June 15th, 2004
@NEUTRINO2004

New K2K Results

T. Nakaya (Kyoto University)
for K2K collaboration

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

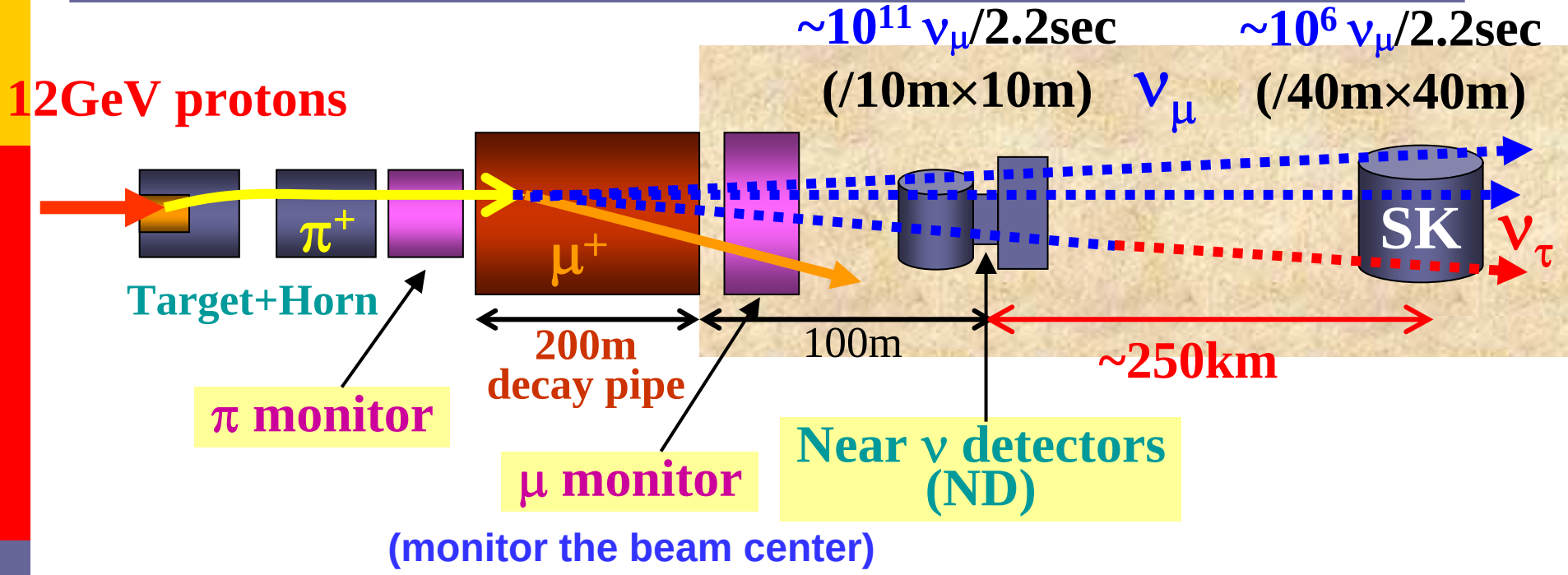
RUSSIA: INR-Moscow

1. Introduction and 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
  - *Confirm neutrino oscillation with both a deficit of ν_μ and the distortion of the E_ν spectrum.*

2. K2K experiment

~1 event/2days

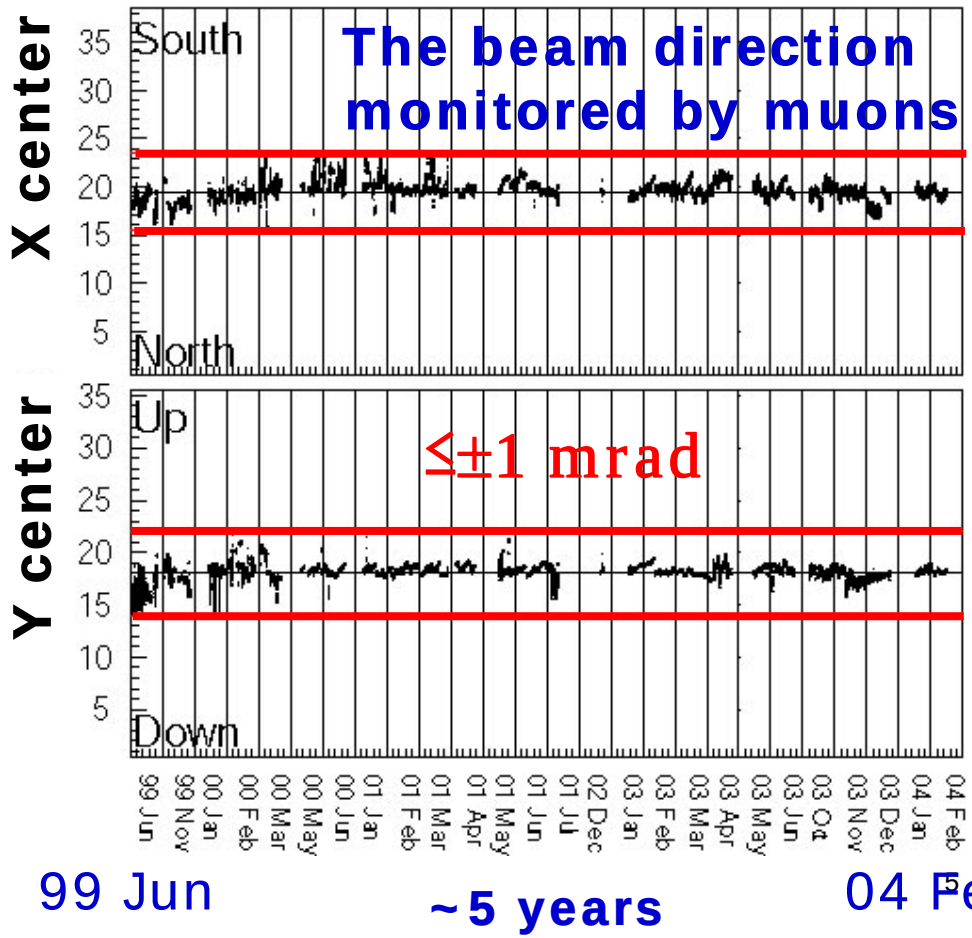


Signal of ν oscillation at K2K

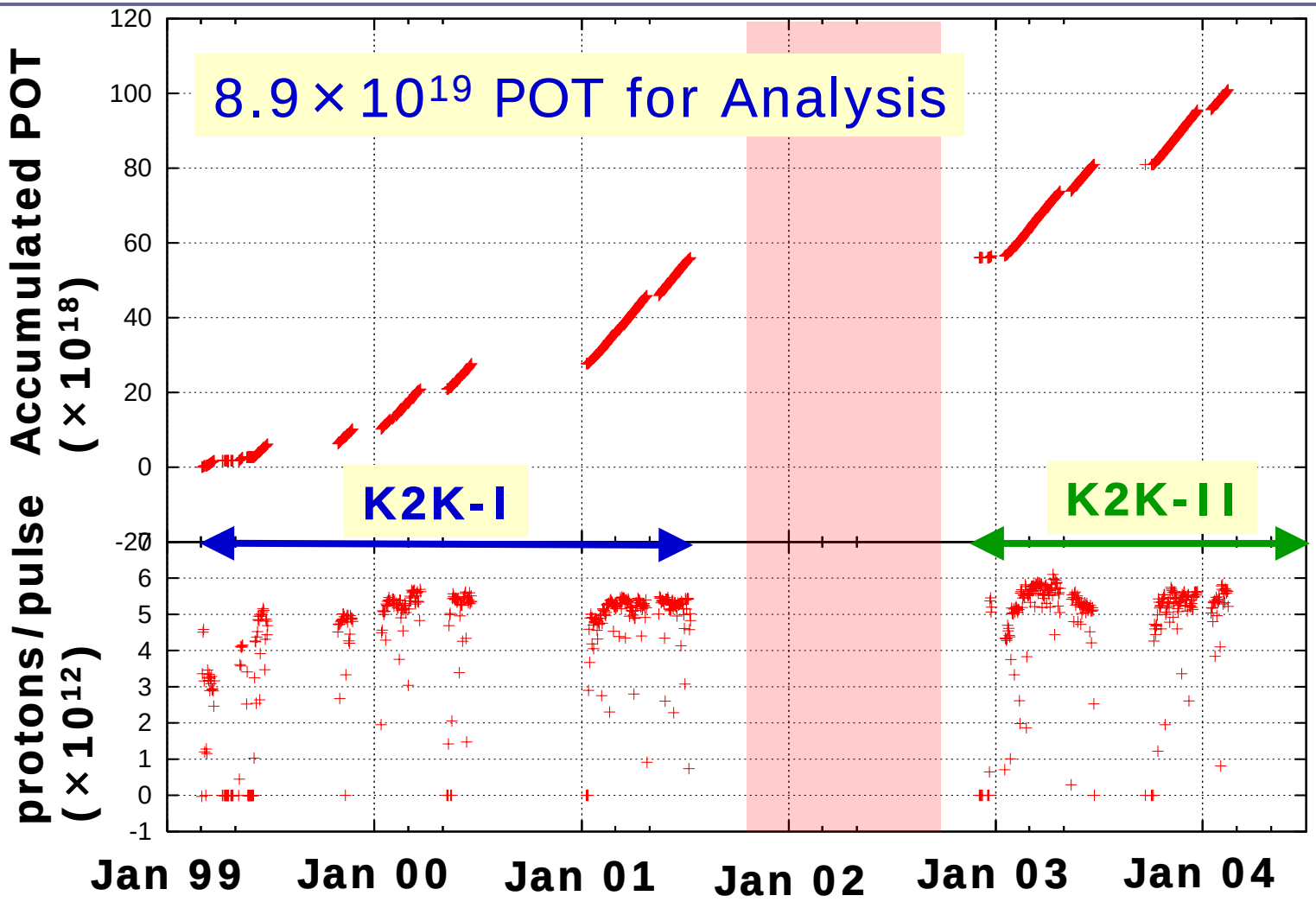
- Reduction of ν_μ events
- Distortion of ν_μ energy spectrum

Neutrino beam and the directional control

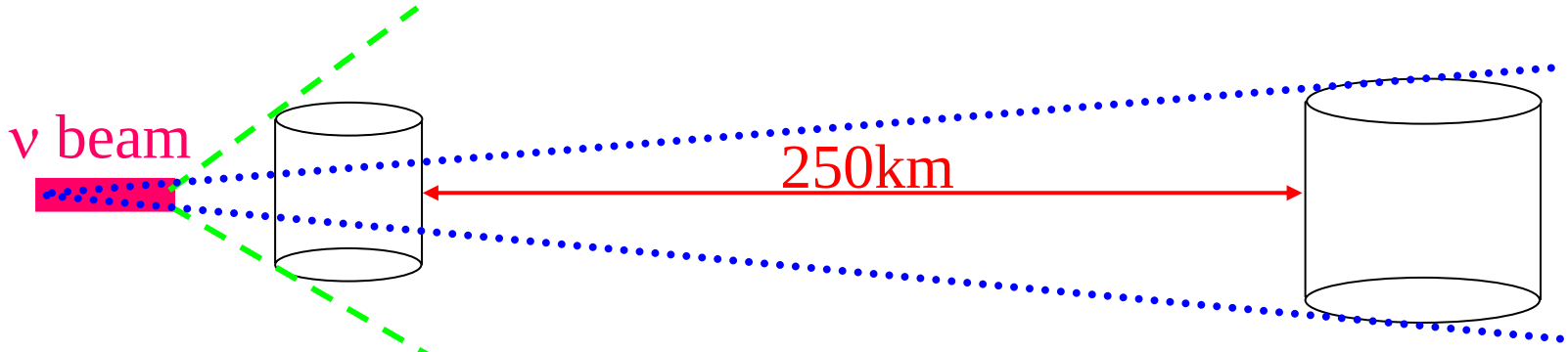
- ~1GeV neutrino beam by a dual horn system with 250kA.

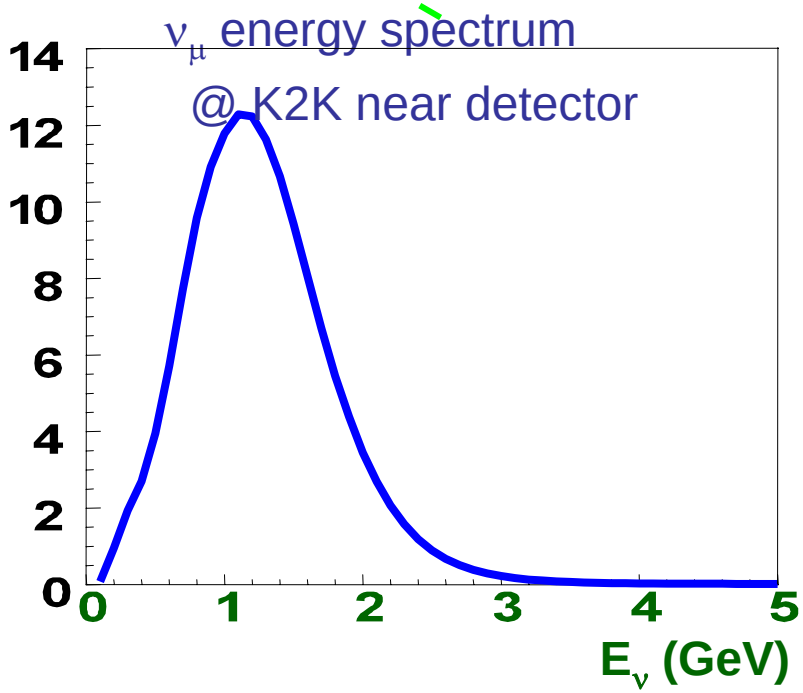


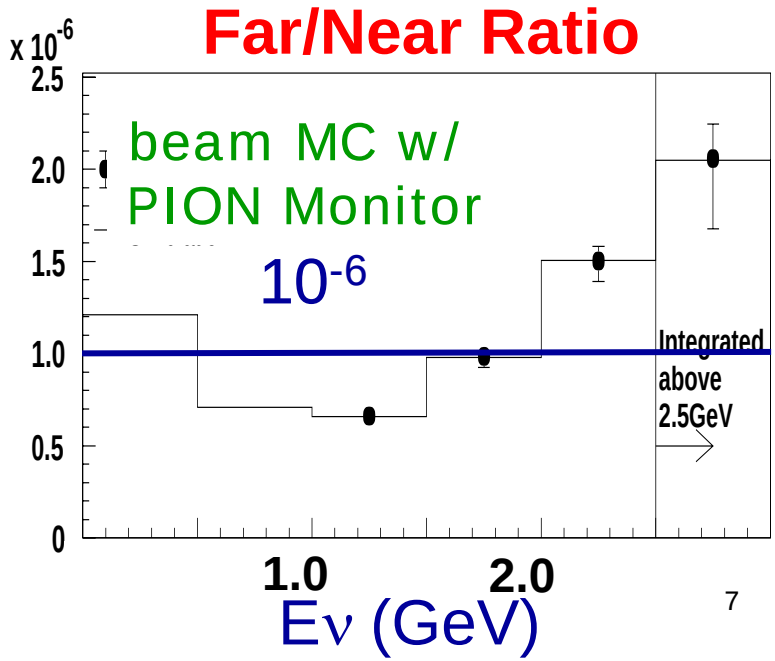
Accumulated POT (Protons On Target)



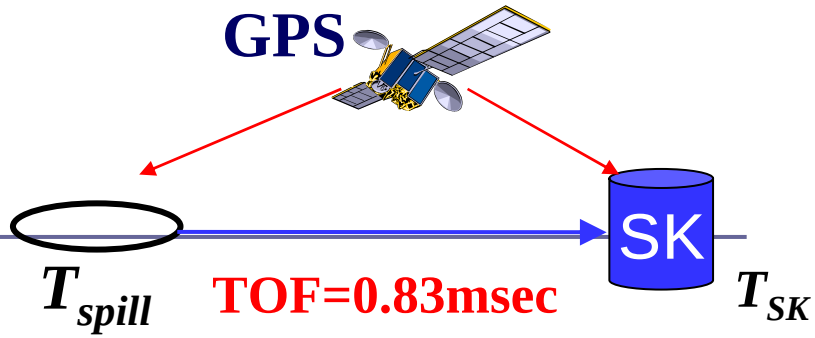
Neutrino spectrum and the far/near ratio



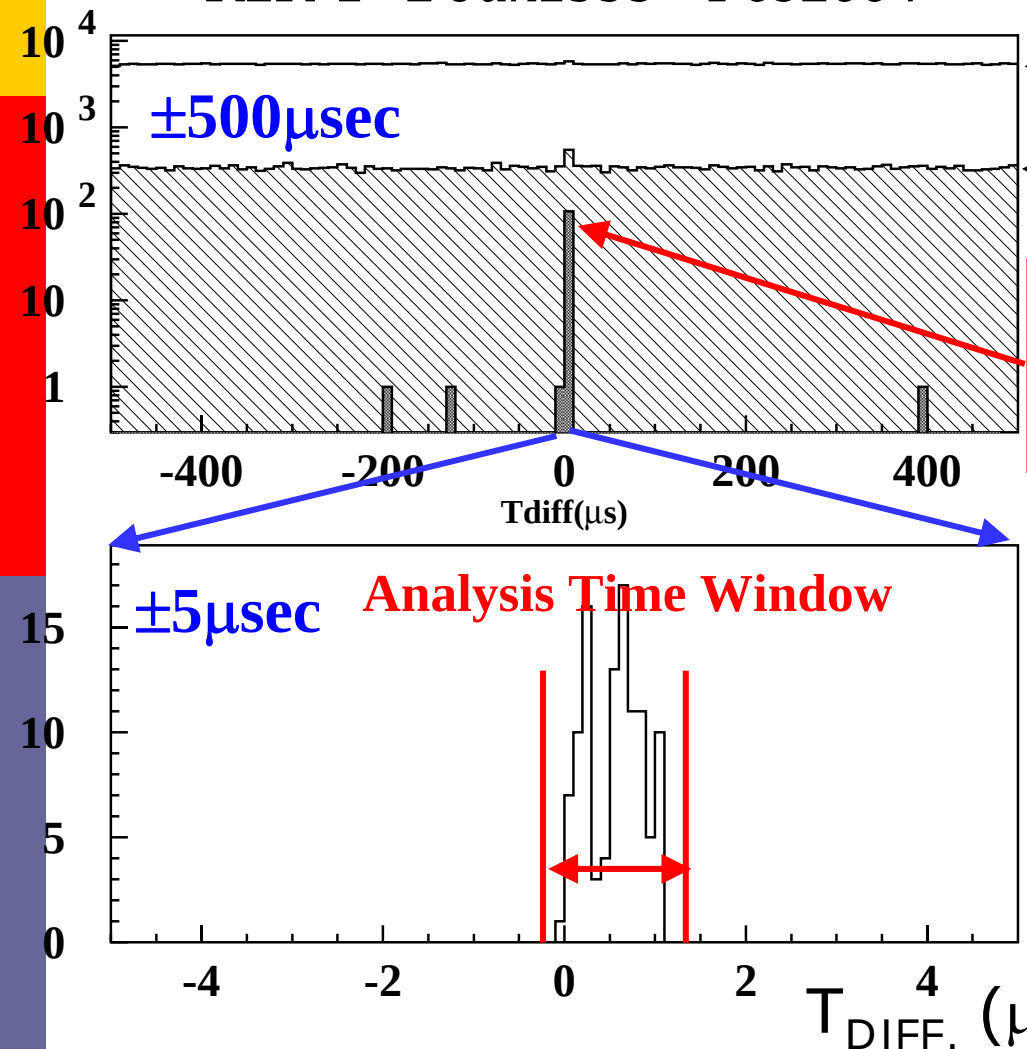




SK Events



K2K-1+2 Jun1999 - Feb2004



Decay electron cut.

≥20MeV Deposited Energy

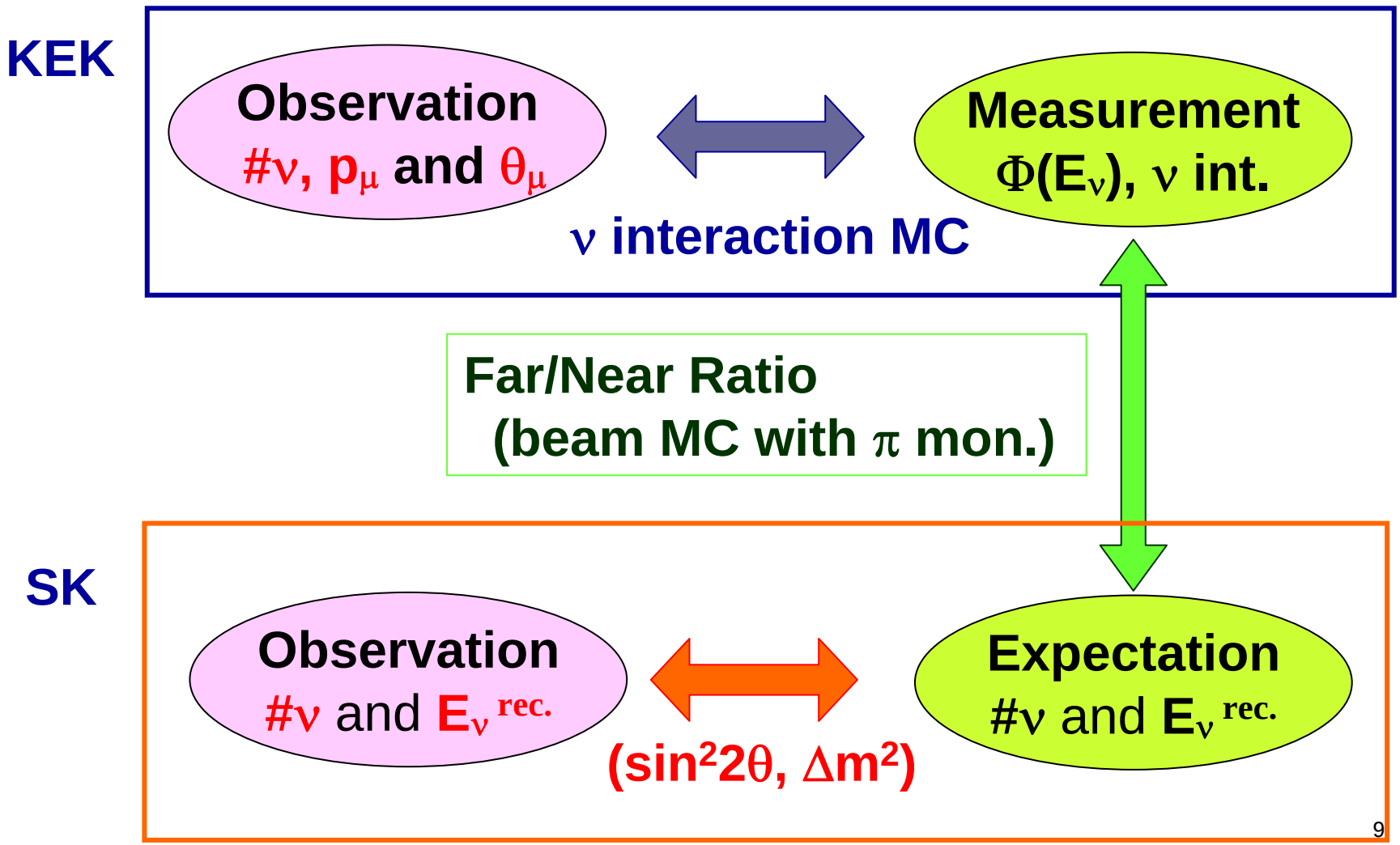
No Activity in Outer Detector
Event Vertex in Fiducial Volume
More than 30MeV Deposited Energy

108 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)

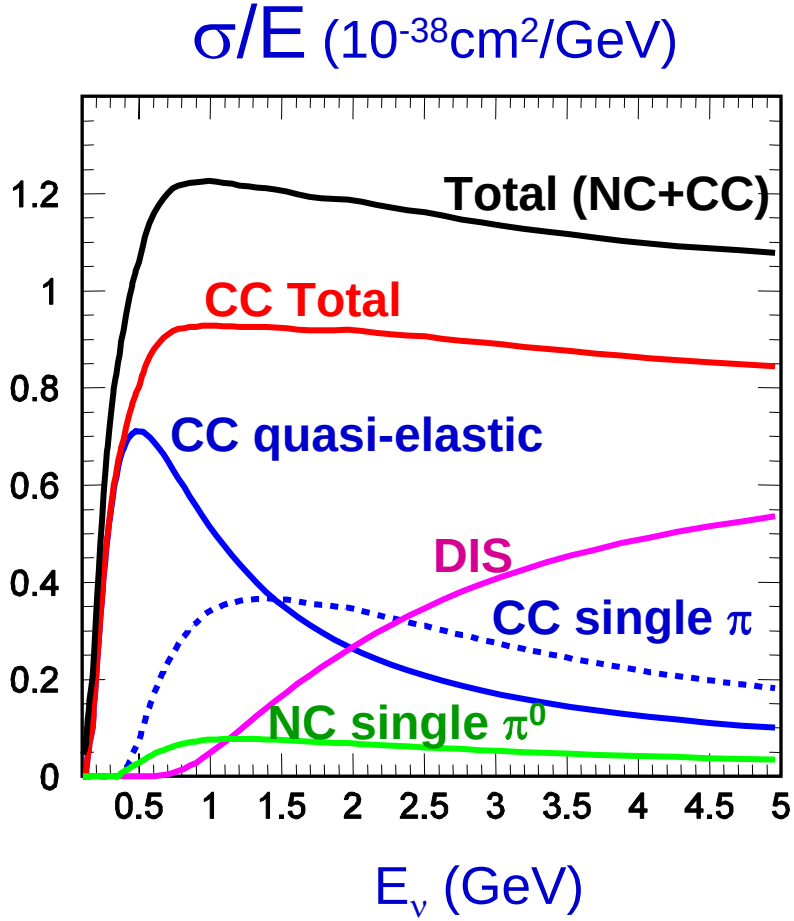
3. Analysis Overview



NEUT: K2K Neutrino interaction MC

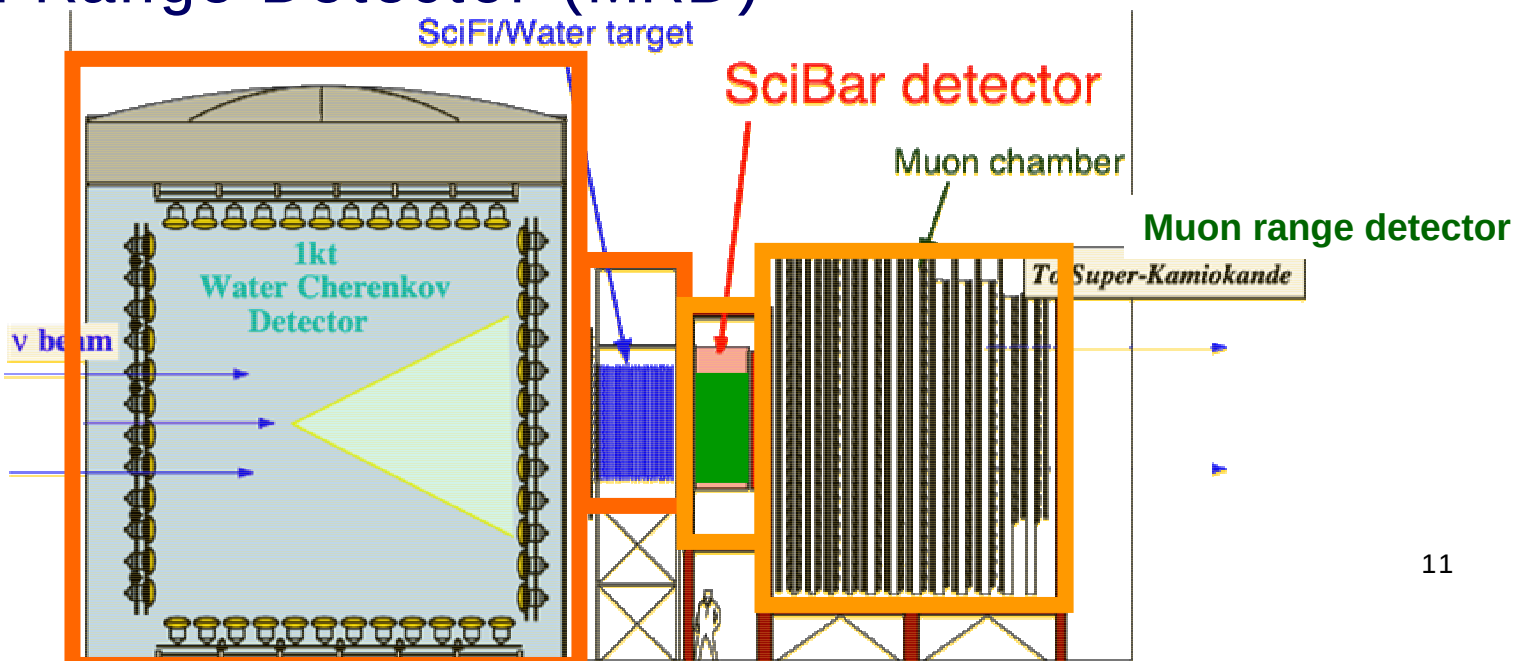
- **CC quasi elastic (CCQE)**
  - Smith and Moniz with $M_A = 1.1$GeV
- **CC (resonance) single π (CC-1π)**
  - Rein and Sehgal's with $M_A = 1.1$GeV
- **DIS**
  - GRV94 + JETSET with Bodek and Yang correction.
- **CC coherent π**
  - Rein&Sehgal with the cross section rescale by J. Marteau
- **NC**

+ Nuclear Effects



4. Near detector measurements

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



4.1 1KT Flux measurement

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

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

≡Far/Near Ratio (by MC) ~ 1×10^{-6}

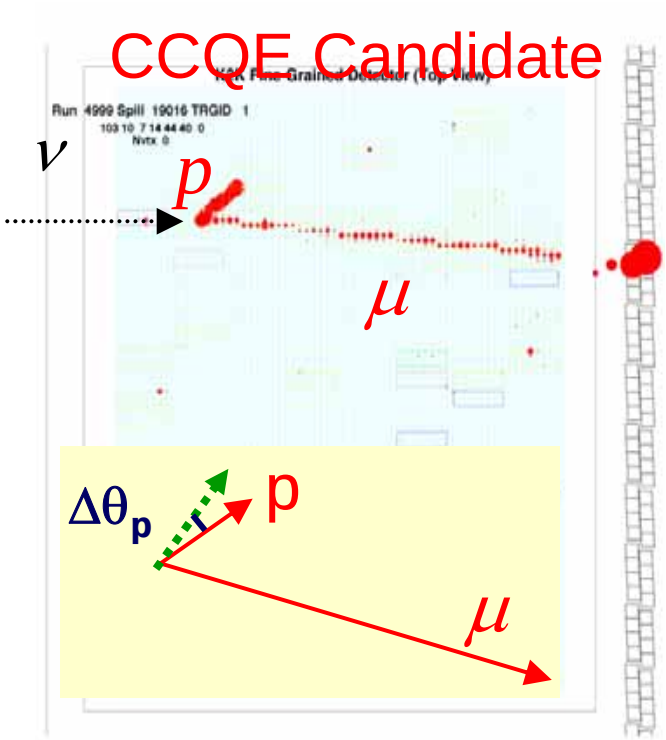
M: Fiducial mass M_{SK} = 22,500ton, M_{KT} = 25ton

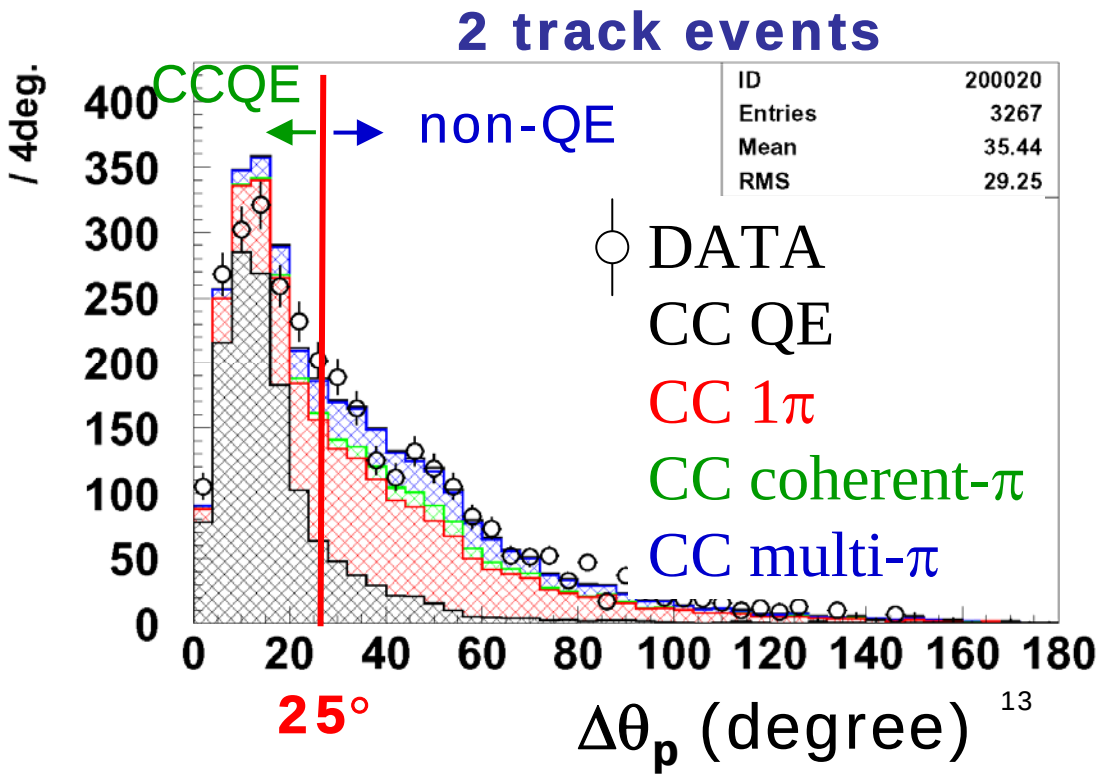
ε: efficiency $\varepsilon_{SK\text{-}I(II)}$ = 77.0(78.2)%, ε_{KT} = 74.5%

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

4.2 SciBar neutrino interaction study.

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





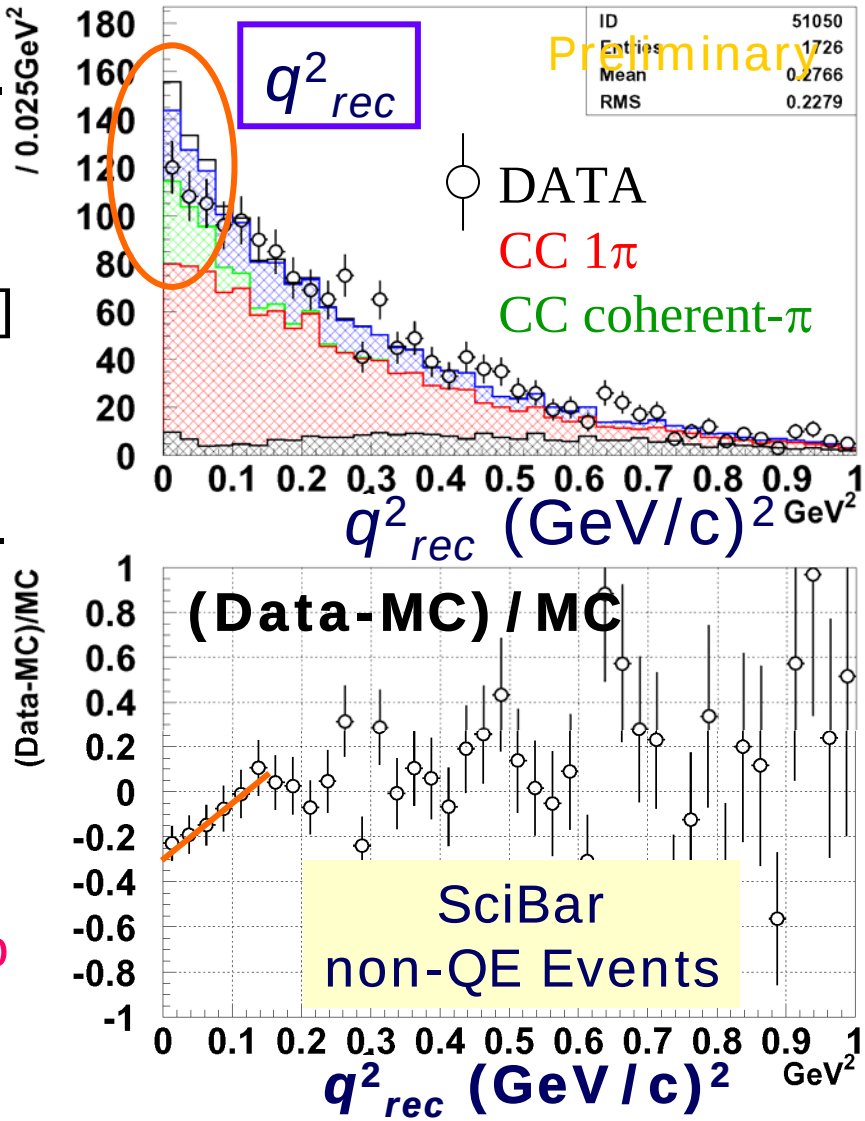
A hint of K2K forward μ deficit.

K2K observed forward μ deficit.

- 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 phenomenologically.

Oscillation analysis is insensitive to the choice.

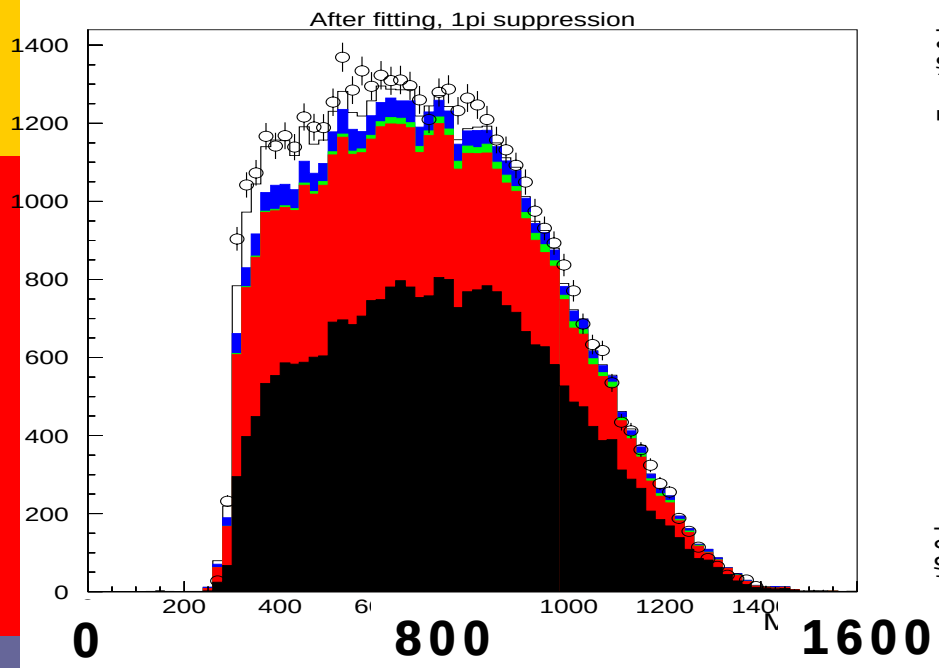


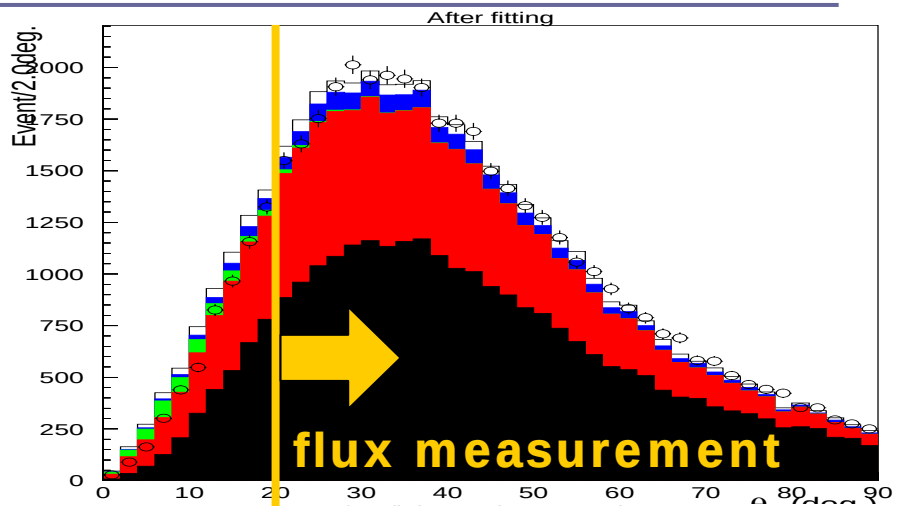
4.3 Near Detector Spectrum Measurements

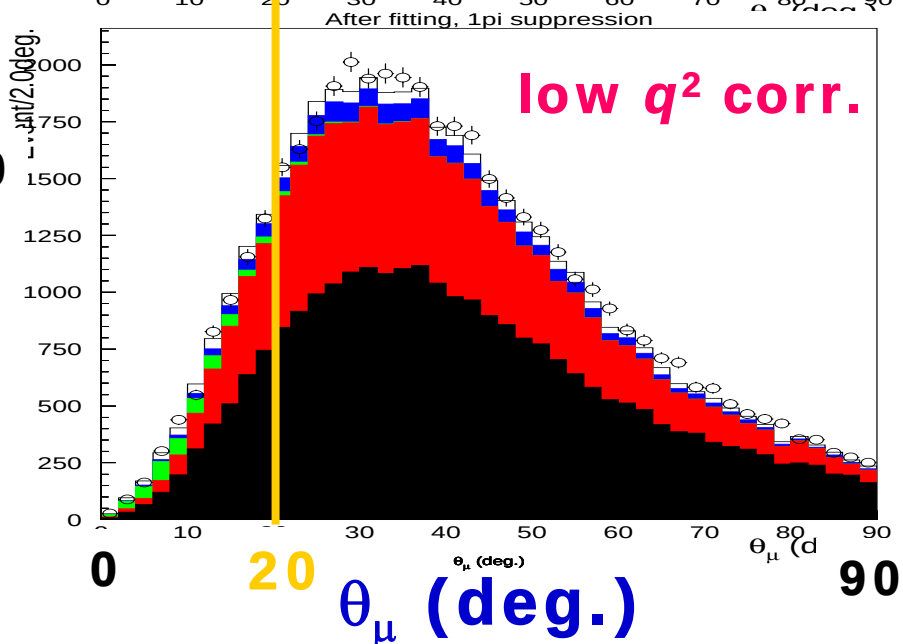
- 1KT
  - Fully Contained 1 ring μ (FC1Rμ) sample.
- SciBar
  - 1 track, 2 track QE ($\Delta\theta_p \leq 25°$), 2 track nQE ($\Delta\theta_p > 25°$) where one track is μ.
- SciFi
  - 1 track, 2 track QE ($\Delta\theta_p \leq 25°$), 2 track nQE ($\Delta\theta_p > 30°$) where one track is μ.

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

1KT: μ momentum and angular distributions. with measured spectrum



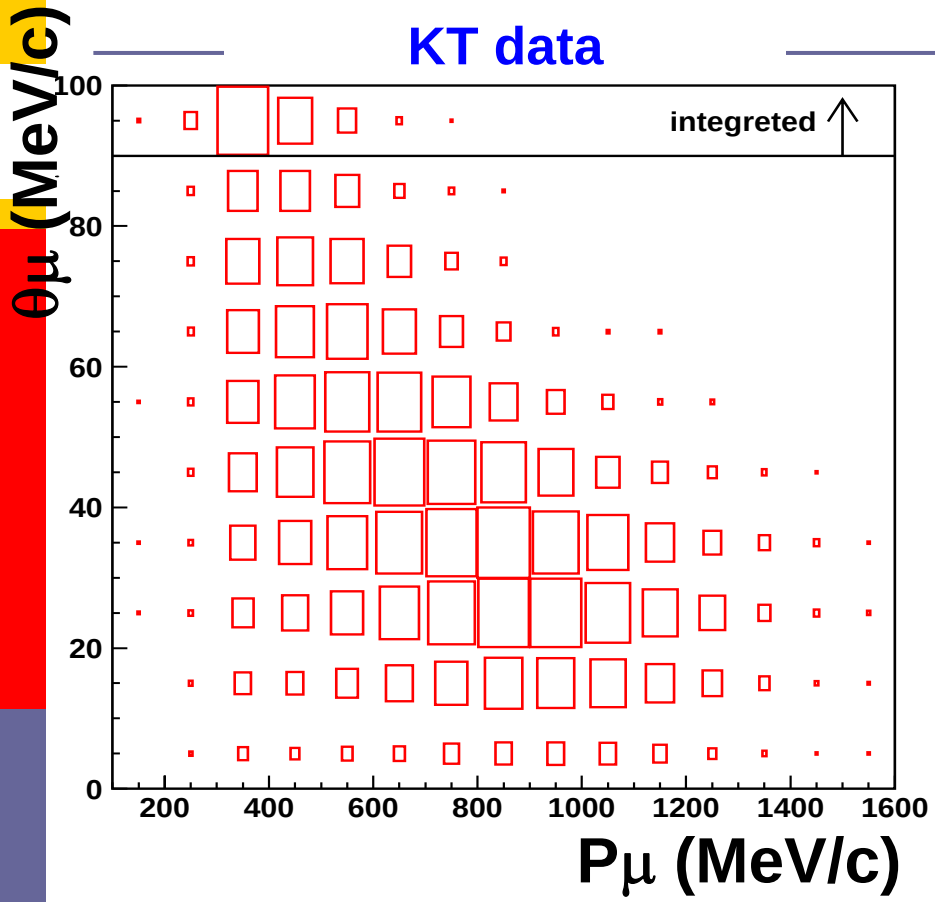




4.4 Near Detectors combined measurements

(p_μ,θ_μ) for 1track, 2trackQE and 2track nQE samples
$\rightarrow \Phi(E\nu)$, 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).
  ③ Measure nQE/QE ratio for the entire θ_μ range.



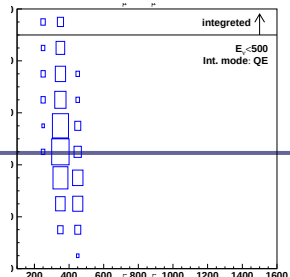
Eν

QE (MC)

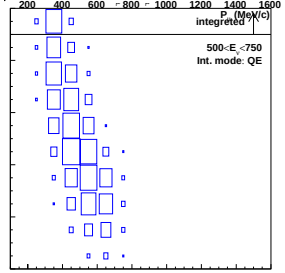
nQE(MC)

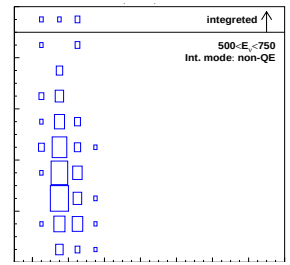
MC templates

0-0.5 GeV

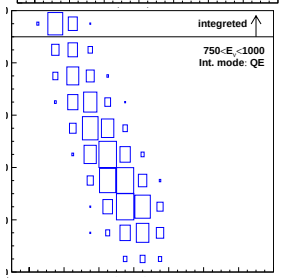


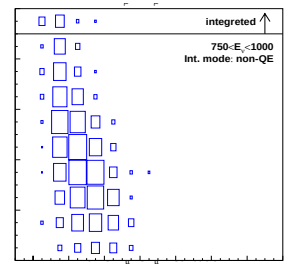
0.5-0.75GeV



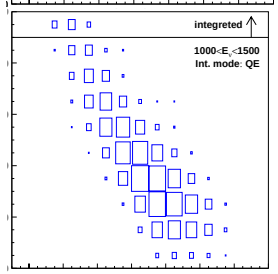


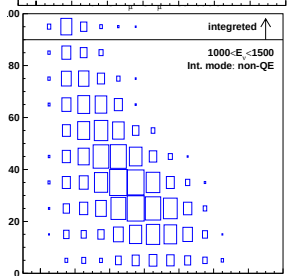
0.75-1.0GeV





1.0-1.5GeV





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

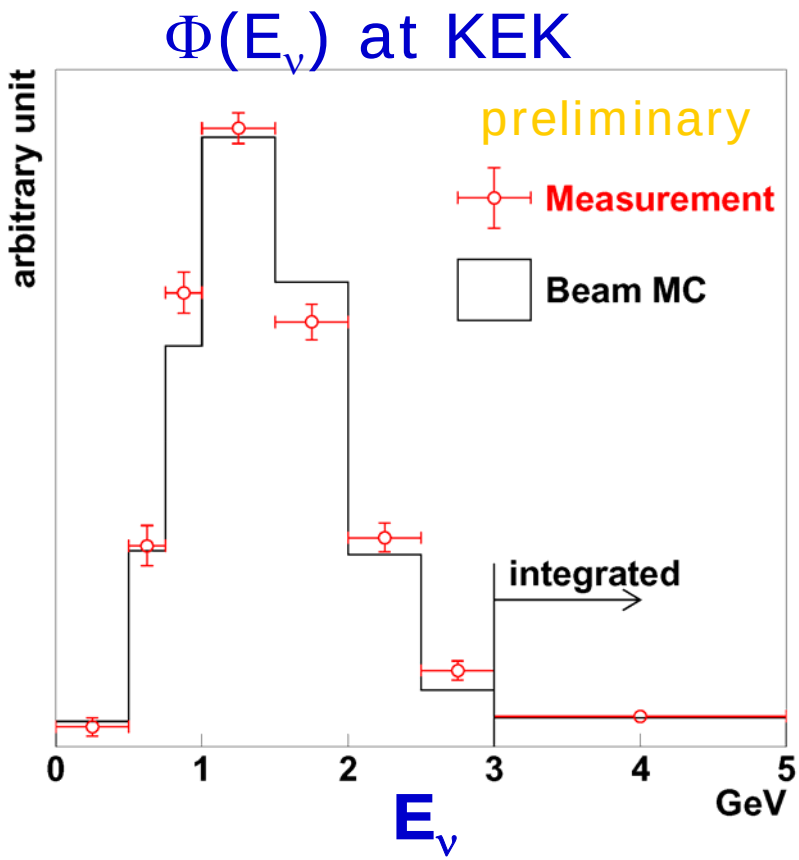
Flux measurements

χ^2=638.1 for 609 *d.o.f*

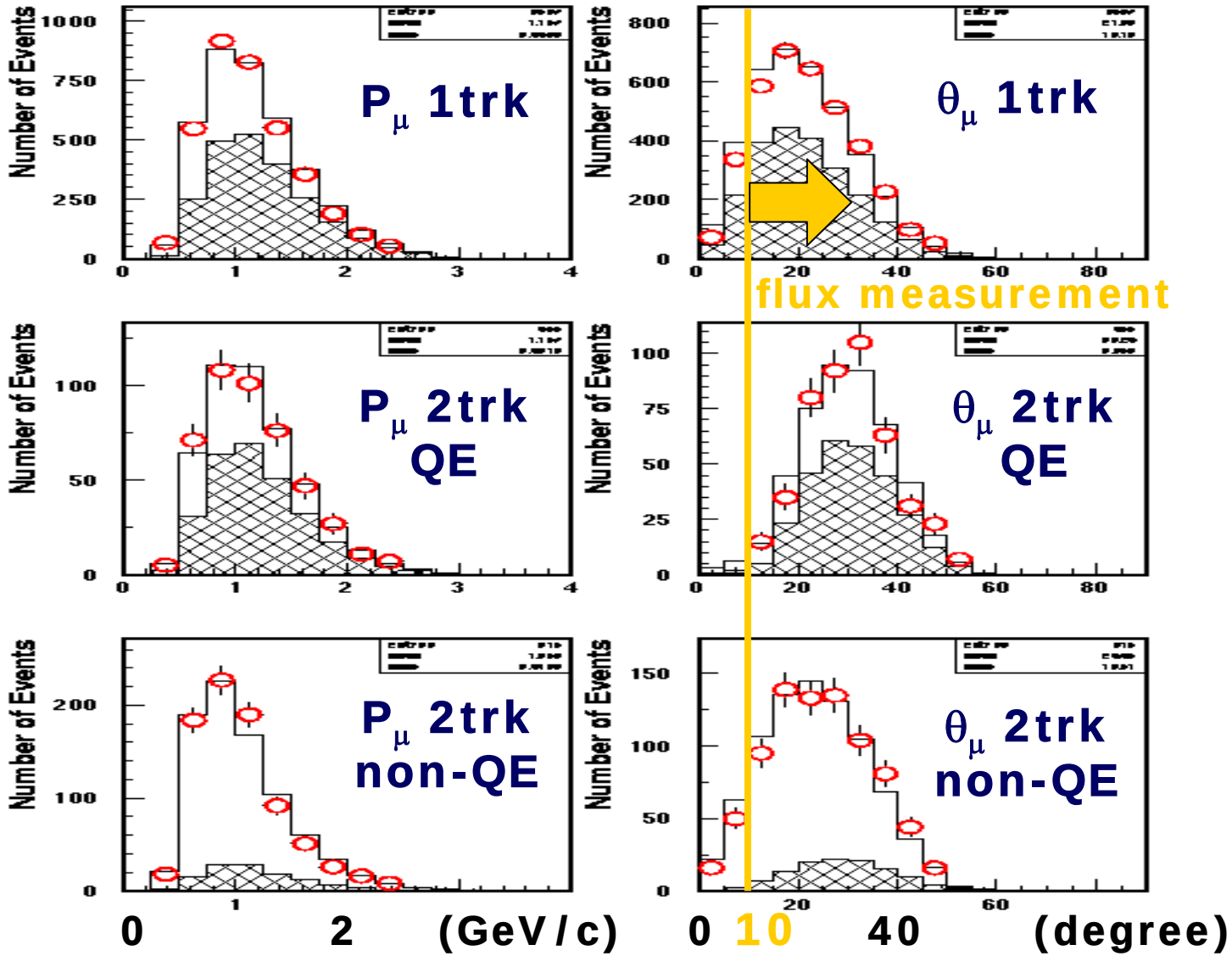
- Φ1 (Eν < 500) = 0.78 ± 0.36
- Φ2 (500≤ Eν < 750) = 1.01 ± 0.09
- Φ3 (750≤ Eν <1000) = 1.12 ± 0.07
- Φ4 (1000≤ Eν <1500) = 1.00
- Φ5 (1500≤ Eν <2000) = 0.90 ± 0.04
- Φ6 (2000≤ Eν <2500) = 1.07 ± 0.06
- Φ7 (2500≤ Eν <3000) = 1.33 ± 0.17
- Φ8 (3000≤ Eν) = 1.04 ± 0.18
- nQE/QE = 1.02 ± 0.10

The nQE/QE error of 10% is assigned based on the sensitivity of the fitted nonQE/QE value by varying the fit criteria.

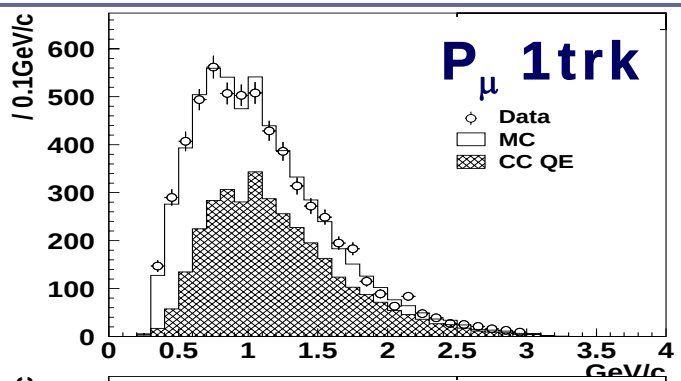
- θ>10°(20 °) cut: nQE/QE=0.95 ±0.04
- standard(CC-1π low q^2 corr.): nQE/QE=1.02 ±0.03
- No coherent: π=nQE/QE=1.06 ±0.03

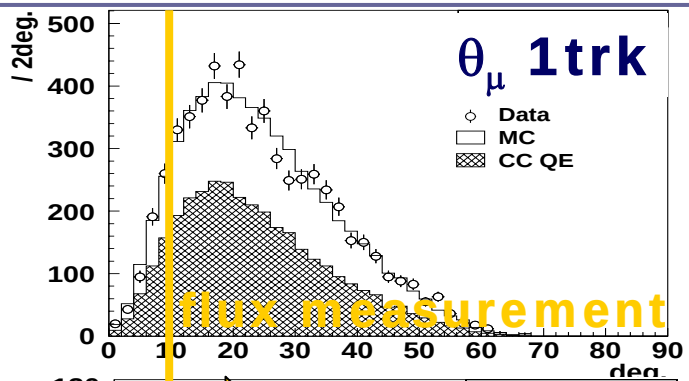


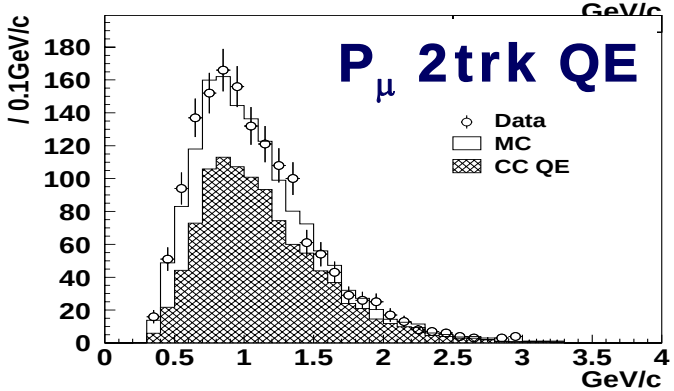
SciFi (K2K-IIa with measured spectrum)

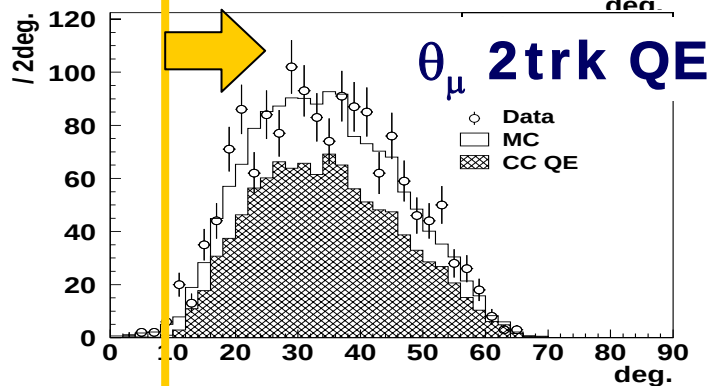


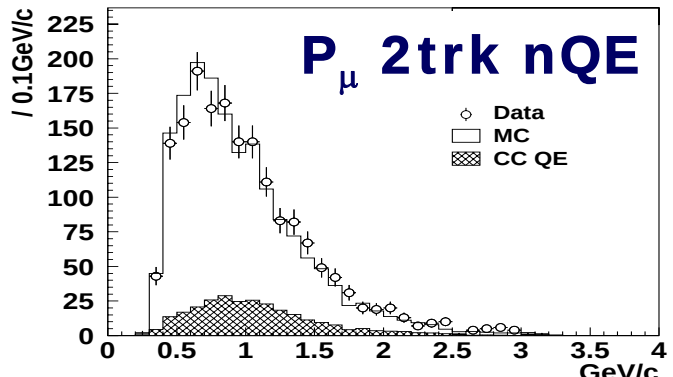
SciBar (with measured flux)

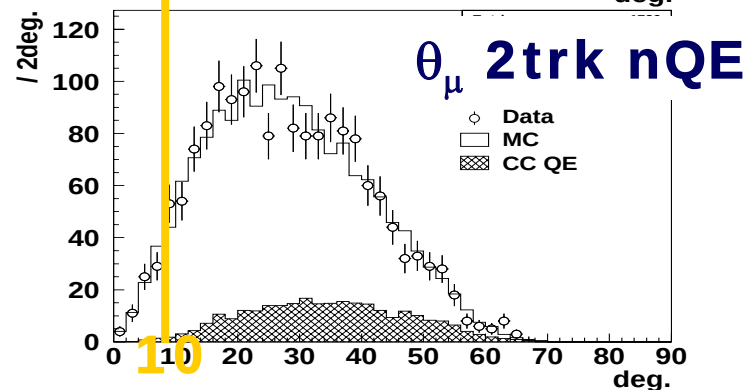












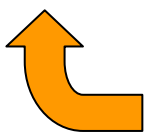
5. Super-K oscillation analysis

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

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

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.

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 for E_ν^{rec}	**57 (56)** (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)

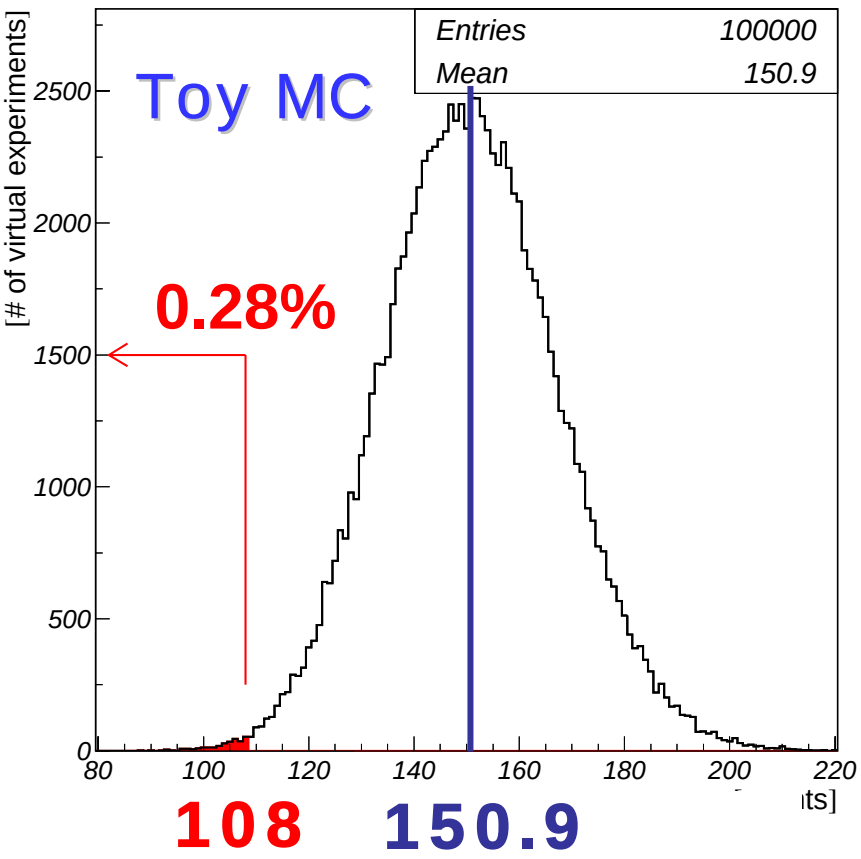
Ref; K2K-I(47.9×10^{18}POT), K2K-II(41.2×10^{18}POT)

*: The number is changed from the previous one.

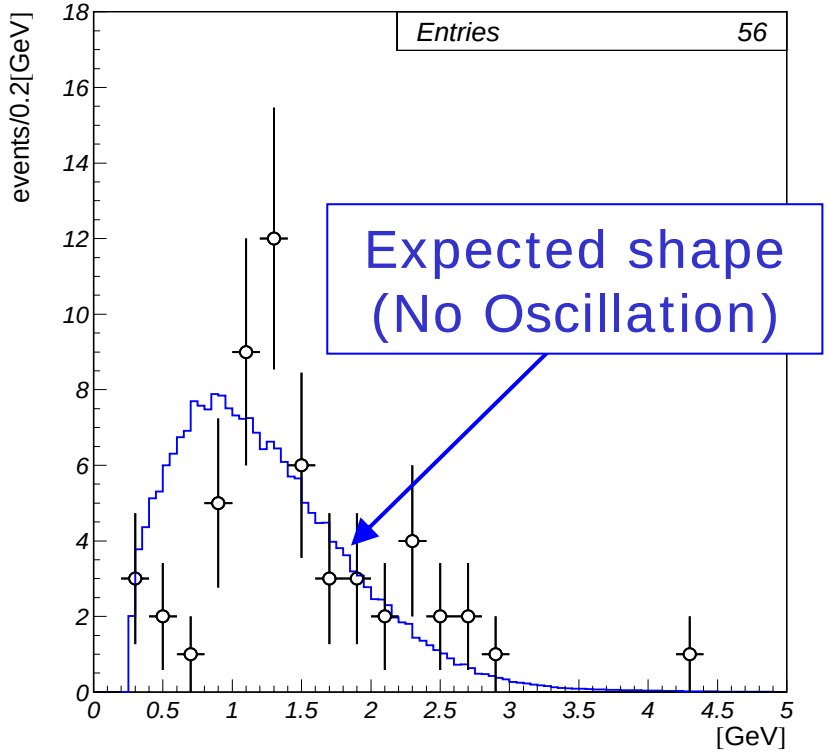
$L_{norm}(f^x)$

$L_{shape}(f^x)$

#SK Events



KS probability=0.11%



$E\nu^{rec}$[GeV]

CC-QE assumption

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

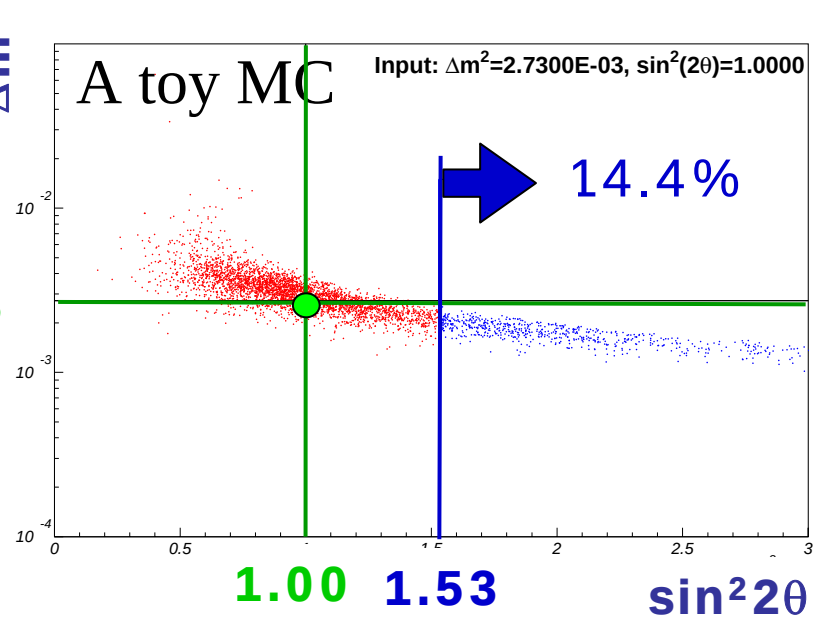
V: Nuclear potential

6. Results preliminary

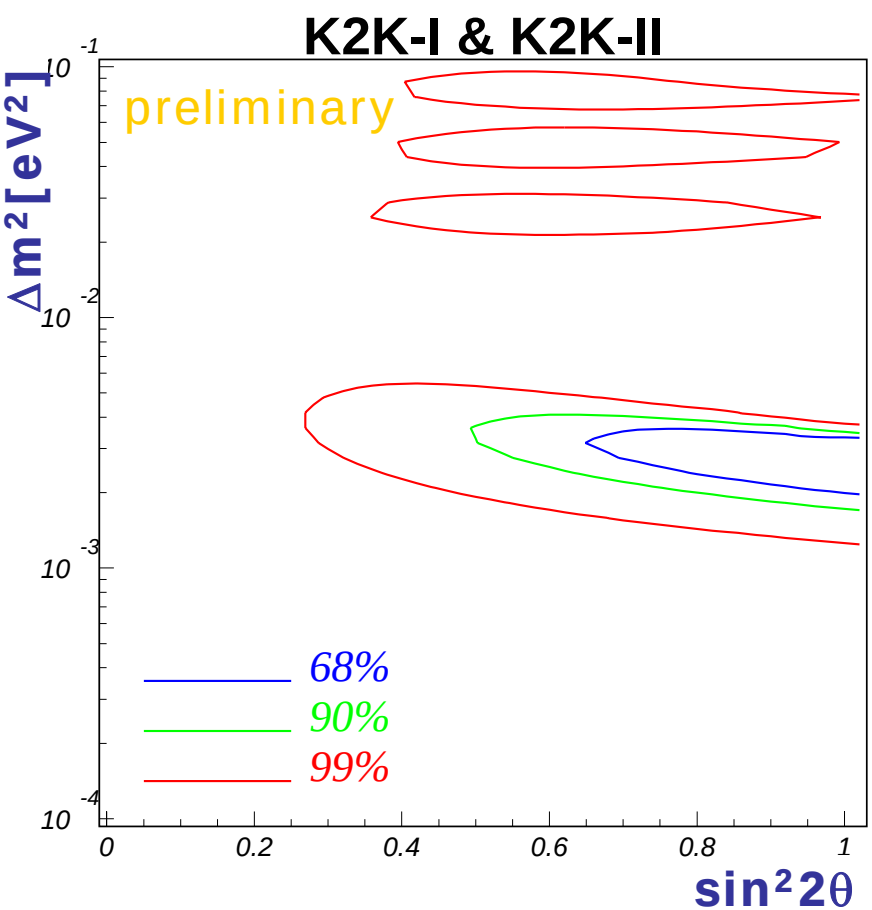
- Best fit values.
  - $\sin^2 2\theta = 1.53$
  - $\Delta m^2\ [eV^2] = 2.12 \times 10^{-3}$
- Best fit values in the physical region.
  - $\sin^2 2\theta = \mathbf{1.00}$
  - $\Delta m^2\ [eV^2] = \mathbf{2.73 \times 10^{-3}}$

$\Delta \log L = 0.64$

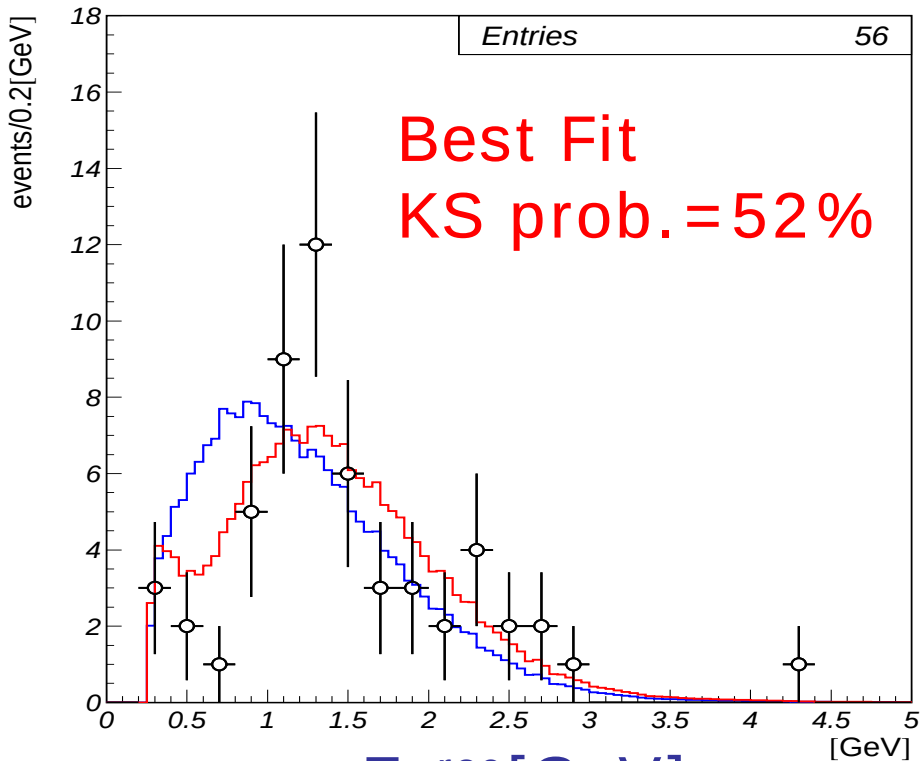
$\sin^2 2\theta = 1.53$ can occurr due to a a statistical fluctuation with 14.4%.



Data are consistent with the oscillation.

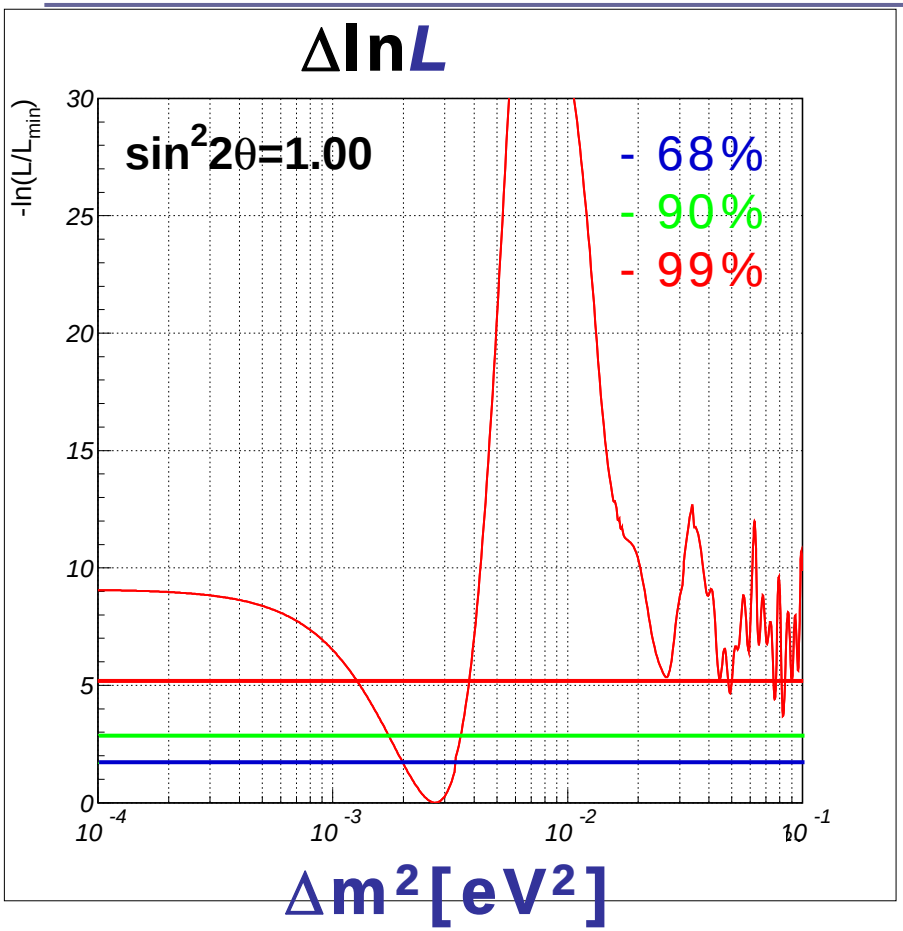


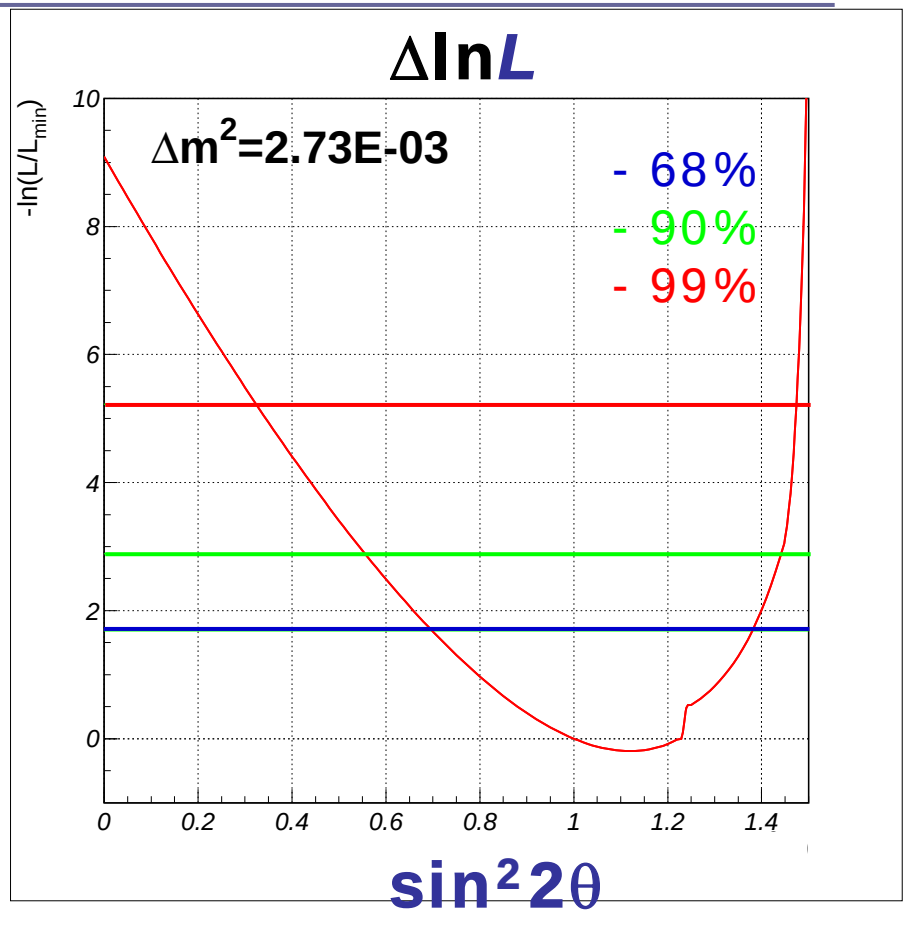
- $N_{SK}^{obs} = 108$
- N_{SK}^{exp} (best fit) = 104.8



Based on $\Delta \ln L$

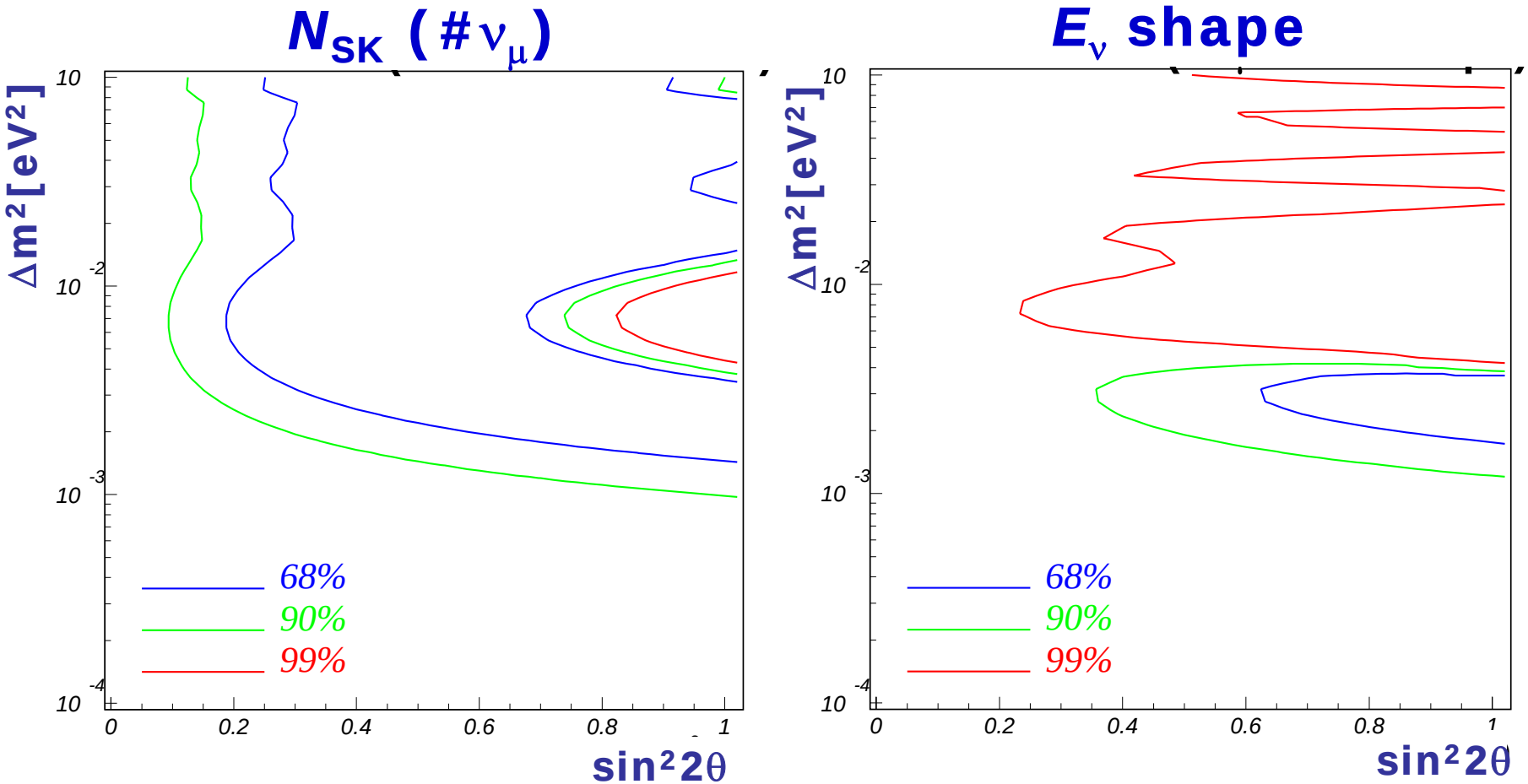
Log Likelihood difference from the minimum.





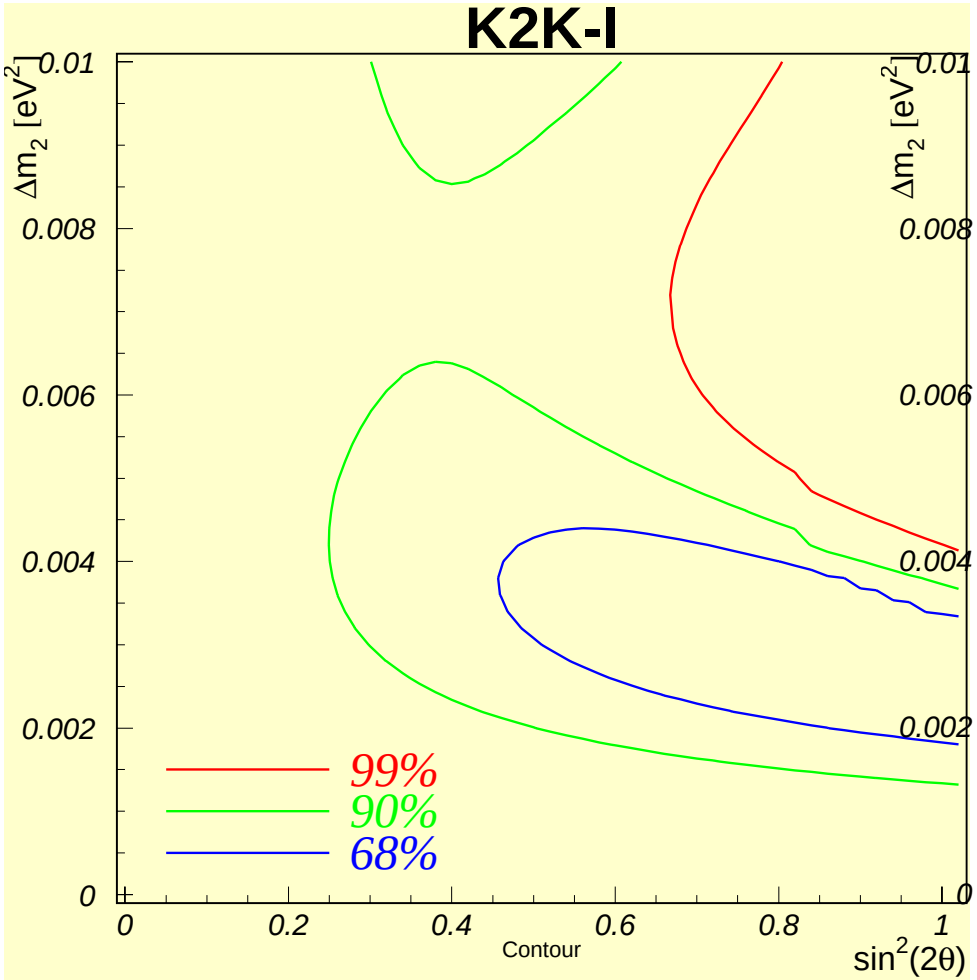
- $\Delta m^2 < (1.7 \sim 3.5) \times 10^{-3}$ eV^2 at $\sin^2 2\theta = 1.0$ (90% C.L.)

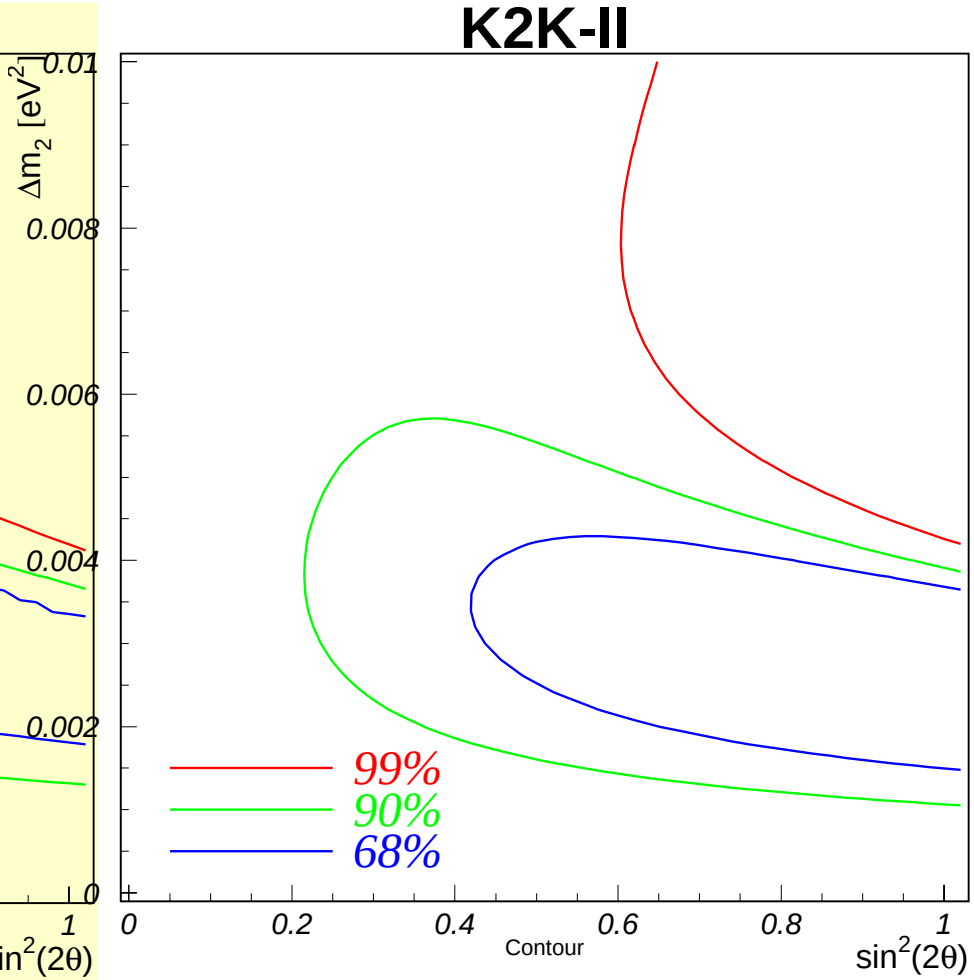
ν_μ disappearance versus E_ν shape distortion



Both disappearance of ν_μ and the distortion of E_ν spectrum have the consistent result.

K2K-I vs K2K-II





Null oscillation probability

preliminary

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

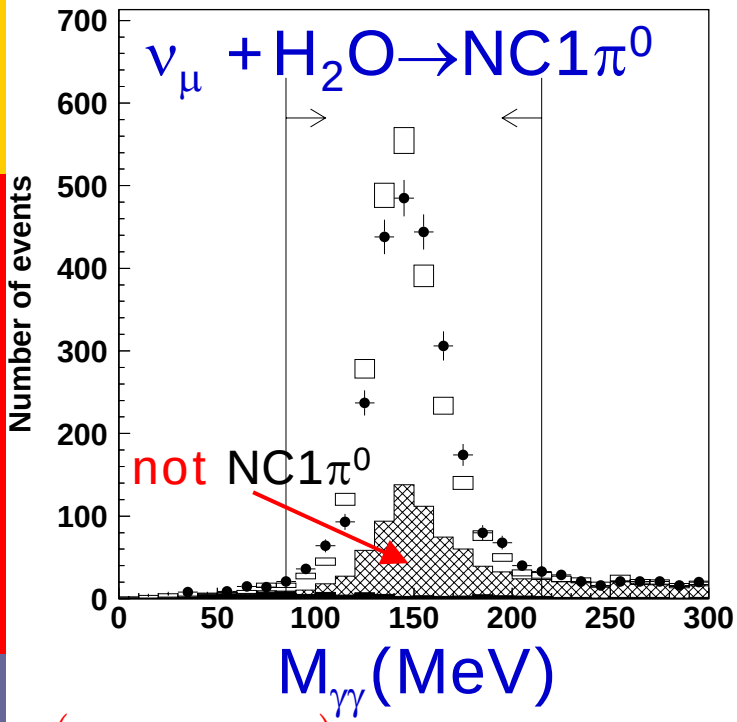
	K2K-I	K2K-II	K2K-all
ν_μ disappearance	2.0%	3.7%	0.33% (2.9σ)
E_ν spectrum distortion	19.5%	5.4%	1.1% (2.5σ)
Combined	1.3%* (2.5σ)	0.56% (2.8σ)	**0.011%** (3.9σ)

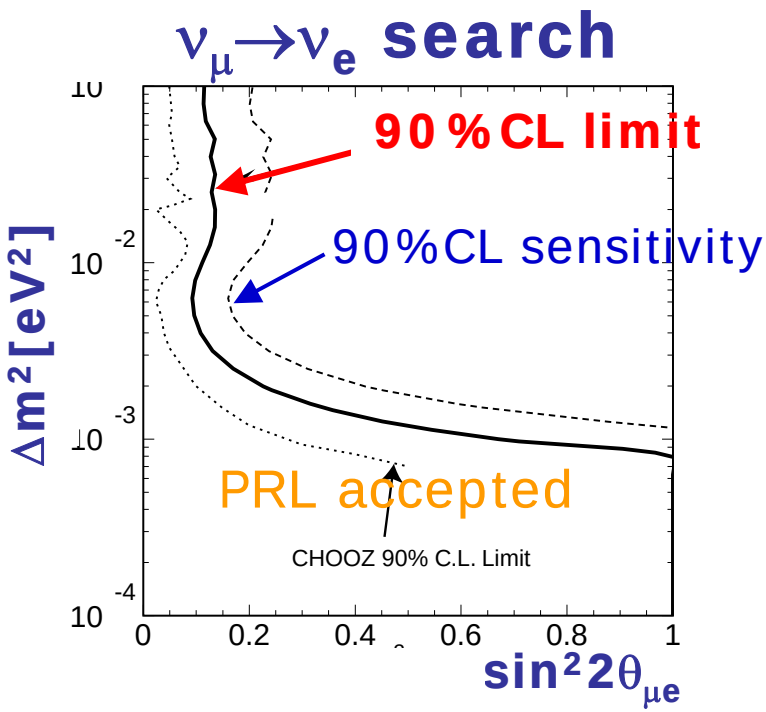
*: The value is changed from the previous one.

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

K2K confirms neutrino oscillation discovered in Super-K atmospheric neutrinos.

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





$$\frac{\sigma(\nu_\mu \rightarrow NC1\pi^0)}{\sigma(\nu_\mu \rightarrow CCall)} = 0.065 \pm 0.001 \pm 0.007$$

$$= 0.064 \text{ (prediction)}$$

preliminary

8. Summary

- With 8.9×10^{19} POT, K2K *has confirmed* neutrino oscillations at **3.9σ**.
  - Disappearance of ν_μ **2.9σ**
  - Distortion of E_ν spectrum **2.5σ**