# New results from K2K experiment

Rik Gran
University of Washington
for the K2K collaboration

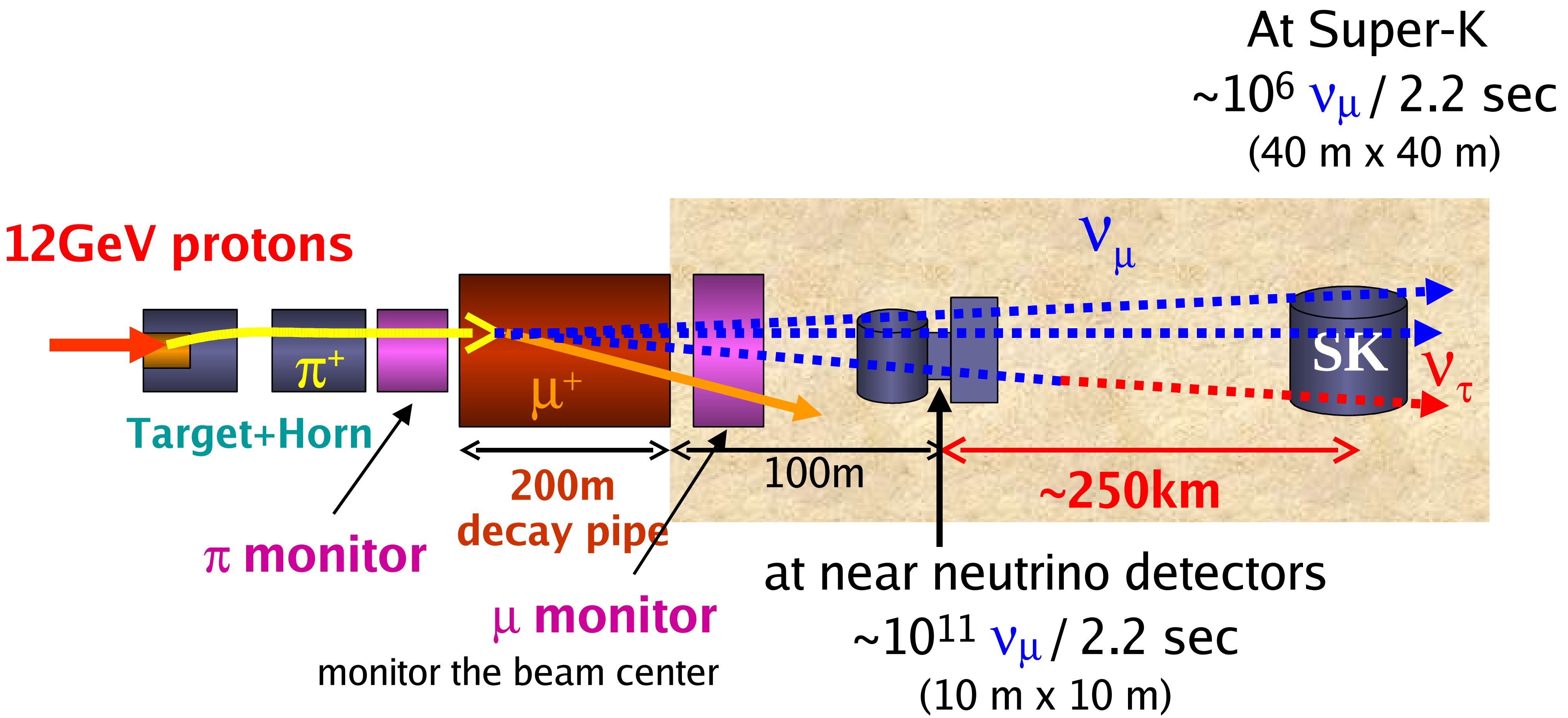
# The K2K Collaboration


**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 U.
**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

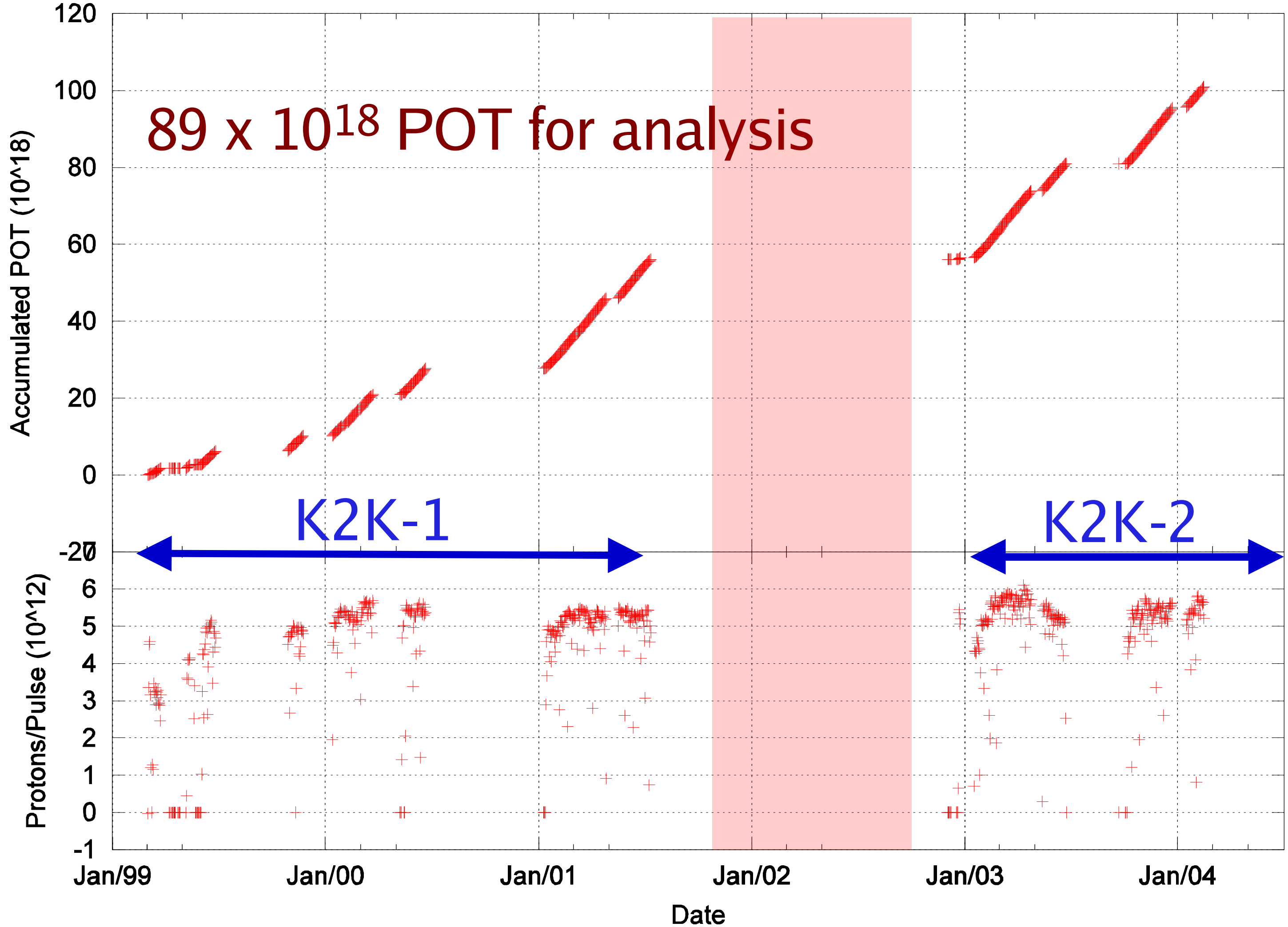
# Experiment Overview



# Accumulated protons on target

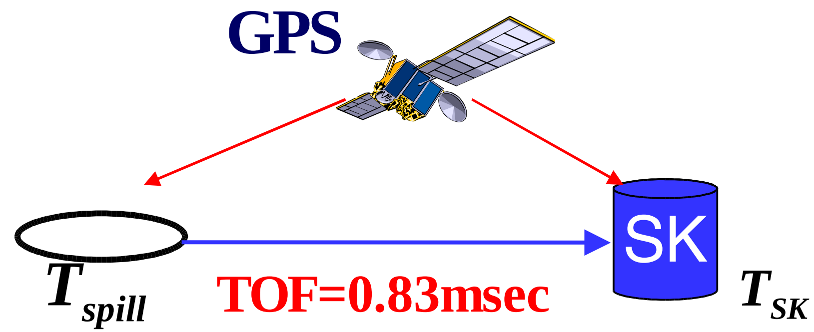
Accumulated protons on target x $10^{18}$

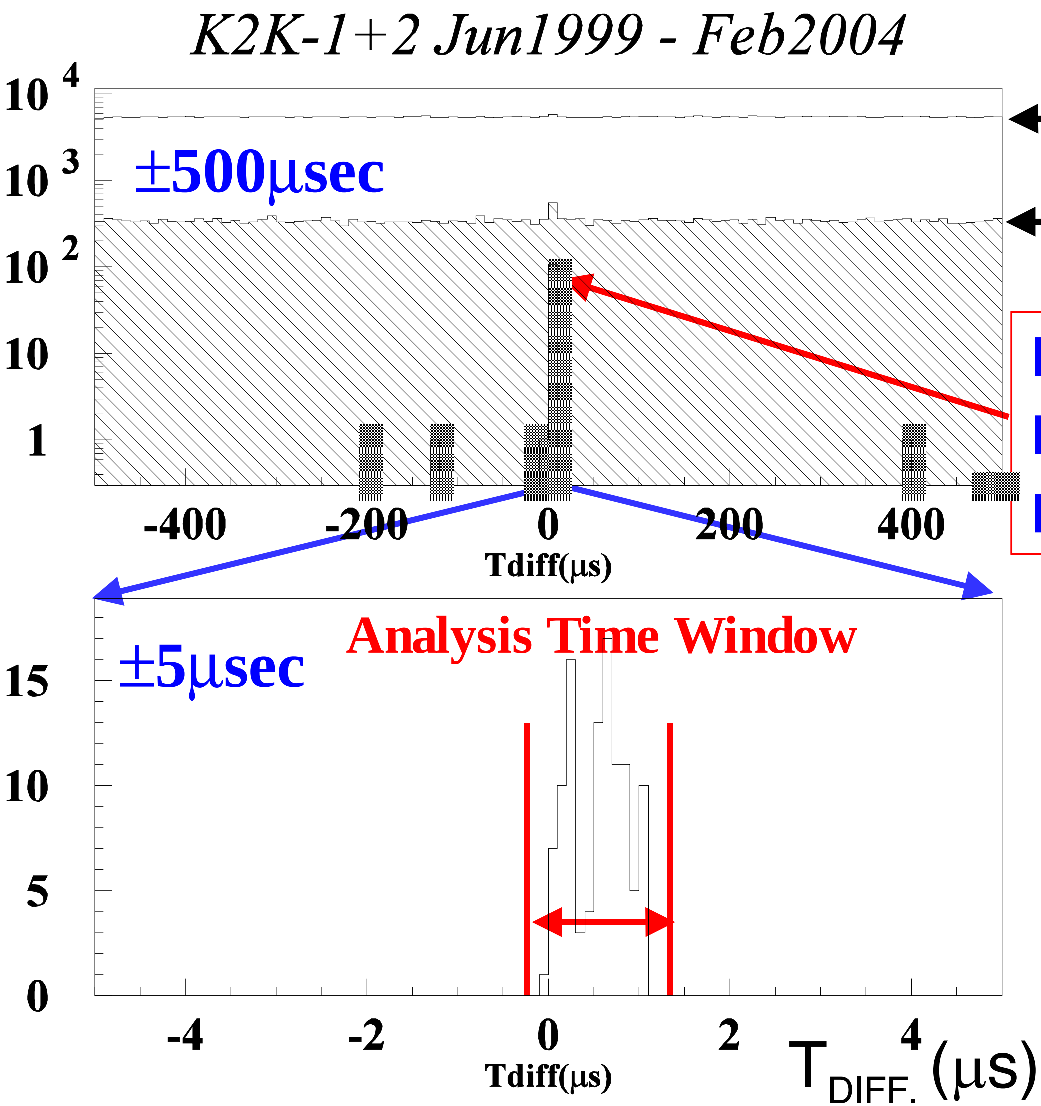
Protons/Pulse x $10^{12}$




Jan 99 Jan 00 Jan 01 Jan 02 Jan 03 Jan 04

# Super-K events
## from time of flight




Decay electron cut.

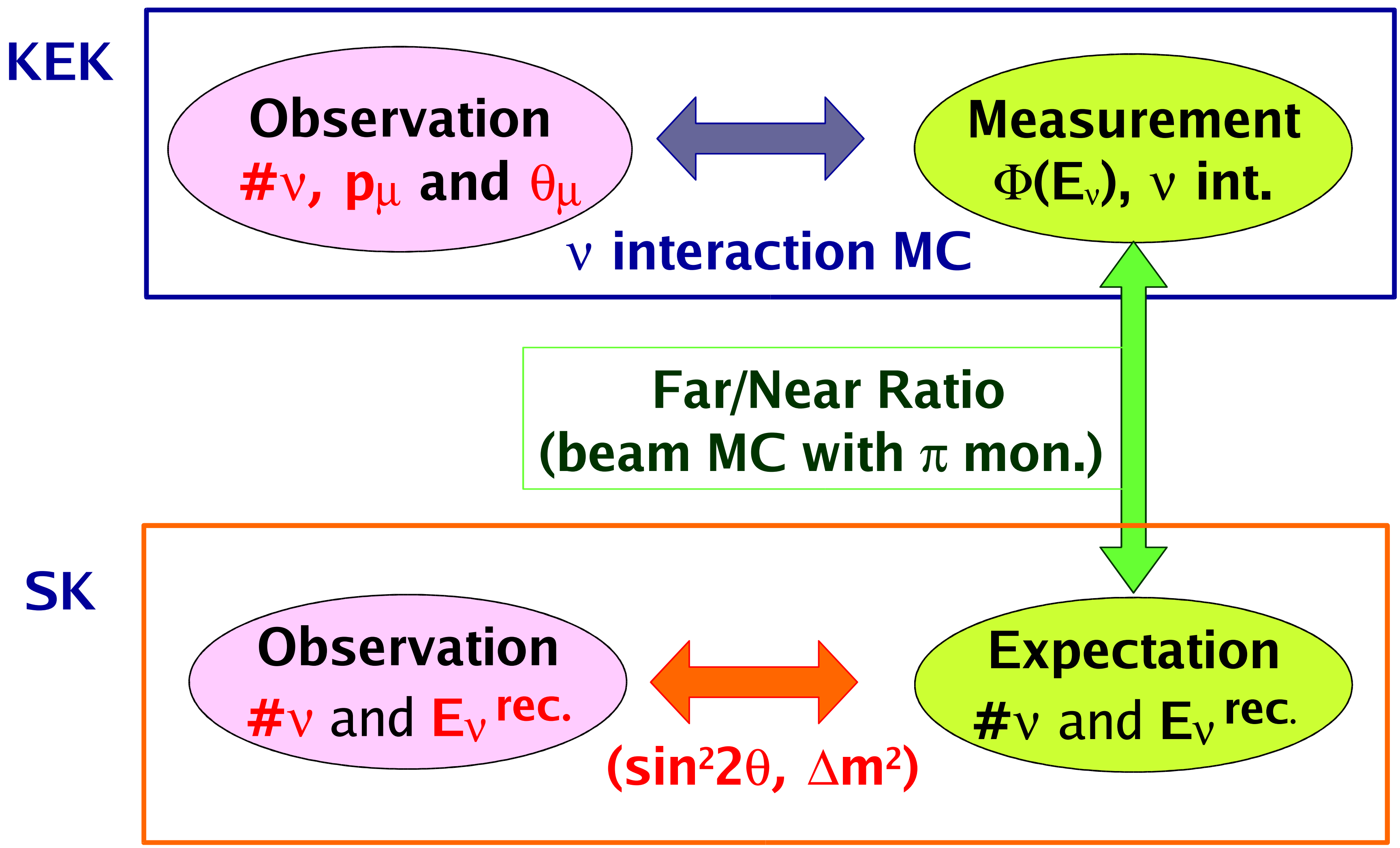
≥20MeV Deposited Energy

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

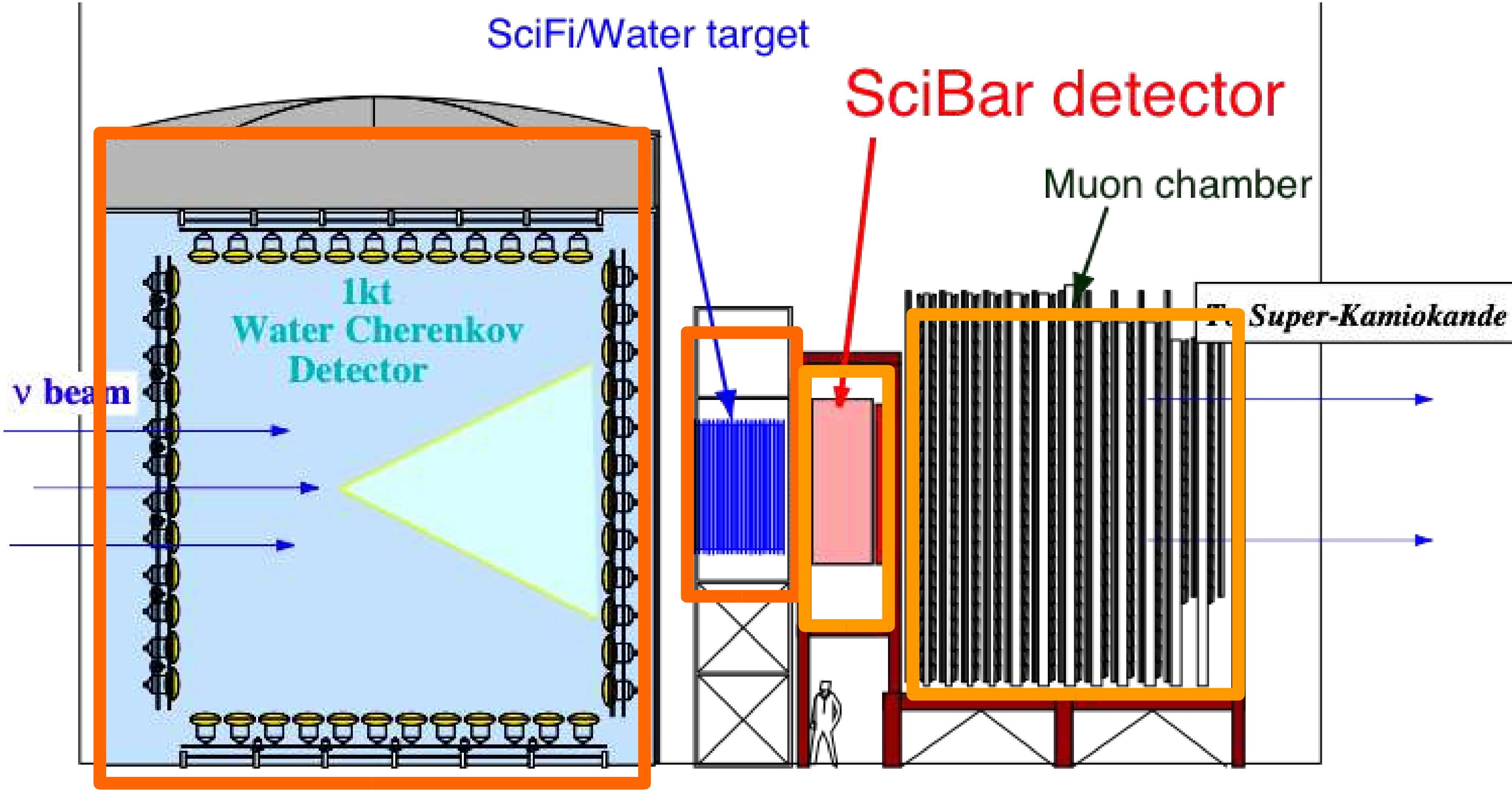
# **108 events**

**background: 1.6 events within 500µs**
**(<u>2.4×10$^{-3}$</u> events in 1.5µs)**

# Analysis overview



# Near detector measurements



# Super-K expected flux from KT measurement

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

≡Far/Near Ratio, ~$1\times10^{-6}$ (from MC)

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

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

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

# NEUT: K2K neutrino interaction Monte Carlo

Charged current quasi-elastic

Smith and Moniz with $M_A = 1.1$

CC (resonance) single pion

Rein and Sehgal with $M_A = 1.1$

Deep inelastic scattering

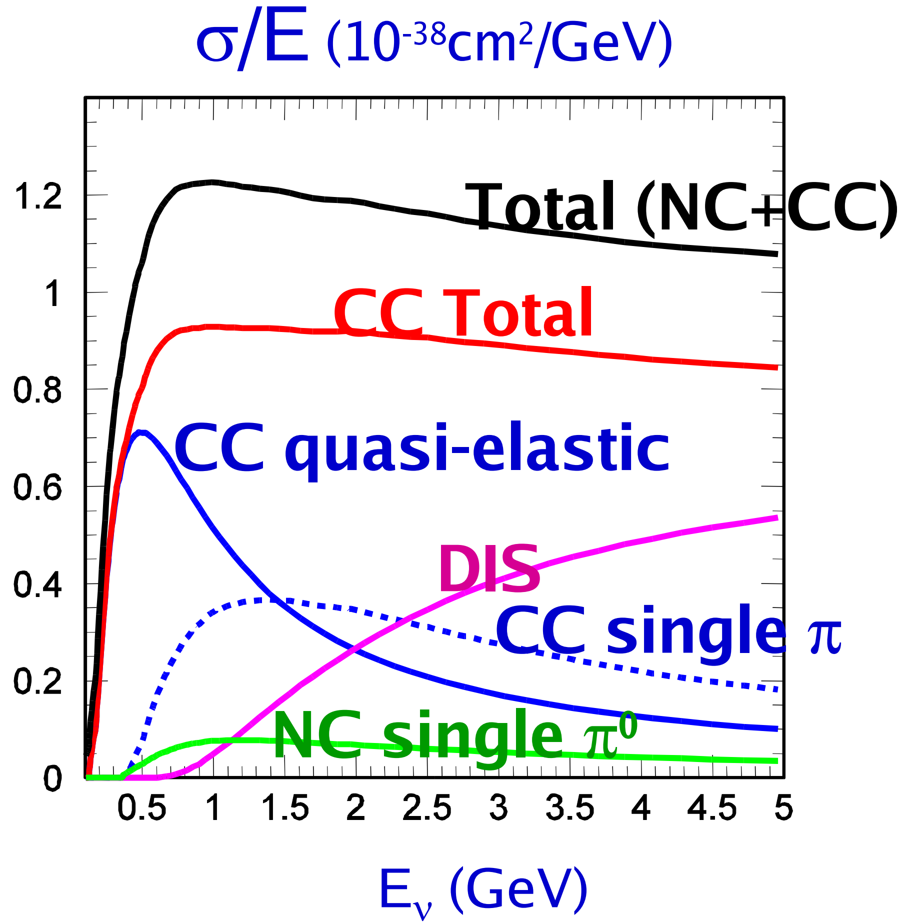
GRV94 + JETSET with
Bodek and Yang correction

CC coherent pion

Rein and Sehgal with cross-section
rescaled by J. Marteau

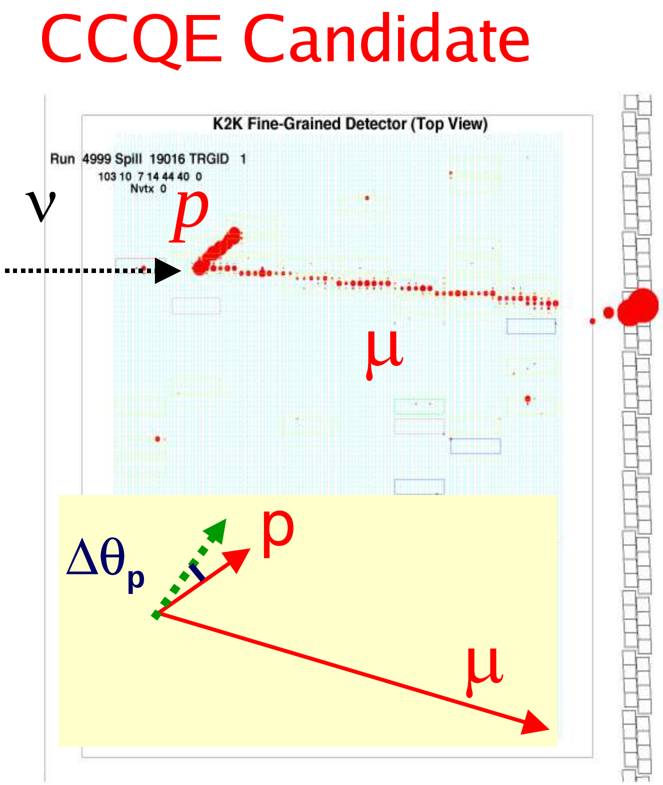
Neutral current events

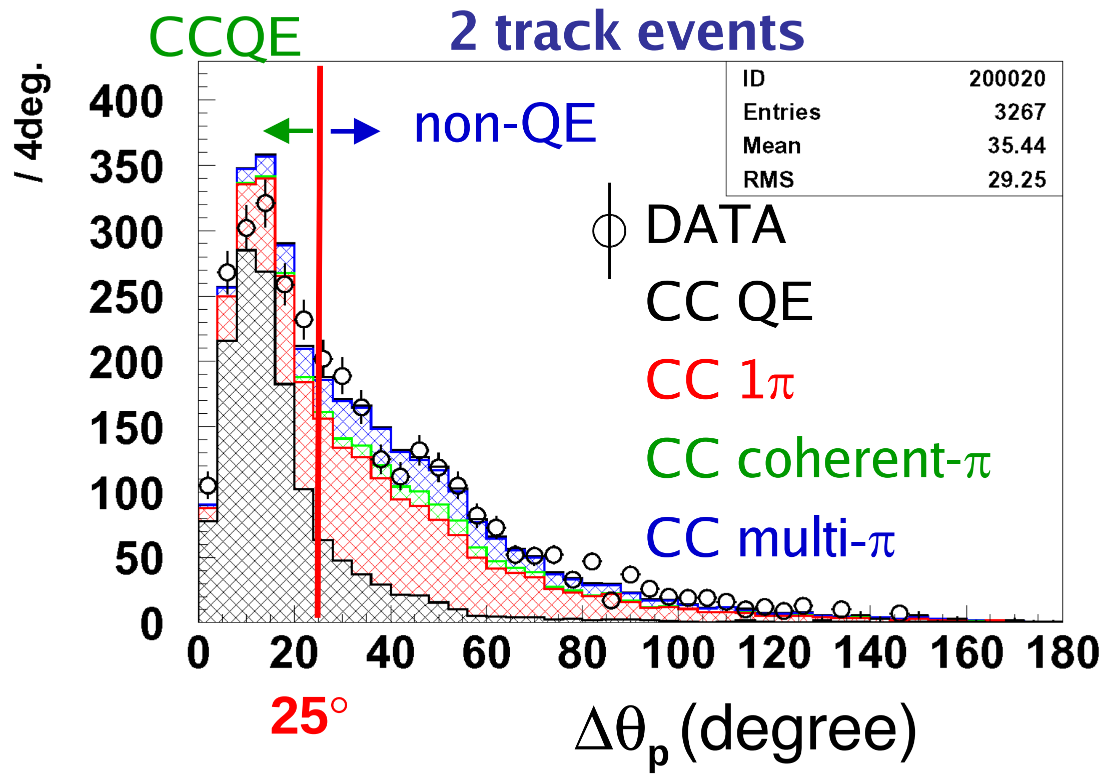
Nuclear effects for oxygen and carbon



# Two track QE and non-QE enhanced samples

Both SciFi and SciBar data (Scibar shown here)



# Hint of forward muon deficit from K2K data

Seen in data from all near detectors (small angle is also small $q^2$)

Most clear in non-QE samples

We do not identify the cause but make two phenomenological models for this suppression:

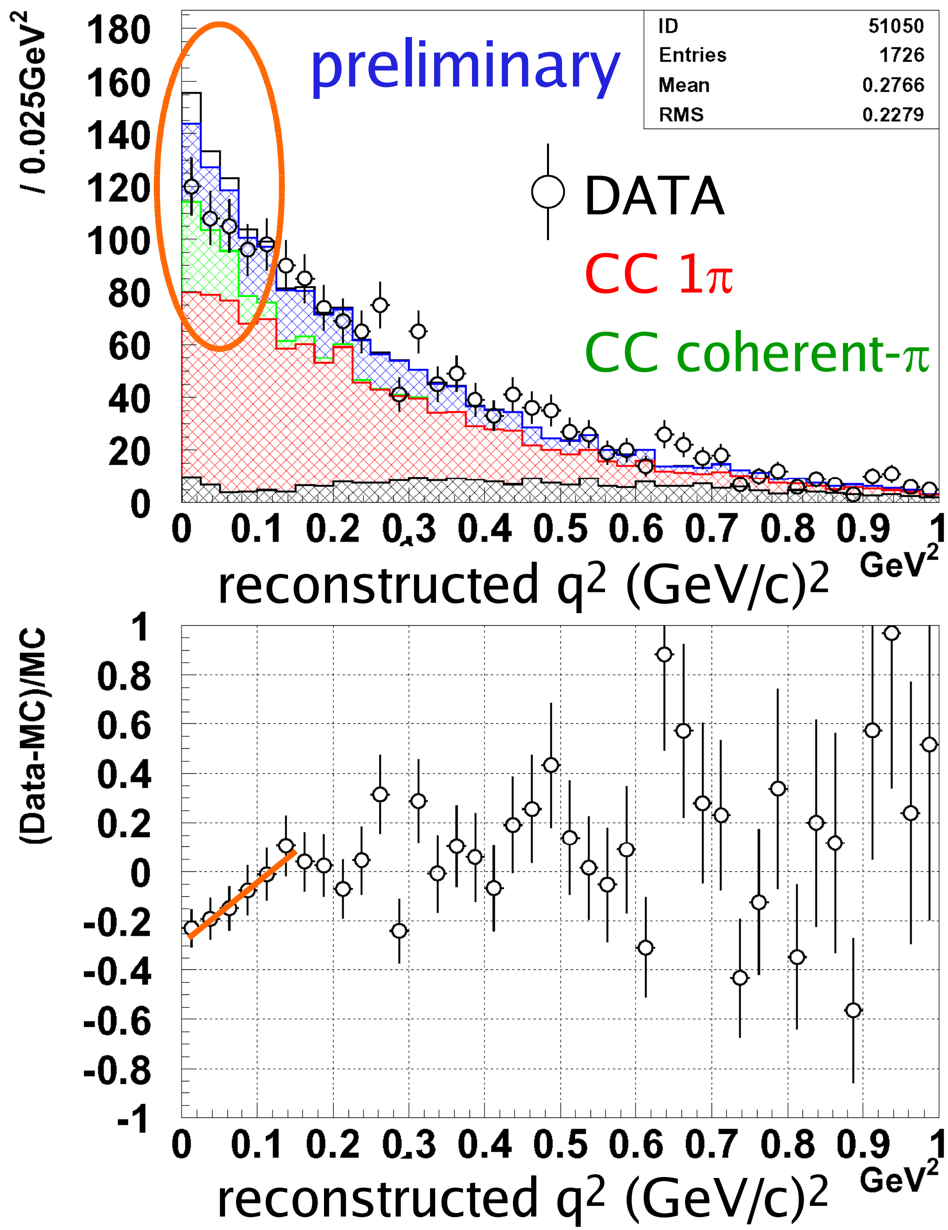
CC-1π suppression of $q^2/0.1$ for events with $q^2 < 0.1$ (GeV/c)$^2$

-- OR --

Zero coherent π

The oscillation analysis is insensitive to this choice.

SciBar non-QE event sample



# Near detector spectrum measurements

1 KT Cerenkov detector (water target)

Fully contained one-ring muon-like events

SciFi fiber tracker (water target)

one-track, two-track QE, two-track non-QE

(two-track non-QE cut is $\Delta\theta_p > 30$ degrees, QE is $\Delta\theta_p < 25$ degrees)

SciBar active scintillator (scintillator target)

one-track, two-track QE, two-track non-QE

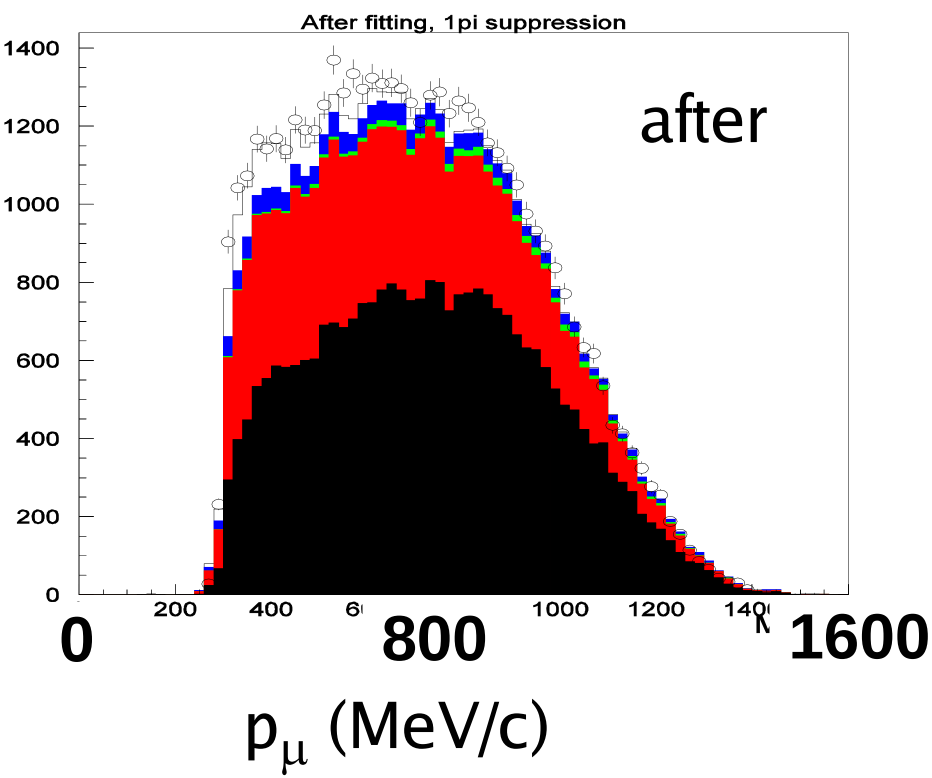
(two-track non-QE and QE cuts are at $\Delta\theta_p = 25$ degrees)

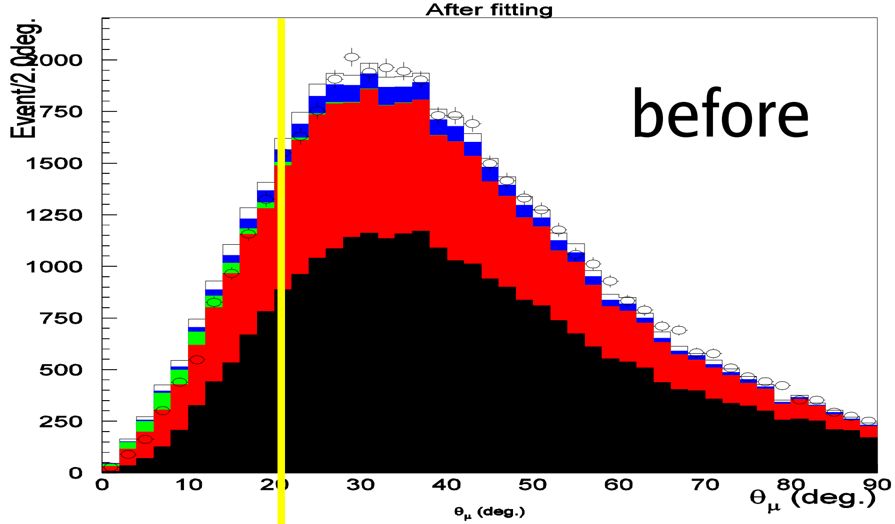
For each event we measure $p_\mu$ and $\theta_\mu$.

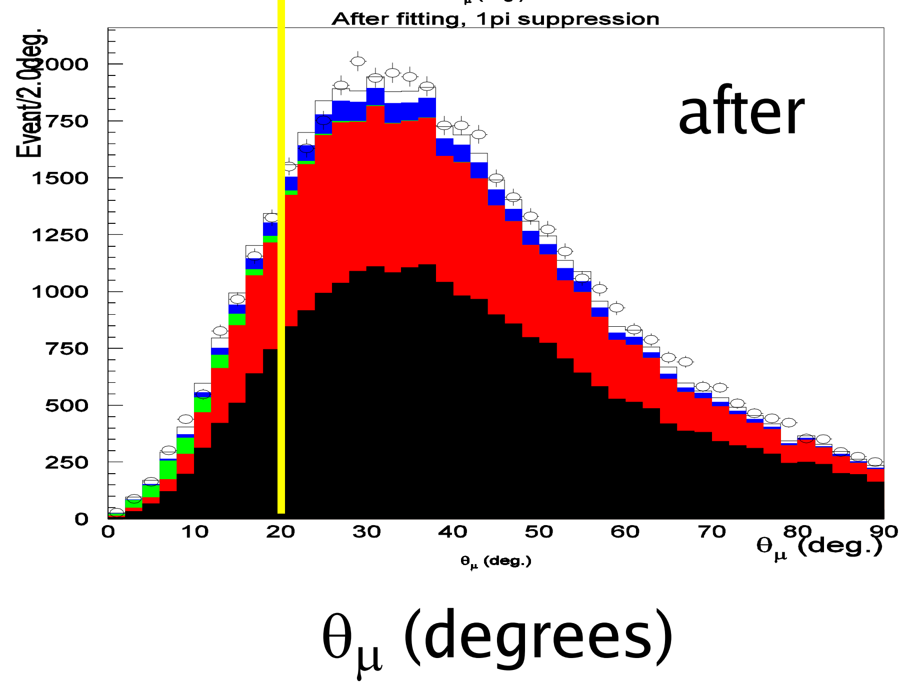
After the low $q^2$ suppression, all data samples agree with the MC.

# Example: $P_\mu$ and $\theta_\mu$ from 1KT detector

before and after applying $1\pi$ suppression




1KT 1-ring muon-like events

Black is quasi-elastic,

Red is single-pion.

# How we turn $p_\mu$ and $\theta_\mu$ into energy spectrum

## Free parameters and other aspects of the fit

Flux for eight energy regions $\Phi(E_\nu)$. (relative to our standard MC)

Ratio nQE/QE.

Detector uncertainties such as $p_\mu$ scale, track counting efficiency.

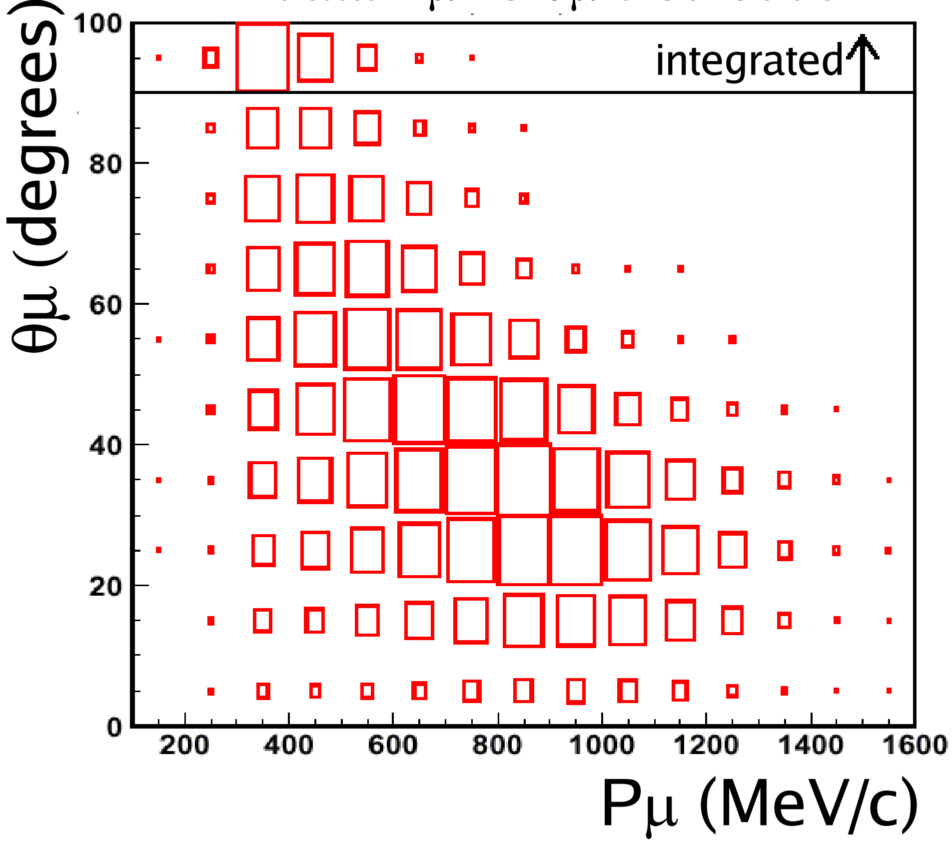
Nuclear effect uncertainties such as proton and pion rescattering.

## Strategy

1. Fit $\Phi(E_\nu)$ without low angle data to avoid discrepancy.
2. Apply either 1-$\pi$ suppression or coherent-$\pi$ suppression at low $q^2$.
3. With $\Phi(E_\nu)$ fixed in step one, fit for nQE/QE ratio.
4. Use these results to calculate the spectrum at Super-K.

# Example: performing the $p_\mu$ and $\theta_\mu$ fit

1KT data Pμ vs θμ distribution




QE MC templates

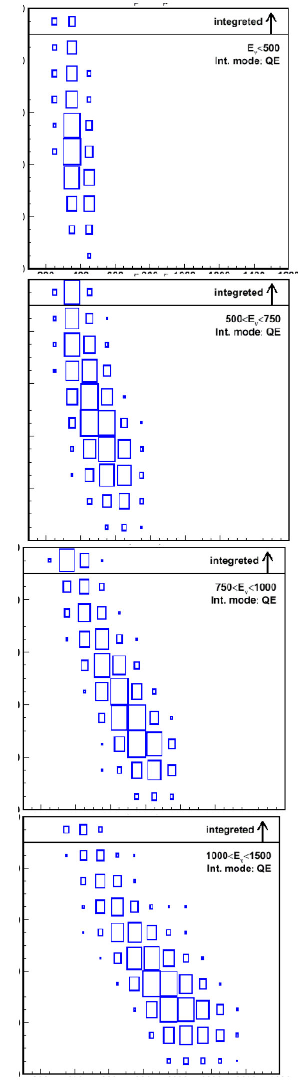
nQE

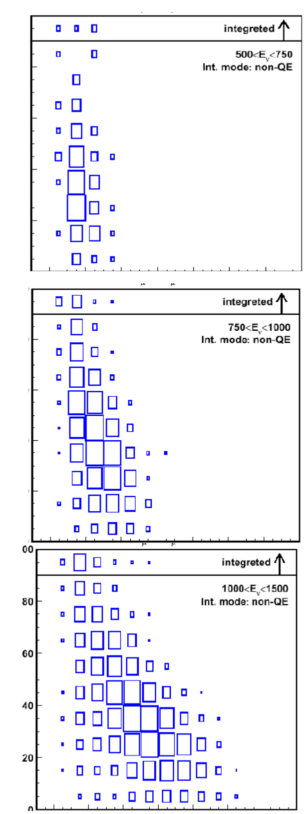
Eν < 0.5 GeV

0.5 to 0.75

0.75 to 1.0

1.0 to 1.5




Free parameters:

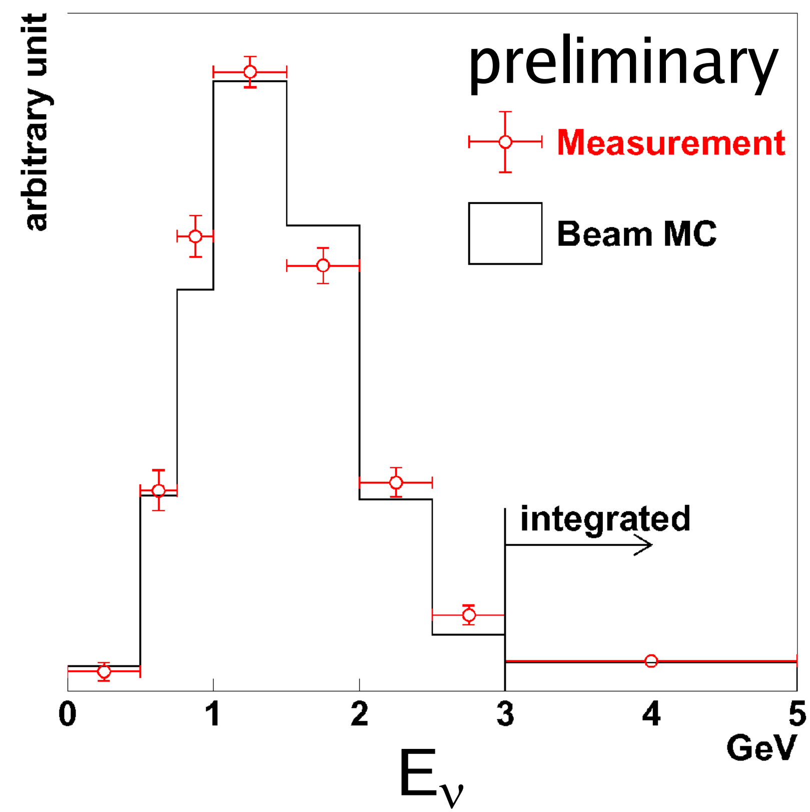
relative flux $\Phi(E_\nu)$ (8 energy regions)

ratio nQE/QE

# Flux measurement results

$\Phi1$ ( $E_\nu$ < 0.50) GeV = 0.78 ± 0.36
$\Phi2$ (0.50 ≤ $E_\nu$ < 0.75 ) GeV = 1.01 ± 0.09
$\Phi3$ (0.75 ≤ $E_\nu$ < 1.00) GeV = 1.12 ± 0.07
$\Phi4$ (1.00 ≤ $E_\nu$ < 1.50) GeV = 1.00 fixed
$\Phi5$ (1.50 ≤ $E_\nu$ < 2.00) GeV = 0.90 ± 0.04
$\Phi6$ (2.00 ≤ $E_\nu$ < 2.50) GeV = 1.07 ± 0.06
$\Phi7$ (2.50 ≤ $E_\nu$ < 3.00) GeV = 1.33 ± 0.17
$\Phi8$ (3.00 ≤ $E_\nu$ < ) GeV = 1.04 ± 0.18
nQE/QE = 1.02 ± 0.10

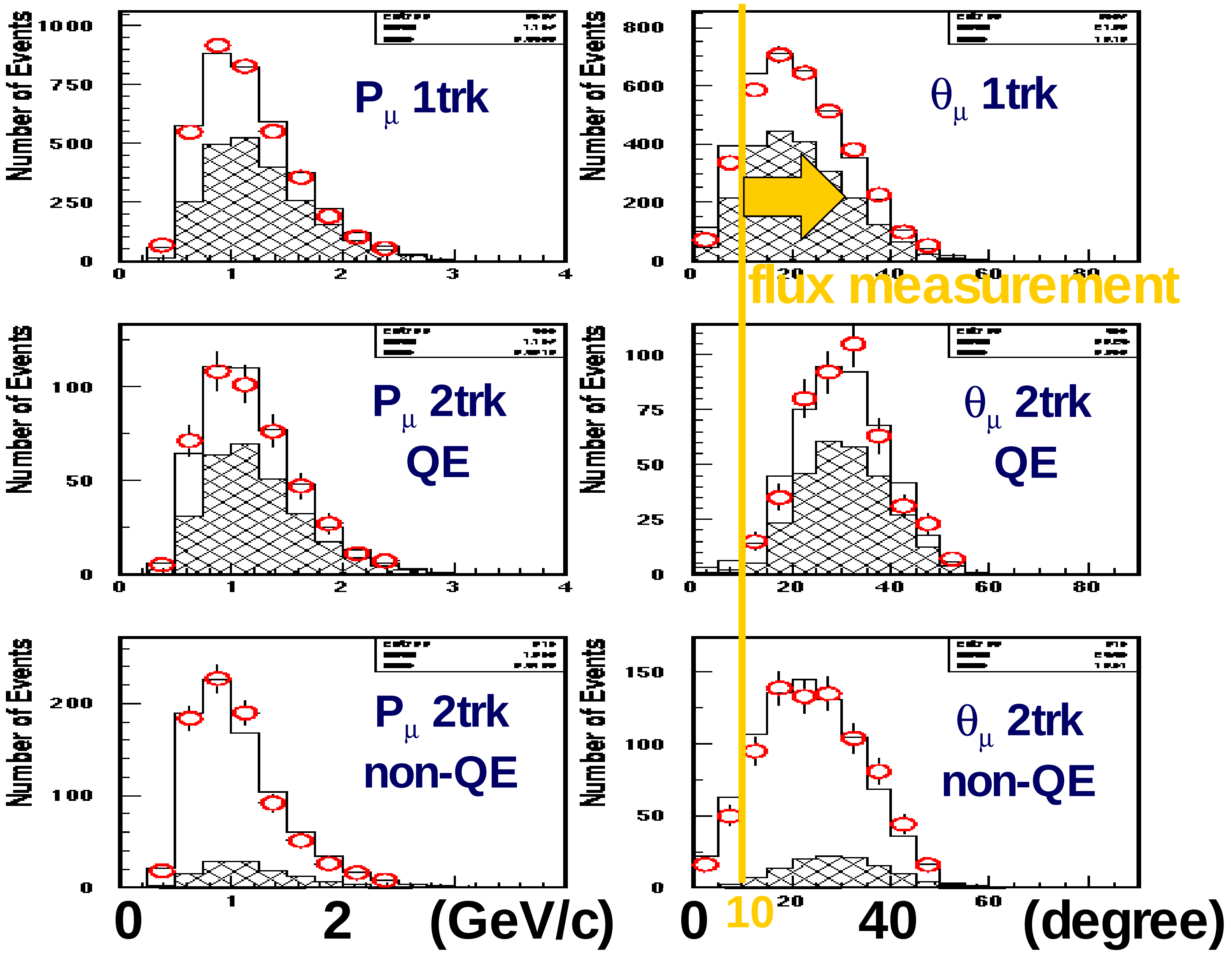
$\Phi(E_\nu)$ at KEK



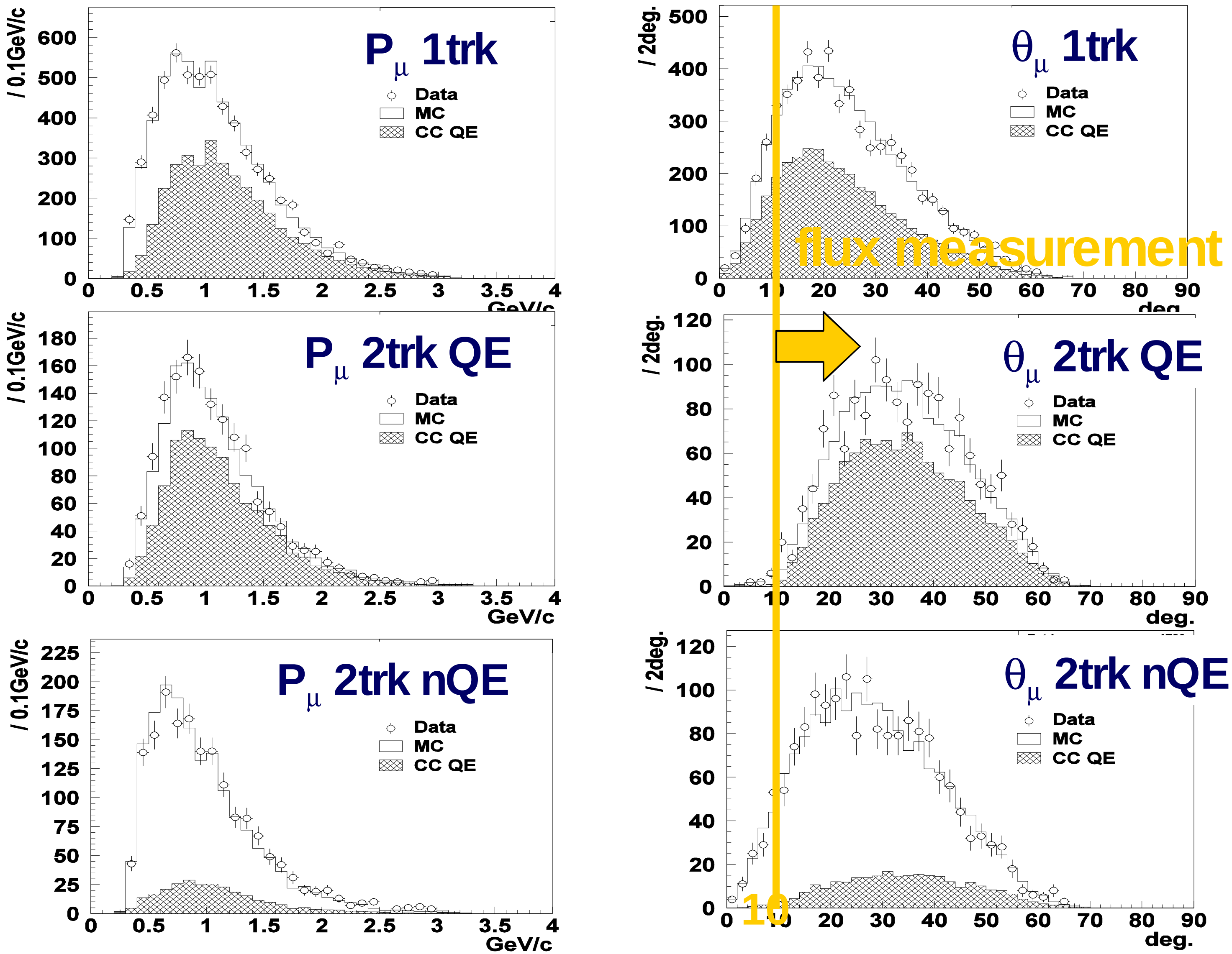

$\chi 2$ is 638.1 for 609 degrees of freedom.

The nQE/QE error is determined from the variation with different fit criteria.
nQE/QE = 0.95 ± 0.04 with theta cut,
nQE/QE = 1.02 ± 0.03 with single pion suppression,
nQE/QE = 1.06 ± 0.03 with no coherent pion.

# Example: Scifi data with measured spectrum



# Example: SciBar data with measured spectrum



# Super-K oscillation analysis

Total number of beam neutrino events
Reconstructed E$\nu$ shape for 1 ring, muon like events
Systematic error terms, $f^x$

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

Systematic error terms include normalization, flux, nQE/QE ratio, pion monitor and beam MC constraints, and Super-K systematic uncertainties.

# K2K beam events in Super-K detector

preliminary

| K2K-all (K2K-I, K2K-II) | DATA (K2K-I, K2K-II) | MC (K2K-I, K2K-II) |
|---|---|---|
| **Fully contained 22.5kt fiducial V.** | **108** (56, 52) | **150.9** (79.1*, 71.8) |
| 1-ring | **66** (32, 34) | **93.7** (48.6, 45.1 ) |
| μ-like | **57** (30, 27) | **84.8** (44.3, 40.5) |
| for $E_\nu^{rec}$ | **(56)** | |
| e-like | **9** (2, 7) | **8.8** (4.3, 4.5) |
| Multi Ring | **42** (24, 18) | **57.2** (30.5, 26.7) |

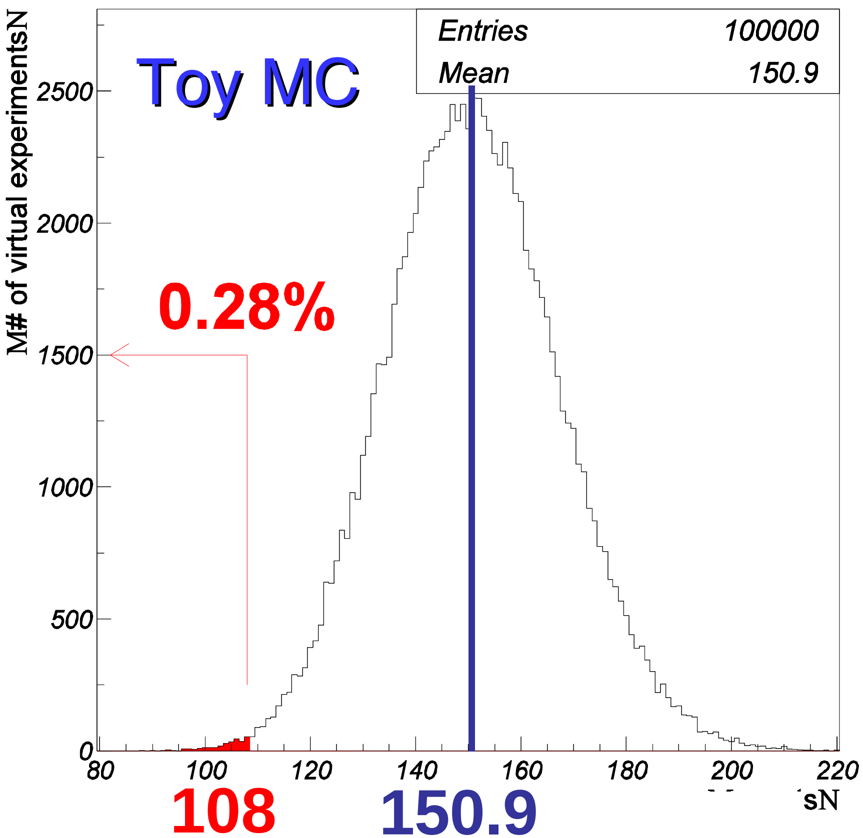
*Ref*, K2K-I(47.9×10[18]POT), K2K-II(41.2×10[18]POT)

*: The number is changed from the previous one.

# Compare each with null-oscillation hypothesis

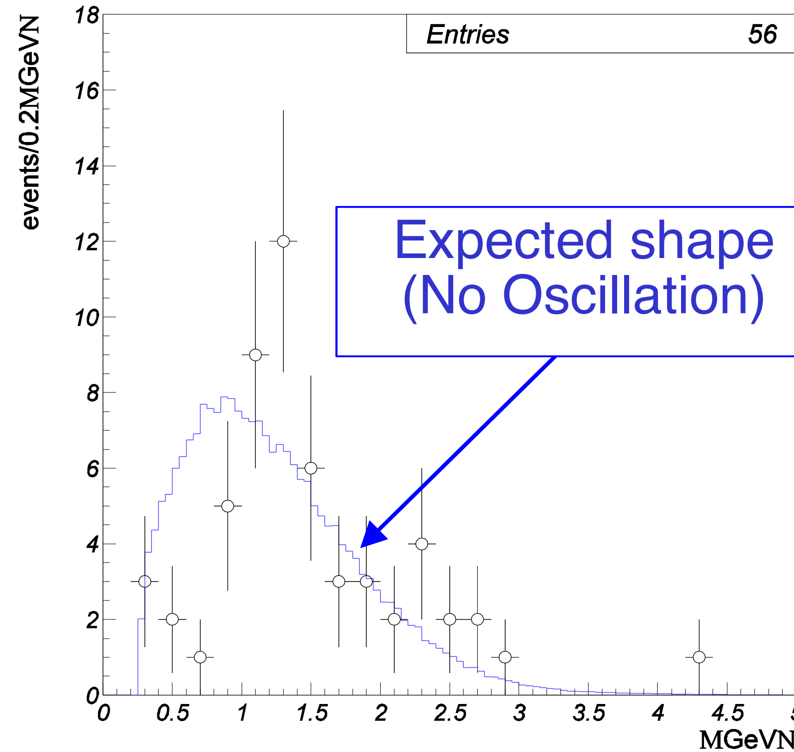
$$L_{norm}(f^x)$$

#SK Events




$$L_{shape}(f^x)$$

KS probability=0.11%




Eν$^{rec}$[GeV]

CC-QE assumption

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

# Best fit oscillation parameters

preliminary

Best fit values:

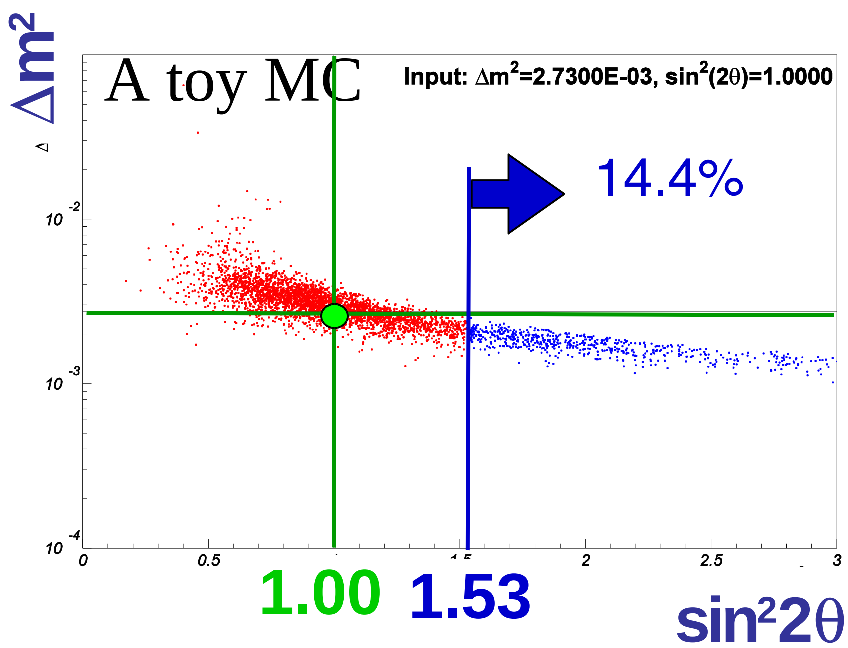
$\sin^2(2\theta) = 1.53$, $\Delta m^2 = 2.12 \times 10^{-3}\ \mathrm{eV}^2$

## Best fit values in the physical region

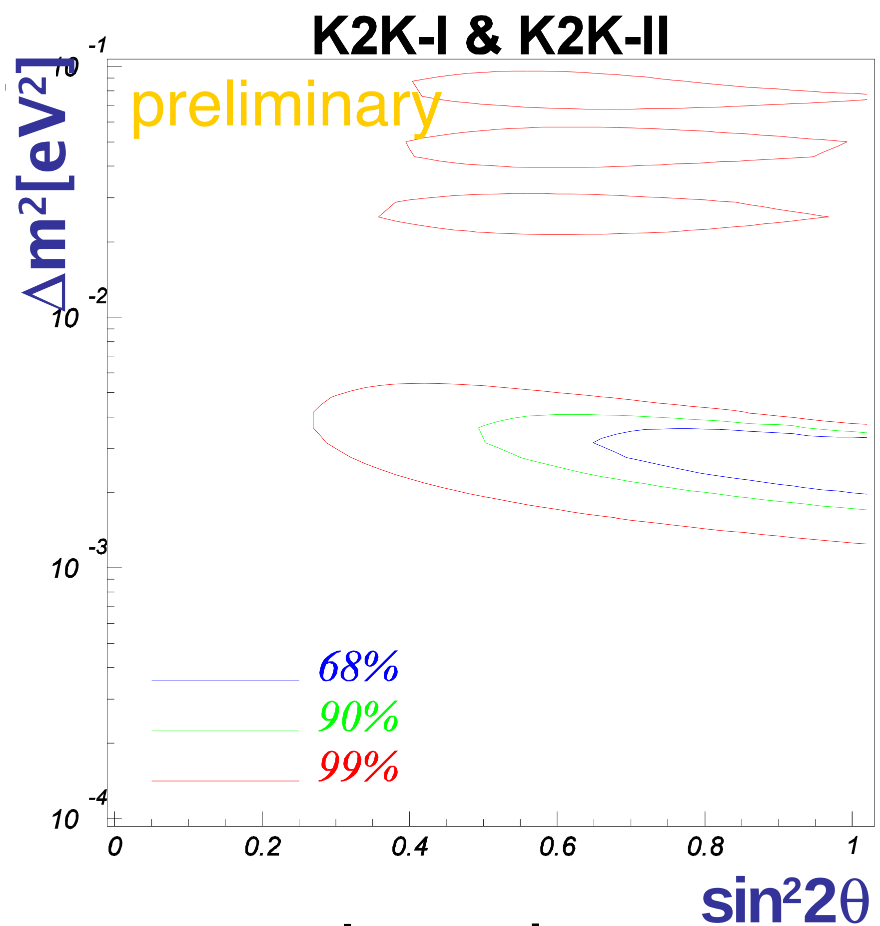
$\sin^2(2\theta) = 1.00$, $\Delta m^2 = 2.73 \times 10^{-3}\ \mathrm{eV}^2$

The difference in these two fits is $\Delta \log L = 0.64$

A value sin2(2θ) > 1.53 can occur due to a statistical fluctuation with a probability of 14%

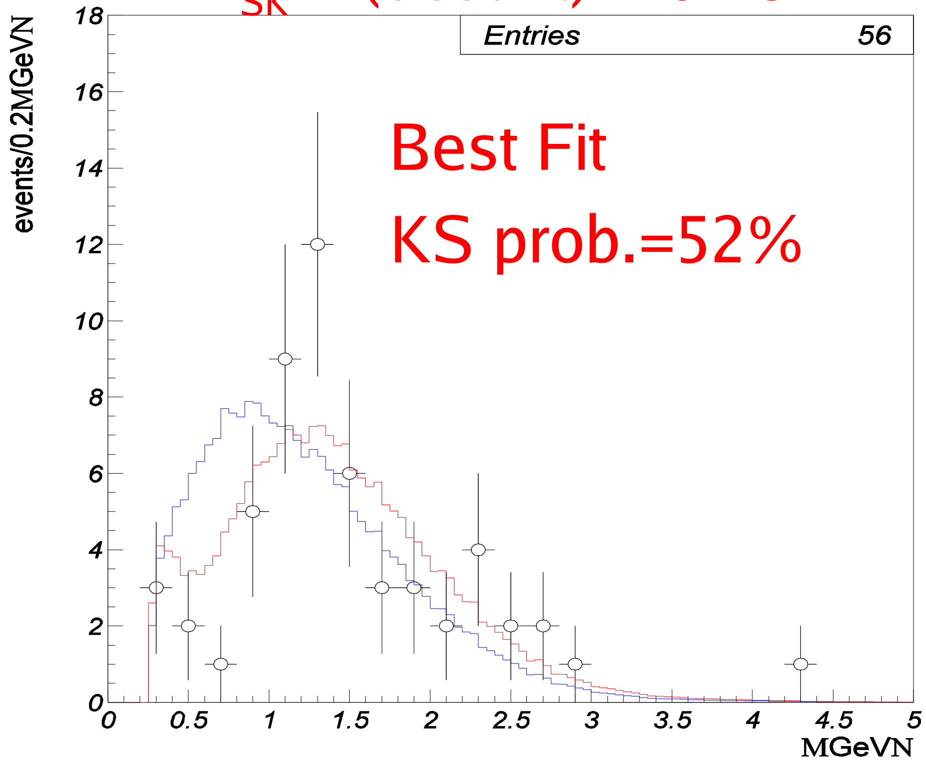


# Data are consistent with best fit result

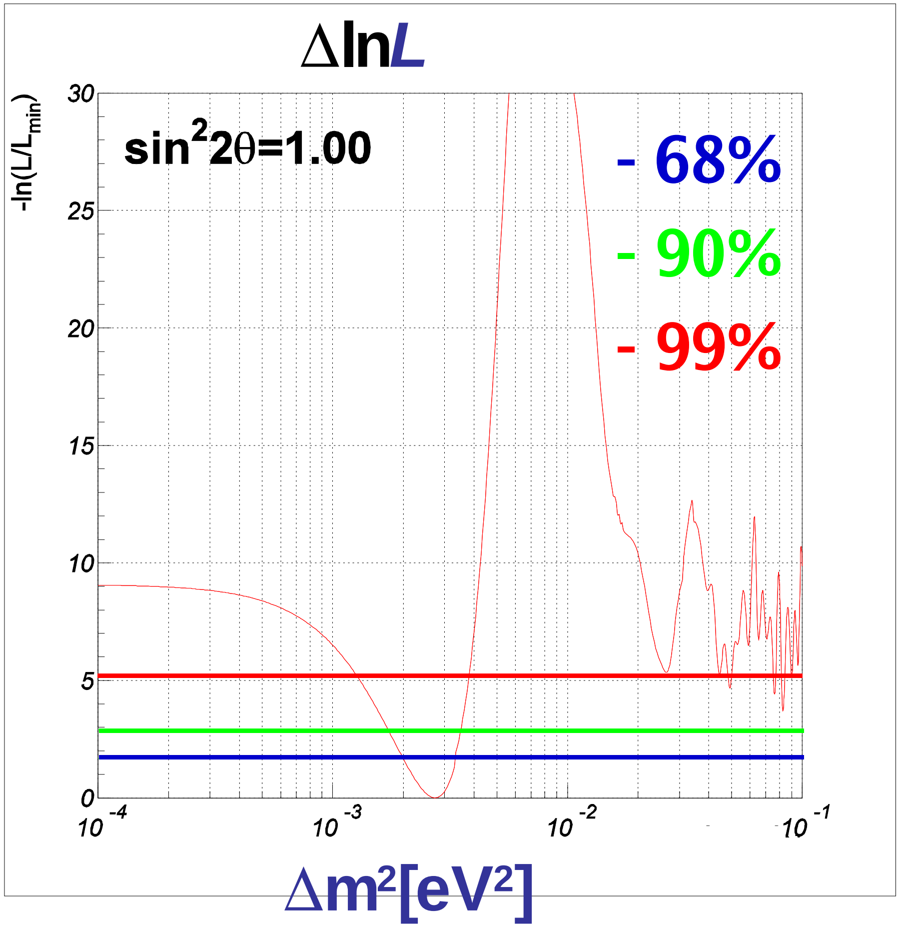


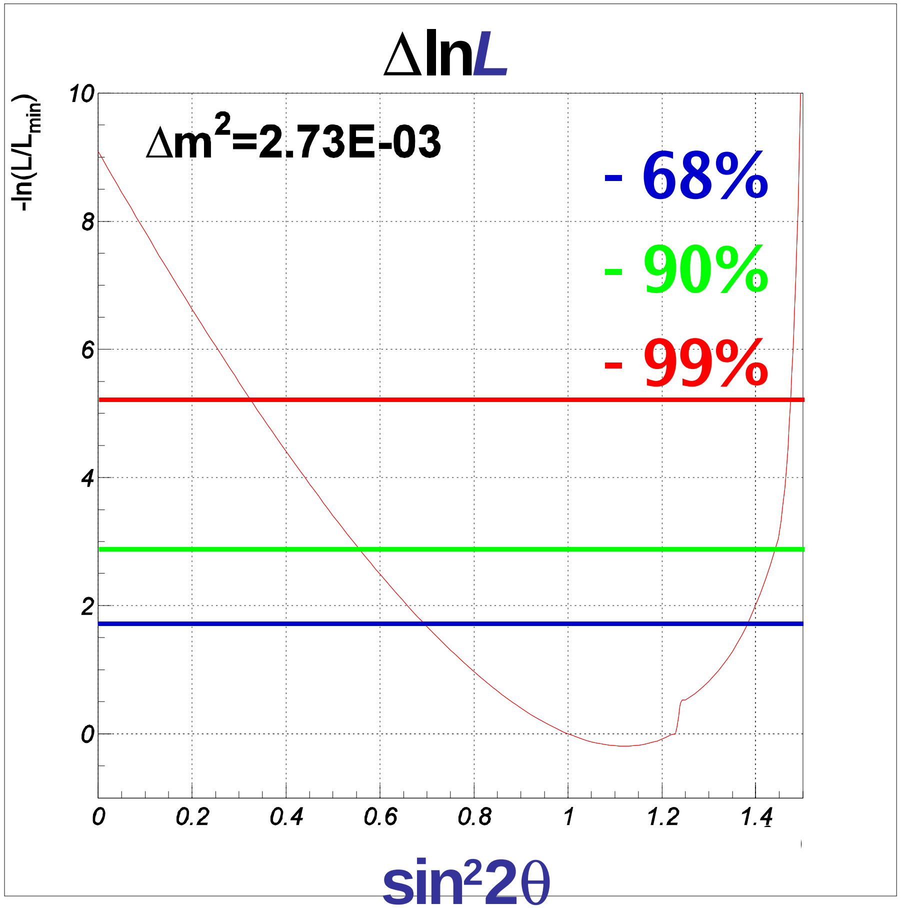

Based on $\Delta \ln L$

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



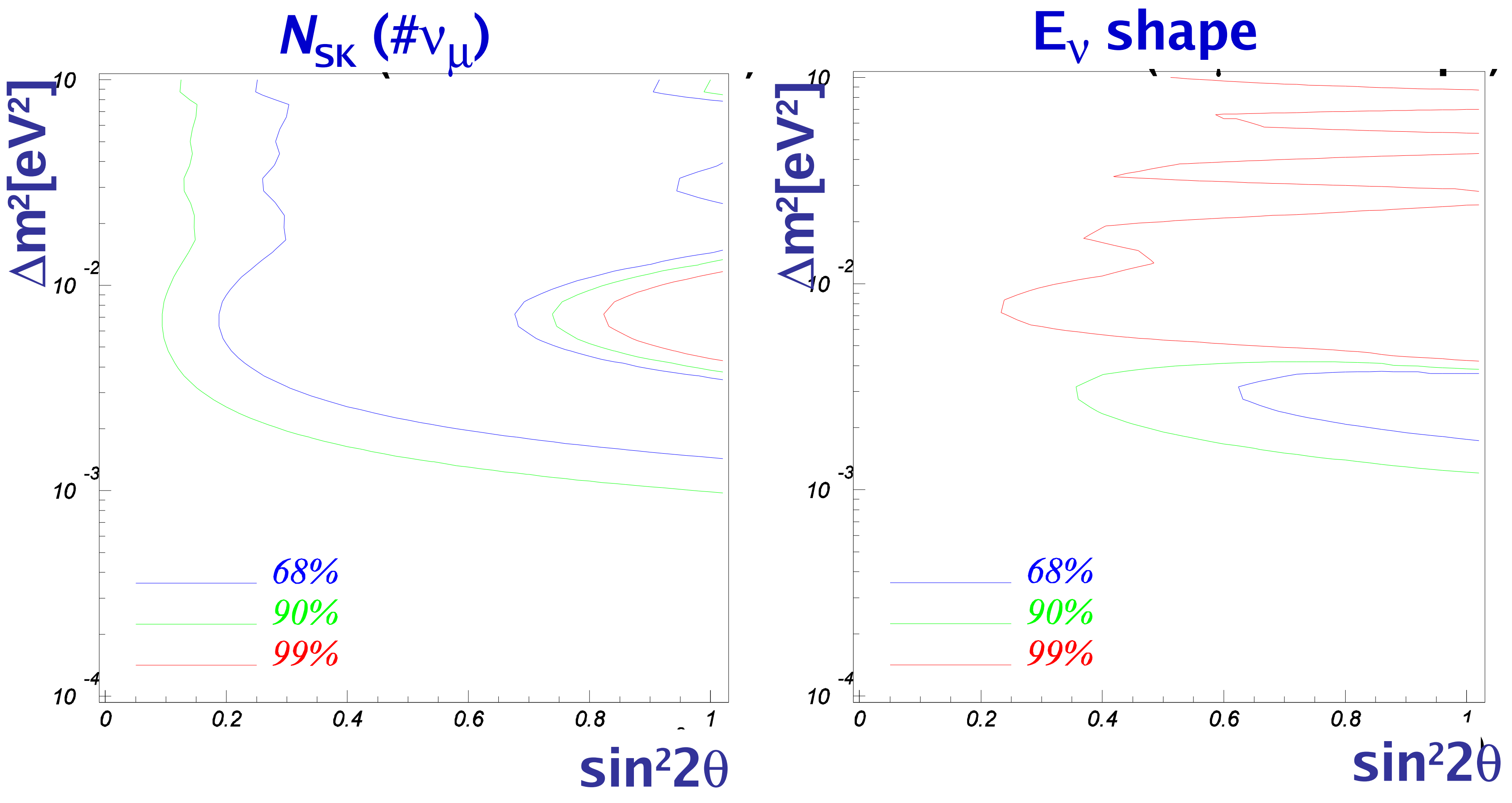
# Log likelihood difference from the minimum



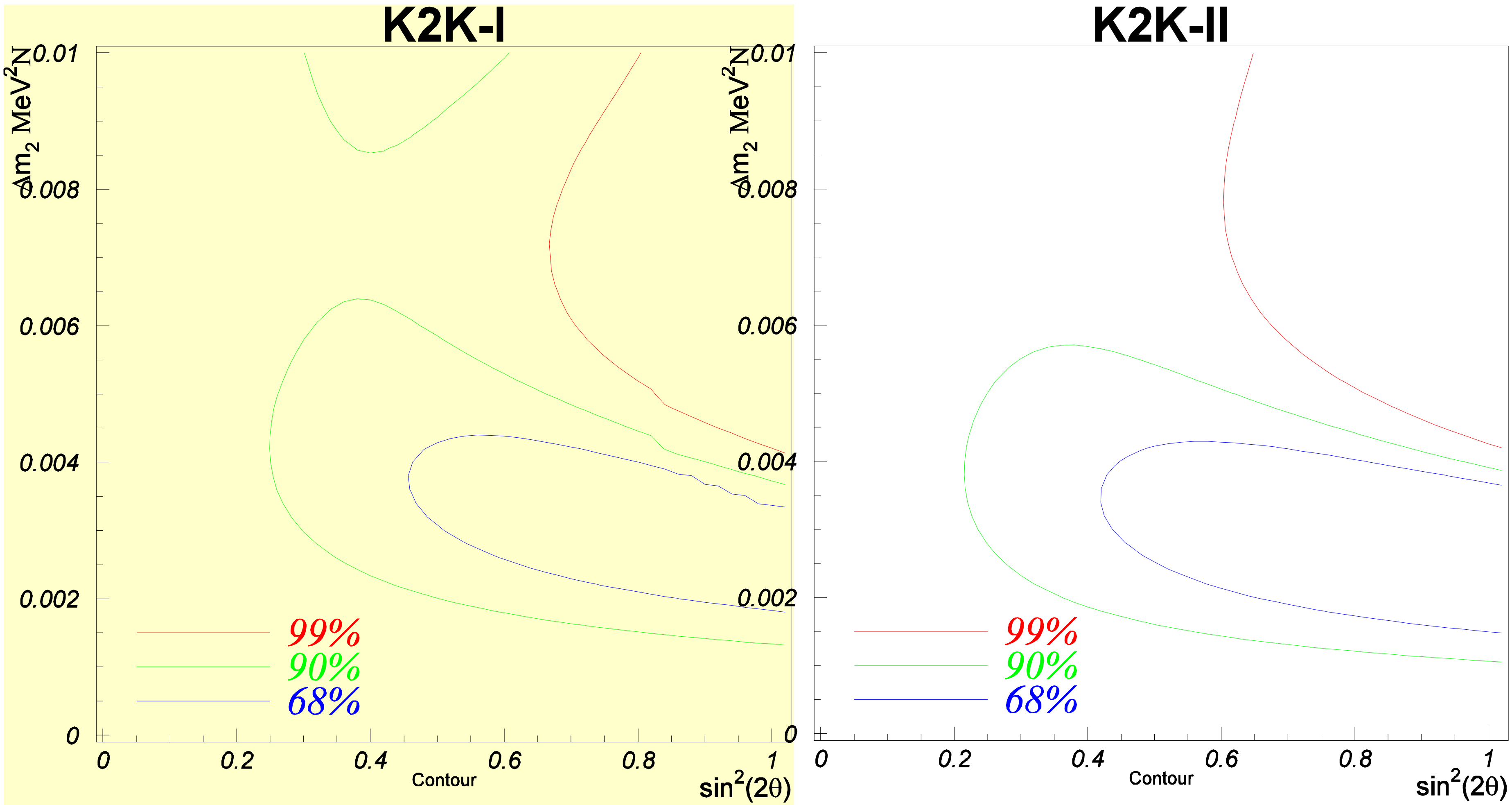

$\Delta m^2 < (1.7 \sim 3.5) \times 10^{-3}$ eV$^2$ at $\sin^2 2\theta = 1.0$ (90% C.L.)

# $\nu_\mu$ disappearance vs $E_\nu$ shape distortion




Both disappearance of $\nu_\mu$ and the distortion of $E_\nu$ are consistent.

# Compare K2K-I and K2K-II separately



# Combined null-oscillation probability preliminary

Null oscillation probabilities calculated based on ΔlogL

| | K2K-I | K2K-II | K2K-all |
|---|---|---|---|
| $\nu_\mu$ disappearance | 2.0% | 3.7% | 0.33%(2.9σ) |
| $E_\nu$ 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 2002 result.

Disappearance of $\nu_\mu$ and distortion of the energy spectrum are as expected from neutrino oscillation.

This result confirms the neutrino oscillations discovered in the Super-K atmospheric neutrino data.

# Summary

With 8.9 x $10^{19}$ protons on target,

K2K has confirmed neutrino oscillations at 3.9 $\sigma$

| | |
|---|---|
| Disappearance alone | 2.9 $\sigma$ |
| Spectrum distortion alone | 2.5 $\sigma$ |