June 10th, 2004
@Kyoto U.

K2K実験の最新結果

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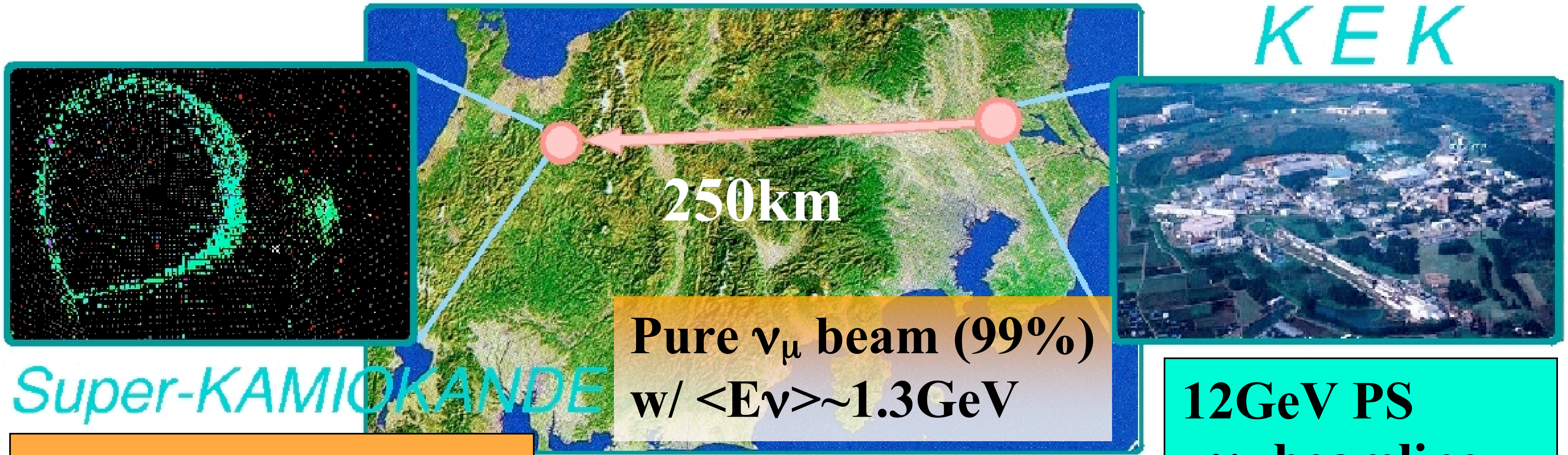
for K2K collaboration

1. Introduction
K2K experiment since 1999

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

Search for **ν_μ disappearance** and ν_e appearance

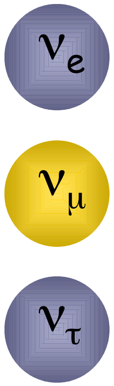


50 kton Water Cherenkov detector

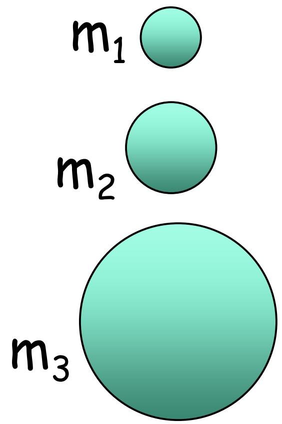
12GeV PS
- **ν_μ beamline**
- **Beam monitor**
- **Near detector**

Flavor mixing in lepton sector

- Flavor eigenstates ≠ mass eigenstates



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix} \begin{pmatrix} C_{13} & 0 & S_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -S_{13}e^{i\delta} & 0 & C_{13} \end{pmatrix} \begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

S_{ij}:sinθ_{ij}, C_{ij};cosθ_{ij}

Parameters: 3 mixing angle (θ_{12},θ_{23},θ_{13})
1 complex phase (δ)

Neutrino Oscillation

- Time evolution of neutrino
  - Consider mixing b/w two flavors

Consider neutrino generated as pure $\nu\mu$ ($=\cos\theta|\nu_2>+\sin\theta|\nu_3>$)

$$\left|\nu_{\mu}, t\right\rangle = \cos\theta \, e^{-im_2^2 t/4p}\left|\nu 2\right\rangle + \sin\theta \; e^{-im_3^2 t/4p}\left|\nu 3\right\rangle$$

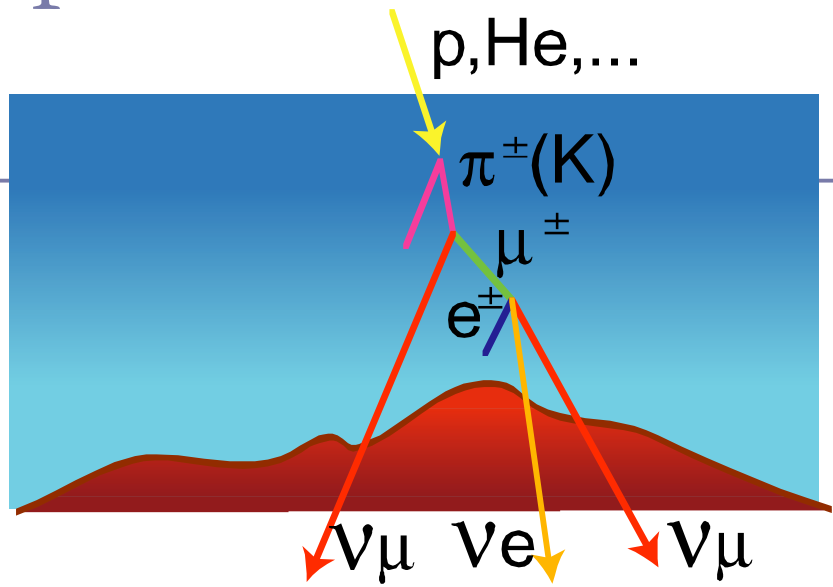
If $m_2 \neq m_3$, ν is in mixed state after time evolution!

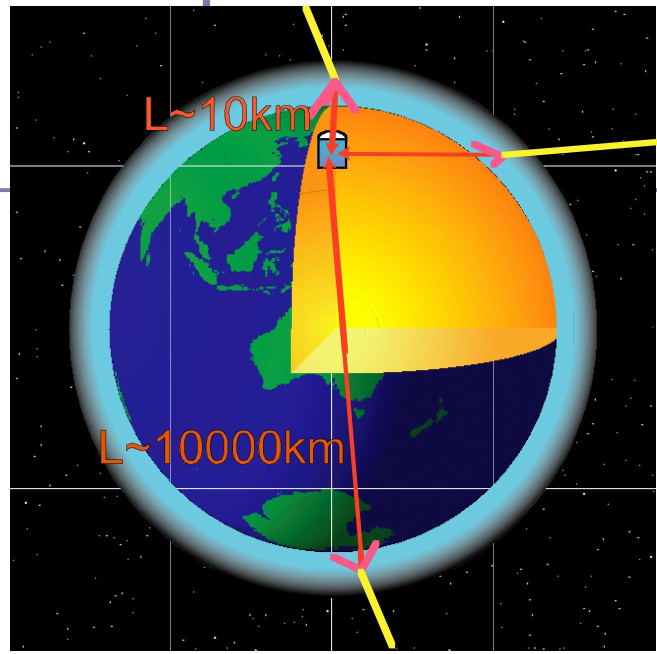
$$P = \left|\left\langle \nu_{\mu} \middle| \nu_{\mu}, t\right\rangle\right|^2 = 1 - \sin^2 2\theta \sin^2\left(1.27 \frac{\Delta m^2}{\mathrm{eV}^2} \frac{L(km)}{E(GeV)}\right)$$

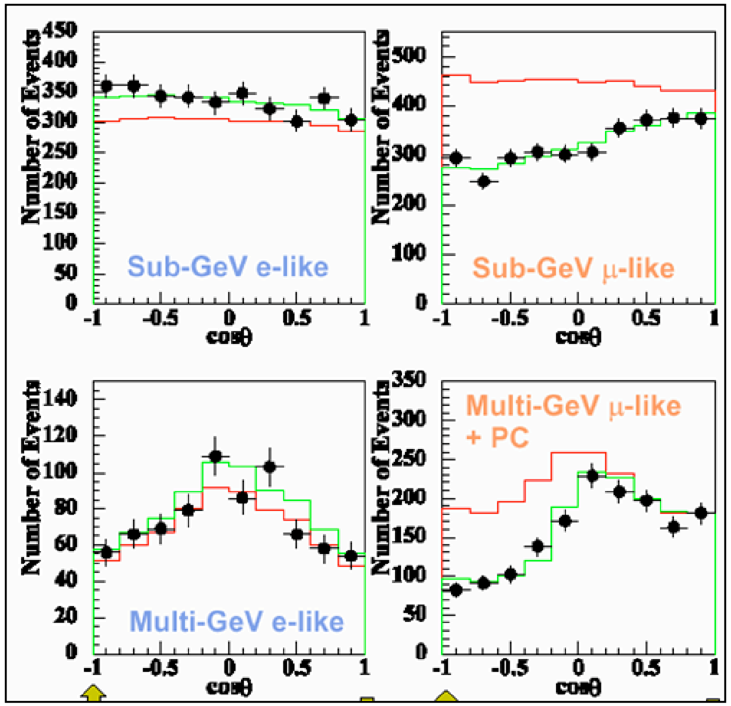
If there is neutrino oscillation $\rightarrow \Delta m^2 \neq 0$

$\rightarrow m \neq 0$!

Super-Kamiokande atmospheric ν







Best fit

$\sin^2 2\theta=1.0$, $\Delta m^2=2.0\times10^{-3}$ eV^2

Null oscillation

$1.3\times10^{-3}<\Delta m^2<3.0\times10^{-3}$eV^2

(@ $\sin^2 2\theta=1$, 90% CL)

$\nu\mu\rightarrow\nu\tau$ oscillation?

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

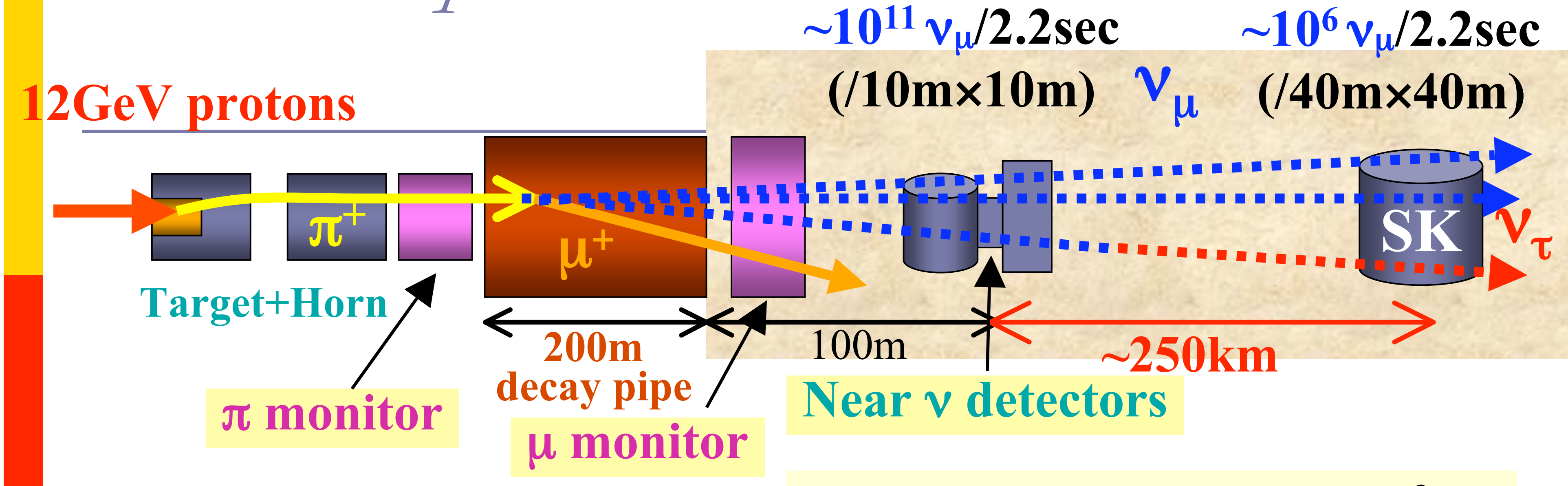
CANADA: TRIUMF / University of British Columbia

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

RUSSIA: INR-Moscow

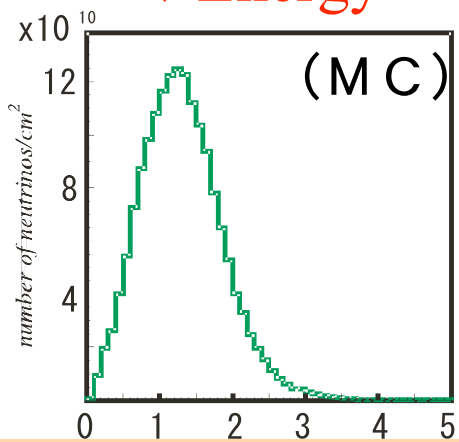
2. K2K experiment overview

~1 event/2days



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

ν Energy

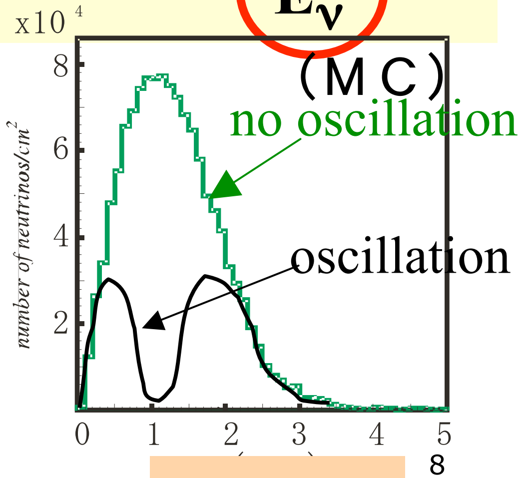


Near detectors at KEK

250km

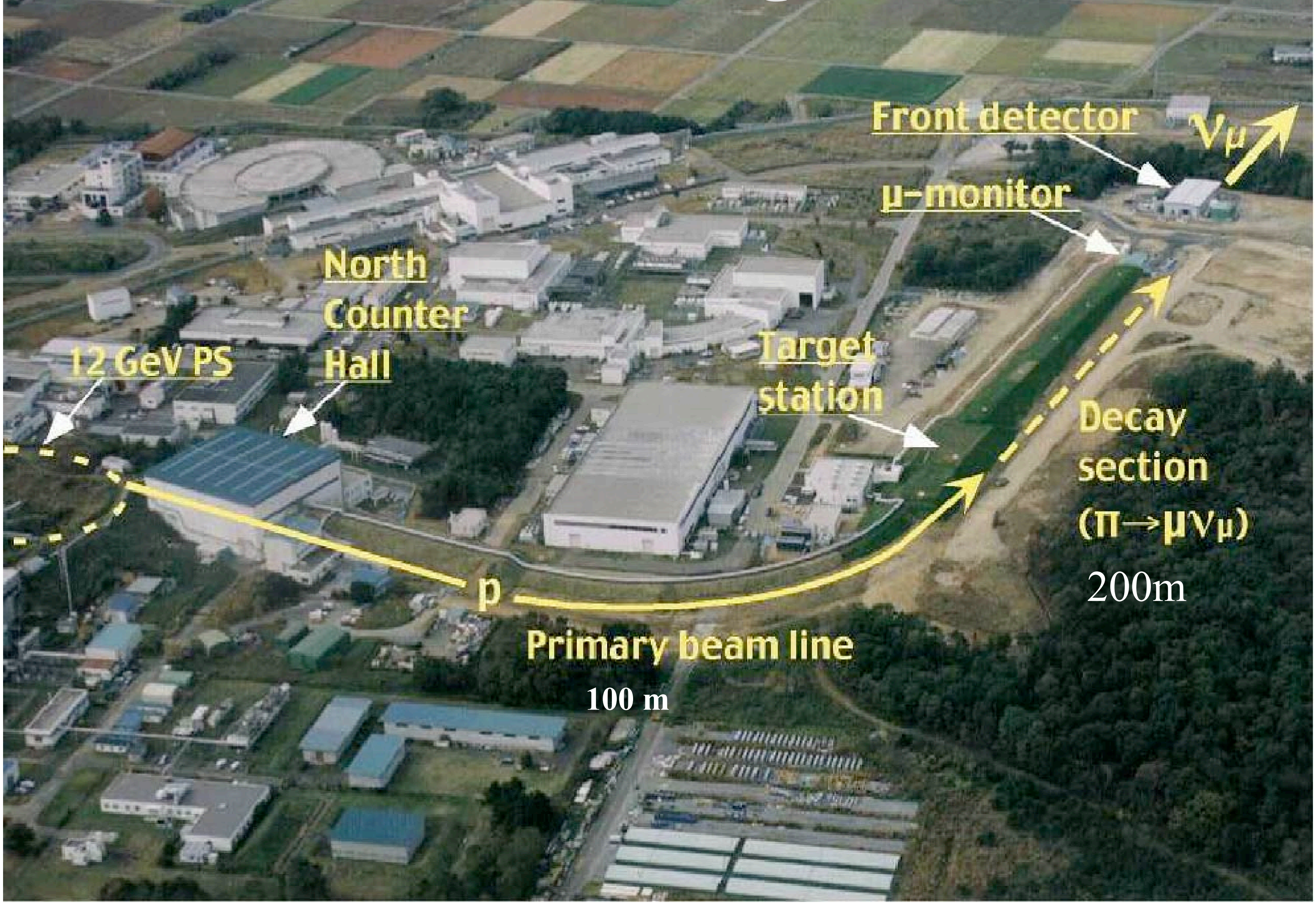
Extrapolation

π monitor + simulation



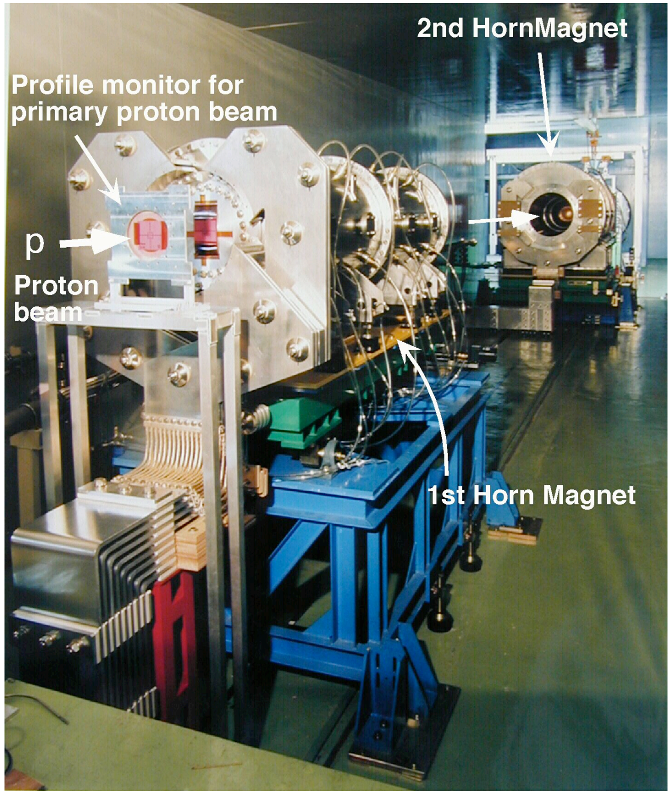
Super-K

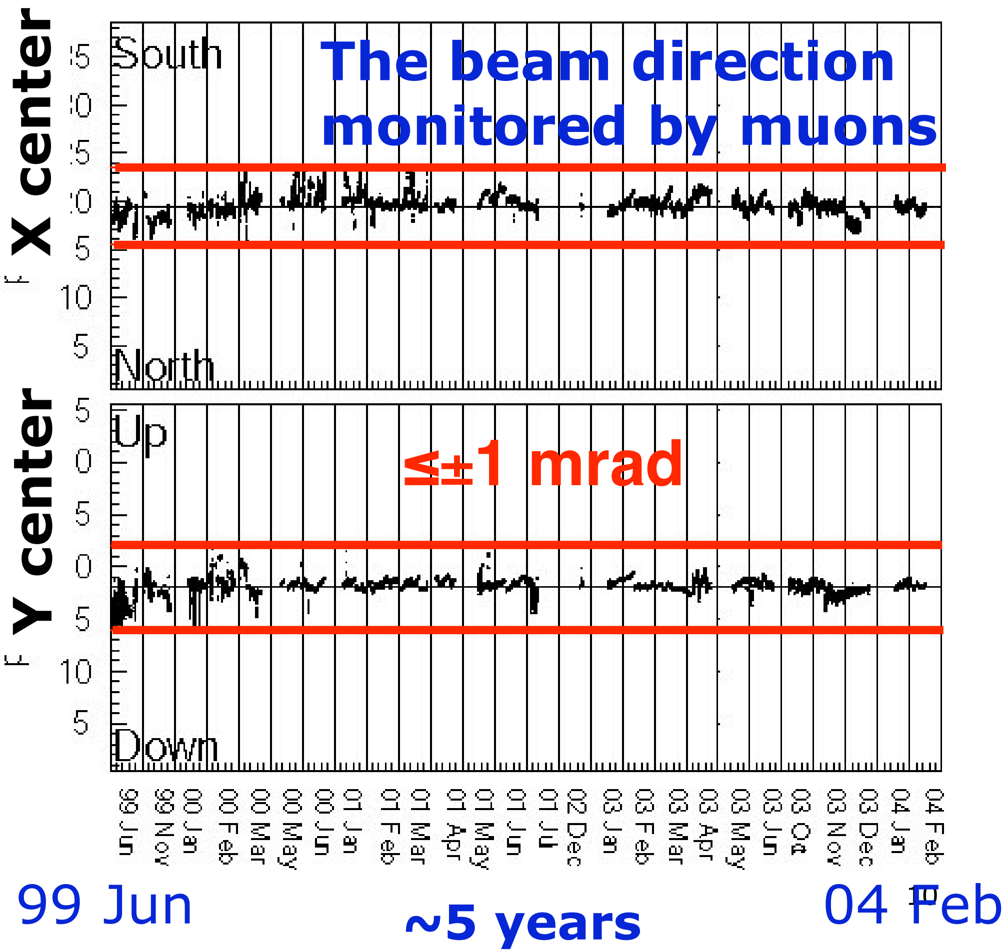
Neutrino beamline @ KEK



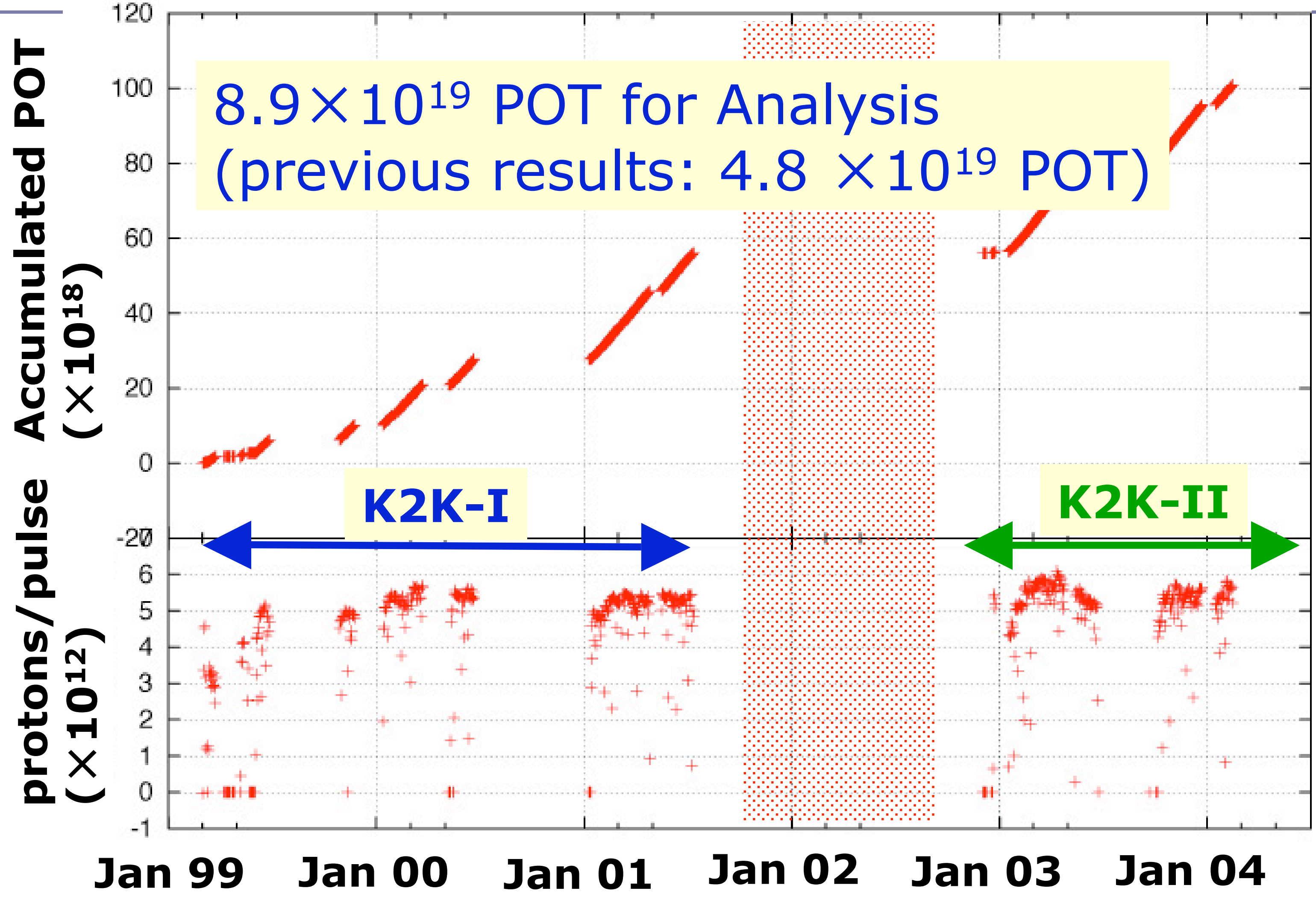
Neutrino beam and the directional control

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



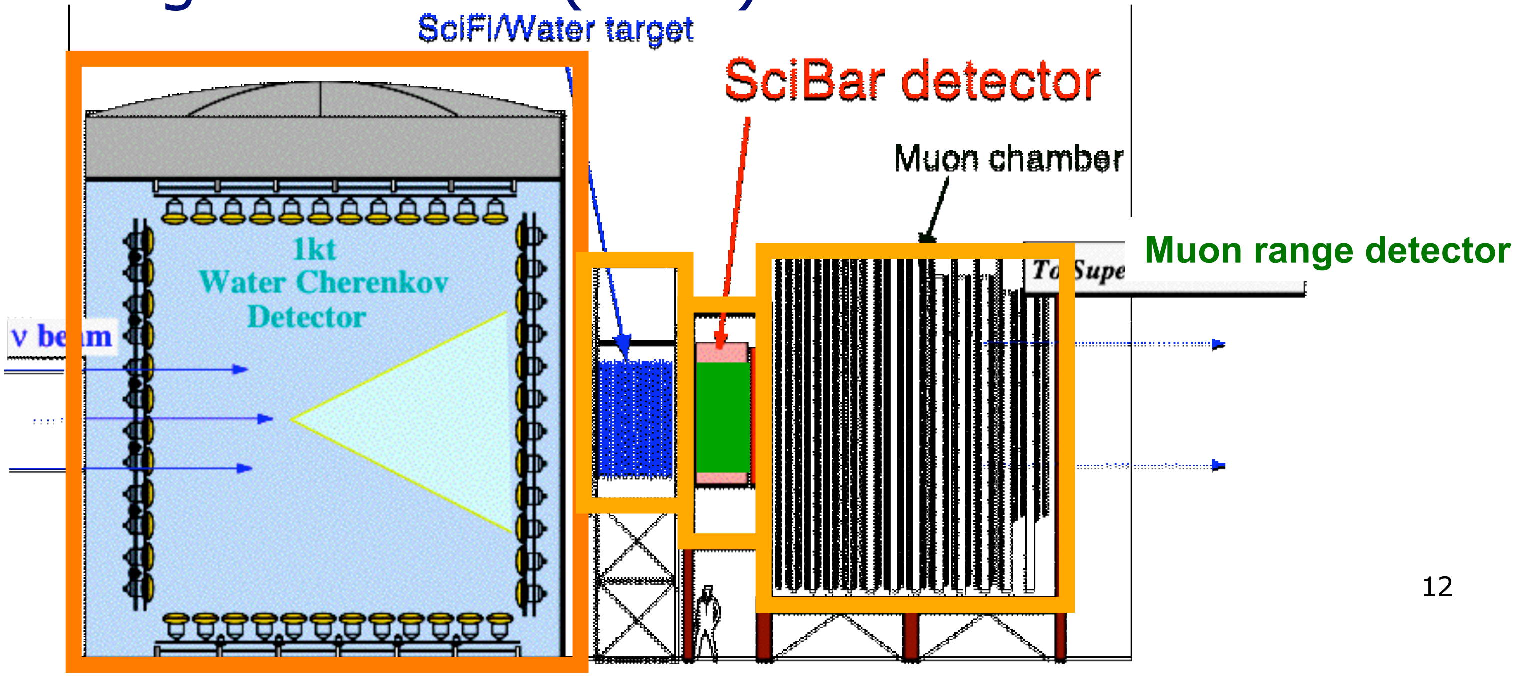


Accumulated POT (Protons On Target)



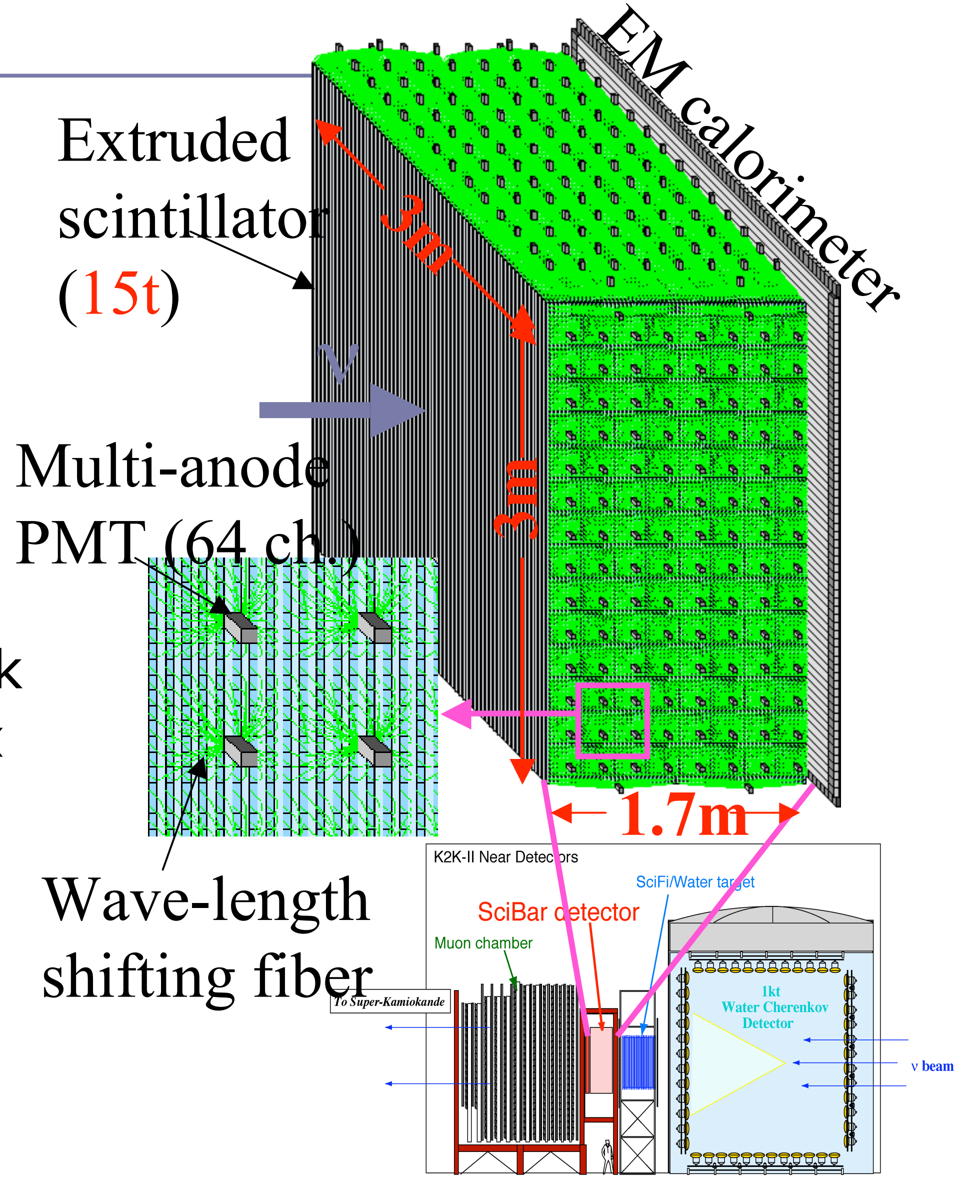
Near detector system at KEK

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

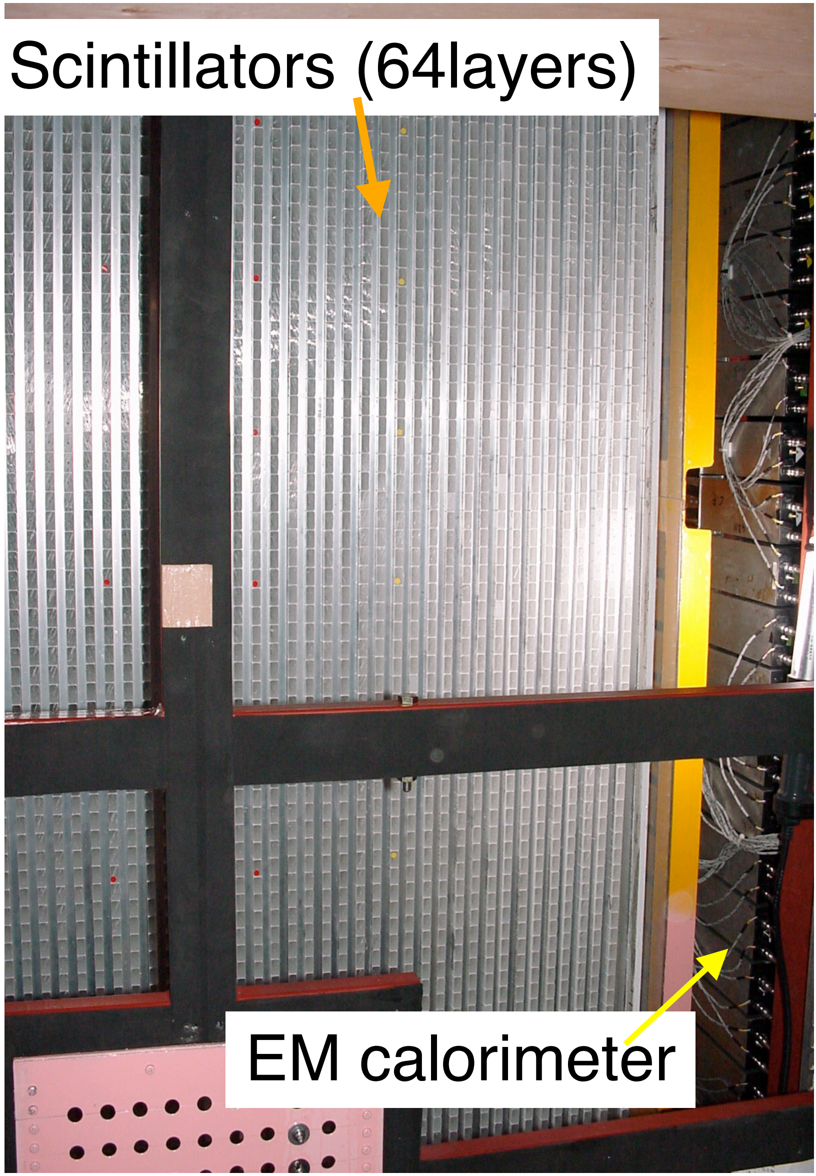


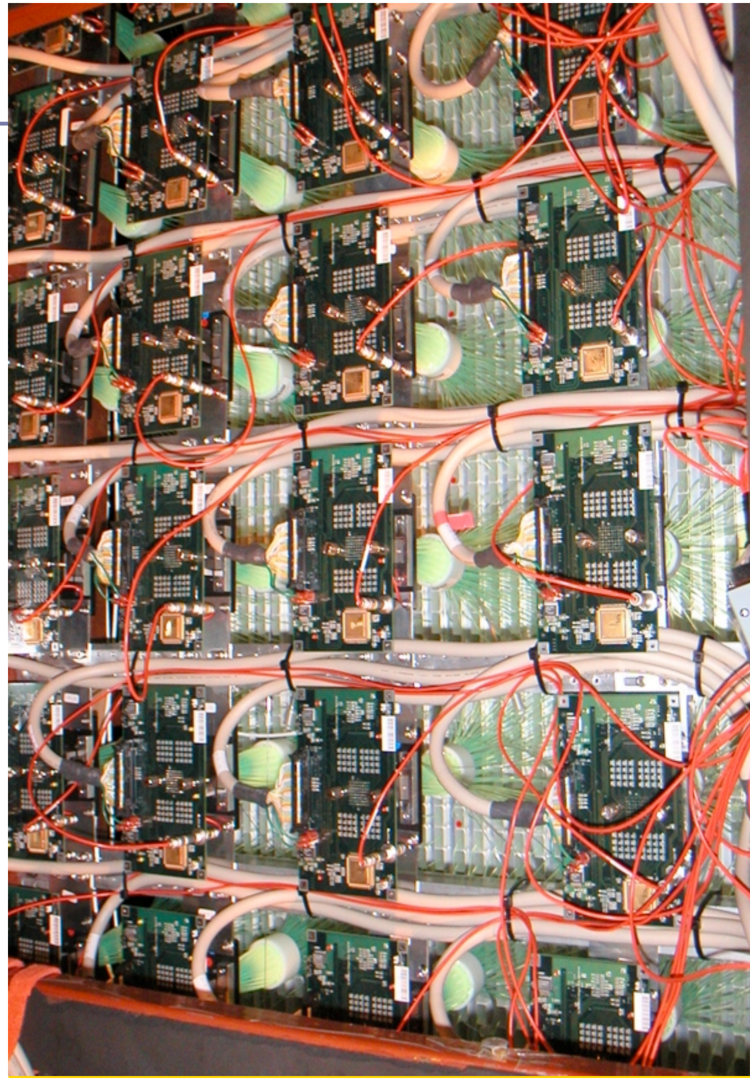
SciBar Detector

- Full-active, fine-segment detector made of Scintillator Bars
  - $2.5 \times 1.3 \times 300 cm^3$ cell
  - ~15000 channels
  - 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.

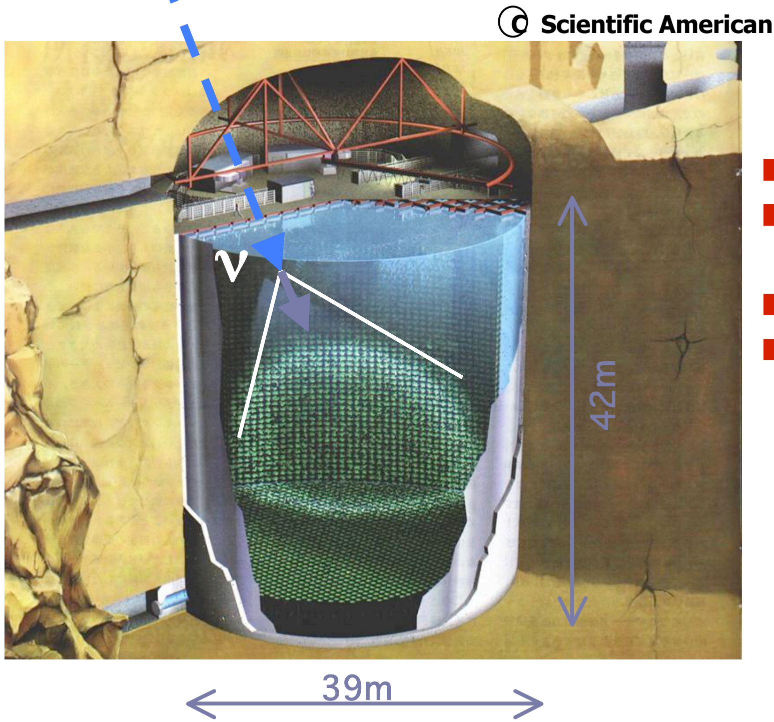
Just Completed!

Aug. 22, 2003

Far detector : *Super-Kamiokande*

SK- I
~5years

- 1996.4 Start data taking (SK- I)
- 1999 K2K start



Water Cherenkov detector

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

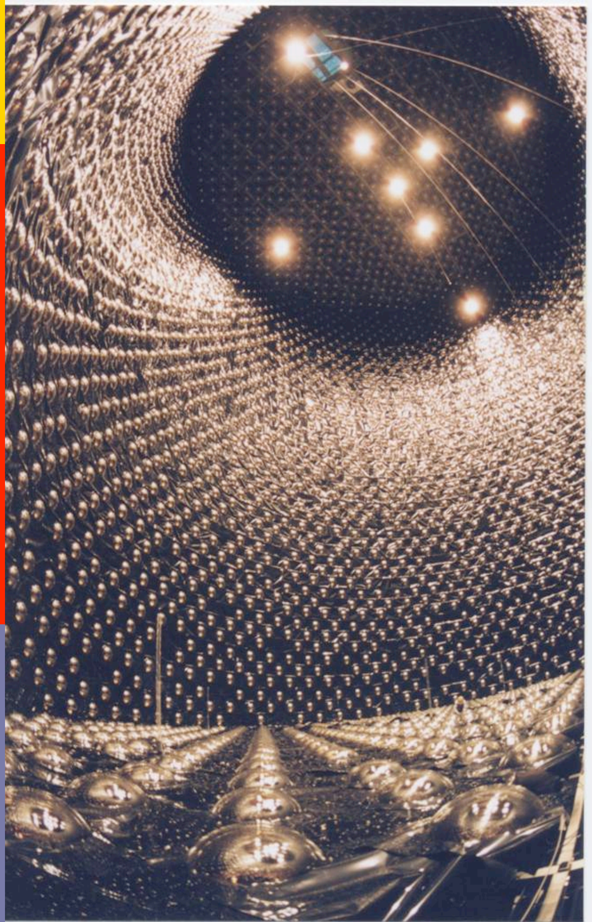
- 2001.7 Stop data taking for detector upgrade
- 2001.11 Accident (~7000 inner PMTs, 1100 outer PMTs were destroyed)
  partial reconstruction of the detector

SK- II
K2K-II

- 2002.10 resume data taking (SK- II)
- 2002.12 resume K2K beam (K2K-II)

SK is back !

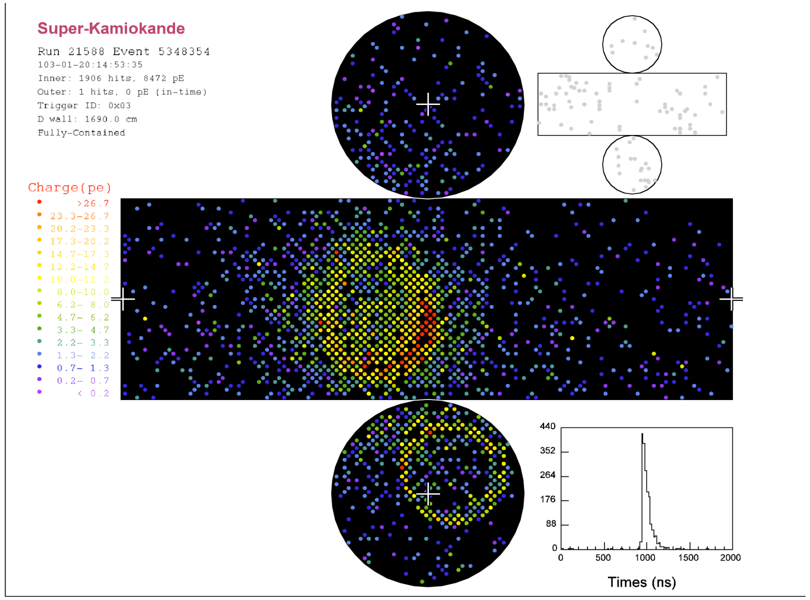
Full water on 10-Dec.-2002



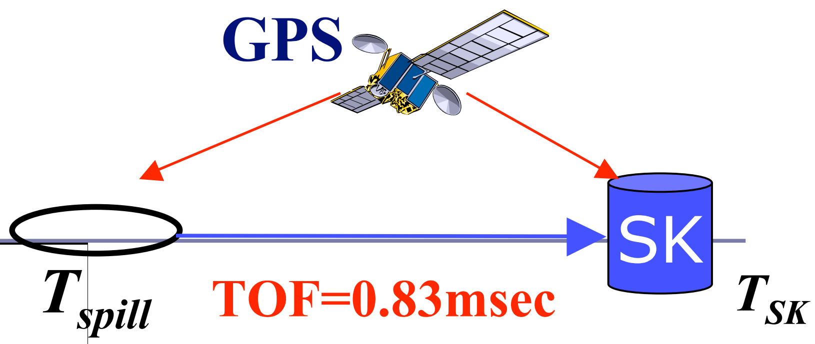
Sep.-2002, before water filling

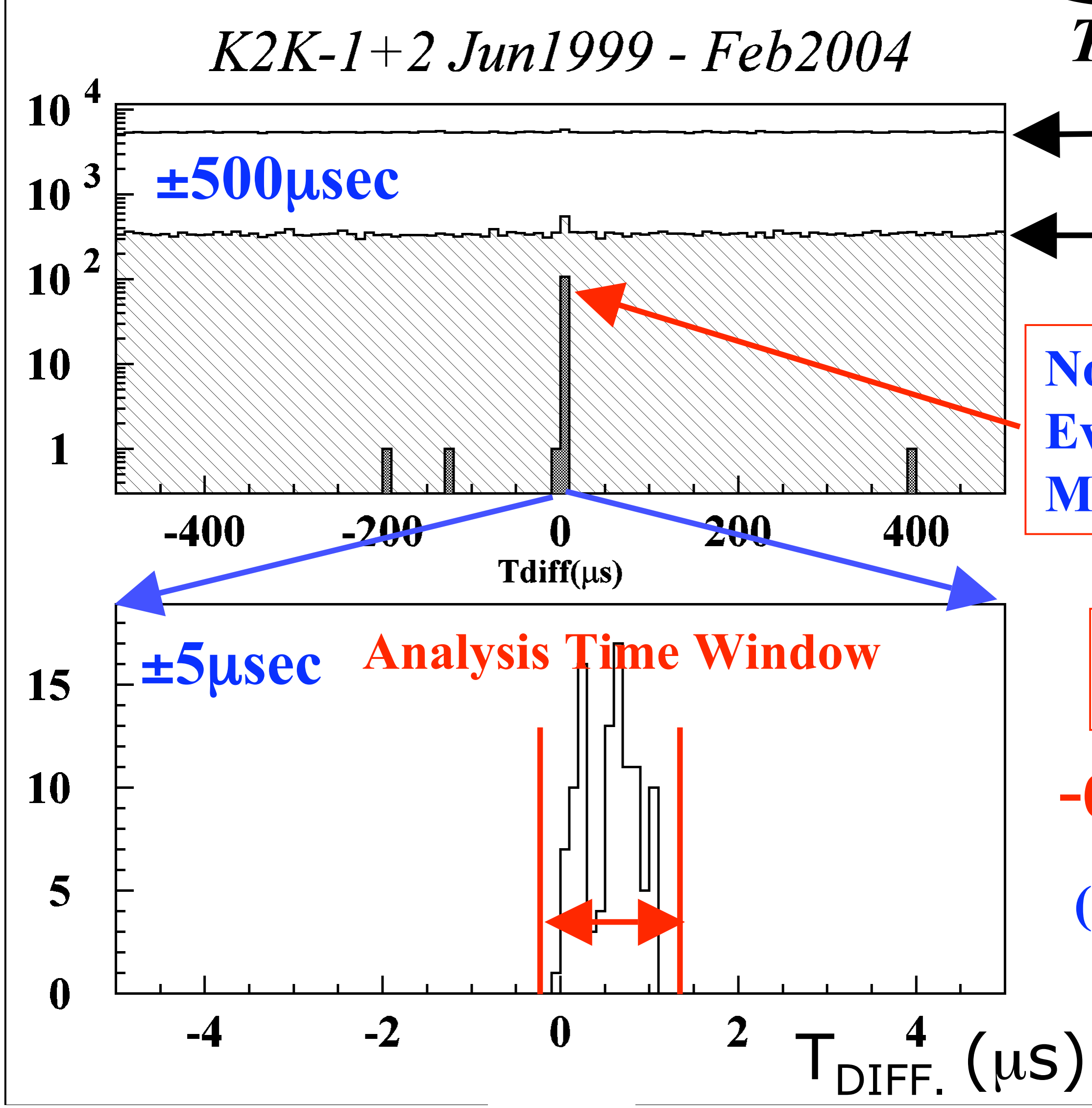
Acrylic + FRP vessel

Jan.-2003, fully contained event



SK Events





Decay electron cut.

≥20MeV Deposited Energy

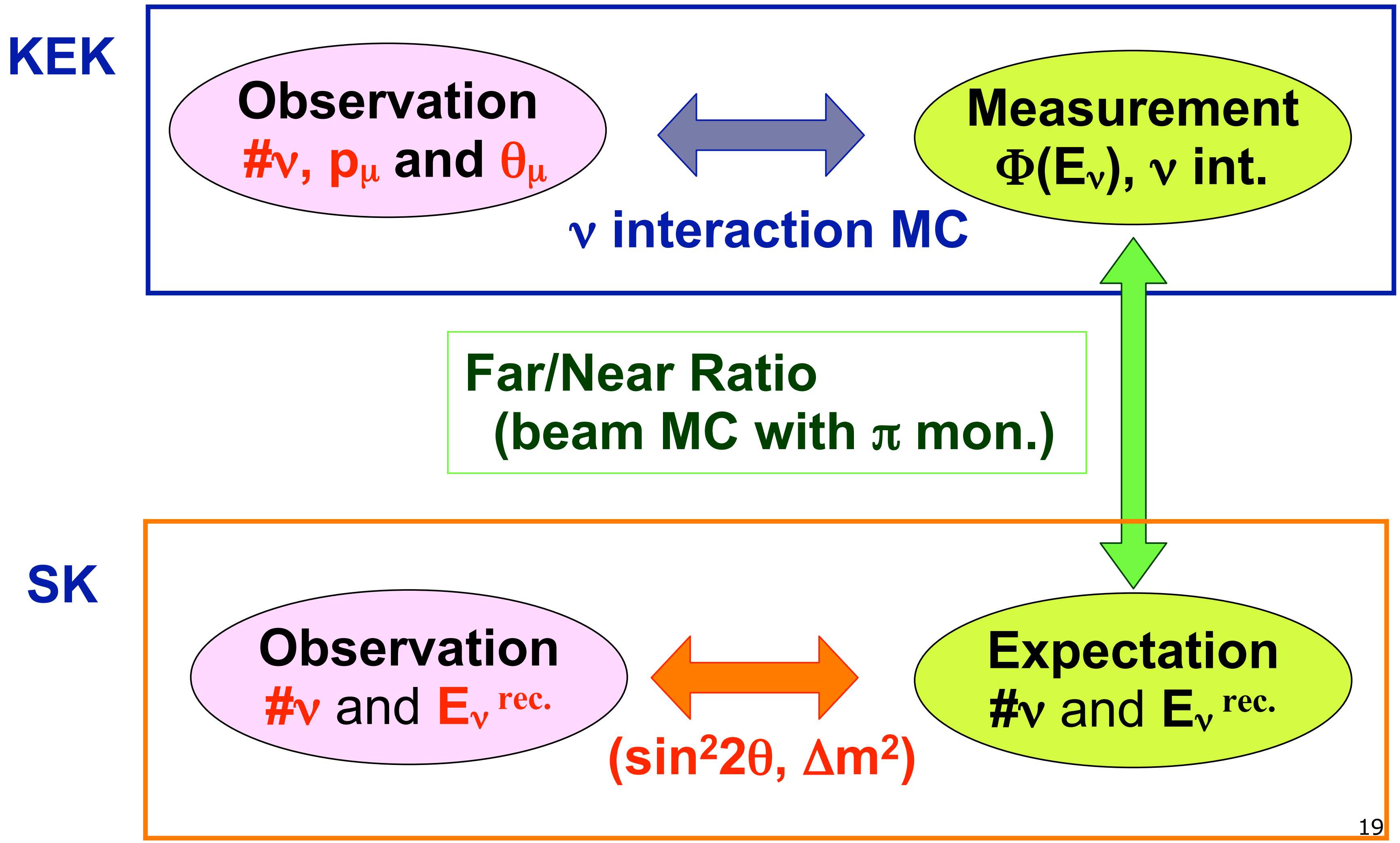
No Activity in Outer Detector
Event Vertex in Fiducial Volume
More than 30MeV Deposited Energy

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)

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)

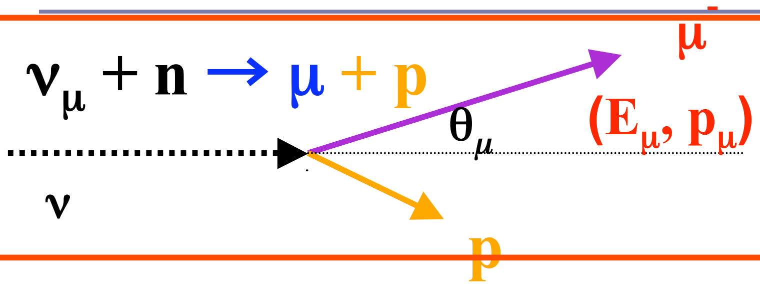
↓

Predict number of event and spectrum shape at SK

Neutrino Interaction @~1 GeV
&
E_ν reconstruction

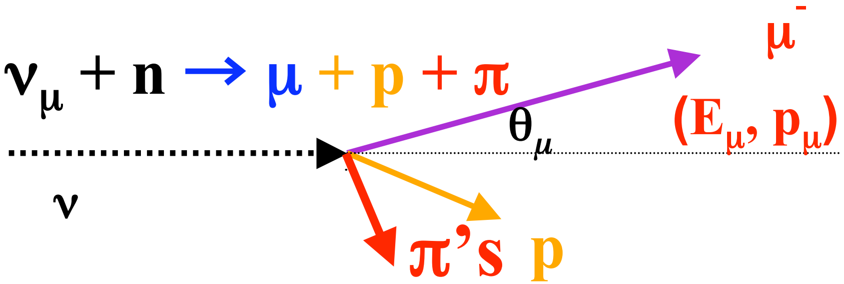
$$E_\nu^{rec} = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

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



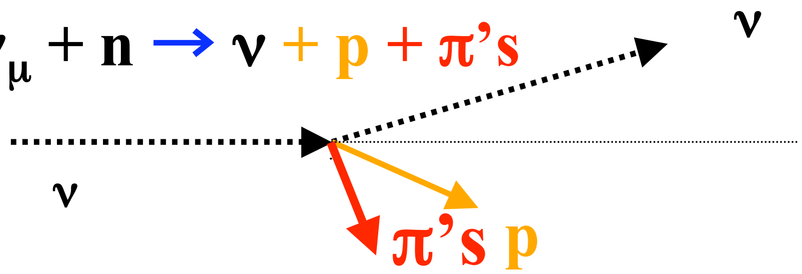
- CC QE
  - ~100% efficiency for N_{SK}
  - can reconstruct $E\nu \leftarrow (\theta_\mu, p_\mu)$

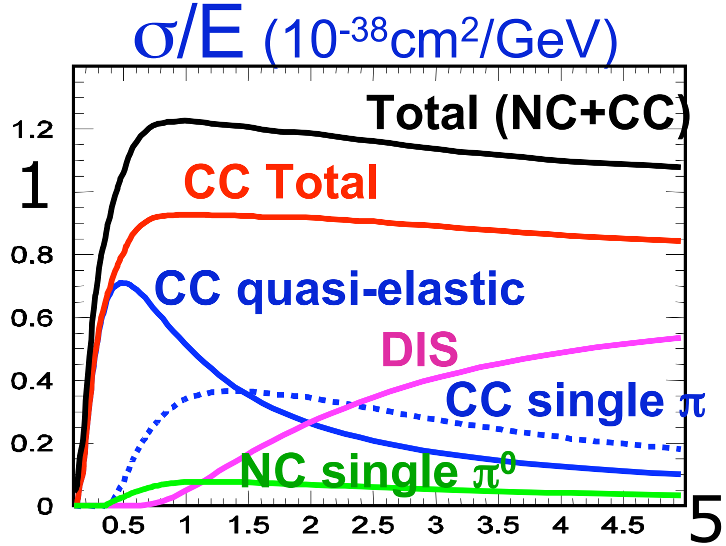
$\nu_\mu + n \rightarrow \mu + p + \pi$



- CC nQE (1pi, multi-pi, coherent,DIS)
  - ~100% efficiency for N_{SK}
  - Bkg. for E_ν measurement
- NC
  - ~40% efficiency for N_{SK}

$\nu_\mu + n \rightarrow \nu + p + \pi\text{'s}$





4.1 Event rate measurement @1KT

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

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

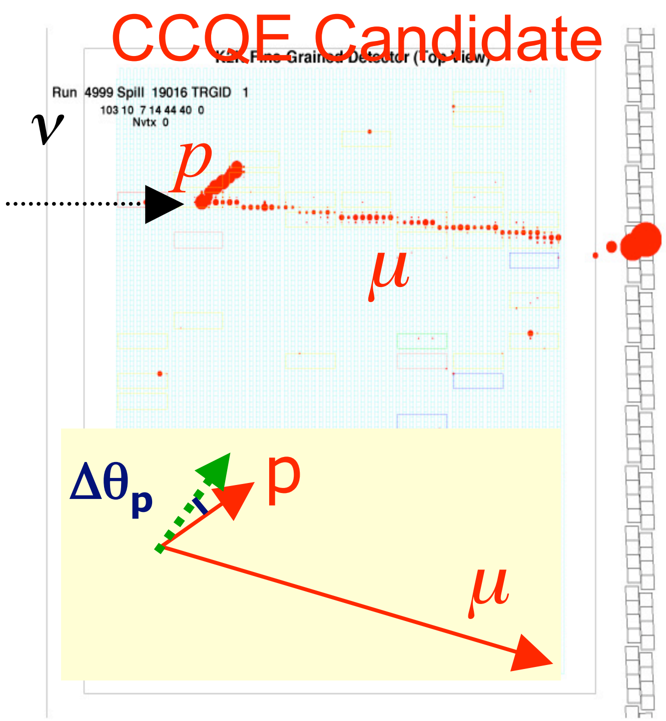
≡Far/Near Ratio (by MC)~1×10^{-6}

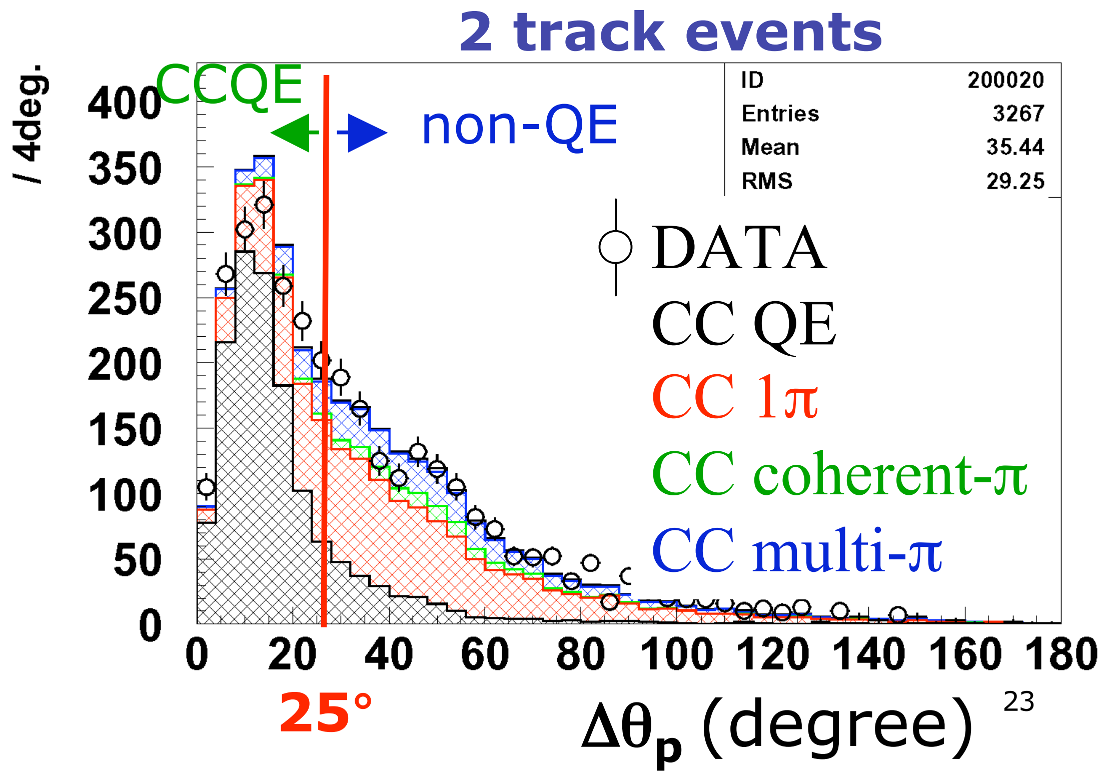
M: Fiducial mass M_{SK}=22,500ton, M_{KT}=25ton
ε: efficiency $\varepsilon_{SK\text{-}I(II)}$=77.0(78.2)%, ε_{KT}=74.5%

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

4.2 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.





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.

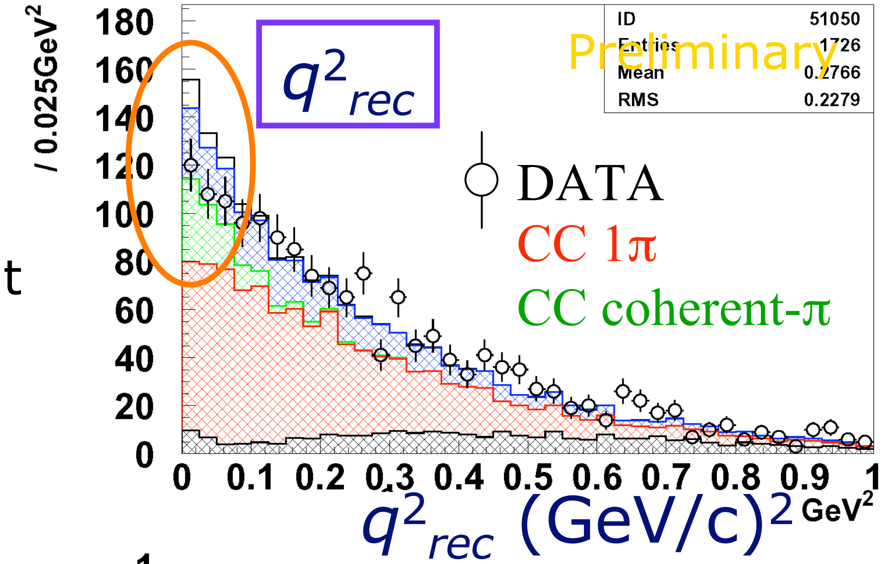
A hint of K2K forward μ deficit.

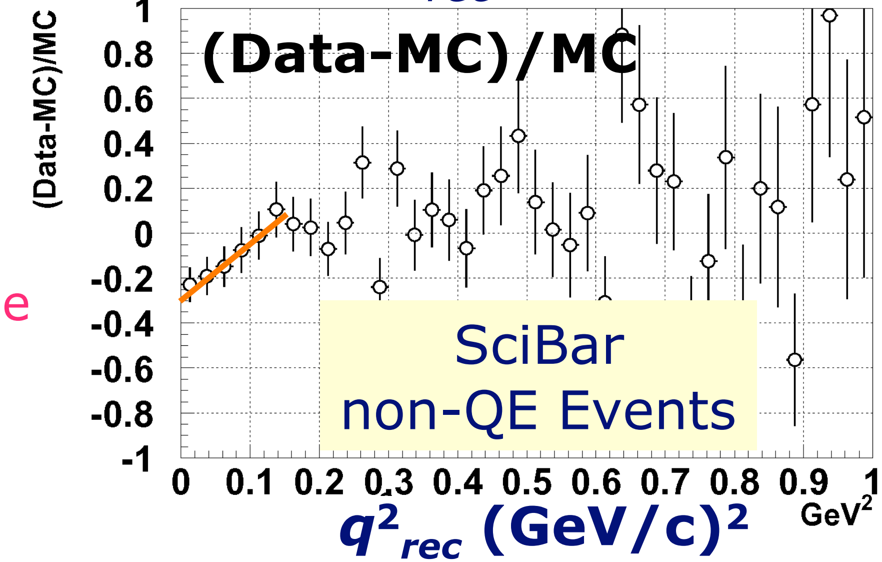
K2K observed forward μ deficit.

- 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.

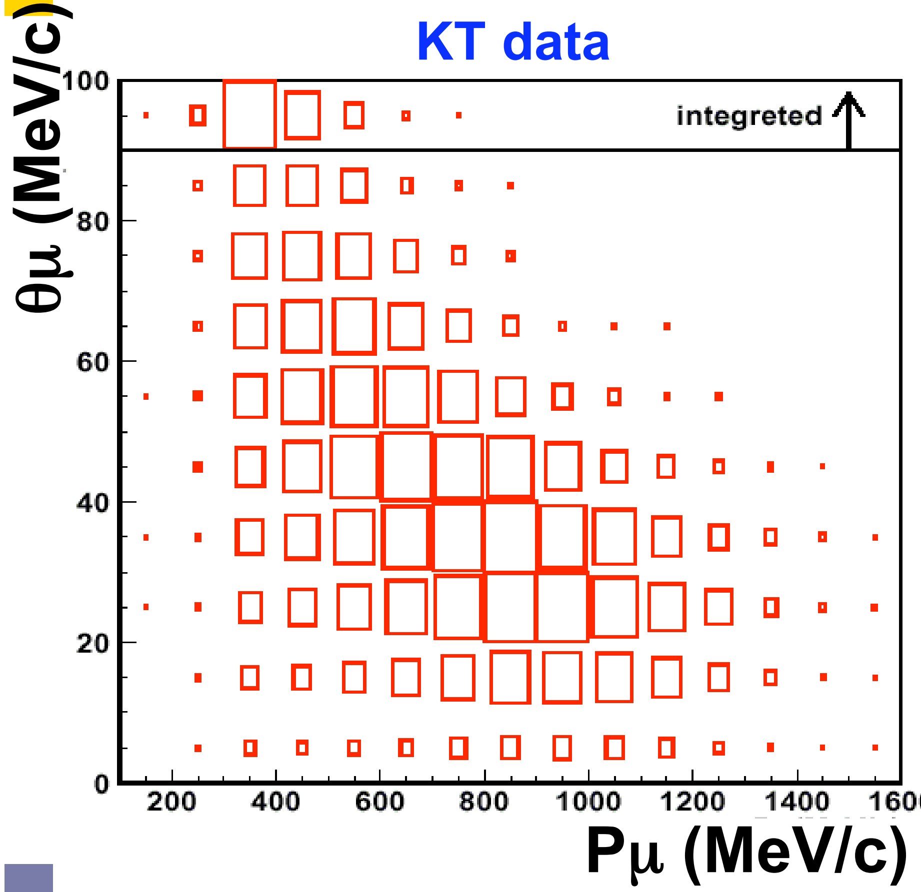




4.4 Near Detectors combined measurements

(p_μ, θ_μ) for 1track, 2trackQE and 2track nQE samples
→ $\Phi(E\nu)$, 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)

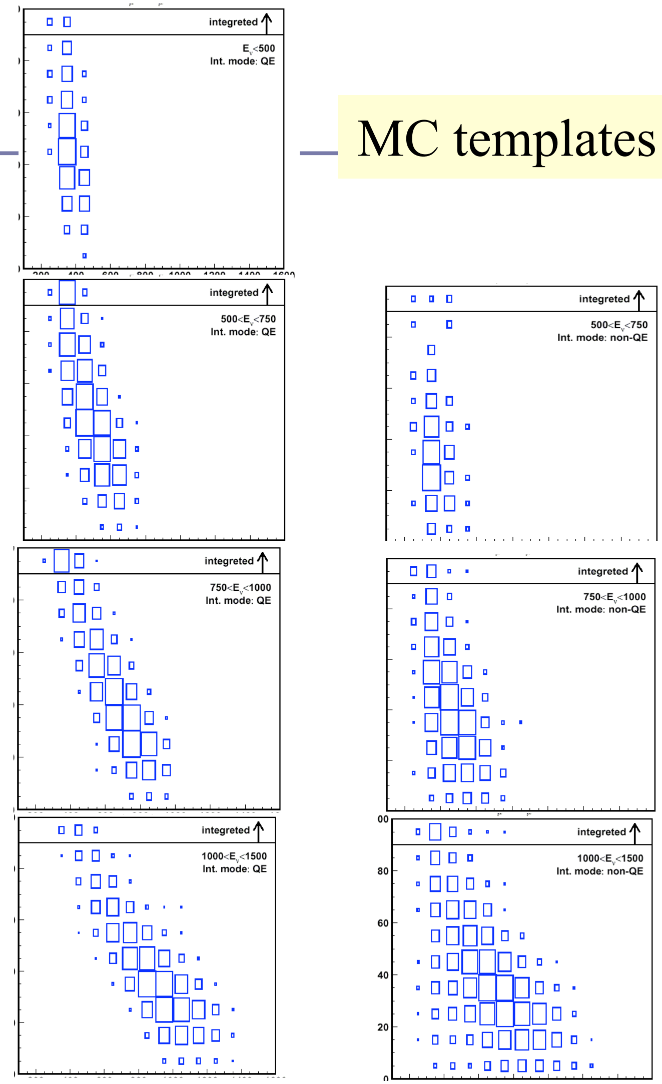
0-0.5 GeV

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)

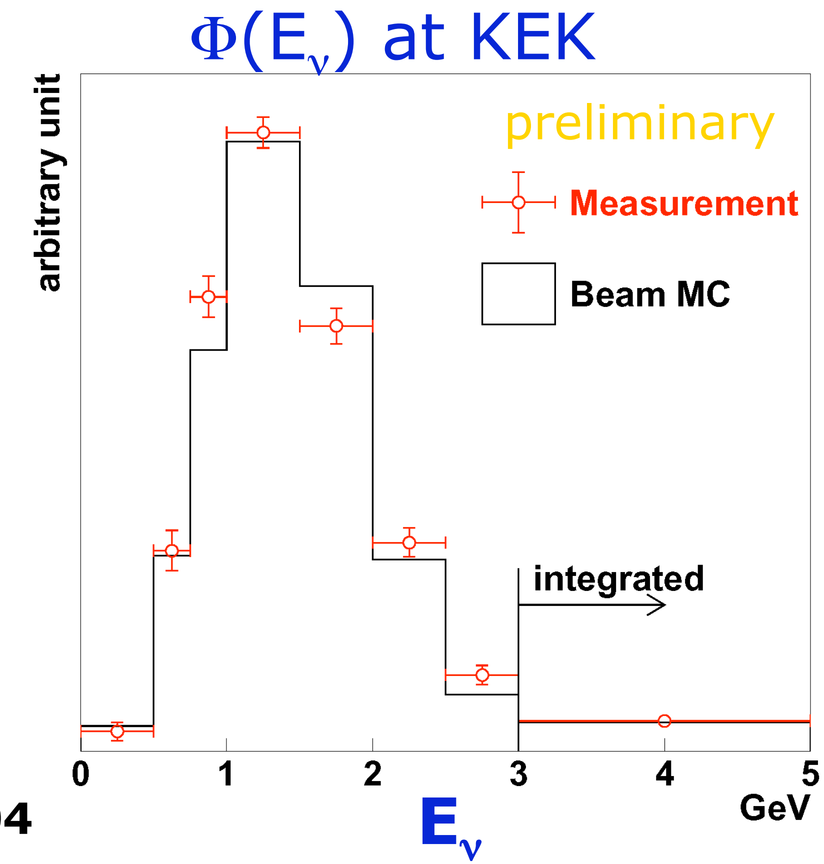
Flux measurements

χ^2=638.1 for 609 *d.o.f*

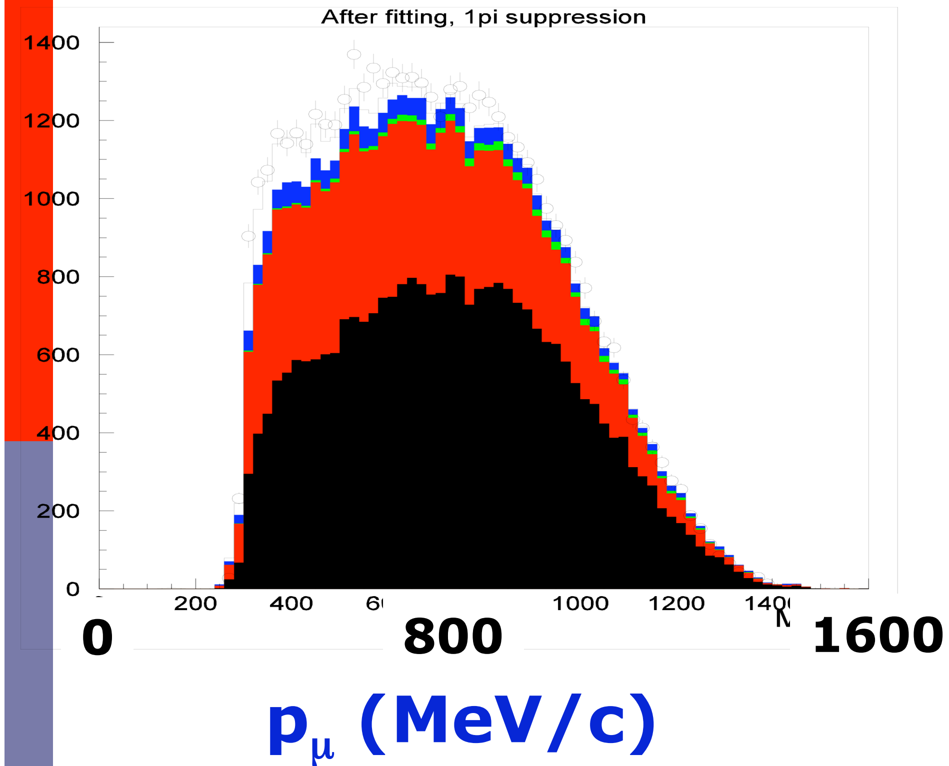
- **Φ1 (Eν < 500) = 0.78 ± 0.36**
- **Φ2 (500≤ Eν < 750) = 1.01 ± 0.09**
- **Φ3 (750≤ Eν <1000) = 1.12 ± 0.07**
- **Φ4 (1500≤ Eν <2000) = 0.90 ± 0.04**
- **Φ5 (2000≤ Eν <2500) = 1.07 ± 0.06**
- **Φ5 (2500≤ Eν <3000) = 1.33 ± 0.17**
- **Φ6 (3000≤ Eν) = 1.04 ± 0.18**
- **nQE/QE = 1.02 ± 0.10**

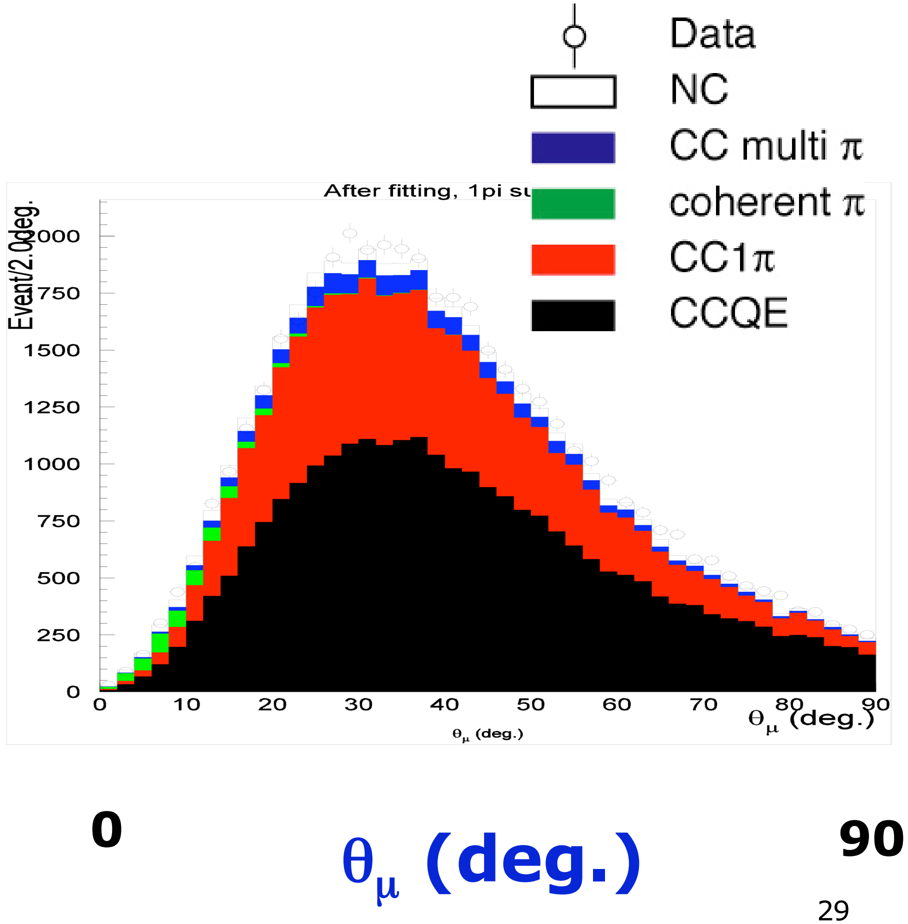
The nQE/QE error of 10% is assigned based on the variation by the fit condition.

- **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**

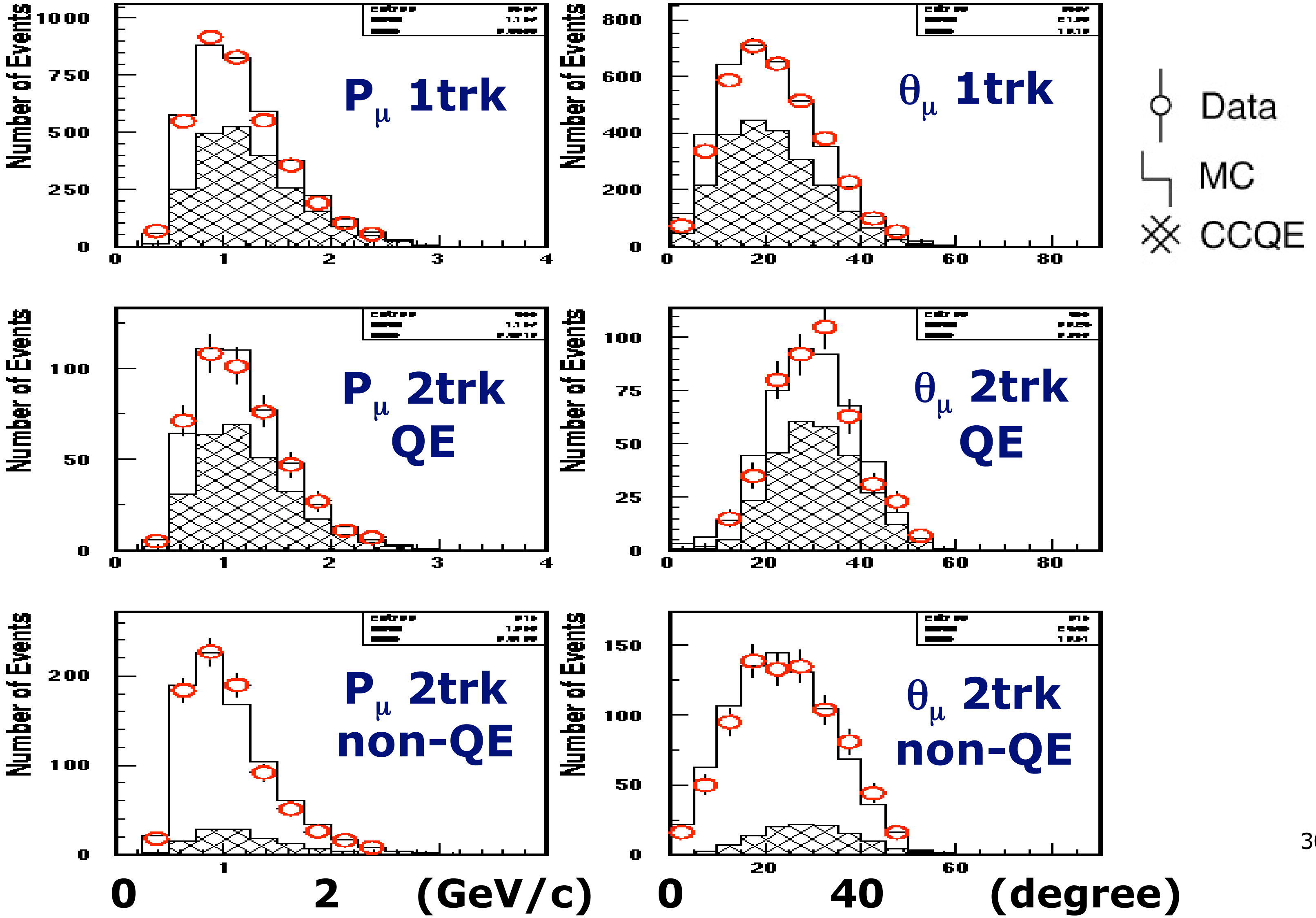


1KT: μ momentum and angular distributions. with measured spectrum

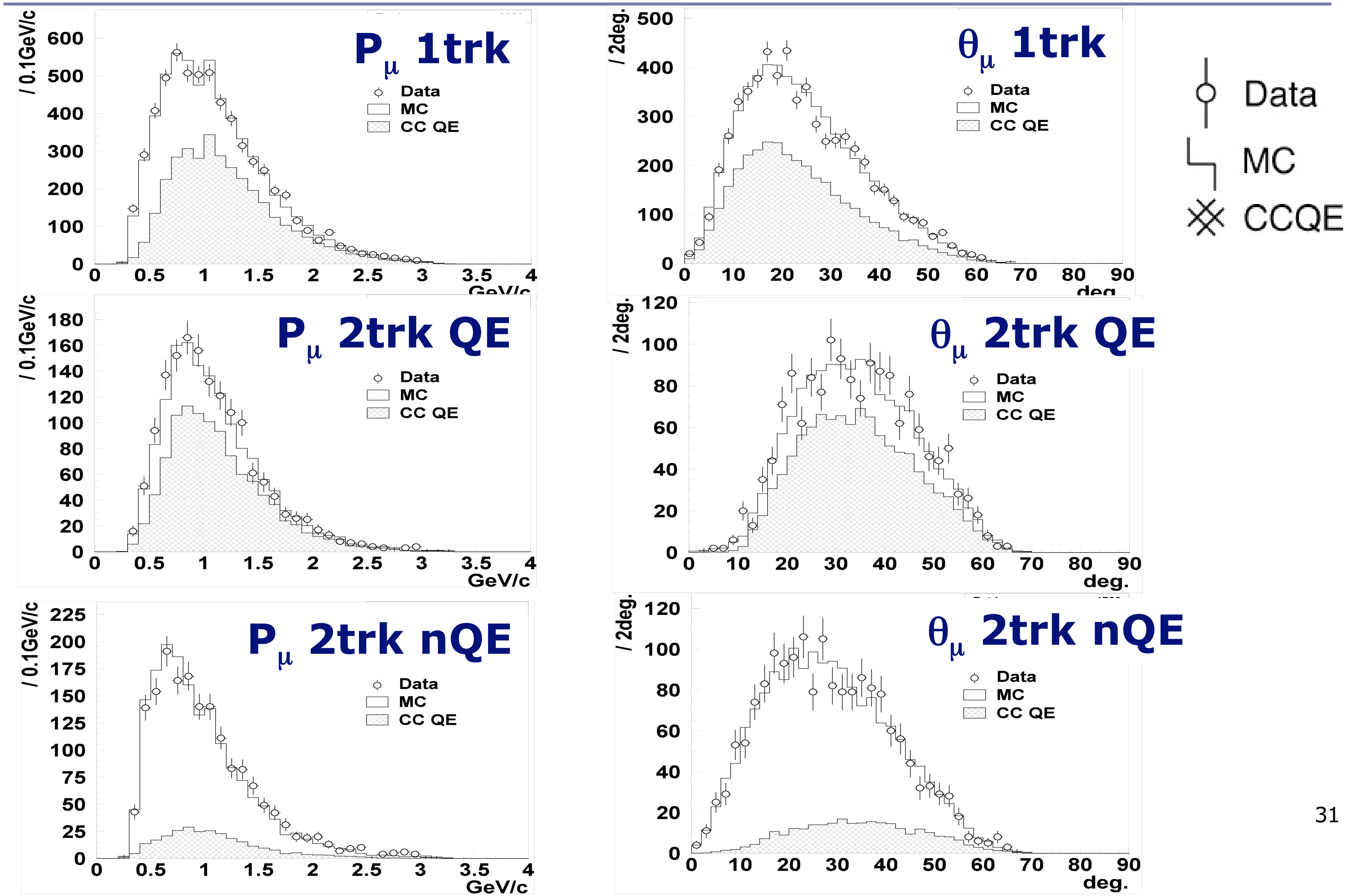




SciFi (K2K-IIa with measured spectrum)



SciBar (with measured spectrum)



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.

K2K-SK events

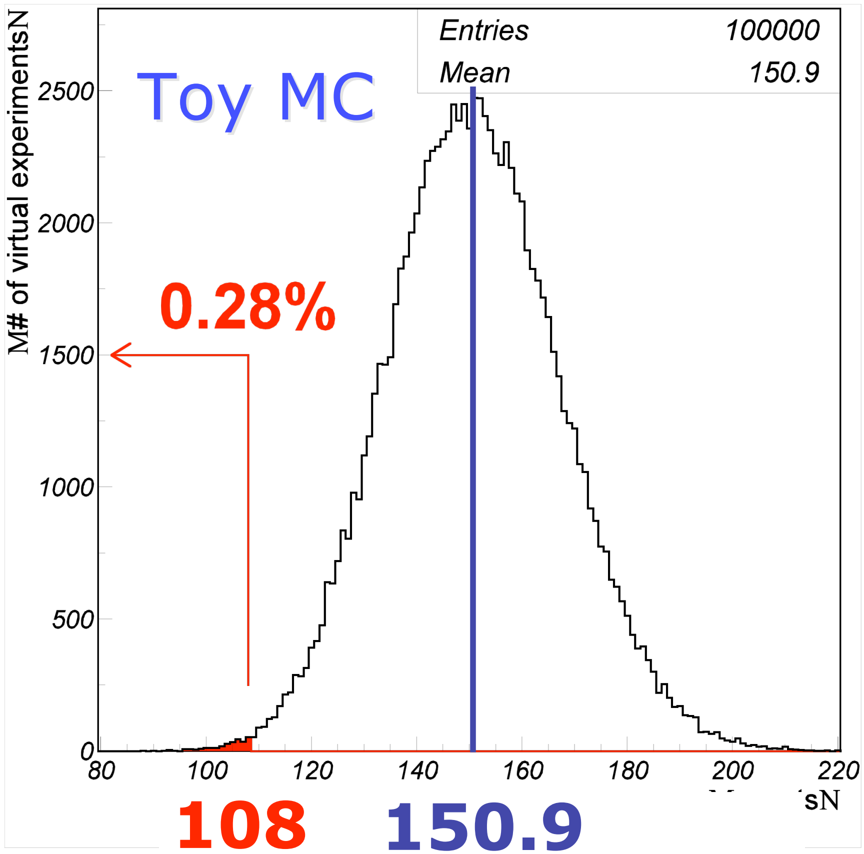
preliminary

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)

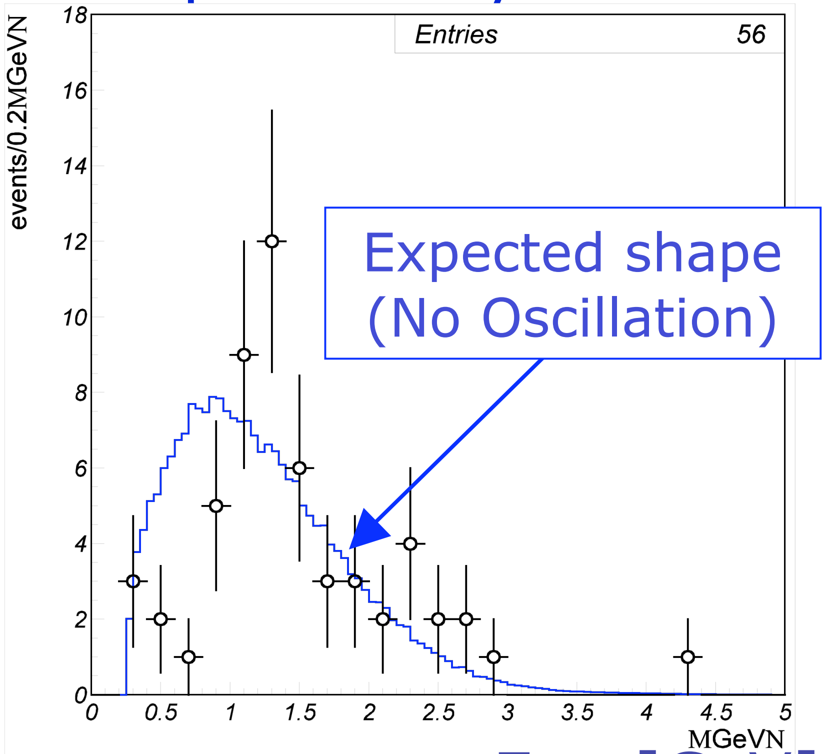
$L_{norm}(\Delta m^2, \sin 2\theta, f^x)$ $L_{shape}(\Delta m^2, \sin 2\theta, f^x)$

#SK Events



108 **150.9**

KS probability=0.11%



E_ν^{rec}[GeV]

CC-QE assumption

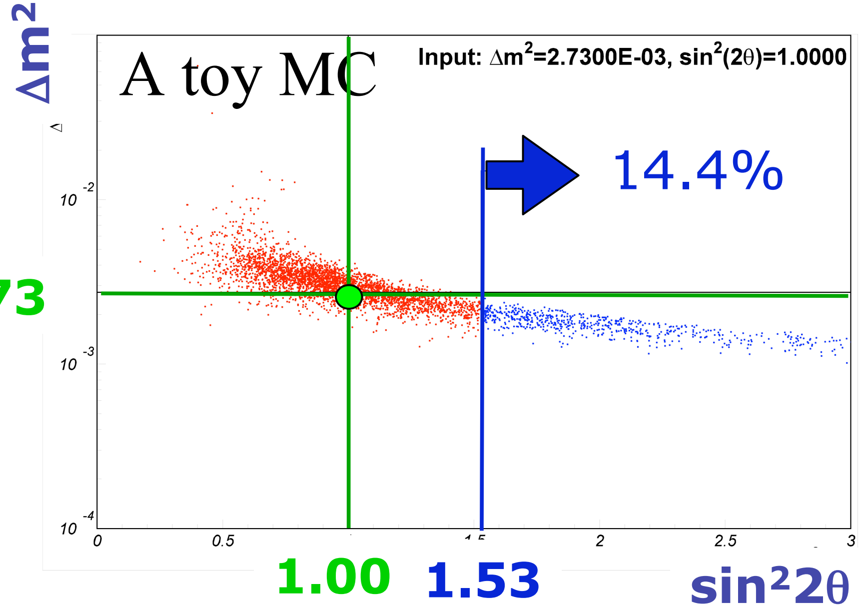
$$E_\nu^{rec} = \frac{(m_N - V)E_\mu - m_\mu^2/2 + m_N V - V^2/2}{(m_N - V) - E_\mu + p_\mu \cos\theta_\mu}$$

V: Nuclear potential

6. Results preliminary

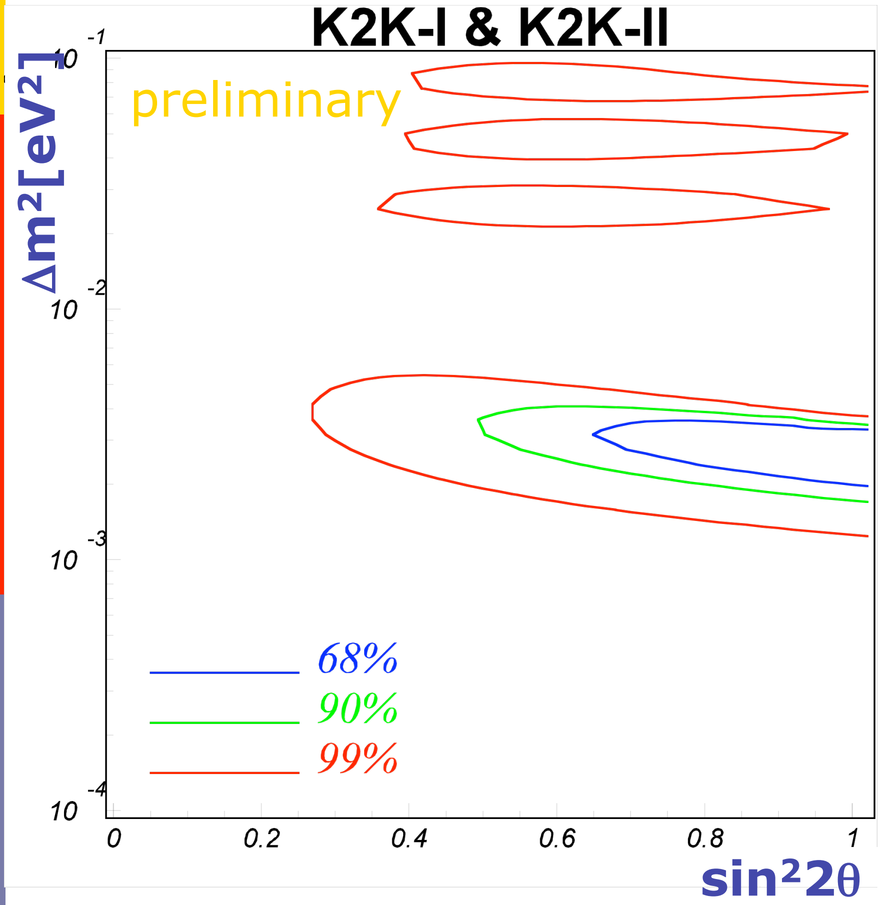
- Best fit values.
  - $\sin^2 2\theta = 1.53$
  - $\Delta m^2\ [eV^2] = 2.12\times10^{-3}$
- Best fit values in the physical region.
  - $\sin^2 2\theta = \mathbf{1.00}$
  - $\Delta m^2\ [eV^2] = \mathbf{2.73\times10^{-3}}$

$\Delta\log L = 0.64$



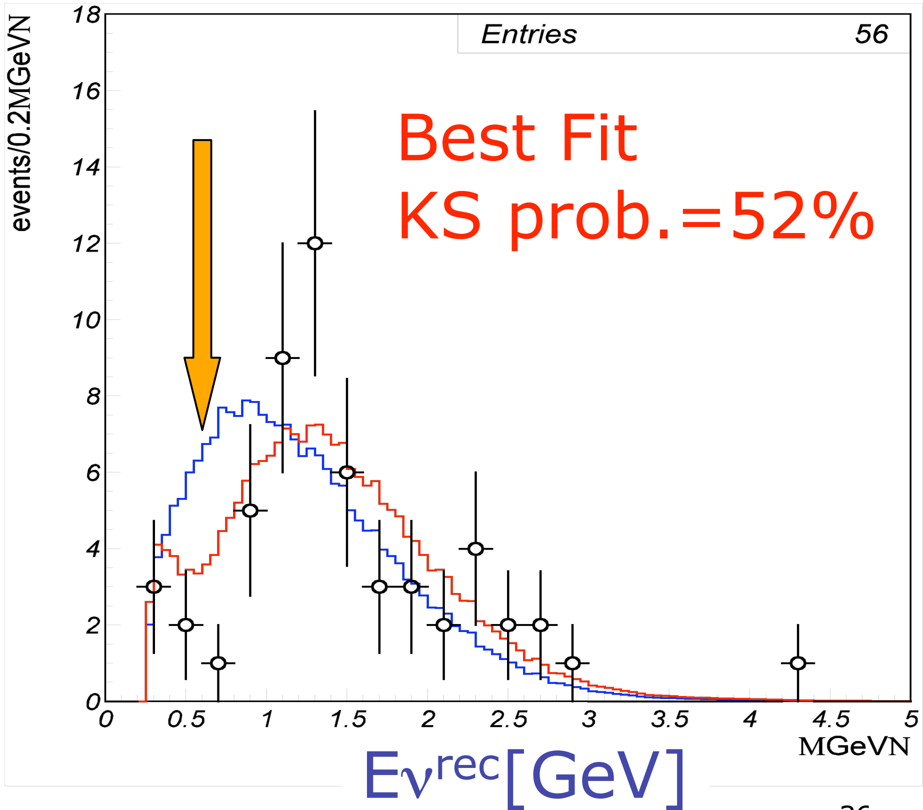
$\sin^2 2\theta = 1.53$ can occur by statistical fluctuation with 14.4% probability.

Data are consistent with the oscillation.

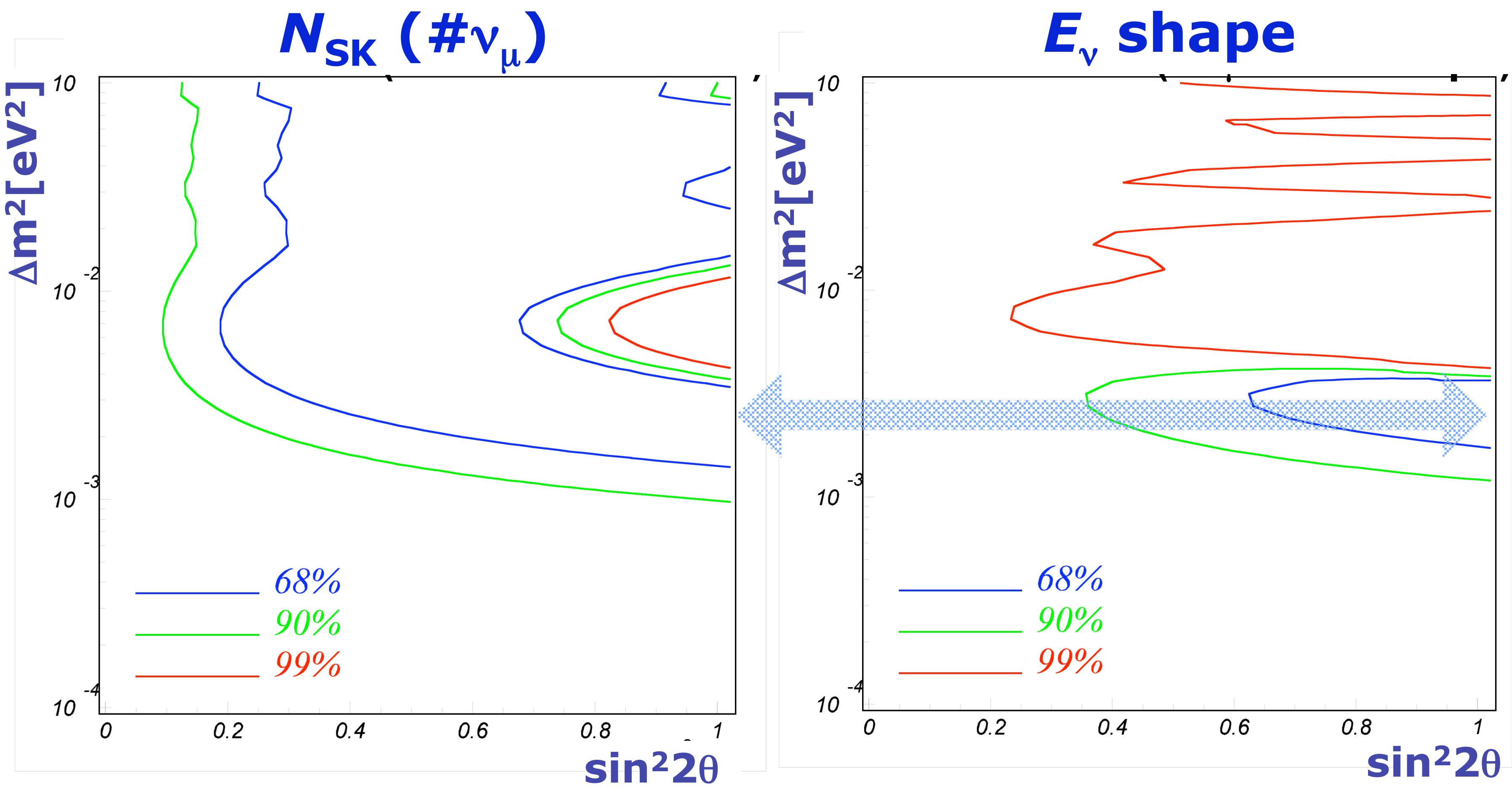


Based on Δln*L*

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



ν_μ disappearance versus E_ν shape distortion



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

Null oscillation probability

preliminary

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

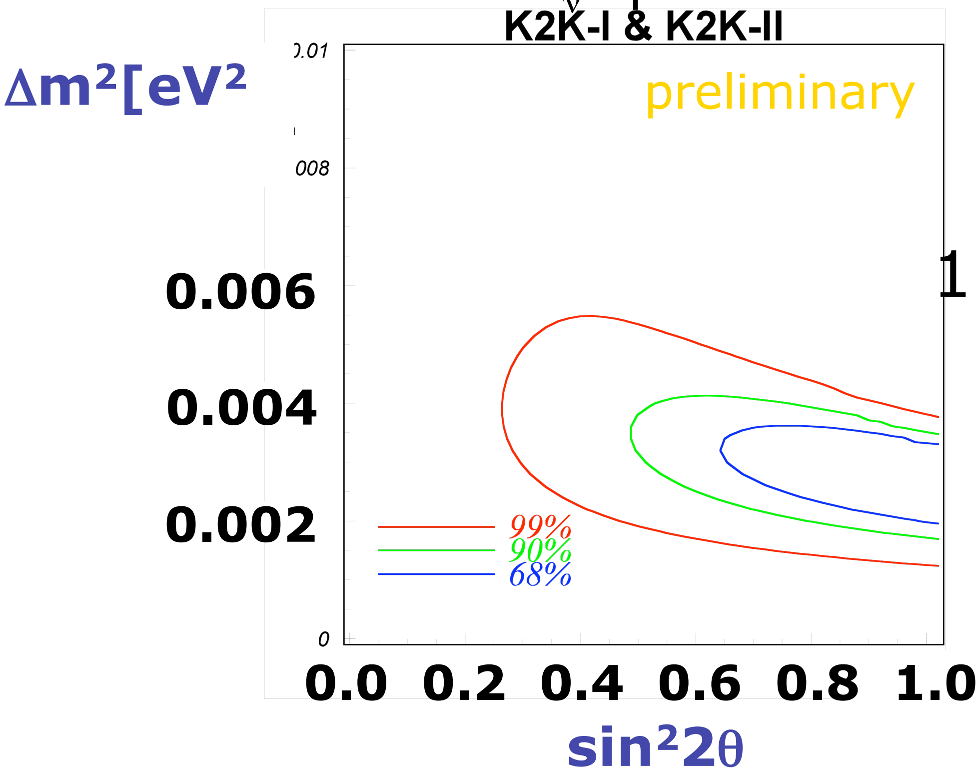
	K2K-I	K2K-II	K2K-all
ν_μ disappearance	2.0%	3.7%	0.33%(2.9σ)
E_ν spectrum distortion	19.5%	5.4%	1.1% (2.5σ)
Combined	1.3% (2.5σ)	0.56% (2.8σ)	**0.011%** (3.9σ)

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

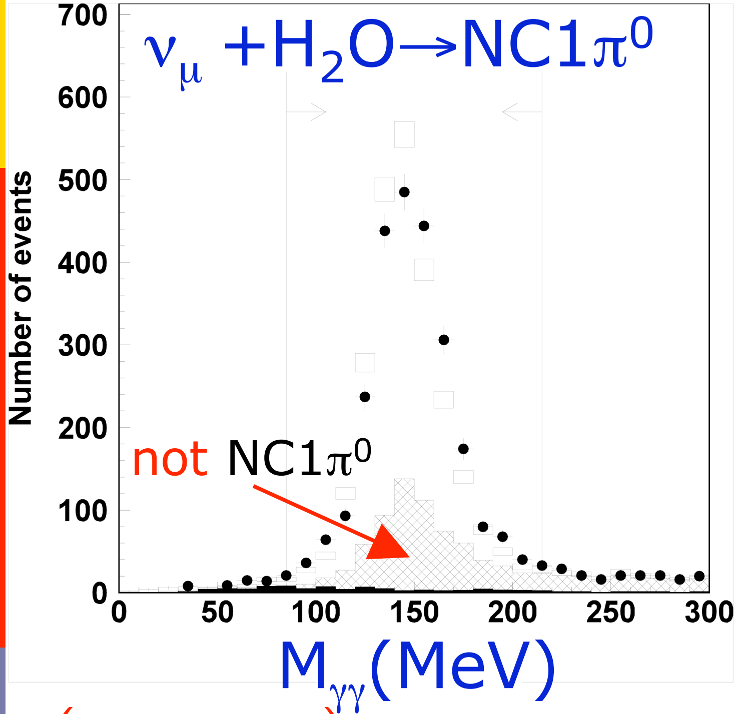
- With 8.9×10^{19} POT, K2K *has confirmed* neutrino oscillations at **3.9σ**.
  - Disappearance of ν_μ **2.9σ**
  - Distortion of E_ν spectrum **2.5σ**



$1.7\times10^{-3}<\Delta m^2<3.5\times10^{-3}eV^2$
@$\sin^2 2\theta=1$ (90%C.L.)

Backup

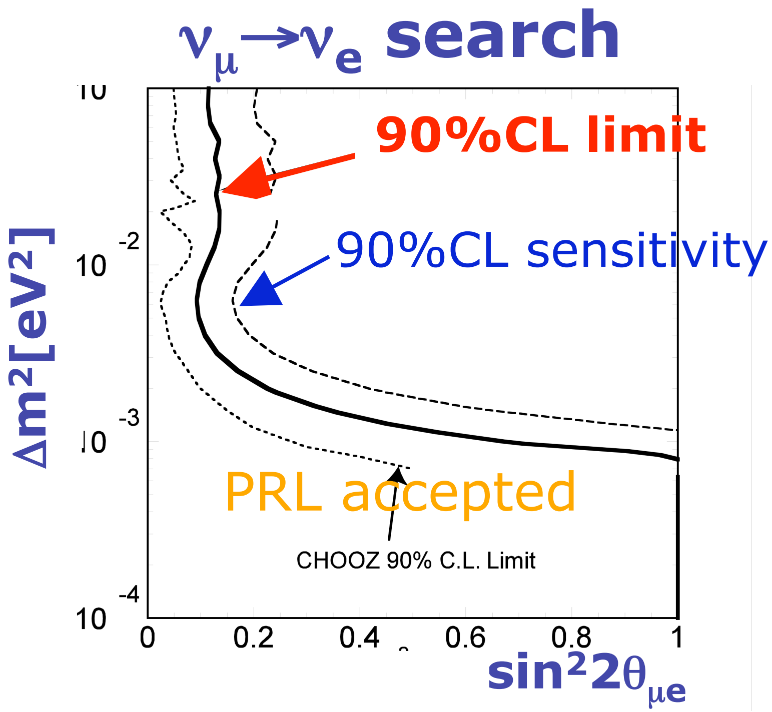
7. *Other Physics in K2K* (based on K2K-I data)



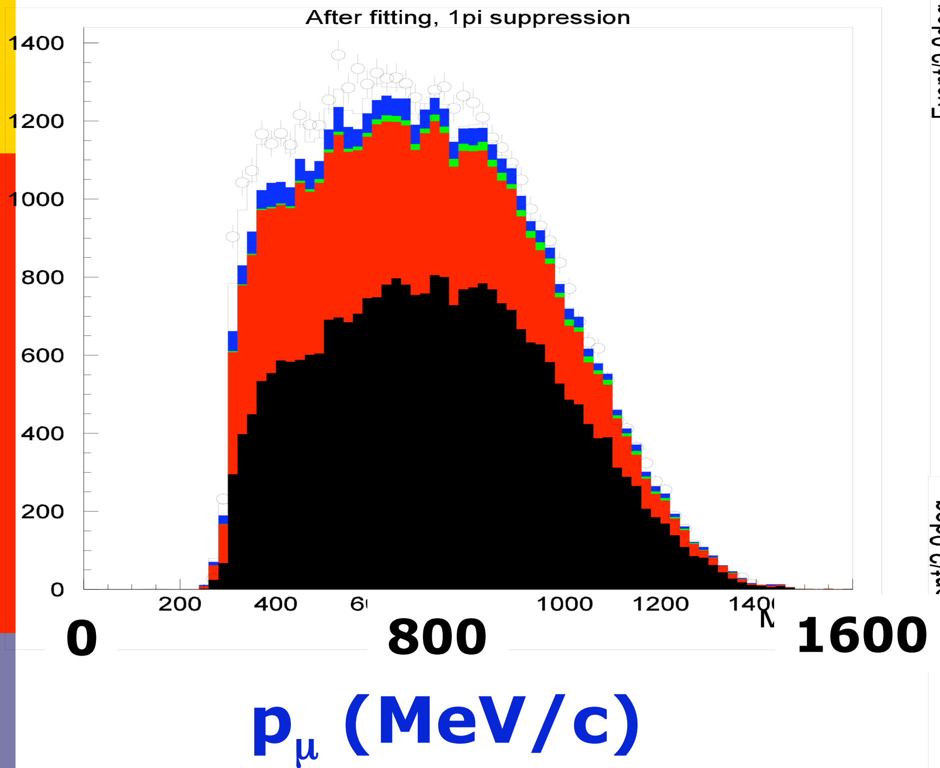
$$\frac{\sigma(\nu_\mu \rightarrow NC1\pi^0)}{\sigma(\nu_\mu \rightarrow CCall)} = 0.065 \pm 0.001 \pm 0.007$$

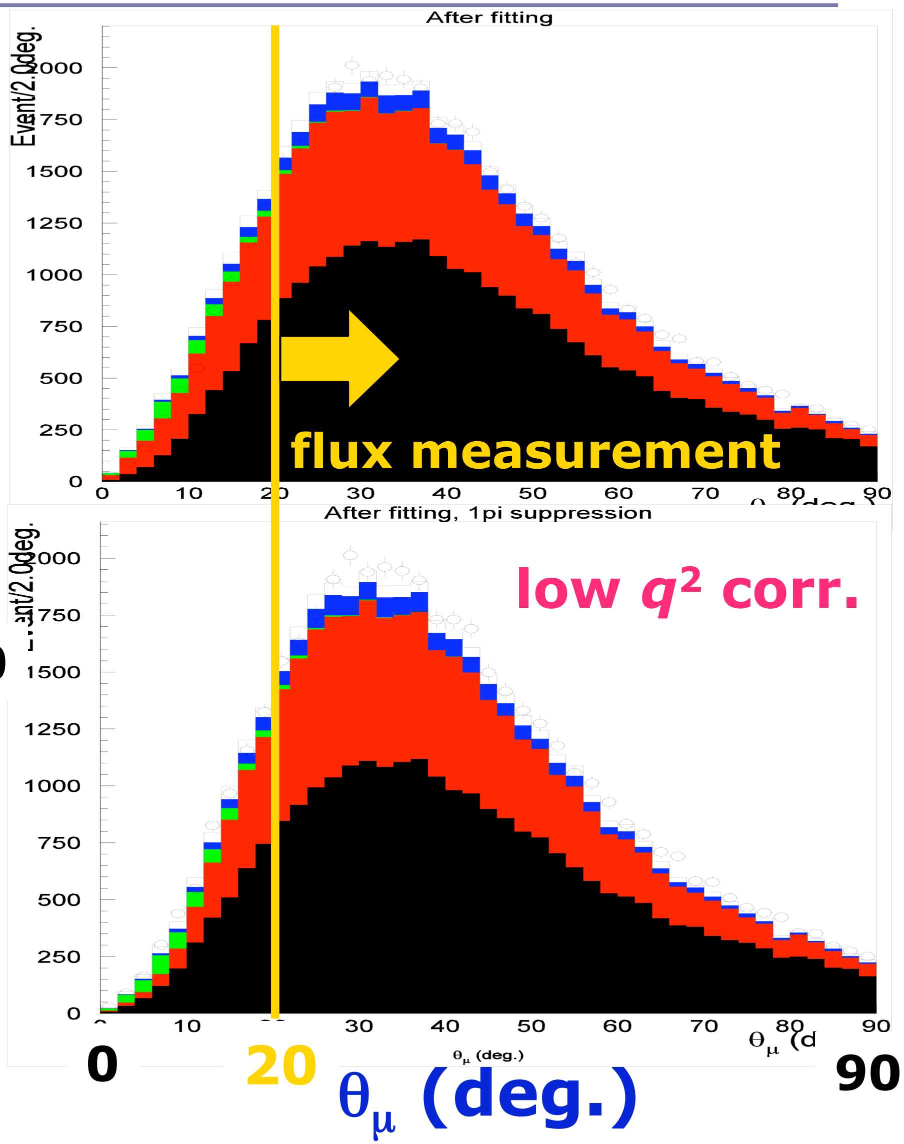
$= 0.064$ (prediction)

preliminary

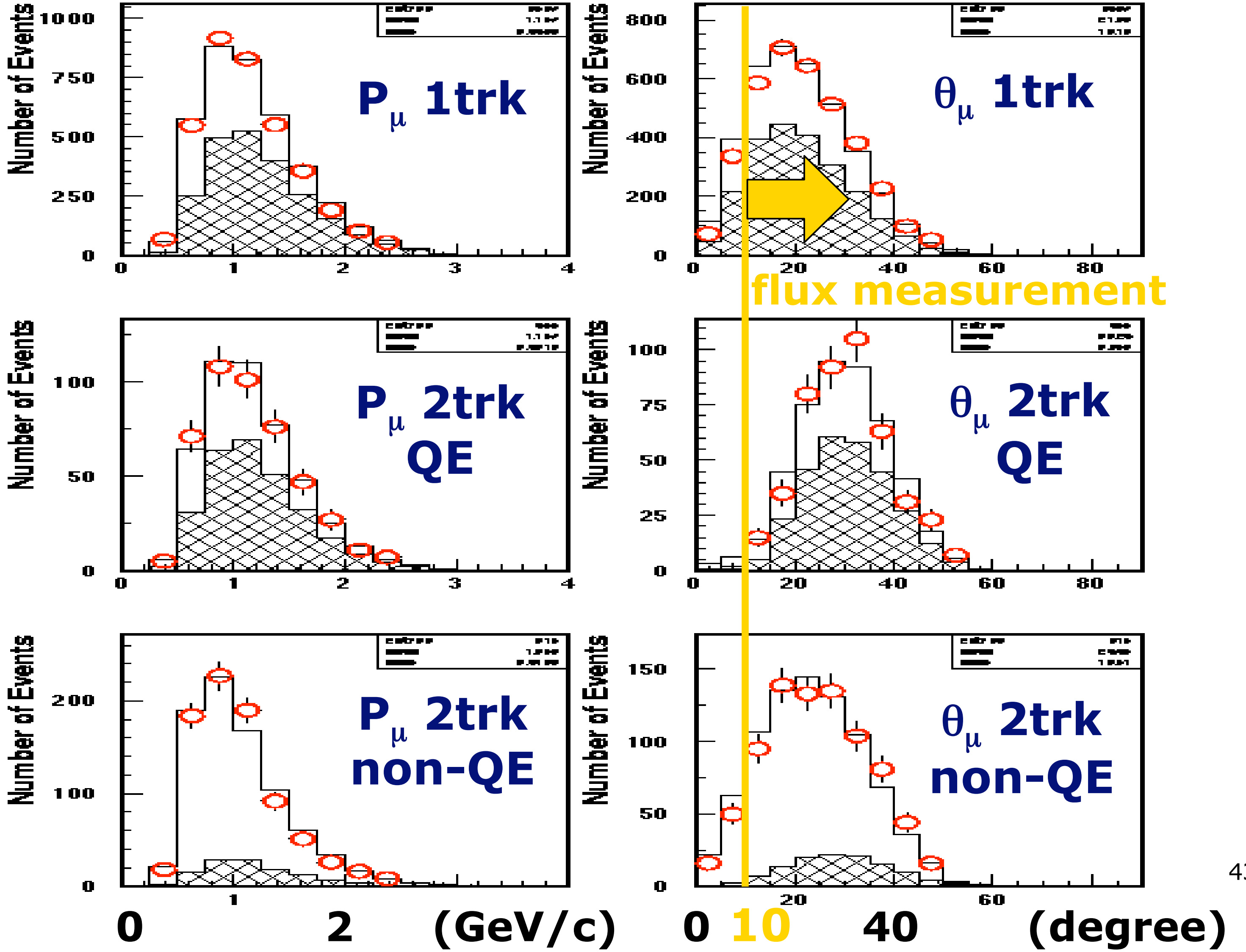


1R1: μ momentum and angular distributions. with measured spectrum

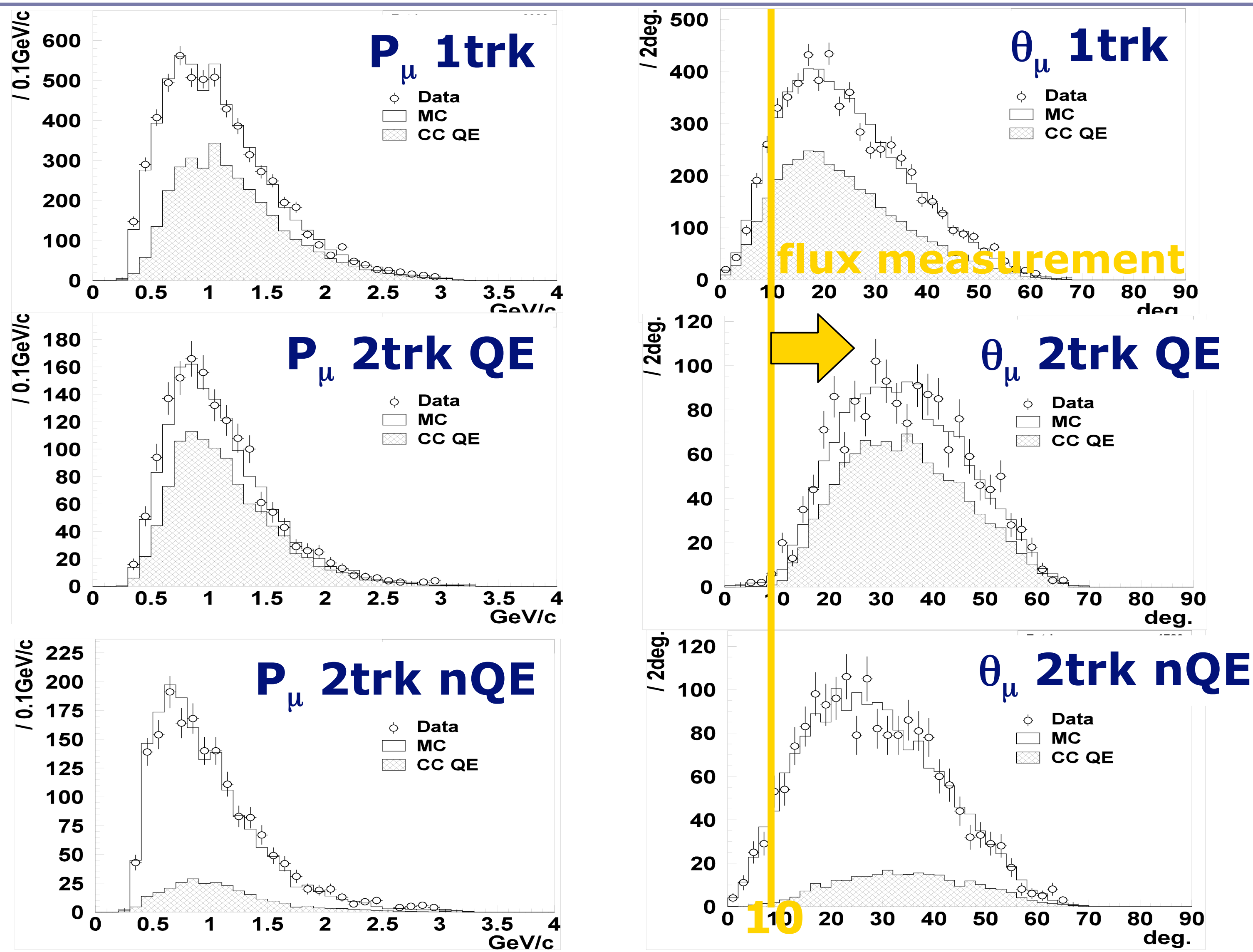




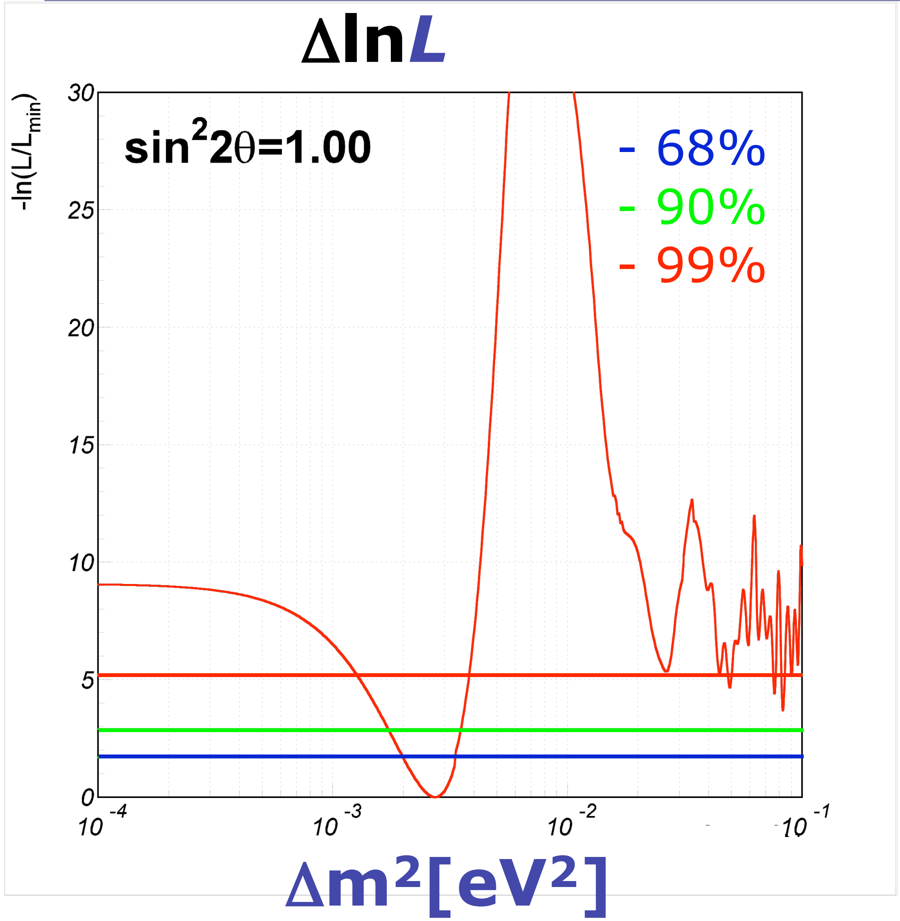
SciFi (K2K-IIa with measured spectrum)

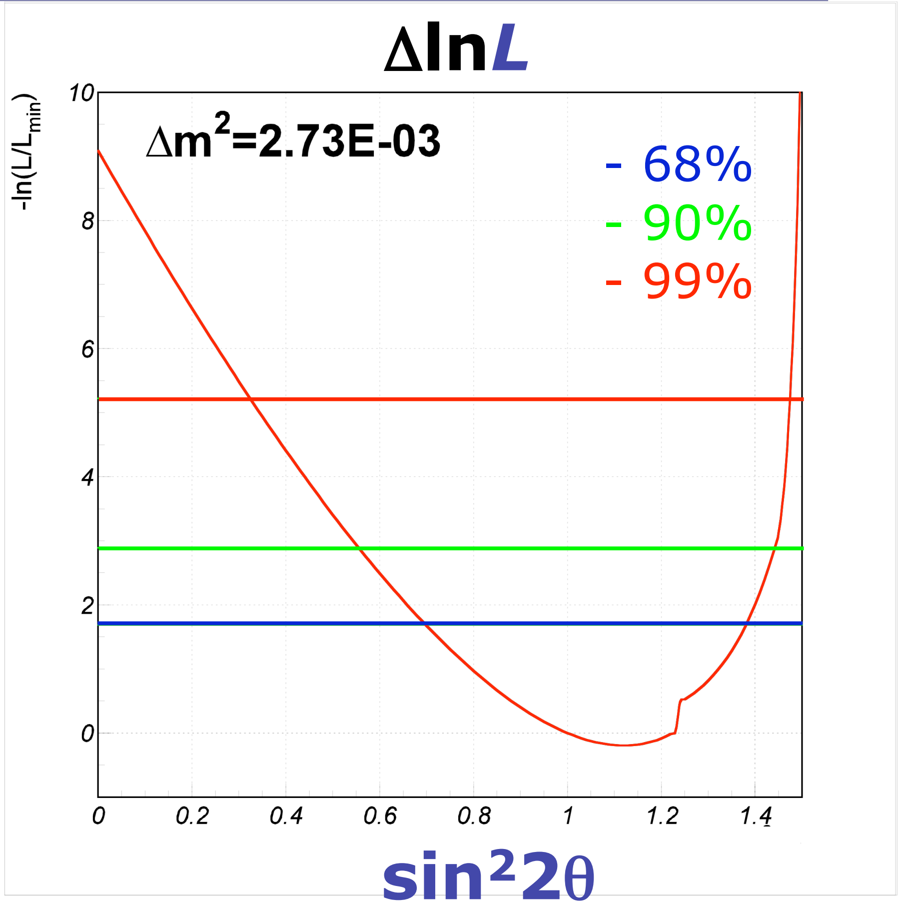


SciBar (with measured flux)



Log Likelihood difference from the minimum.

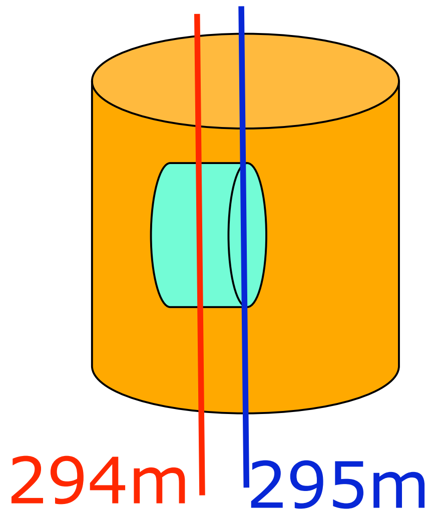




- $\Delta m^2 < (1.7 \sim 3.5) \times 10^{-3}$ eV^2 at $\sin^2 2\theta = 1.0$ (90% C.L.)

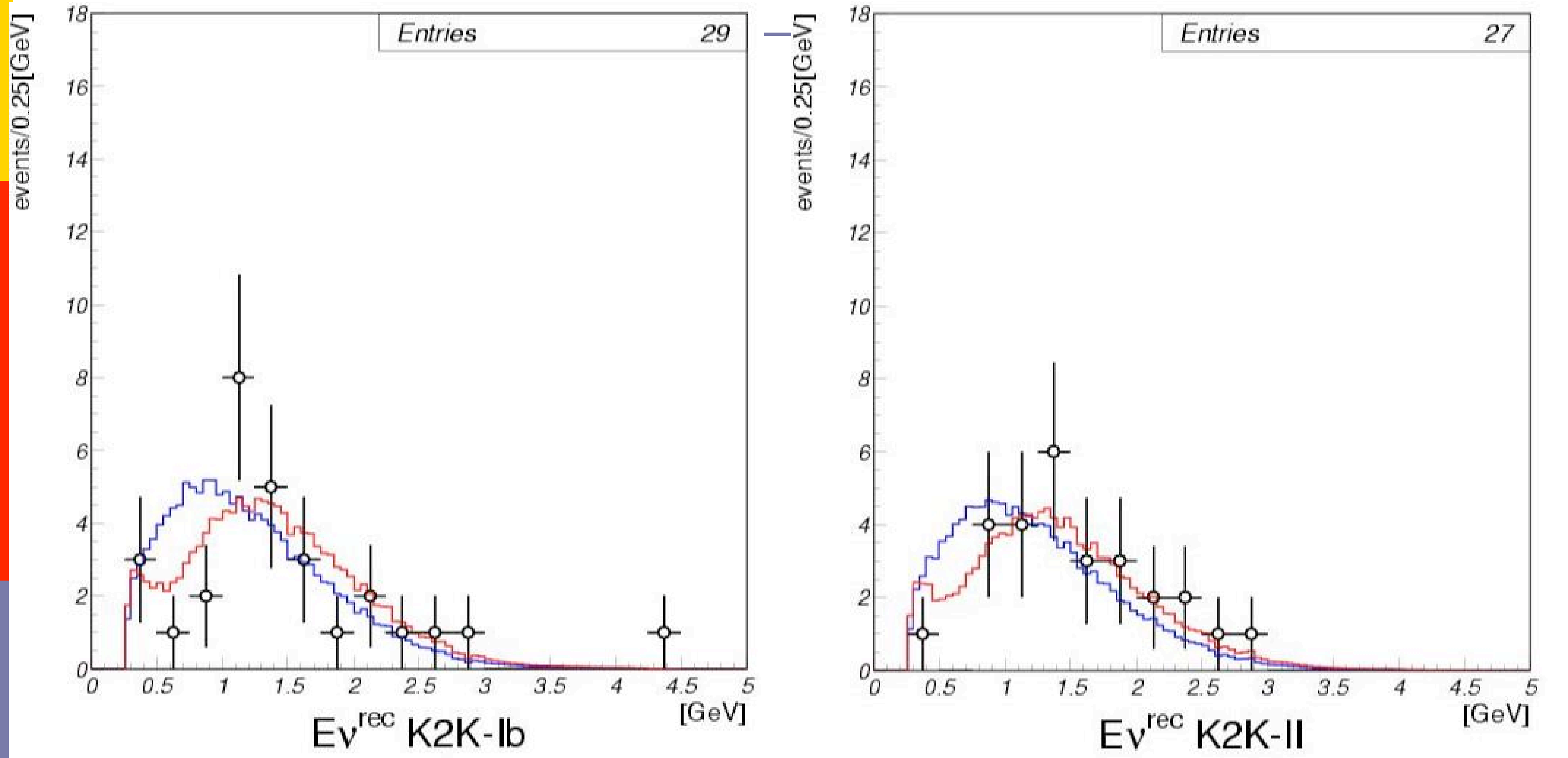
The change of N_{SK}^{exp} in K2K-I (Bugs)

- The detector position
  - 295m → 294m -1%

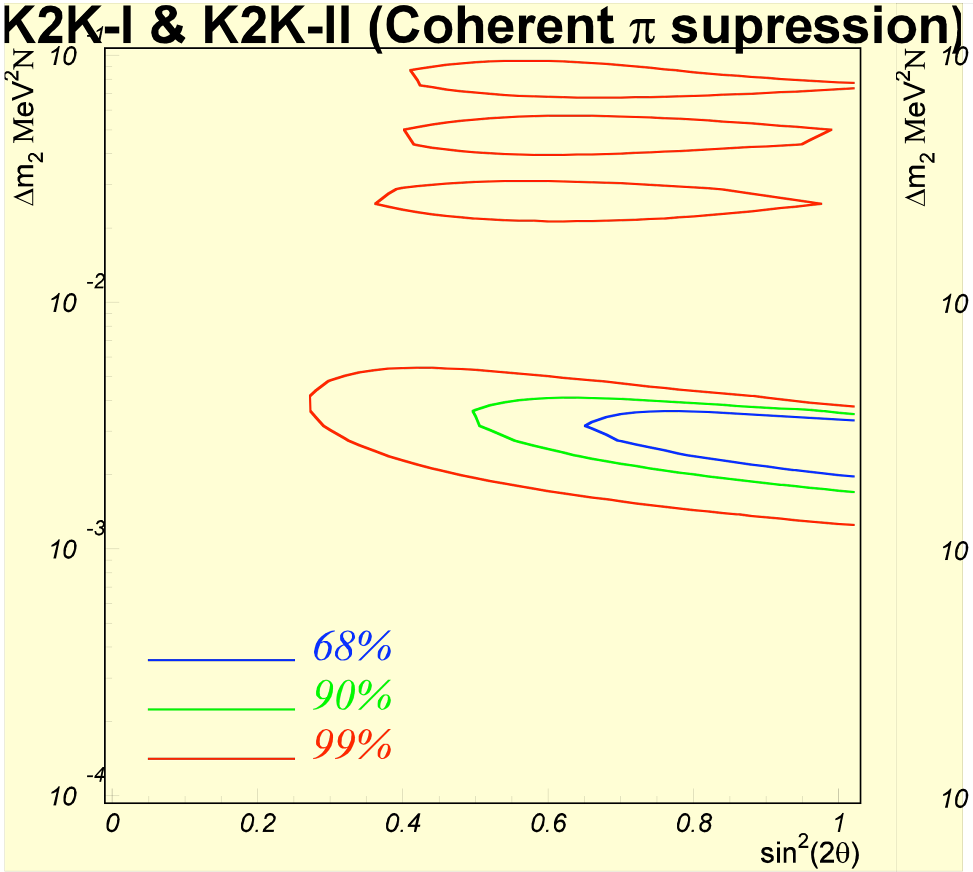


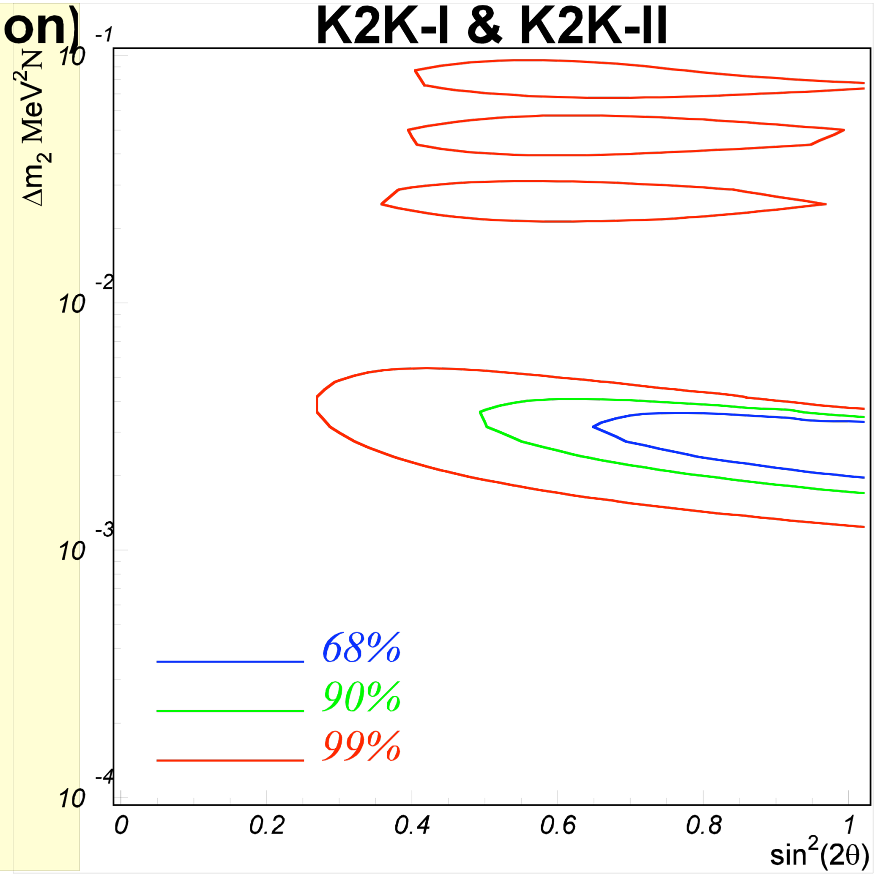
- MC difference between KT and SK
  - KT; $M_A(QE)=1.1$ $\sigma(NC_{el})_{KT}=1.1\times\sigma(NC_{el})_{SK}$
  - SK; $M_A(QE)=1.0$ ⇒ Efficiency change! -1%

N_{SK}^{exp} Change ~2%


Entries 29
events/0.25[GeV]
[GeV]
Eν^rec K2K-Ib
Entries 27
events/0.25[GeV]
[GeV]
Eν^rec K2K-II

CC-1π suppression versus coherent π

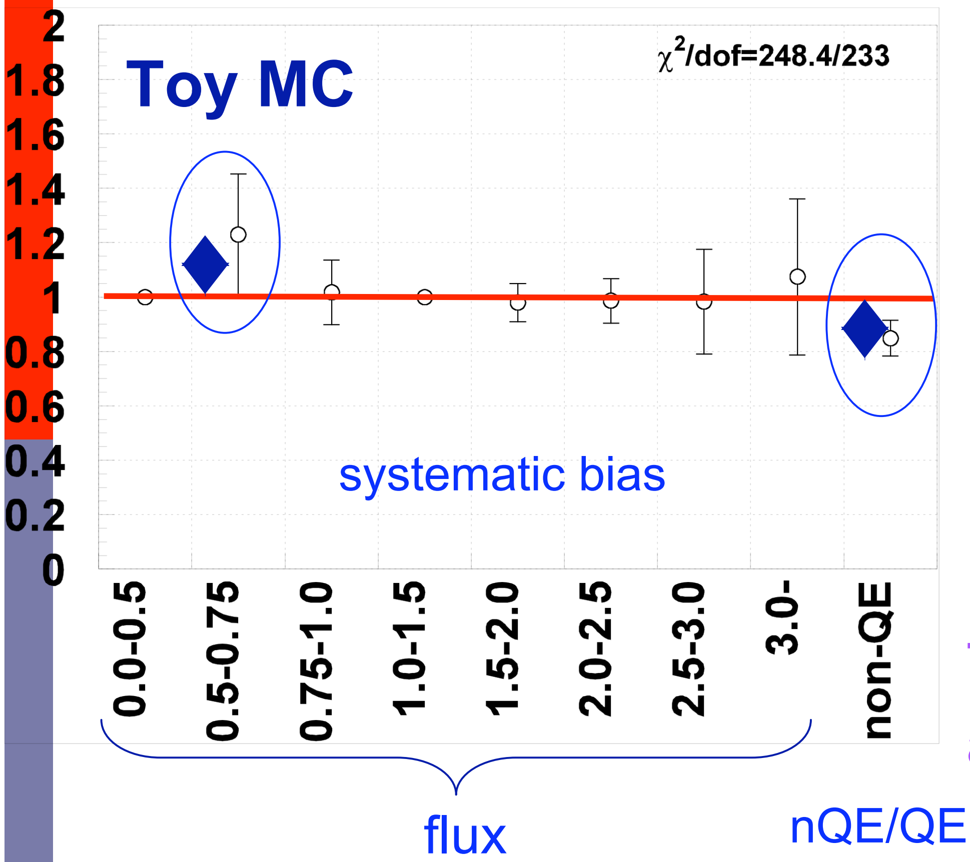




Systematic Bias without the MC correction.

ND (SciBar) measurement

DATA; MC w/ CC-1π suppression
MC template; Default MC



Oscillation Results

Default MC for ND and SK

$\sin^2 2\theta=1.00$

$\Delta m^2=2.73$ _10^{-3} eV^2

Prob.(null oscillation)=0.0049%

Corrected MC

$\sin^2 2\theta=1.00$

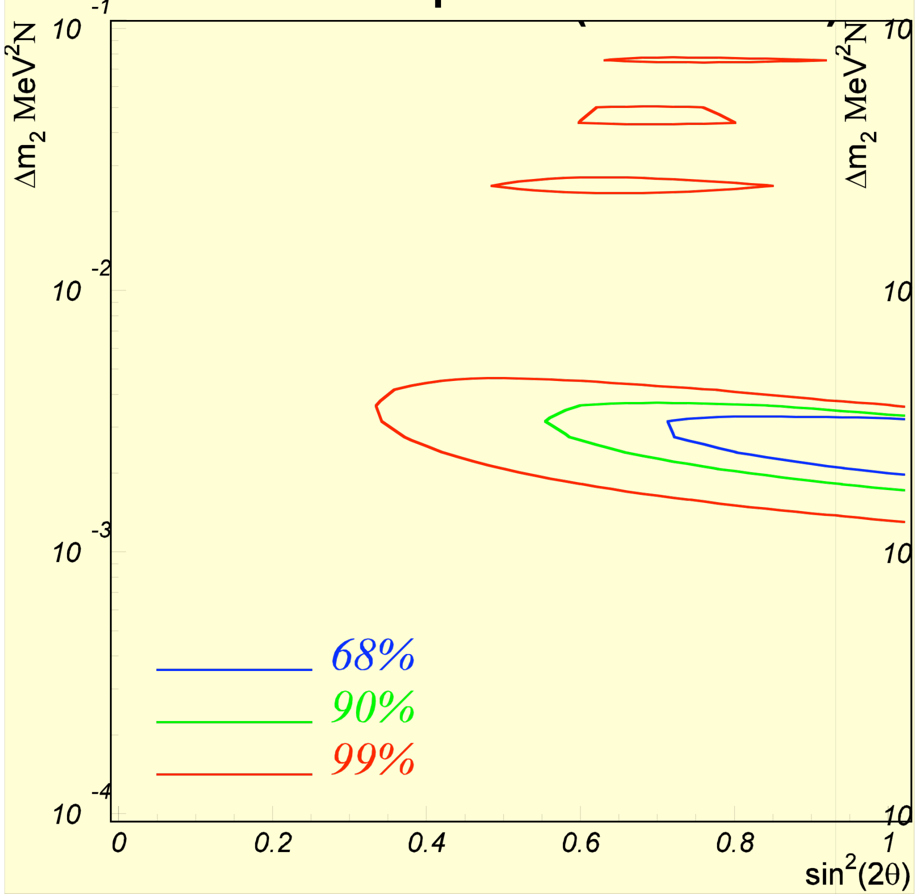
$\Delta m^2=2.65\times10^{-3} eV^2$

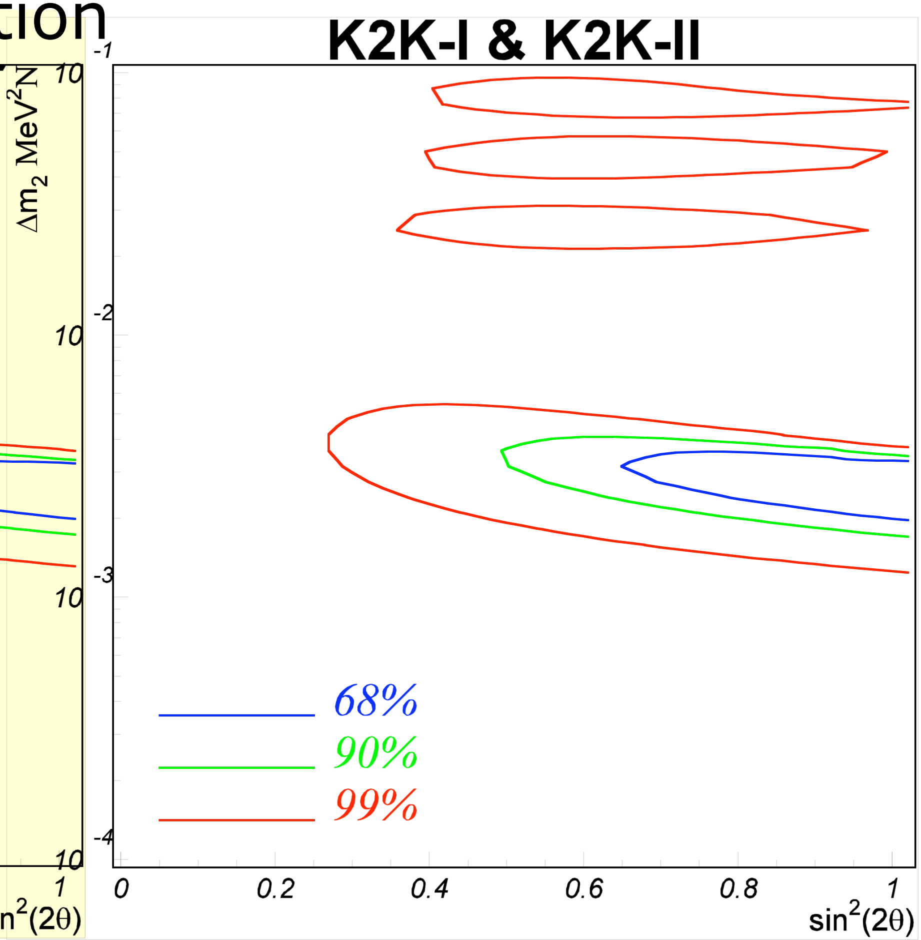
Prob.(null oscillation)=0.011%

There is a small bias in nQE/QE and the low energy flux.

Oscillation result with a default MC

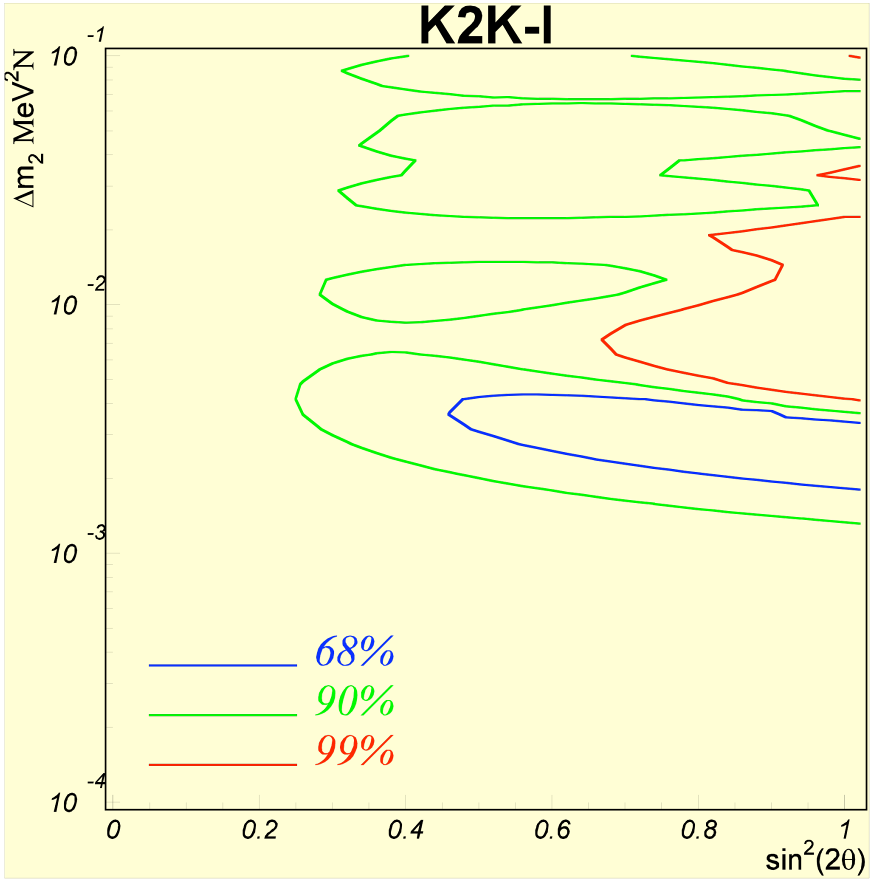
Without low q^2 MC correction

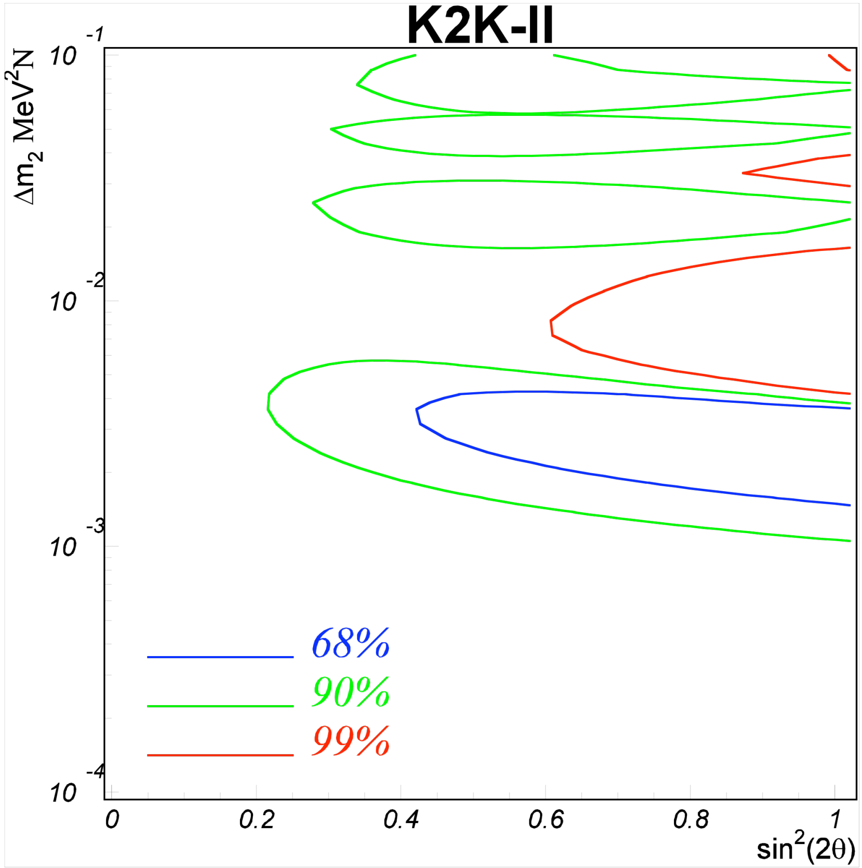




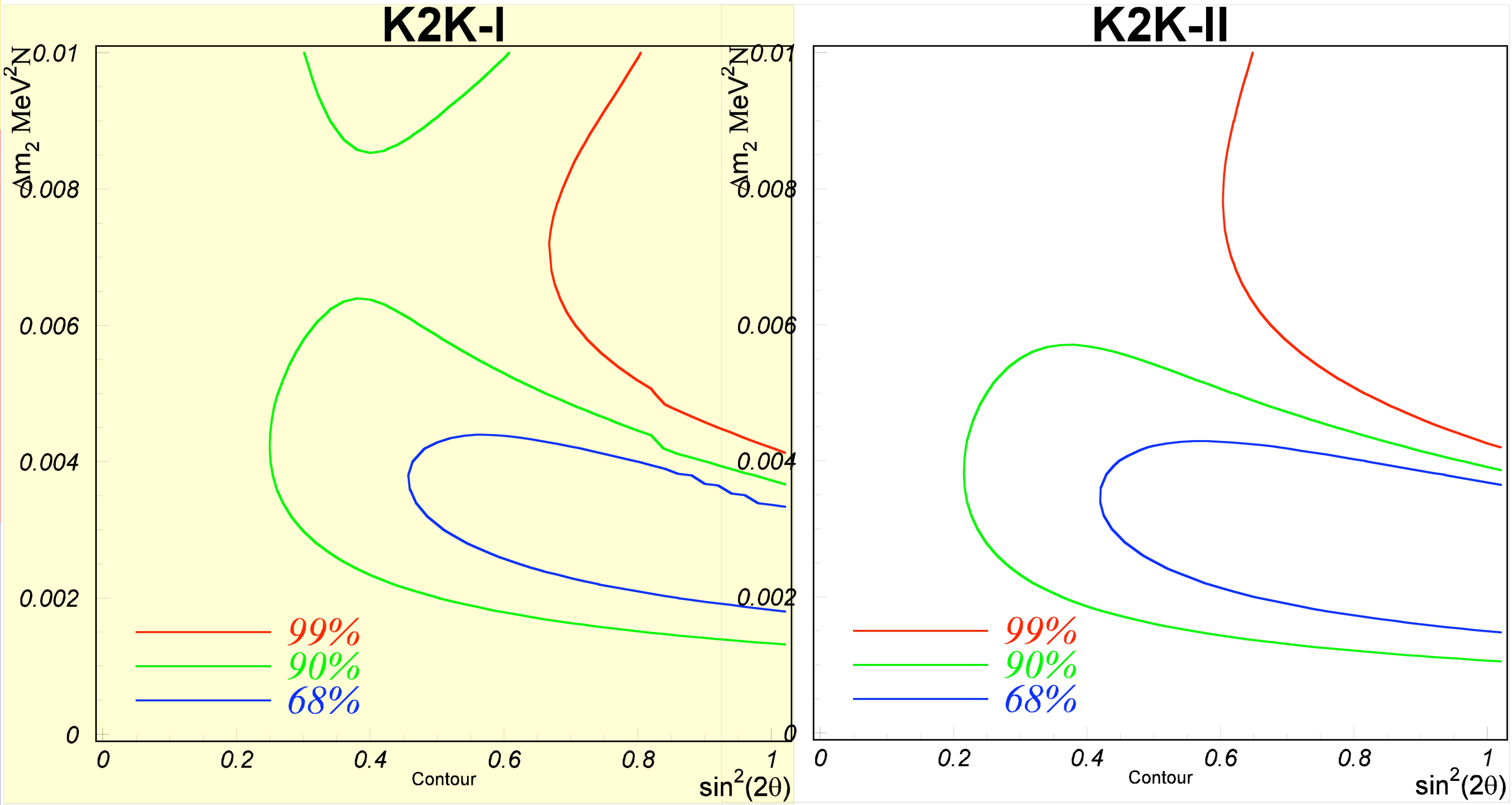
The result w/o low q^2 MC correction gives the better (biased) measurement due to the more low energy flux and the smaller nQE/QE.

K2K-I vs K2K-II





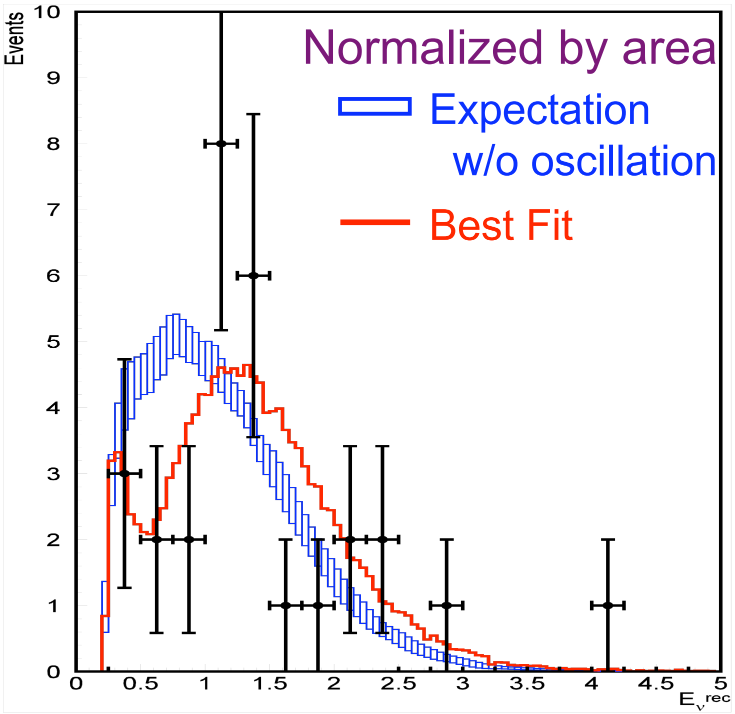
K2K-I vs K2K-II



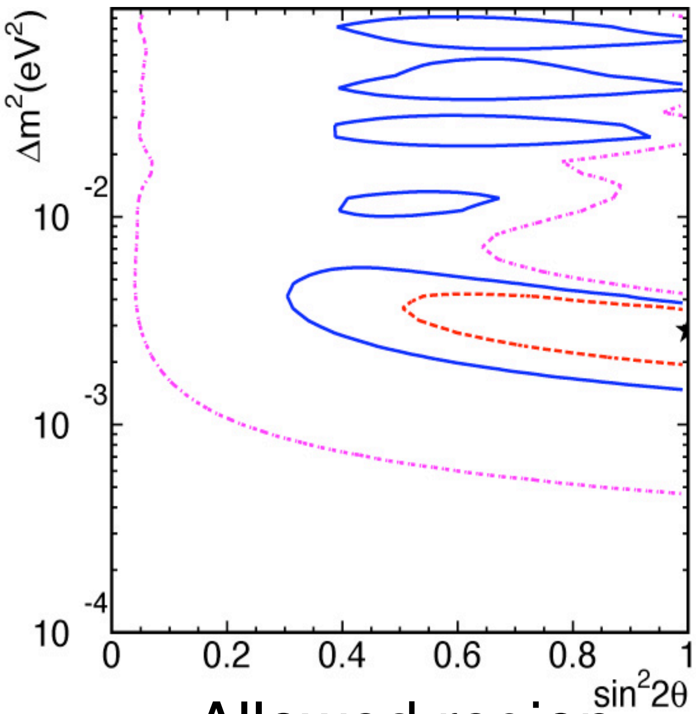
ν_μ Disappearance Result (K2K-I)

PRL 90(2003)041801

- Null oscillation probability: less than 1%.
- $\Delta m^2 = 1.5 \sim 3.9 \times 10^{-3}\ eV^2$ @$\sin^2 2\theta = 1$(90%CL)



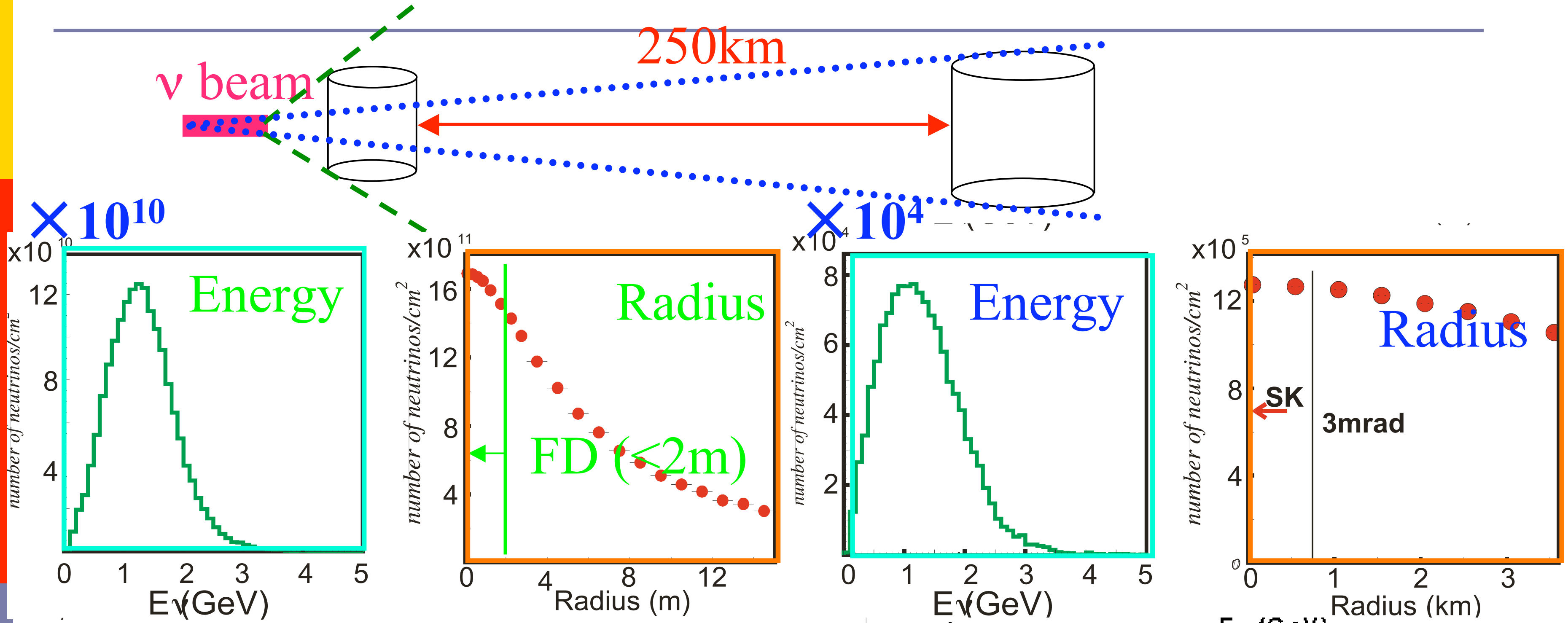
Reconstructed Eν



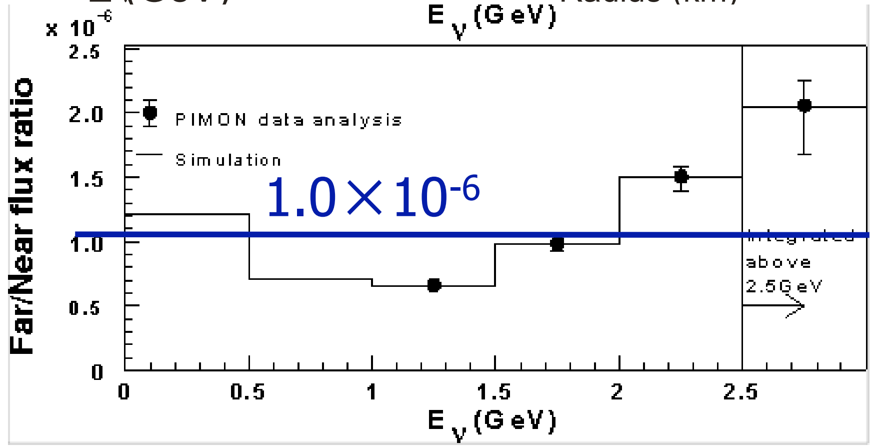
Allowed region

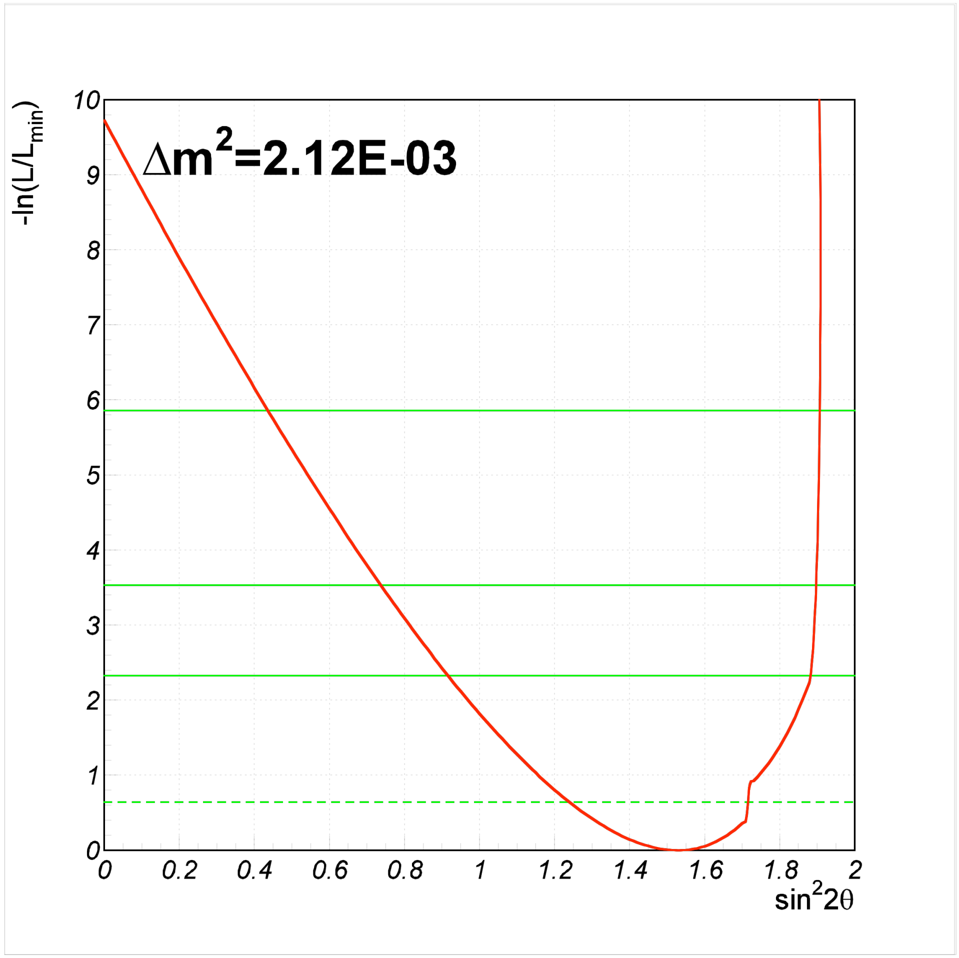
Best fit:
$\Delta m^2 = 2.8 \times 10^{-3} eV^2$

Extrapolation from Near to Far sites



PION moniter
Gas Cherenkov detector:
(insensitive to primary protons)
Measure, $N(p_\pi, \theta_\pi)$
just after the horns.





Δm²=2.12E-03
-ln(L/L_min)
sin²2θ
0
1
2
3
4
5
6
7
8
9
10
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2