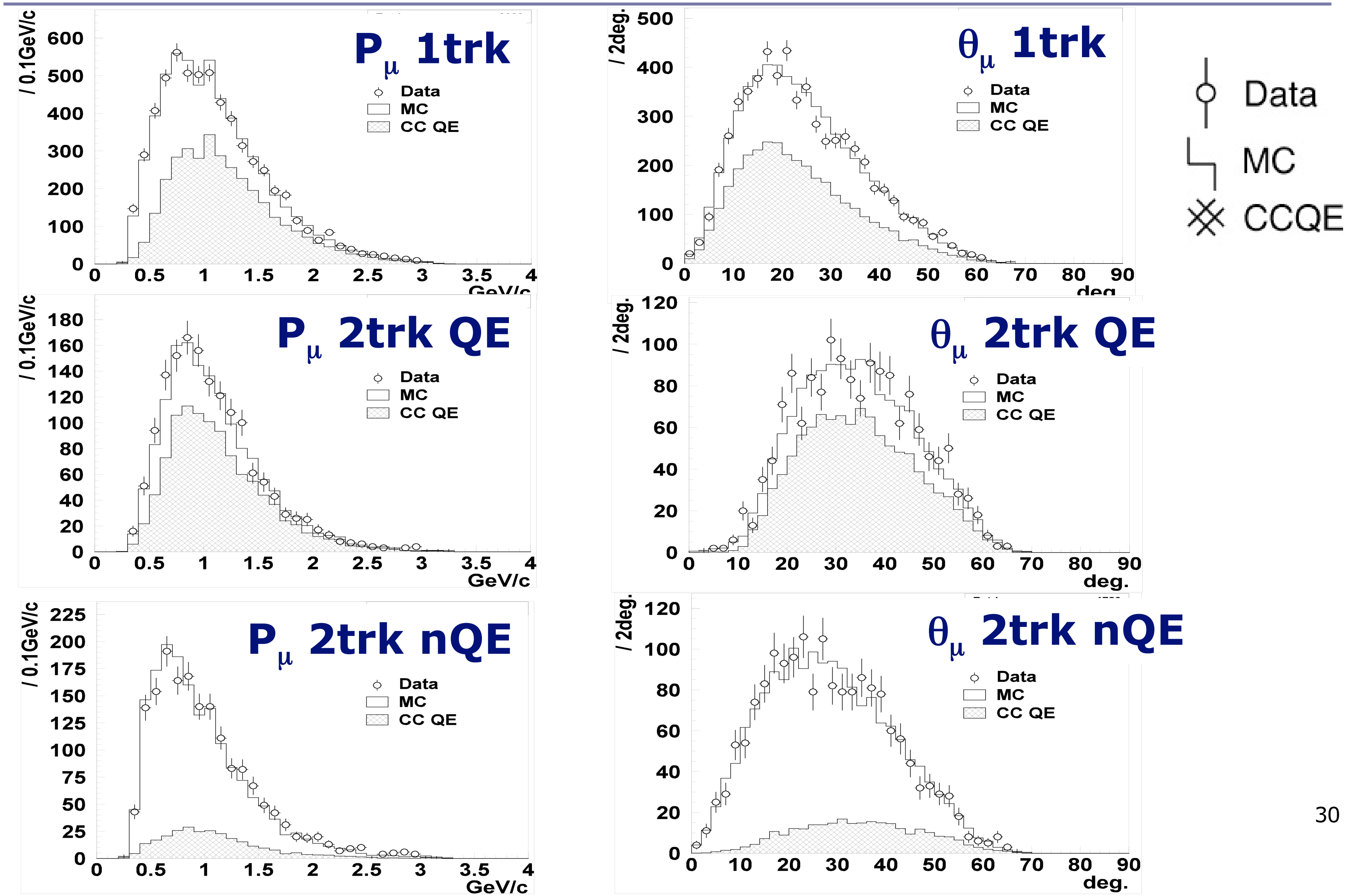




SciFi (K2K-IIa with measured spectrum)



SciBar (with measured spectrum)



ND measurement results

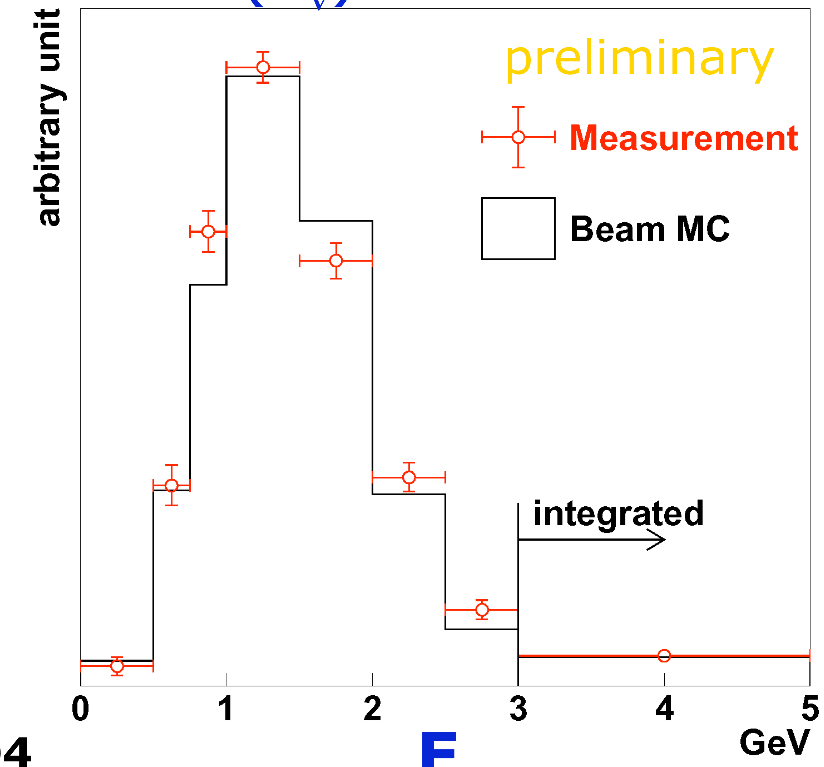
χ^2=638.1 for 609 *d.o.f*

- **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**

Φ(E_ν) at KEK



E_ν

Oscillation Analysis

K2K-SK events

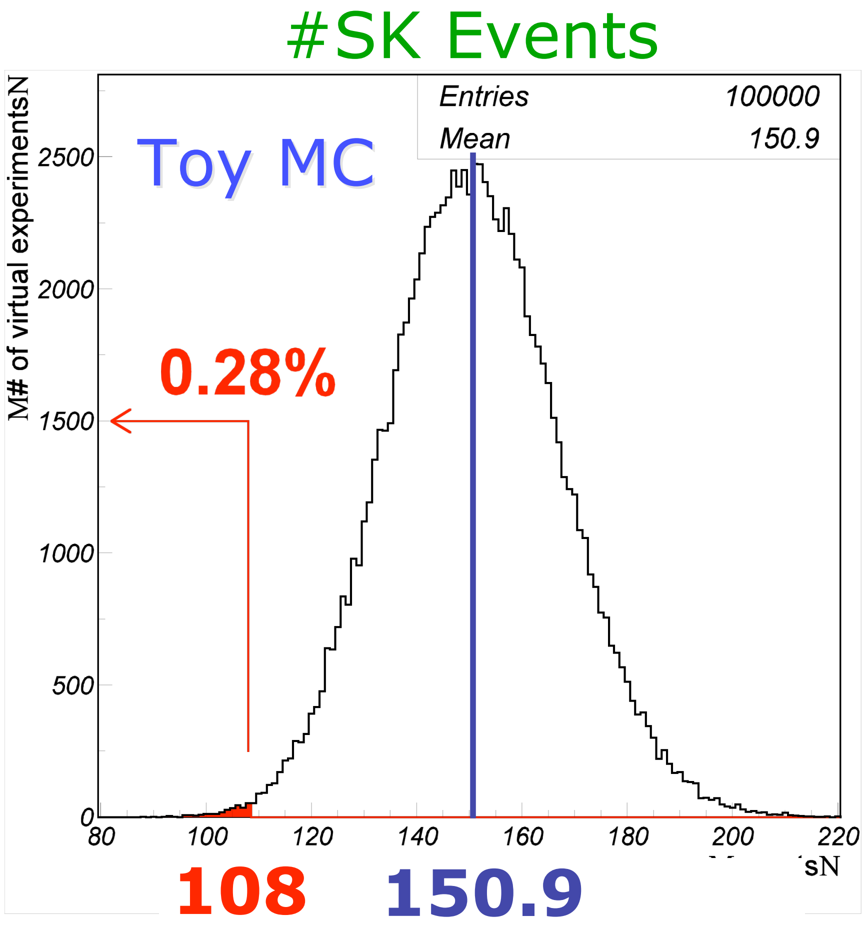
preliminary

K2K-alll (K2K-I, K2K-II)	DATA (K2K-I, K2K-II)	MC (K2K-I, K2K-II)
FC 22.5kt	**108** (56, 52)	**150.9** (79.1, 71.8)
1ring	**66** (32, 34)	**93.7** (48.6, 45.1)
μ-like	**57** **(56)** for E_ν^{rec} (30, 27)	**84.8** (44.3, 40.5)
e-like	**9** (2, 7)	**8.8** (4.3, 4.5)
Multi Ring	**42** (24, 18)	**57.2** (30.5, 26.7)

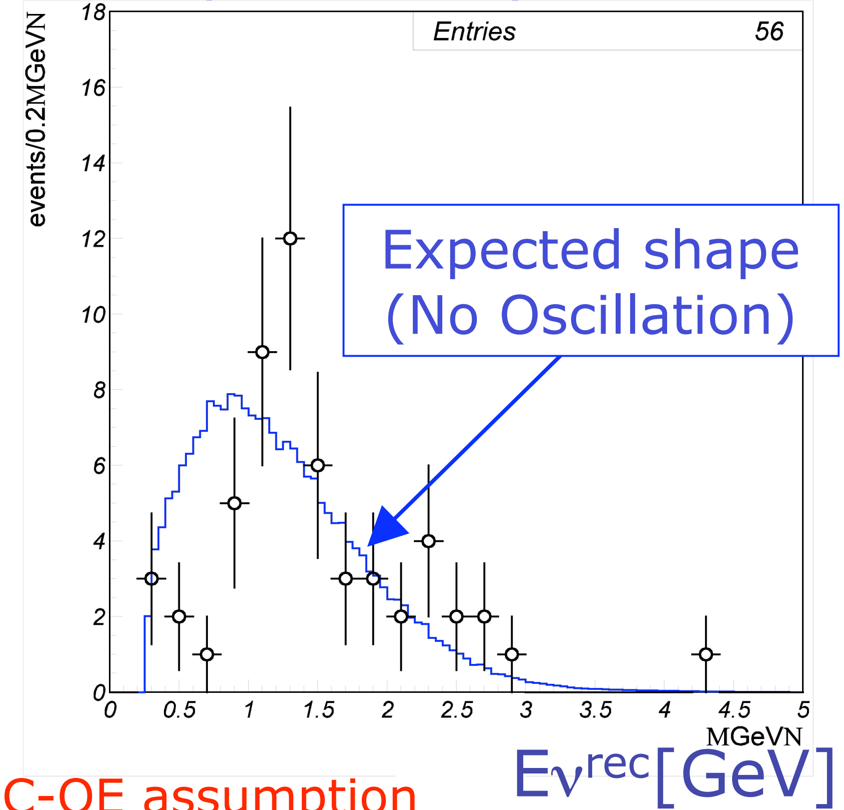
Ref; K2K-I(47.9×10^{18}POT), K2K-II(41.2×10^{18}POT)

Compared with null-oscillation…

$L_{norm}(\Delta m^2, \sin 2\theta, f^x)$ $L_{shape}(\Delta m^2, \sin 2\theta, f^x)$



KS probability=0.11%



CC-QE assumption

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

V: Nuclear potential

5. Super-K oscillation analysis

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

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

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

f^x : Systematic error parameters

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

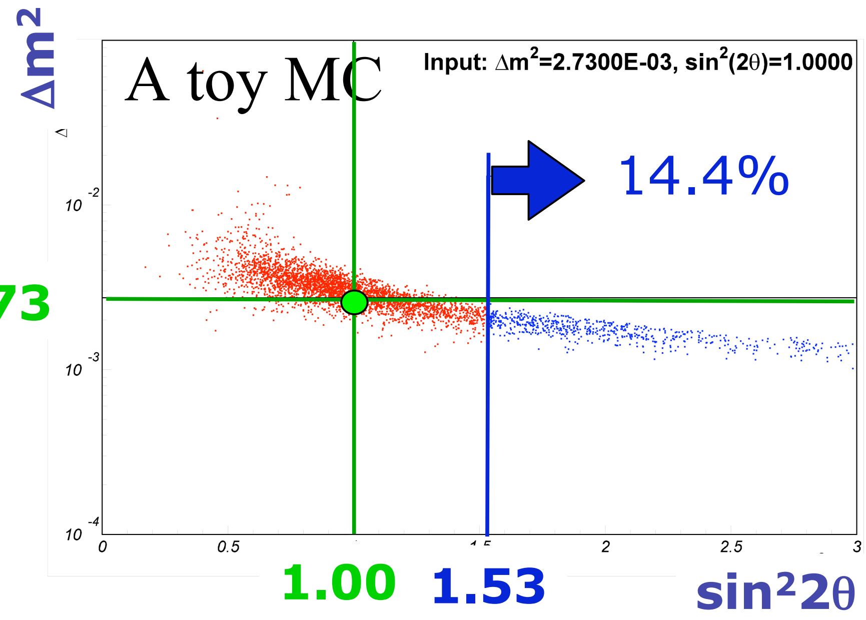
Near Detector measurements, Pion Monitor constraint, beam MC estimation, and Super-K systematic uncertainties.

6. Likelihood fit results

preliminary

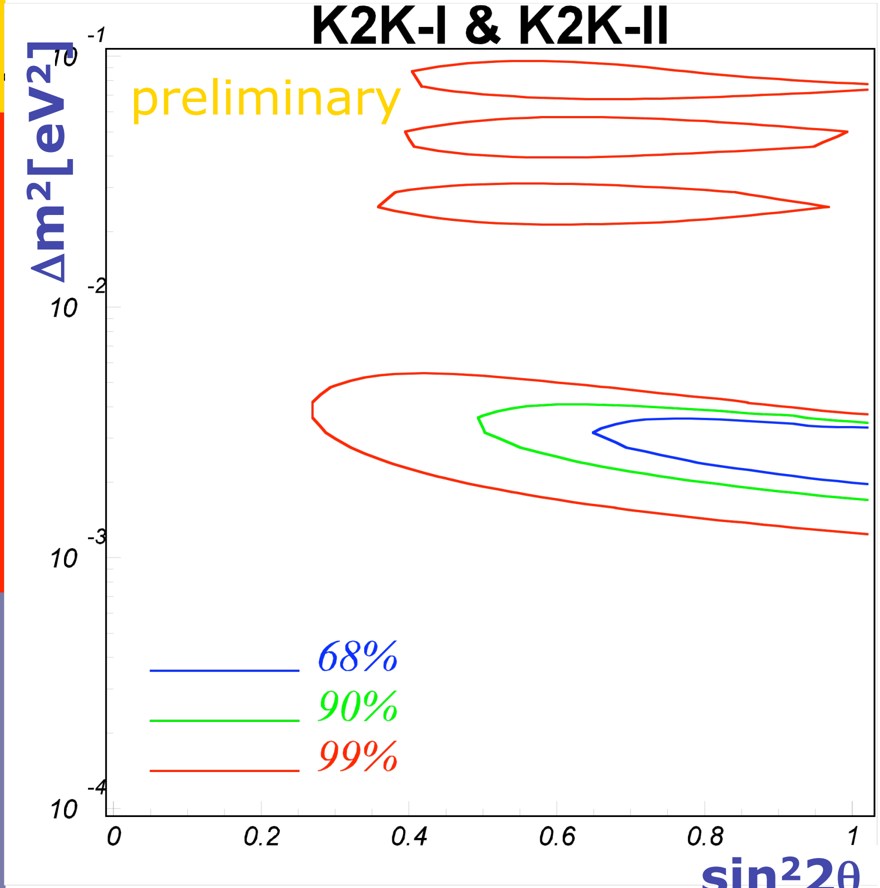
- Best fit values.
  - $\sin^2 2\theta = 1.53$
  - Δm^2 [eV^2] $= 2.12\times10^{-3}$
- Best fit values in the physical region.
  - $\sin^2 2\theta = \mathbf{1.00}$
  - Δm^2 [eV^2] $= \mathbf{2.73\times10^{-3}}$

$\Delta\log \boldsymbol{L} = 0.64$



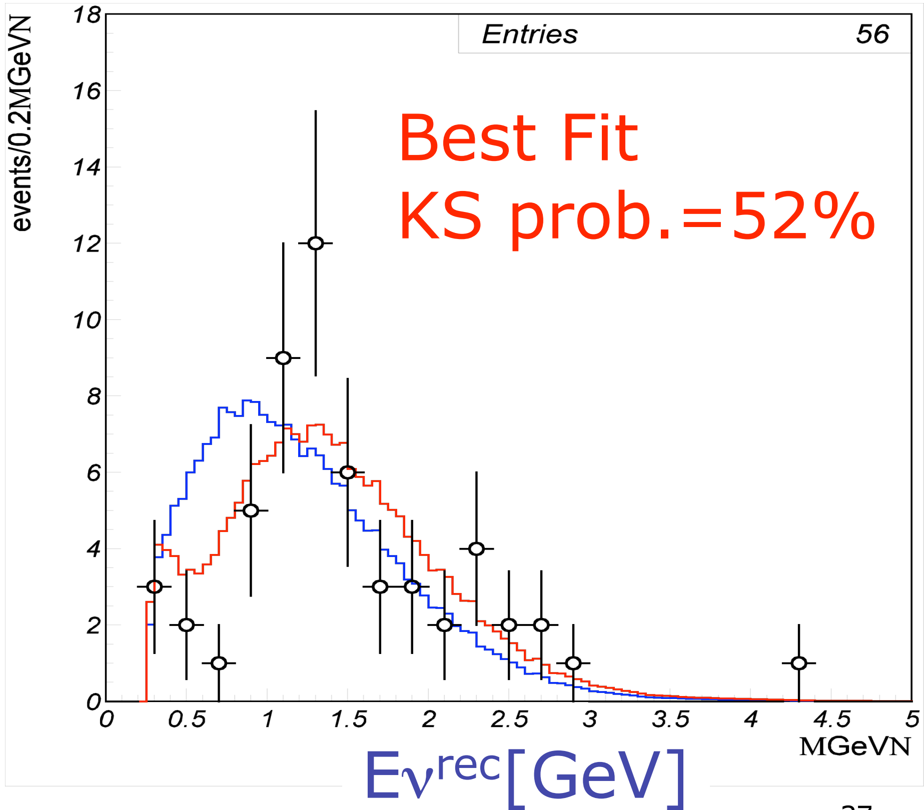
$\sin^2 2\theta = 1.53$ can occur by statistical fluctuation with 14.4% probability.

Data are consistent with the oscillation.

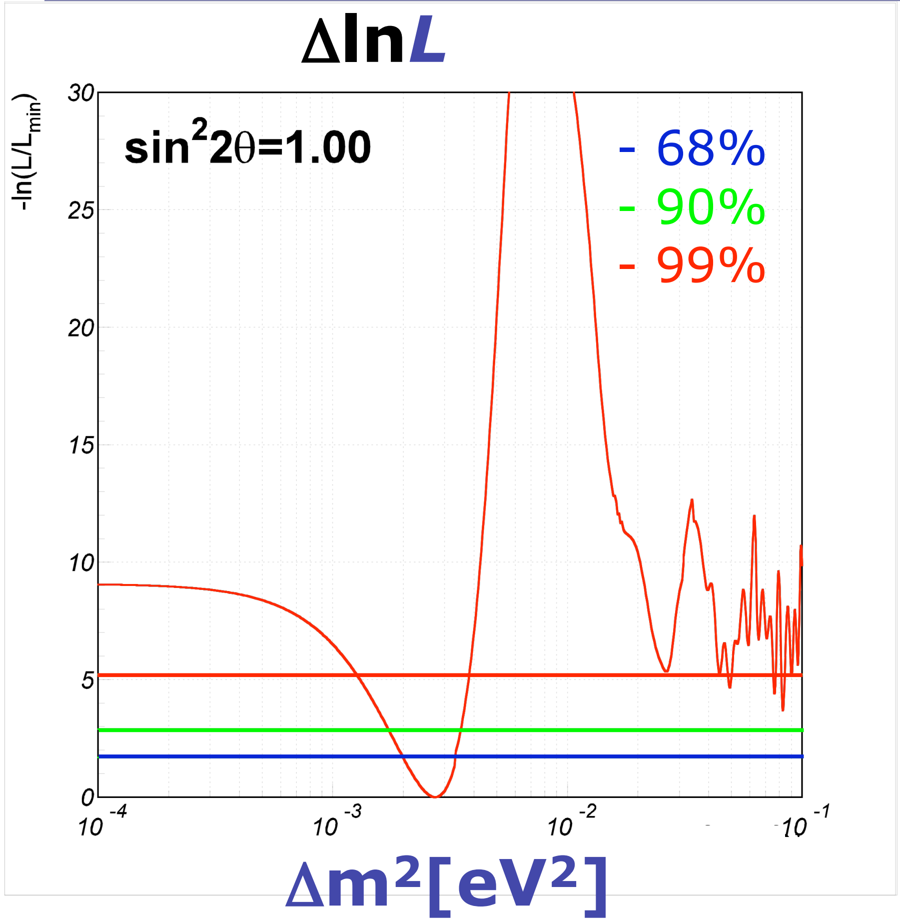


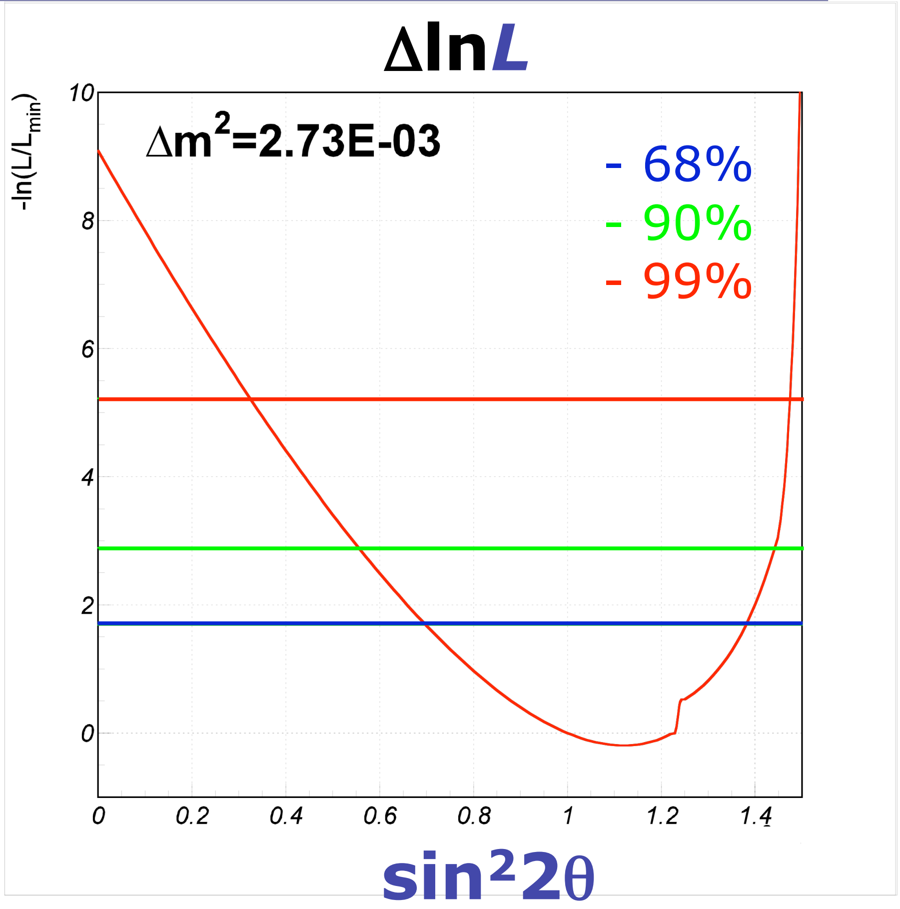
Based on Δln*L*

- N_{SK}^{obs}=108
- N_{SK}^{exp} (best fit)=104.8



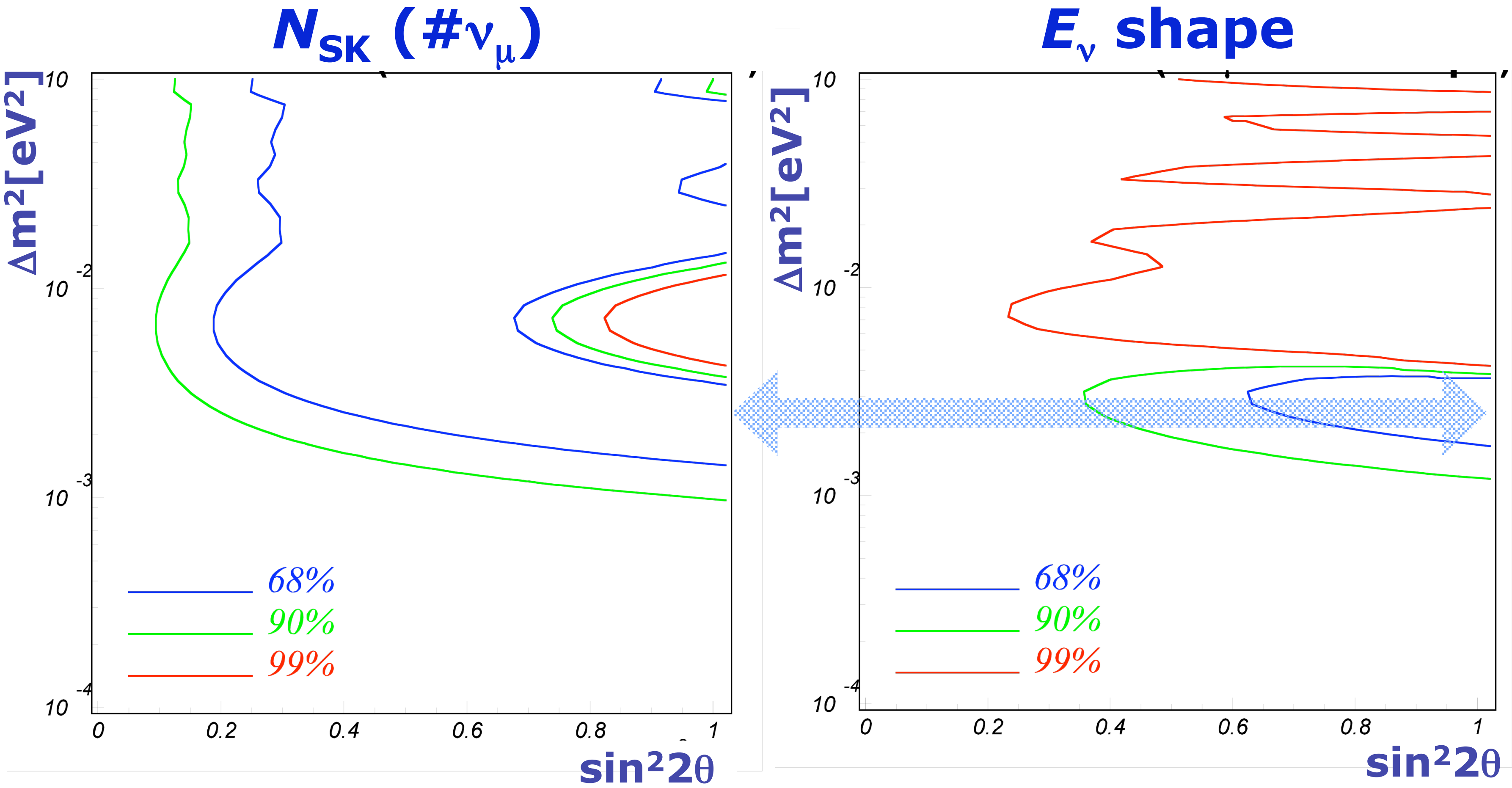
Log Likelihood difference from the minimum.





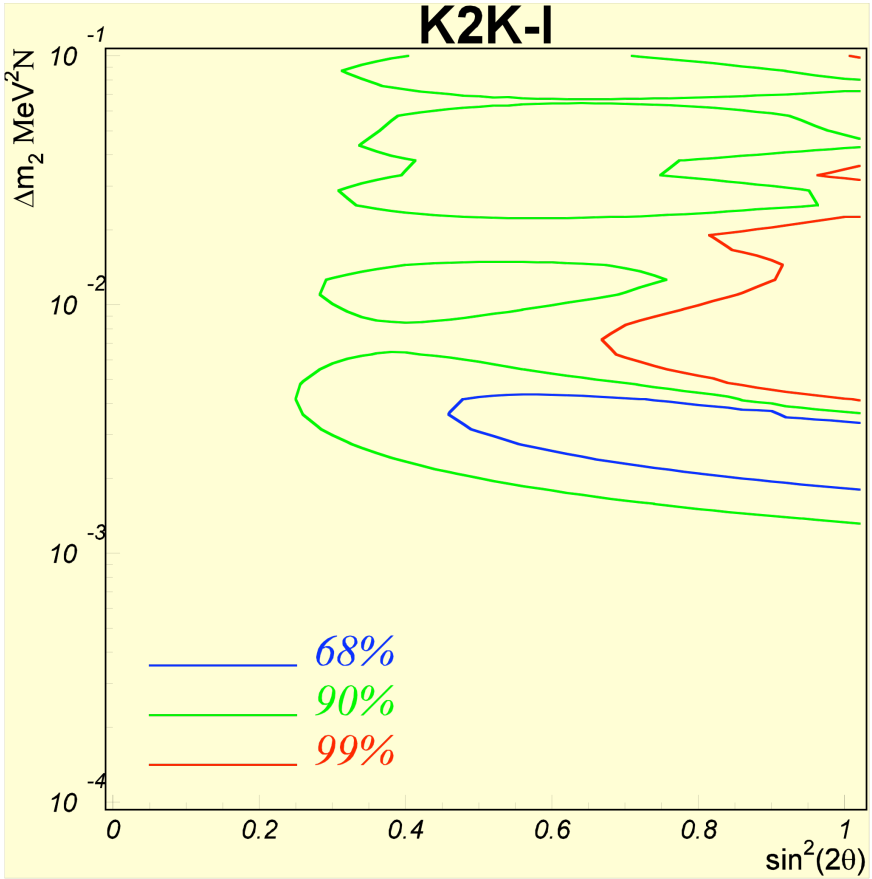
- $\Delta m^2 < (1.7 \sim 3.5) \times 10^{-3}$ eV² at $\sin^2 2\theta = 1.0$ (90% C.L.)

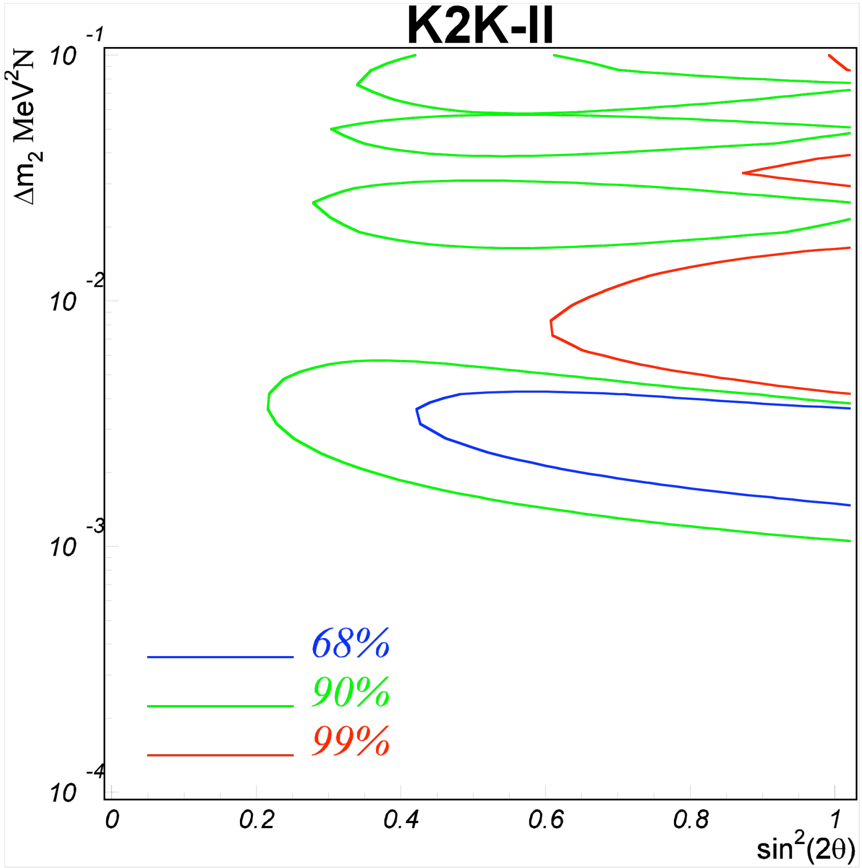
ν_μ disappearance versus E_ν shape distortion



Both disappearance of ν_μ and the distortion of E_ν spectrum give consistent results.

K2K-I vs K2K-II





Consistent results from both sub-samples.

Null oscillation probability

preliminary

The null oscillation probabilities are calculated based on $\Delta\ln\boldsymbol{L}$.

	K2K-I	K2K-II	K2K-all
ν_μ disappearance	2.0%	3.7%	0.33%(2.9σ)
E_ν spectrum distortion	19.5%	5.4%	1.1% (2.5σ)
Combined	1.3% (2.5σ)	0.56% (2.8σ)	**0.011%** (3.9σ)

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.*

8. Summary

With 8.9×10^{19} POT,

K2K *has* *confirmed* neutrino oscillation with 3.9σ.

- Disappearance of ν_μ
  2.9σ
- Distortion of E_ν spectrum
  2.5σ