# K2K KEK-to-Kamioka Long Baseline Neutrino Oscillation Experiment

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KEK

For the K2K Collaboration

Les Houches EuroConference on Neutrino Masses and Mixings

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Les Houches Physics Center, France

# K2K Collaboration

| | | |
|---|---|---|
| Chonnum National Univ. | ICRR, Univ. of Tokyo | Boston Univ. |
| Donshin Univ. | KEK | Univ. of California at Irvine |
| Seoul National Univ. | Kobe Univ. | Univ. of Hawaii at Manoa |
| | Kyoto Univ. | SUNY at Stony Brook |
| | Niigata Univ. | Univ. of Washington at Seattle |
| | Okayama Univ. | |
| | Osaka Univ. | Warsaw Univ. |
| | Science Univ. of Tokyo | |
| | Tohoku Univ. | |

# K2K (KEK-to-Kamioka)

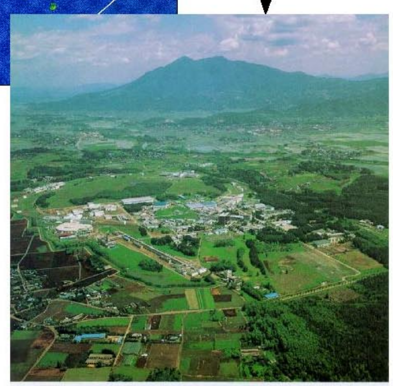
Super Kamiokande

Water Cherenkov detector

Total mass 50 kton

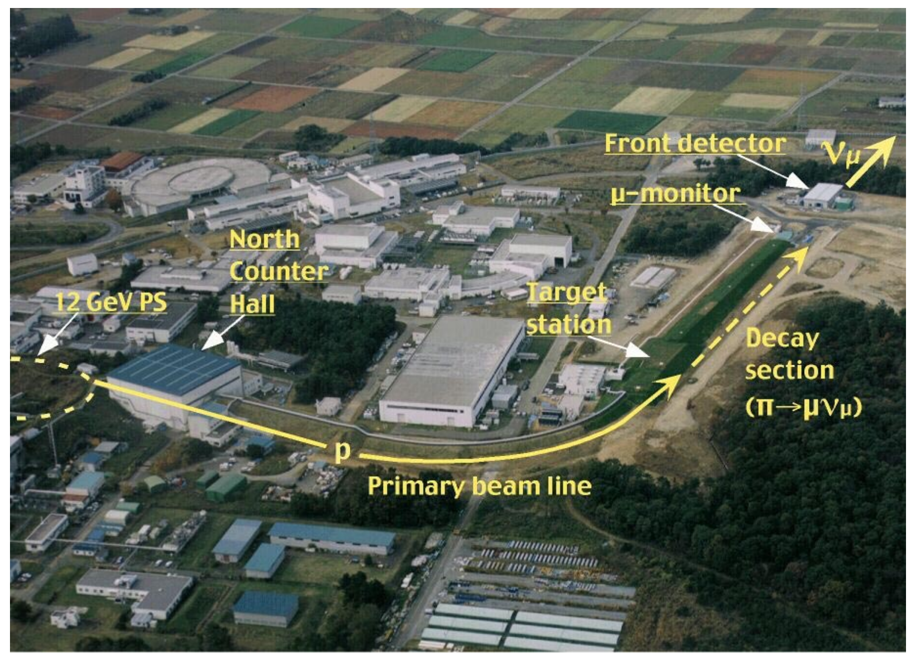
Inner mass 32 kton

Fiducial mass: 22.5 kton

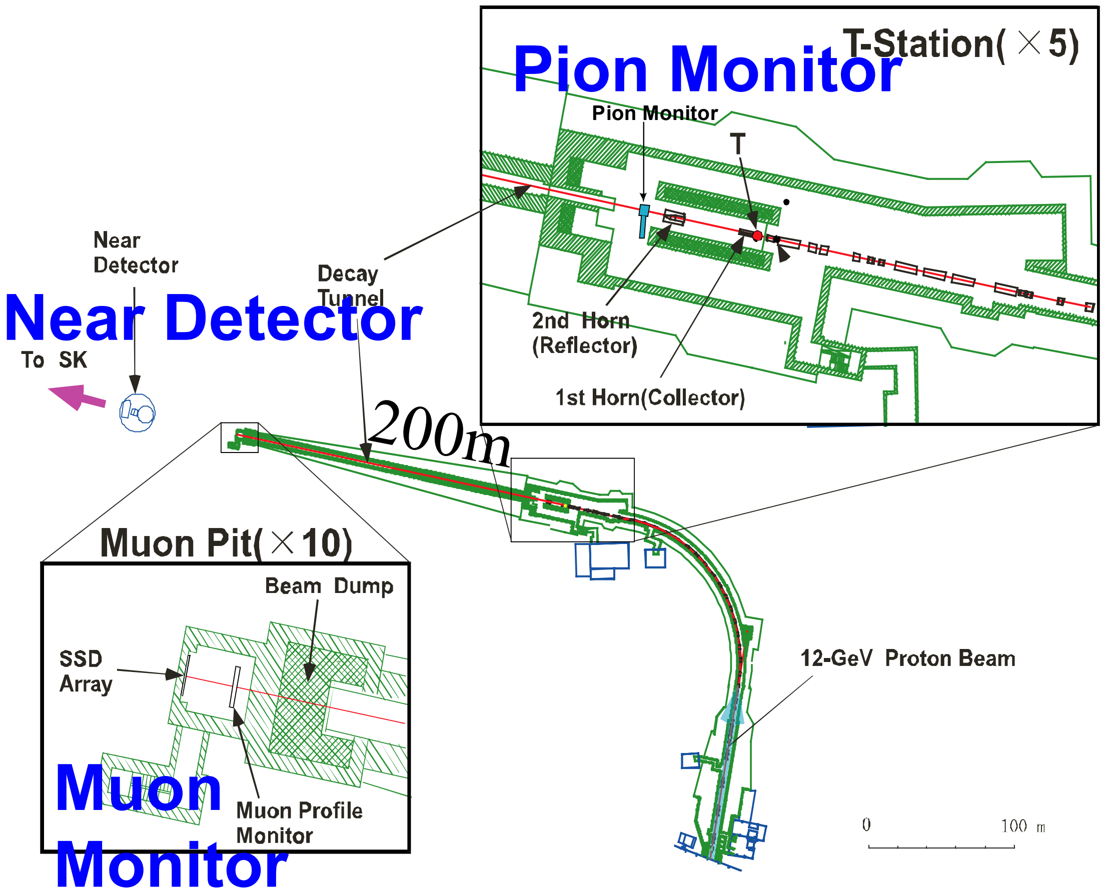
KEK

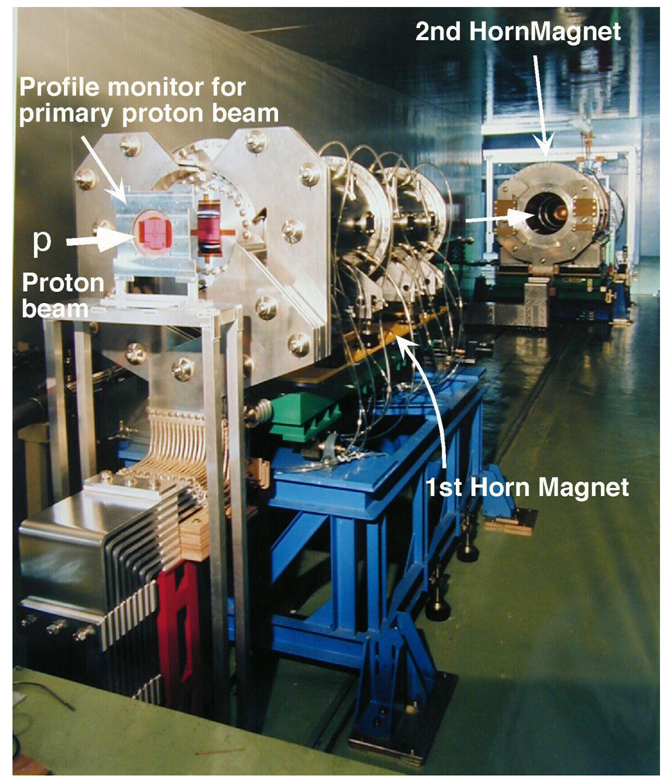
- Accelerator : 12 GeV proton synchrotron
  - Beam intensity : $6\times10^{12}$ protons / pulse
  - Repetition 1 pulse / 2.2 sec
  - Pulse width 1.1 μs (9 bunches)
- Horn-focused wide-band beam
  - Average neutrino energy 1.3 GeV
- Near detector 300 m from the target
- Far detector (Super-Kamiokande) : 250 km from the target
- Goal : $10^{20}$ protons on target



# Beam Line and Magnetic Horn

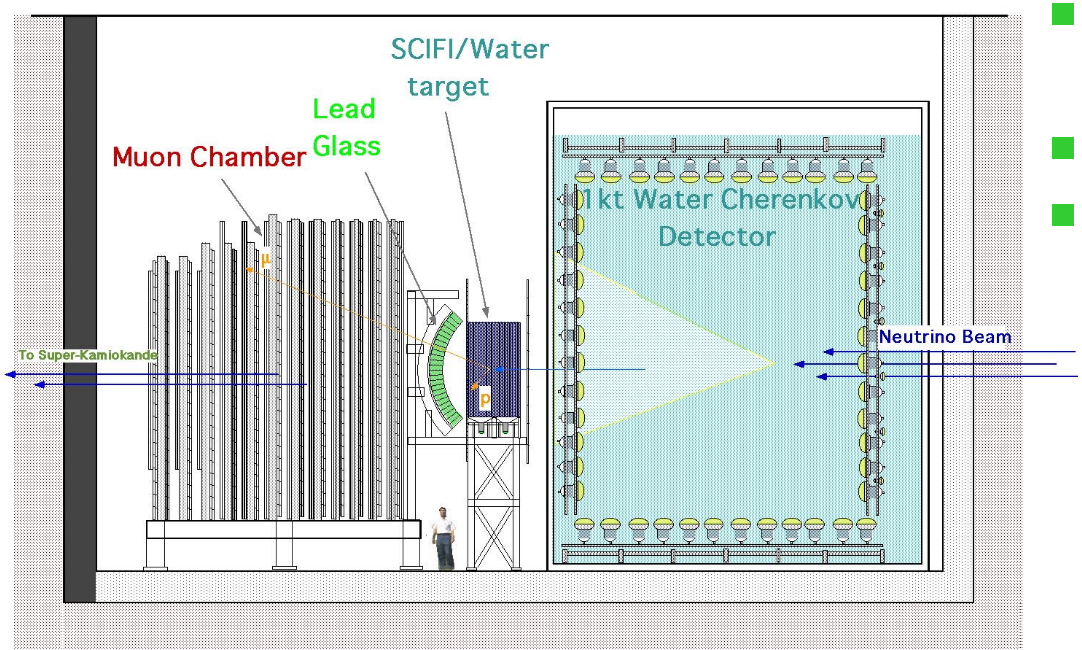
- Horn current: 250 kA
- Production target: Al 66cm×3cmφ



# K2K Near Detector

- Measure $\nu_\mu$ flux, spectrum, profile
- Measure $\nu_e$ contamination
- Study $\nu$ interactions at ~ 1 GeV

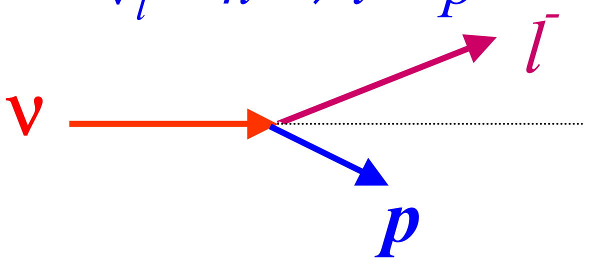



- 1 kton water Cherenkov detector
  - Same structure and systematics as SuperK
  - Common water target
- Scintillating-Fiber tracker
  - Active area: 2.4 m × 2.4 m × 20 (x,y) layer
- Water target
  - 19 layers of 60-mm thick water
- Lead-glass counter
- Muon/Fe
  - 12 layers of iron plates (total mass ~ 1,000 tons interleaved with muon drift chambers

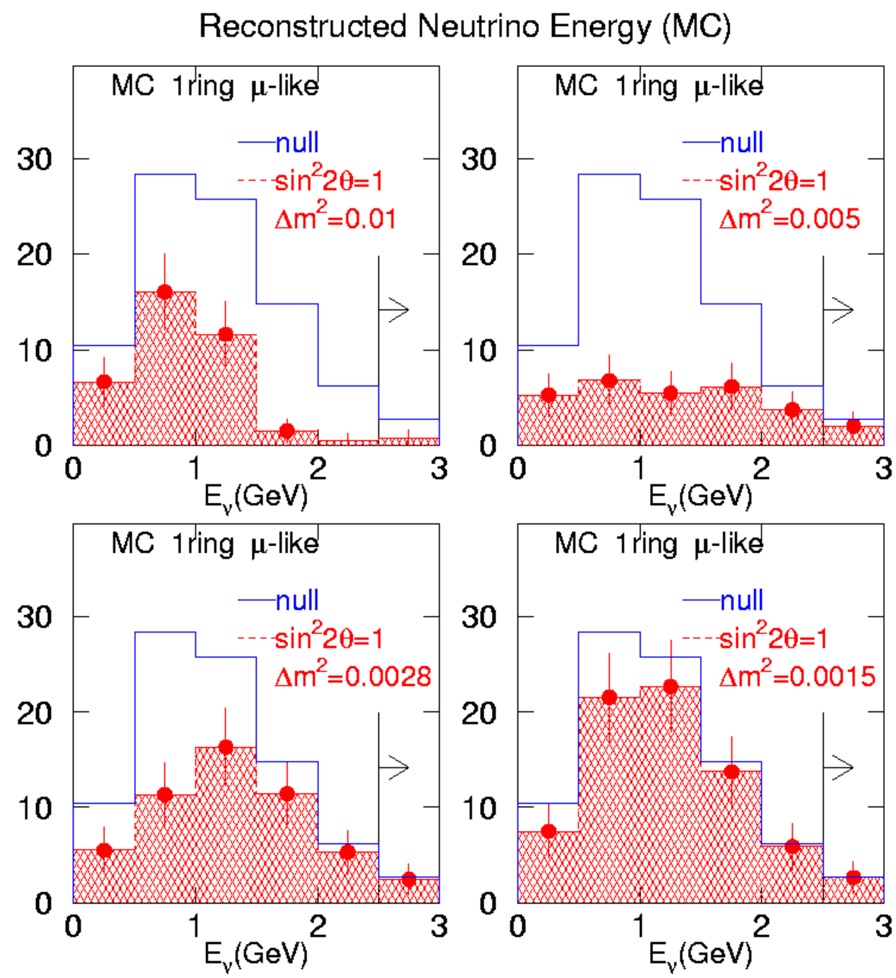
# Reconstructed Neutrino Energy Spectra with $10^{20}$ POT

The neutrino energy is reconstructed by assuming quasi-elastic (QE) scattering.

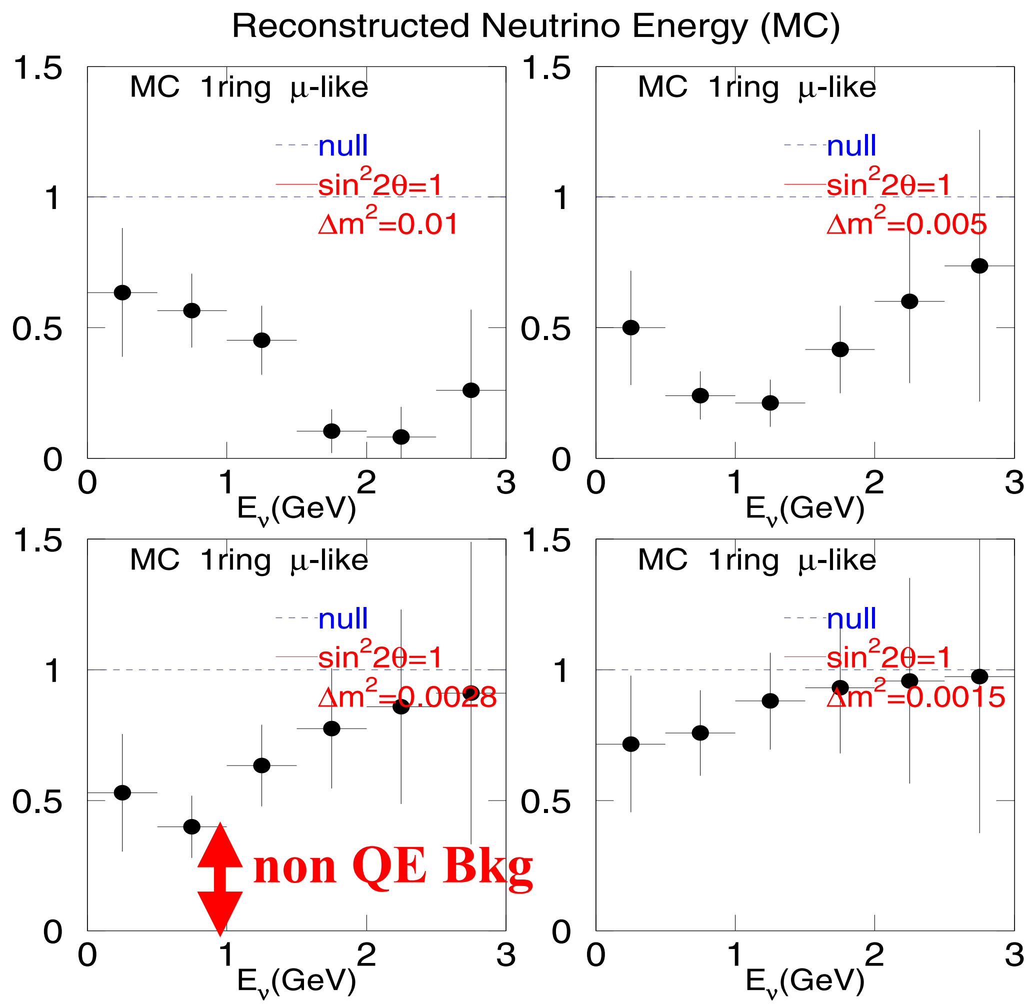
$$\nu_l + n \rightarrow l + p \qquad (E_l, p_l)$$




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

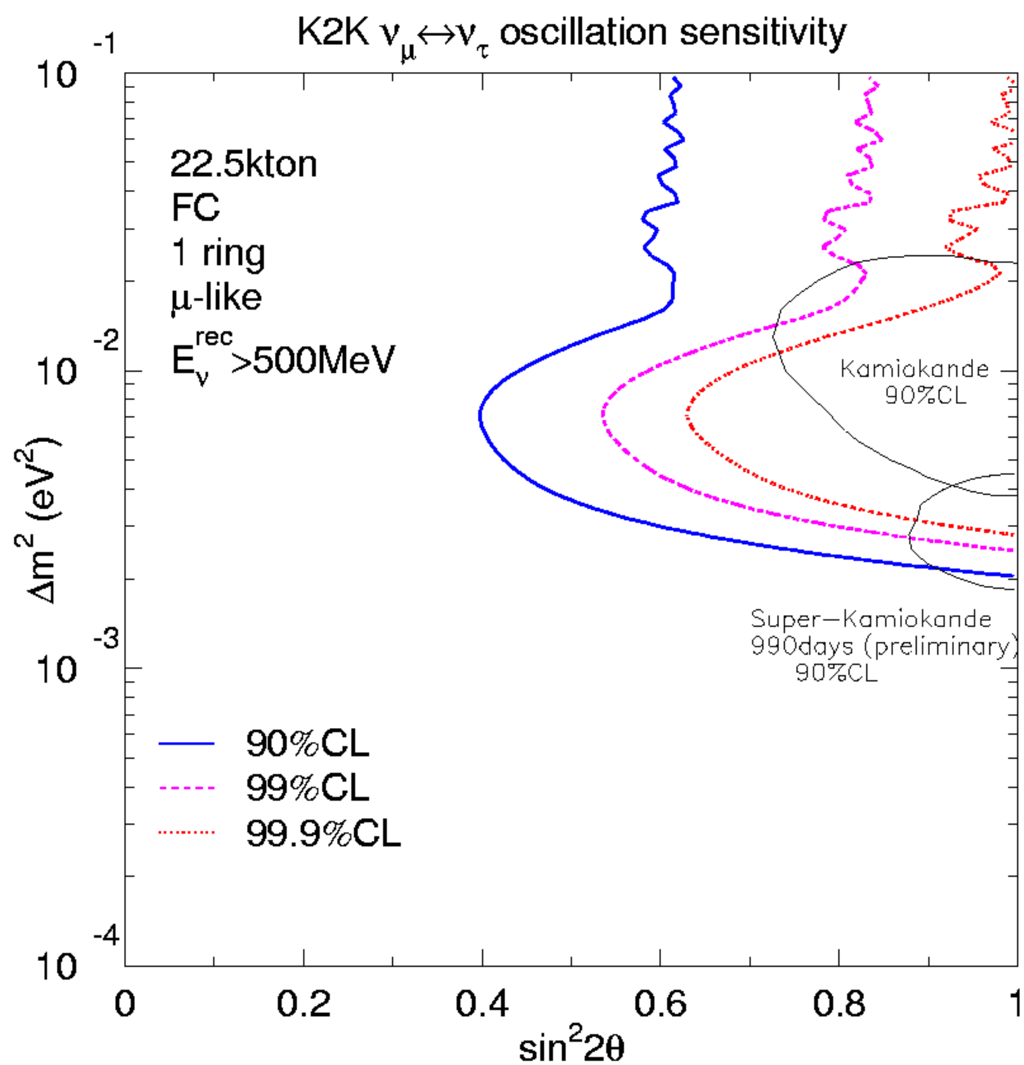


# Oscillated/Non-oscillated with $10^{20}$ POT

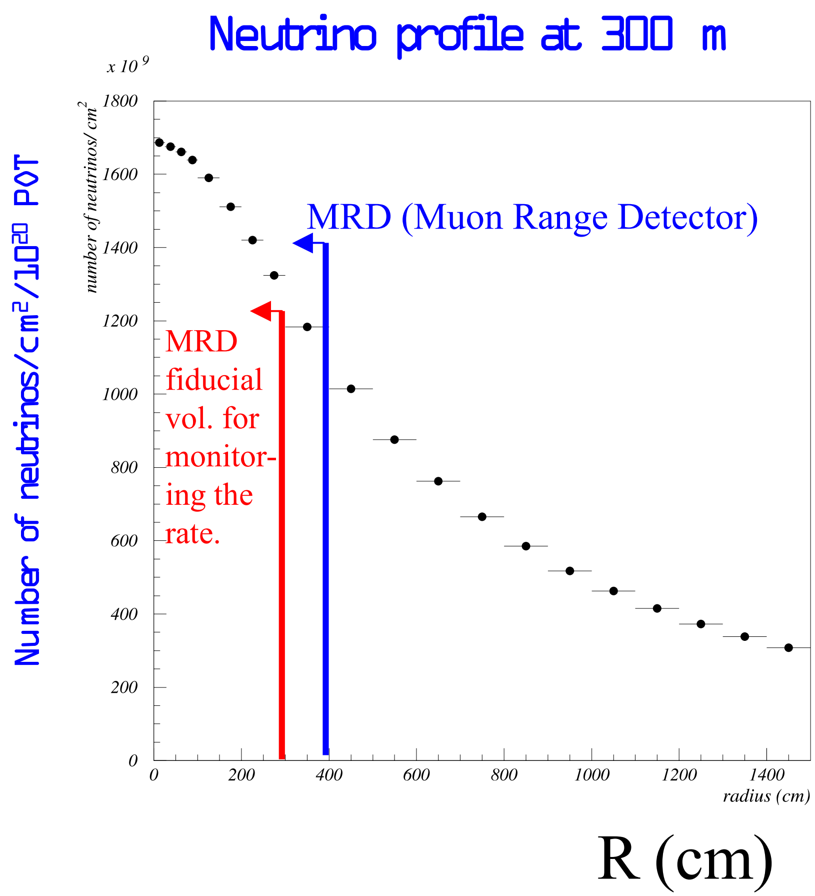


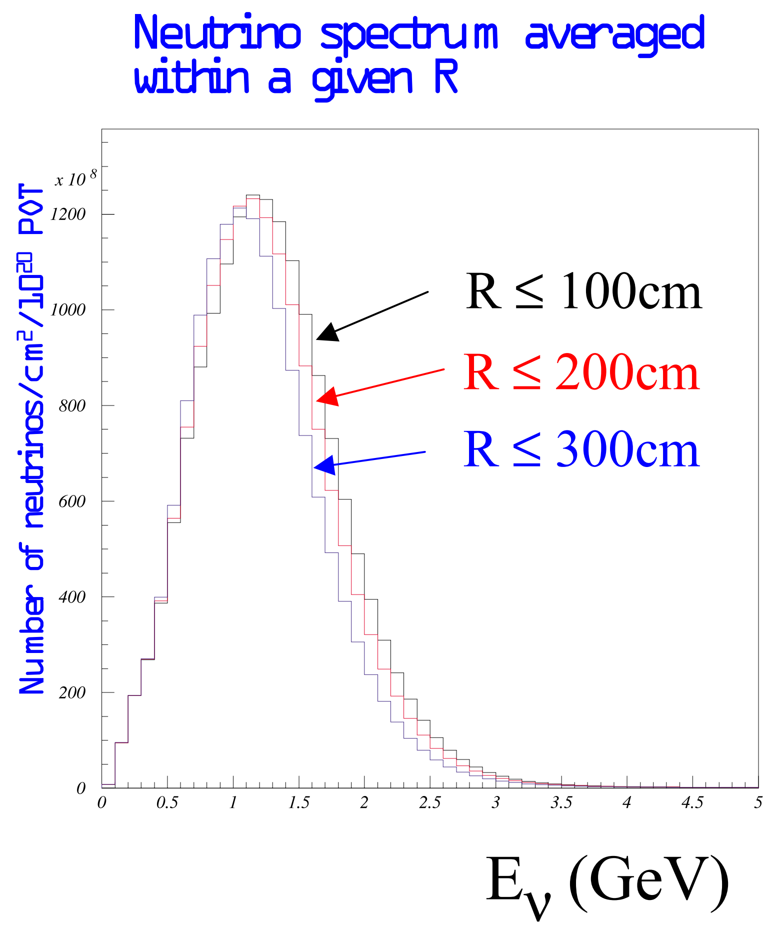
# Expected Sensitivity

$10^{20}$ protons on target in ≤5 years

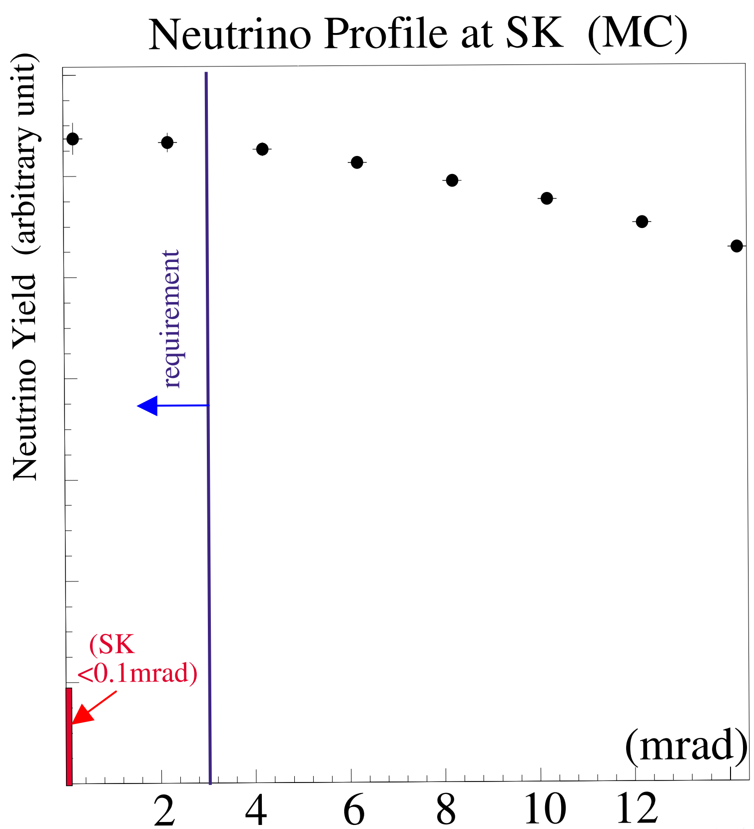


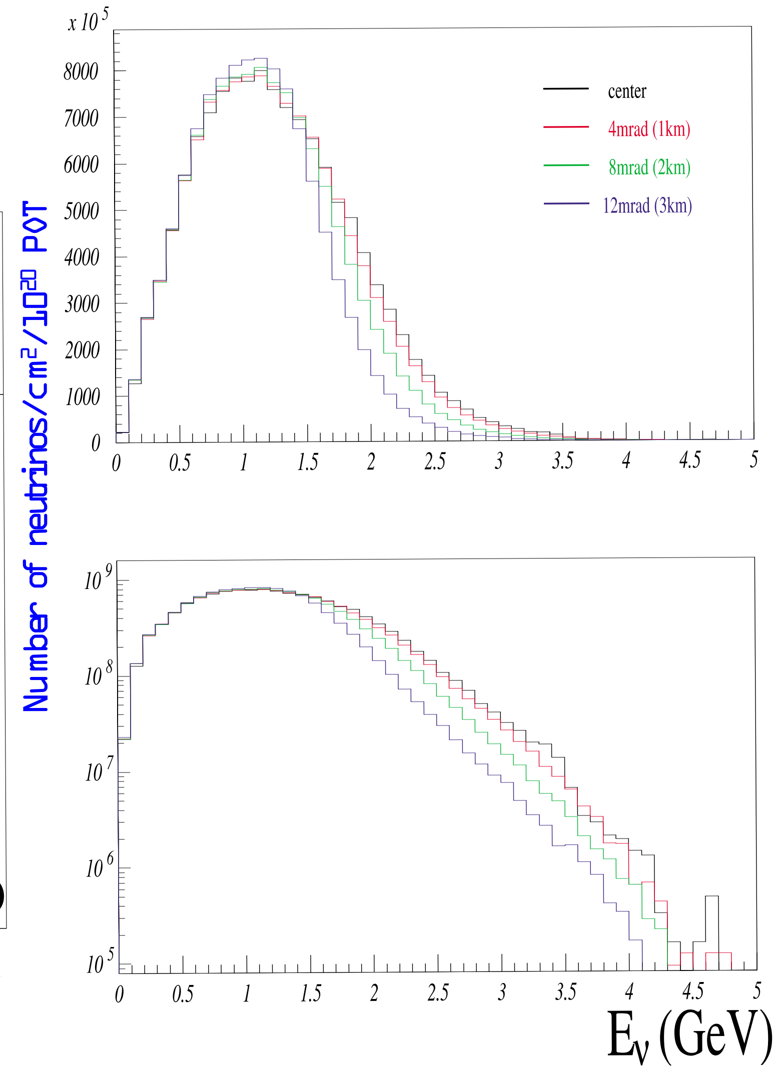
# Profile and Spectrum at the Near Detector



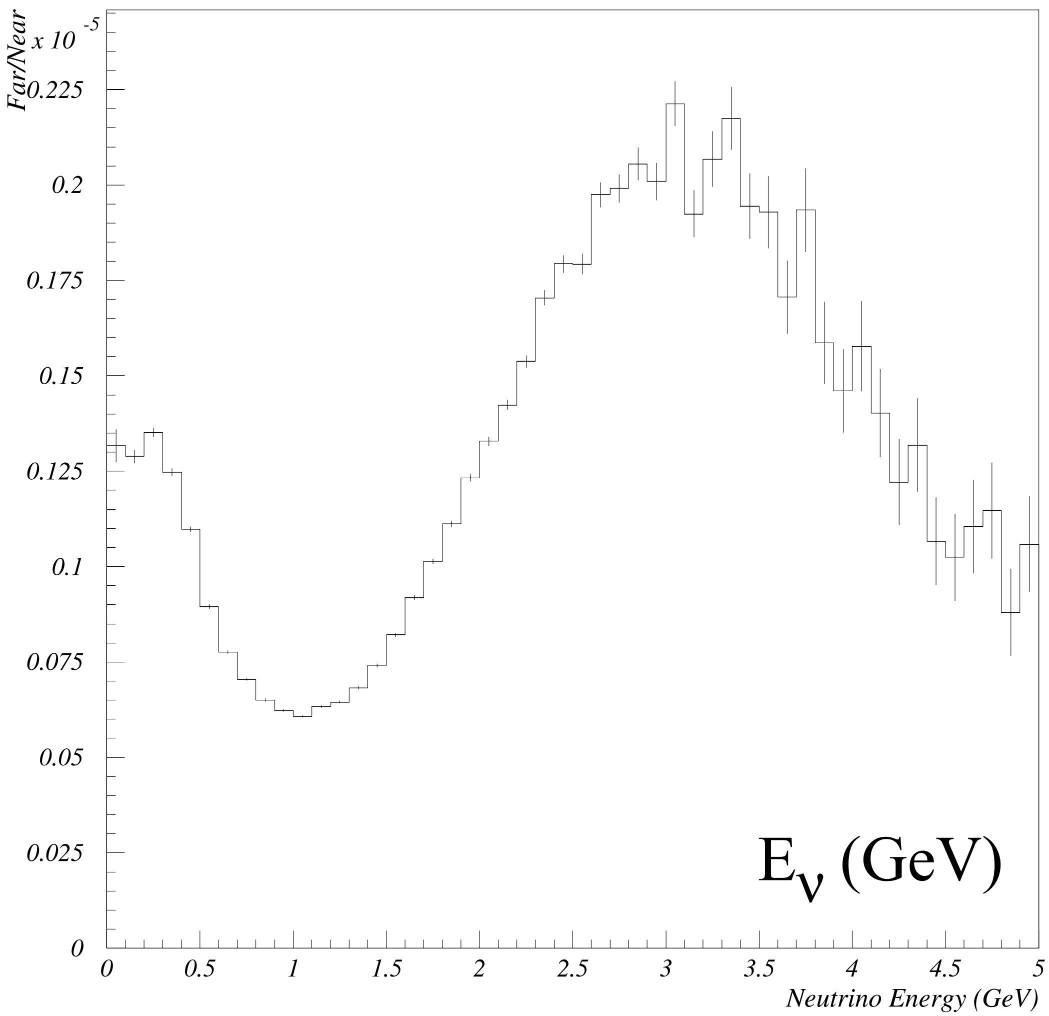



# Profile and Spectrum at the Far Detector



# Far/Near($R \leq 300$ cm) Flux Ratio



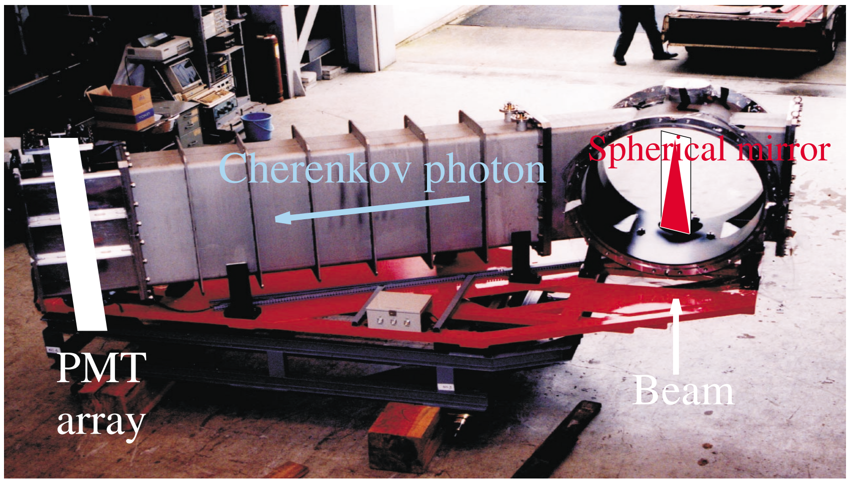

- It is vitally important to predict the far spectrum model-independently from the spectrum measured at the near site.

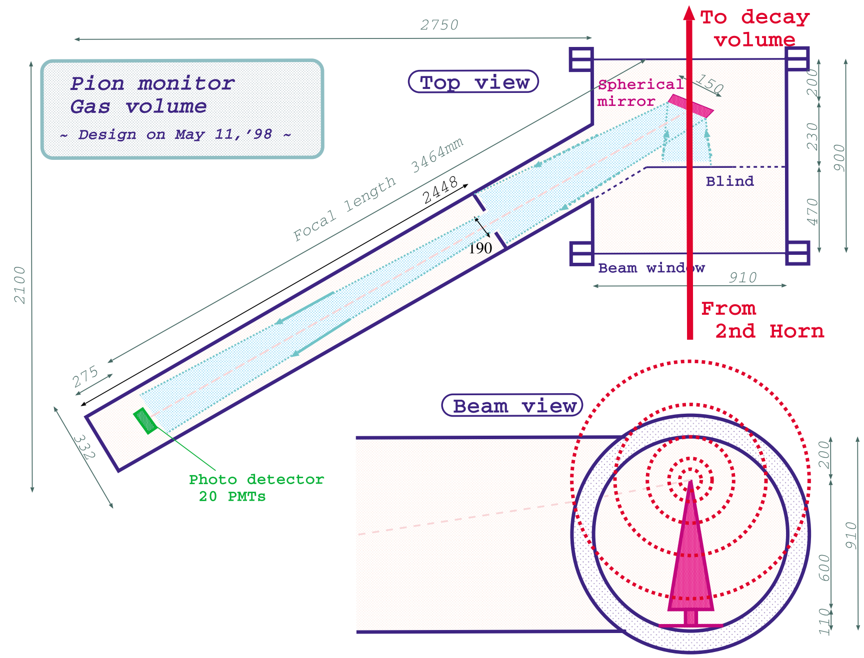
⇒ Measure momentum and angular distribution of pions, $N(p_\pi, \theta_\pi)$.

⇒ Neutrino flux $\Phi(E_\nu)$ at any distance using only decay kinematics.

# Pion Monitor

**Pion monitor** Ring image Cherenkov counter

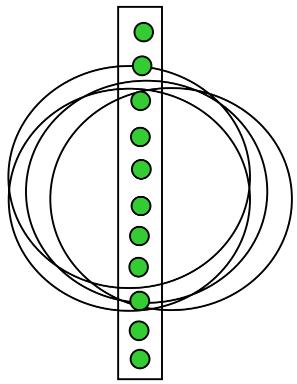


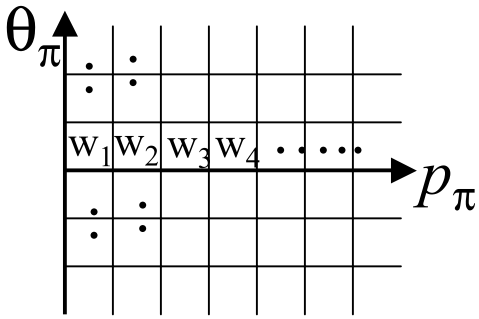



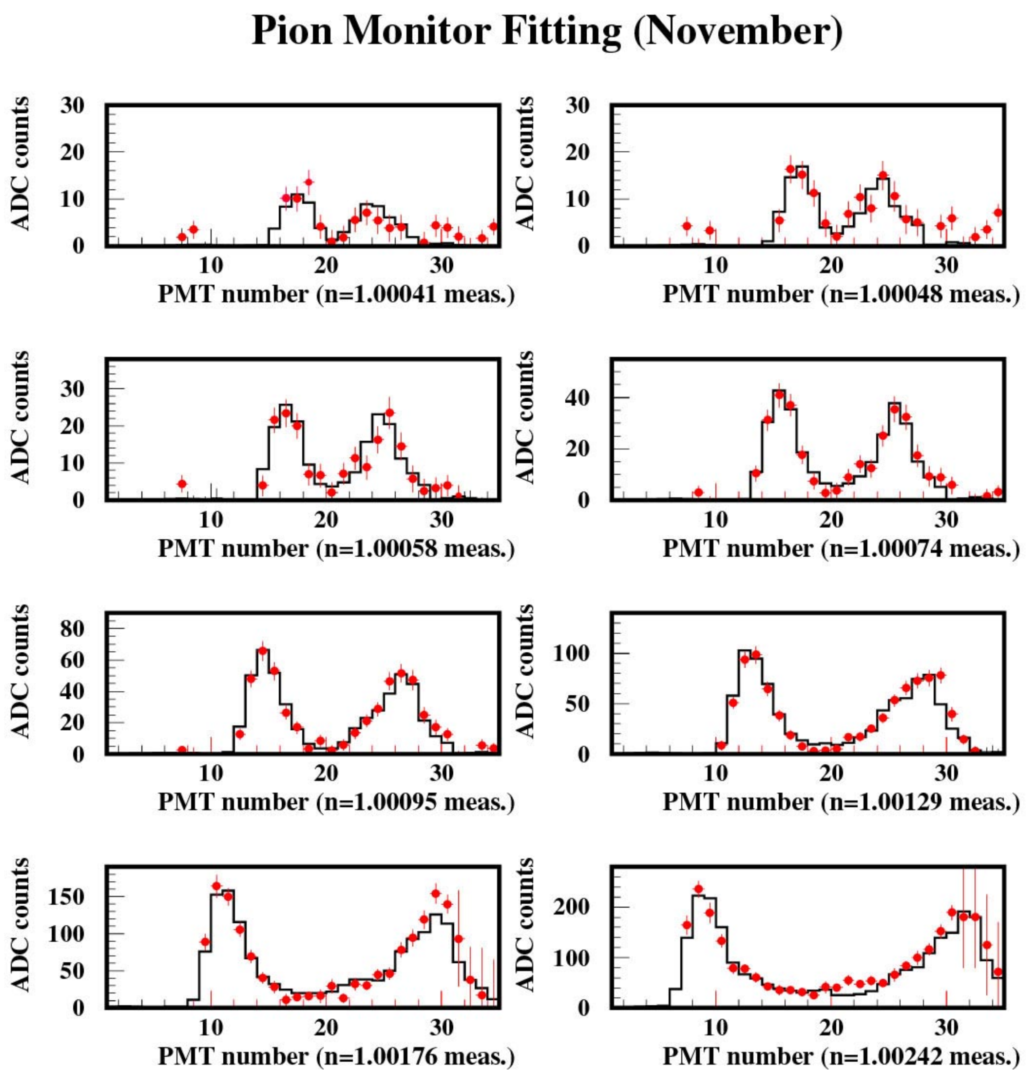

Pion monitor is a gas-Cherenkov counter which measures the pion $p_\pi$-$\theta_\pi$ distribution just after the magnetic horn.

- Sensitive to $p_\pi$ >2 GeV ($E_\nu$ > 1 GeV) to avoid background from 12 GeV protons.
- Predict far/near flux ratio above 1 GeV
- Normally retracted from the beam line
- Special low-intensity runs for measurement

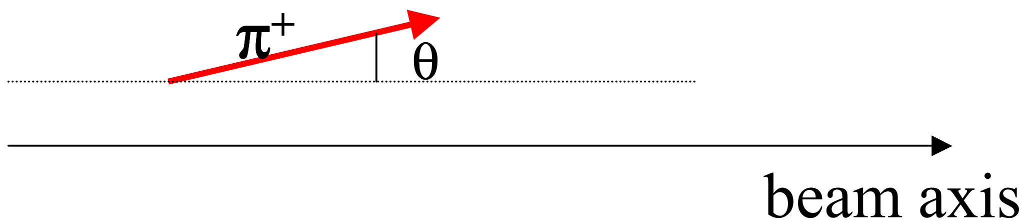
# Pion Monitor Results and Fitting



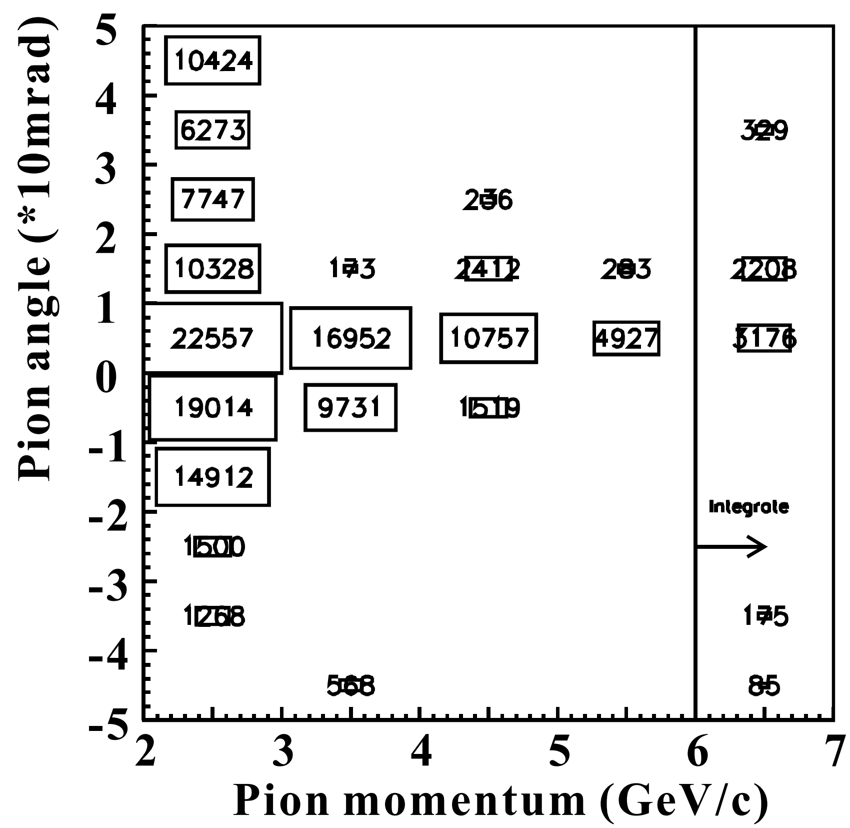


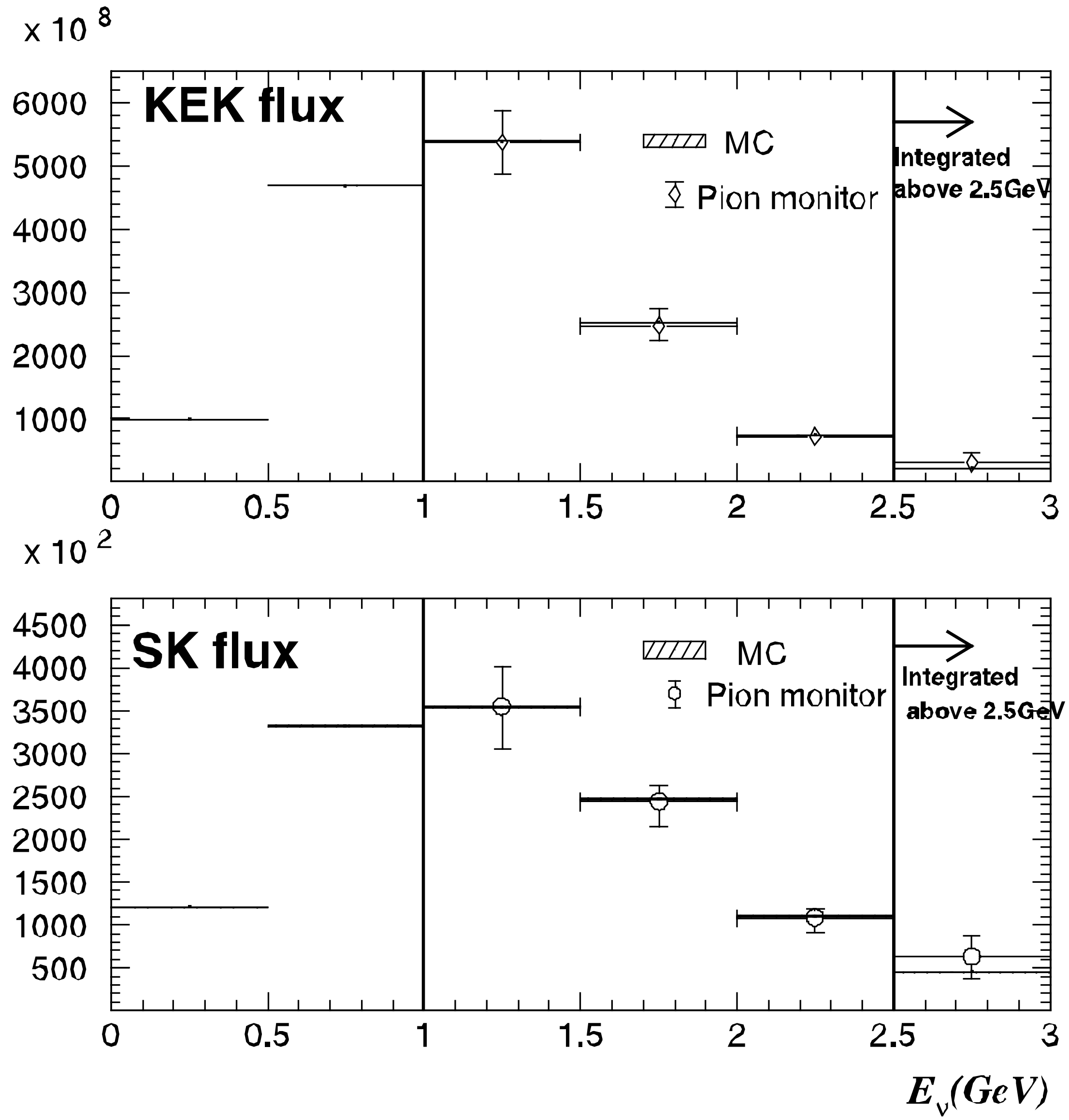
# Pion Monitor: Unfolded Result




Relative Pion Population
in $p_\pi$-$\theta_\pi$ plane

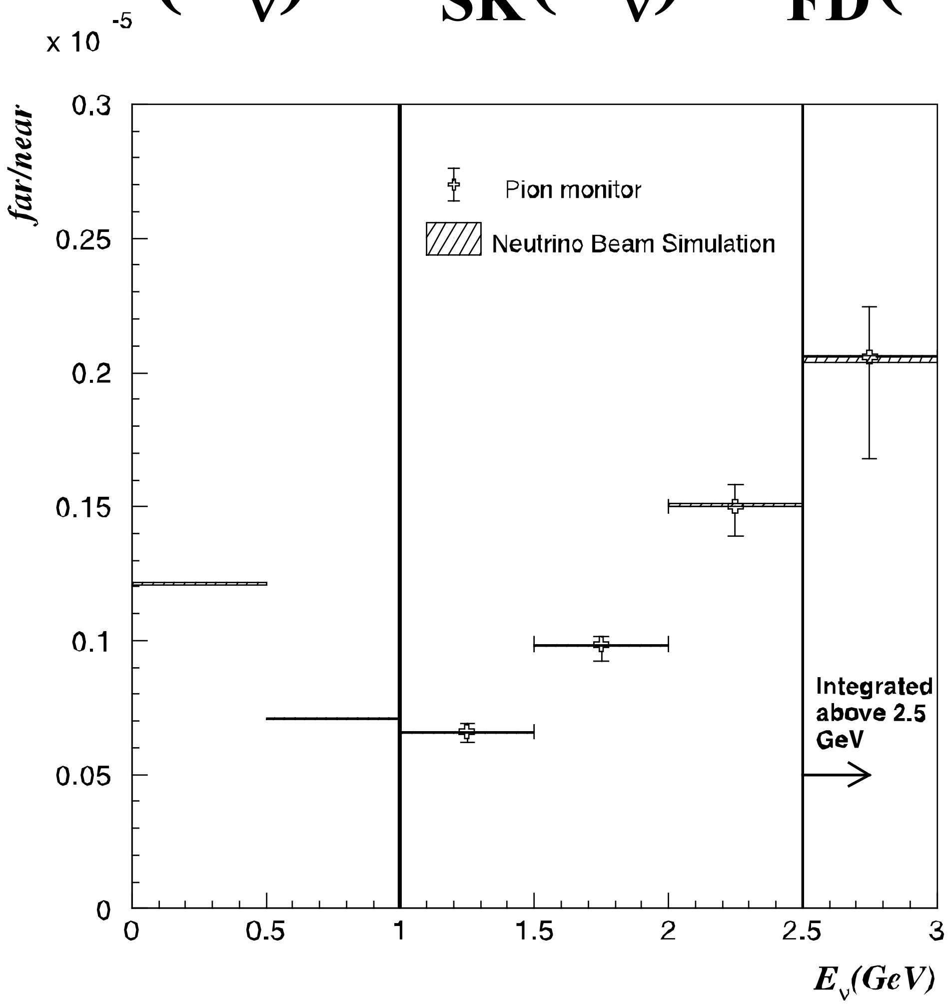


# Spectra from Pion Monitor Measurement



# Flux Ratio from Pion Monitor Measurement

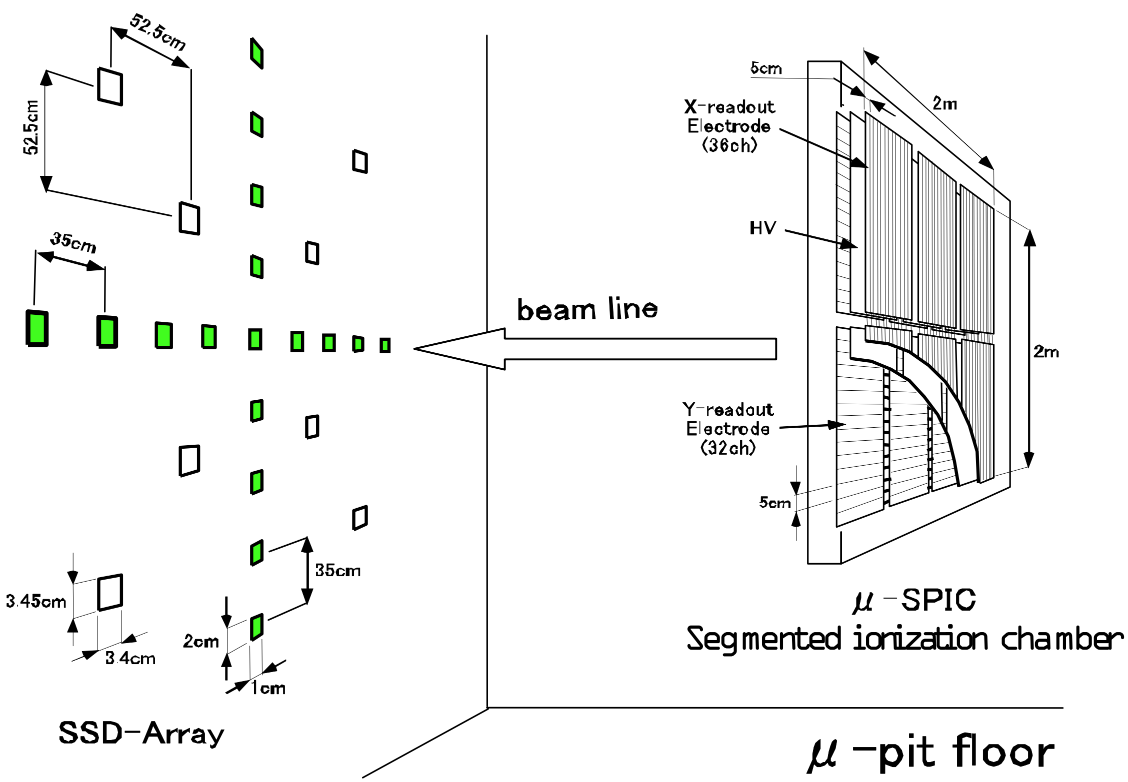
$$\mathrm{R}(E_\nu)=\Phi_{\mathrm{SK}}(E_\nu)/\Phi_{\mathrm{FD}}(E_\nu)$$




- Good agreement between the pion monitor results and the beam Monte Carlo above 1 GeV.
- Thus, for the extrapolation of the event rate, MC calculation is used.
- Systematic error estimated from pion monitor:

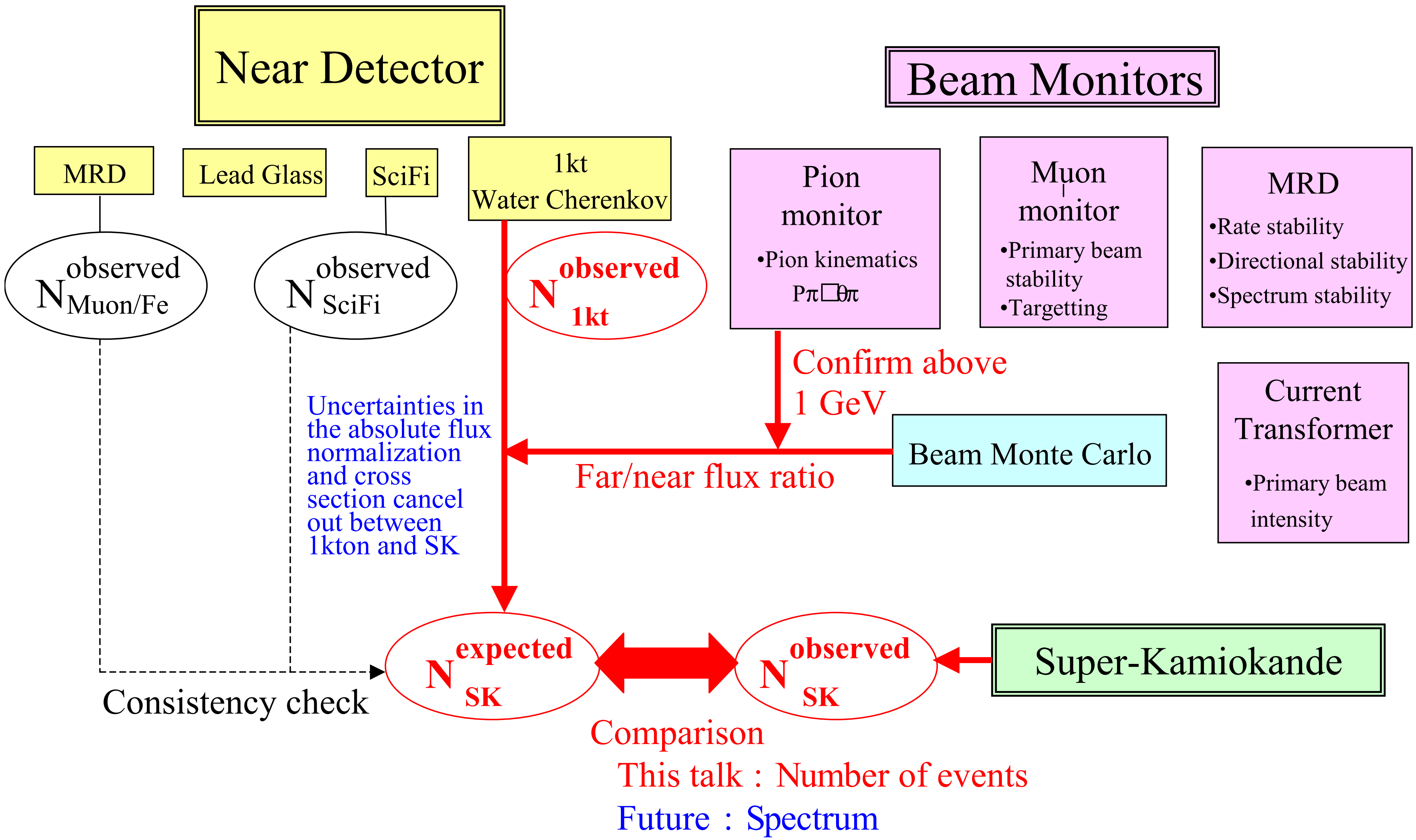
$$\Delta R = {}^{+6\%}_{-7\%}$$

# Muon Monitor

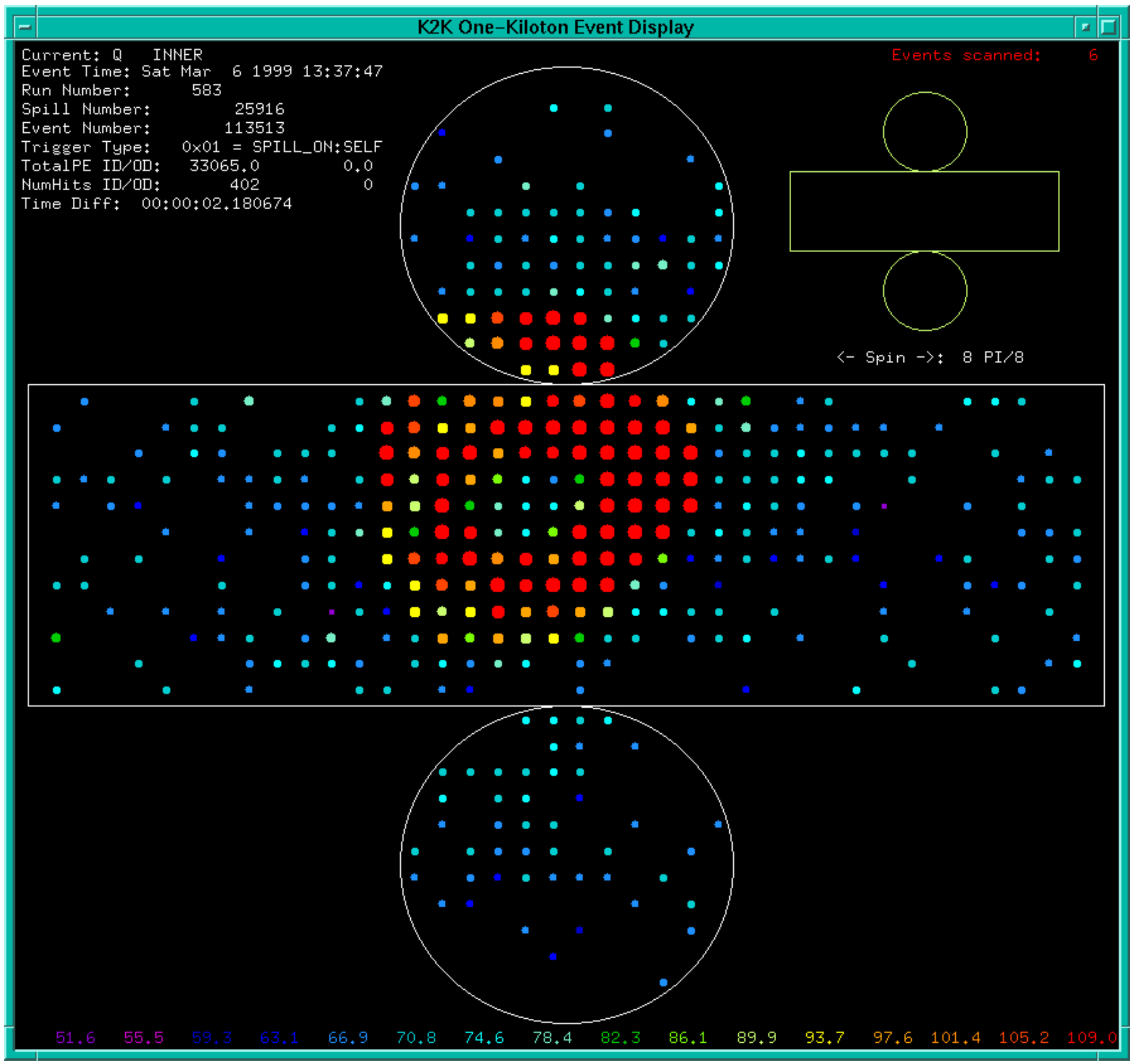



- Sensitive to initially high energy μ (>5.5 GeV)
- Spill-by-spill monitoring of
  - Beam intensity
    - Targetting
    - Horn stability
  - Profile
    - Beam direction

# K2K Experiment: Schematic

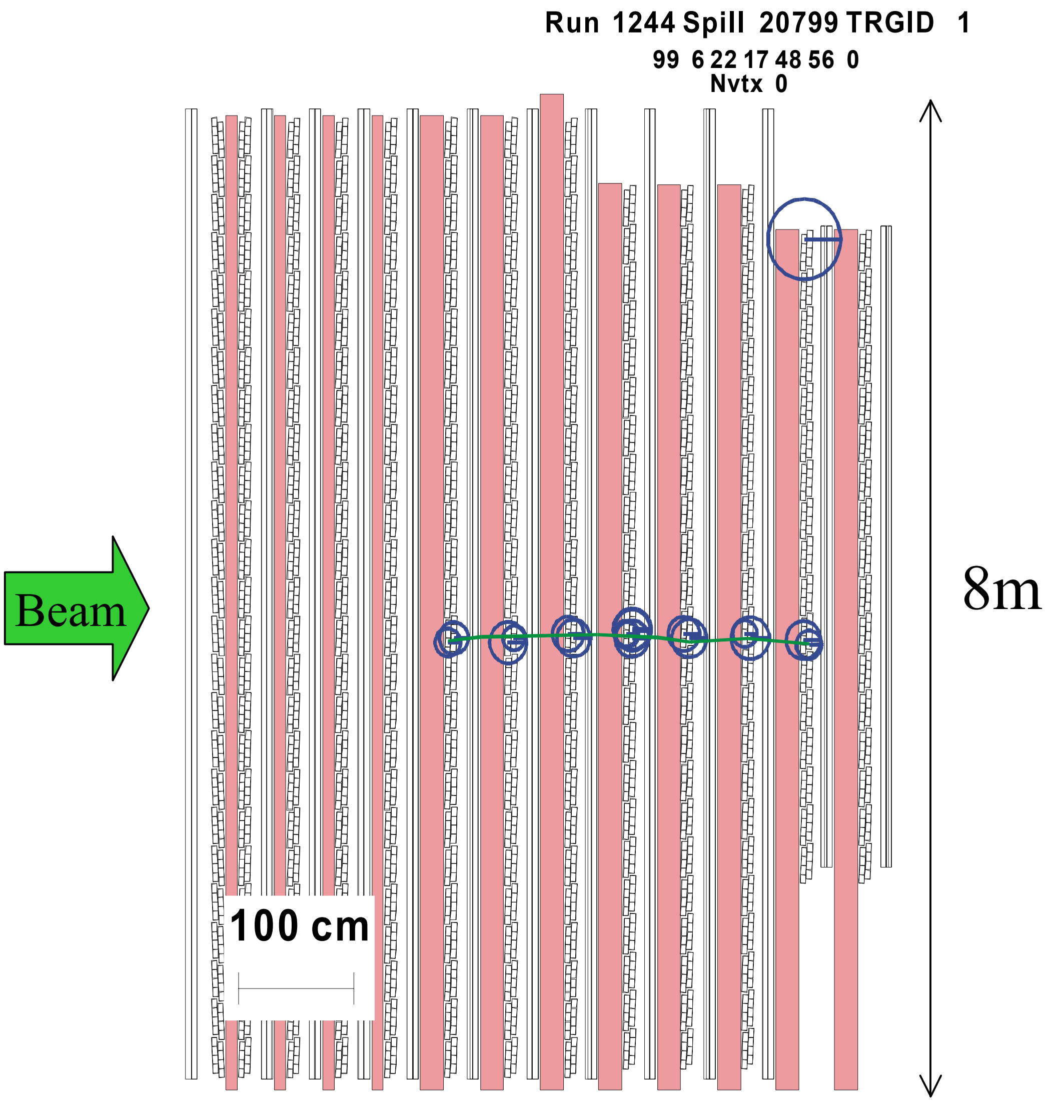


# 1 kton Event



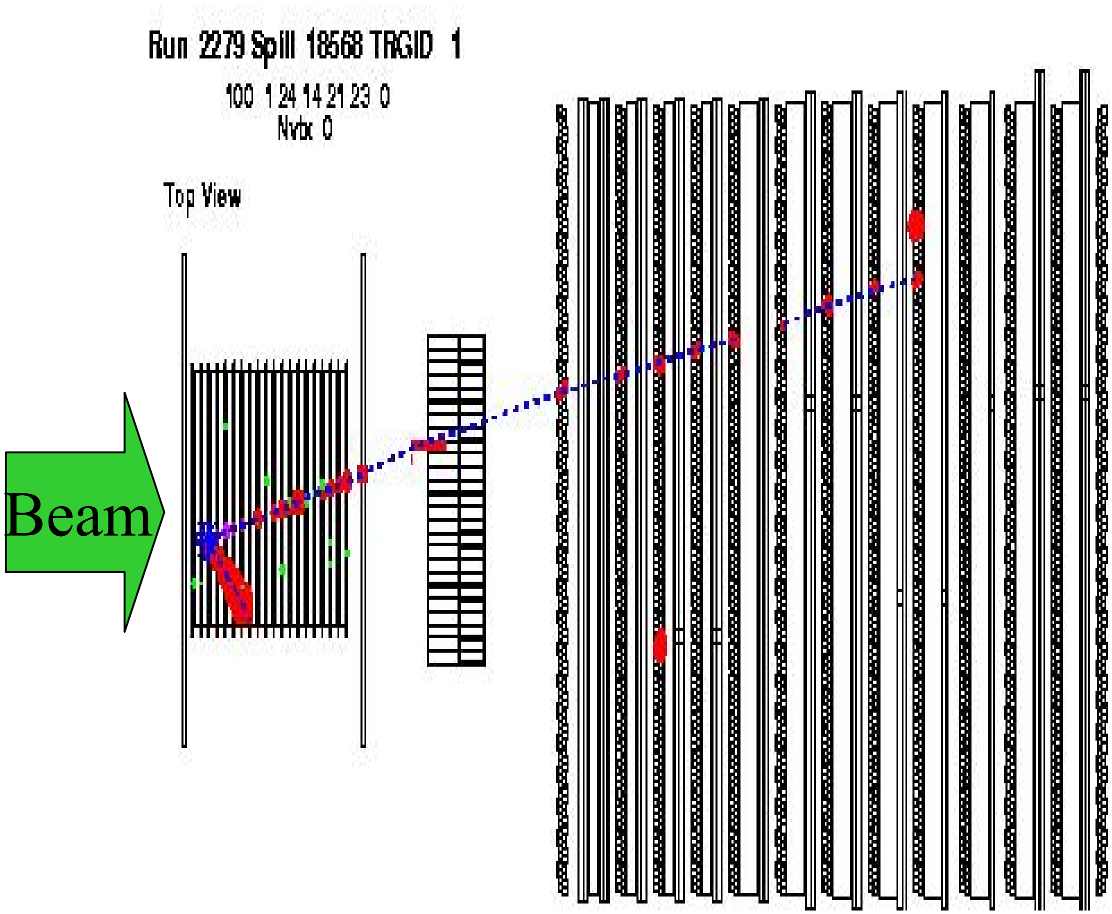

- $H_2O$ target (same as SK)
- Same detection principle as SK
  - ⇒ Rate **normalization in calculating the epected number of nm events at the far site.**
- Fid. Mass: 25 ton
- Event selection: Qtot>1000p.e.
- □2events/100 spill

# MRD Event



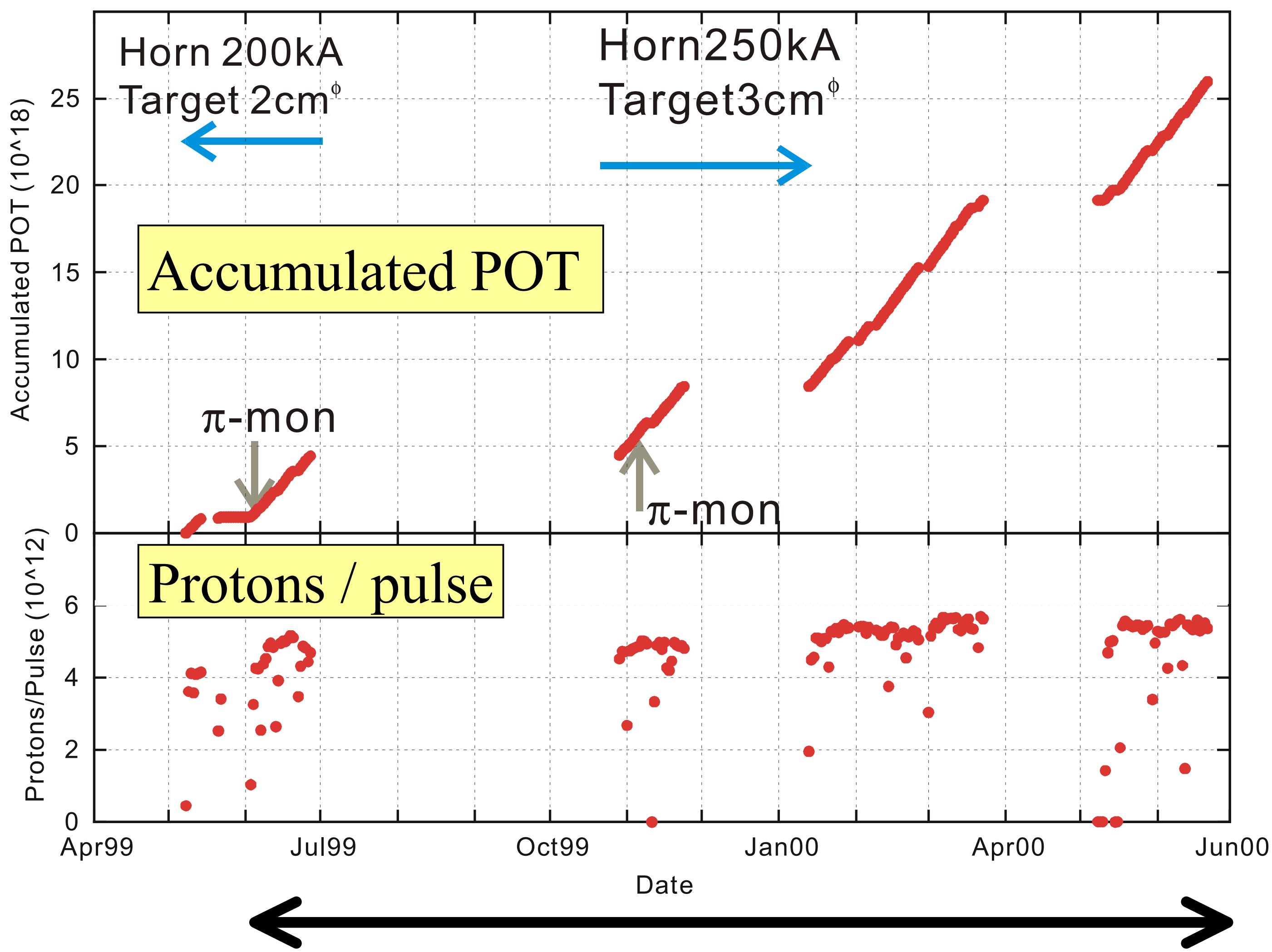

- Neutrino int. in MRD iron plates (CC inclusive)
- Large area coverage (8m)
  - ⇒ profile (vertex dist.)
- Large mass (fid. Mass = 329 ton)
  - ⇒ high rate (□5/100spill)
- Monitor
  - neutrino direction
  - intensity
  - spectrum

# SciFi Event



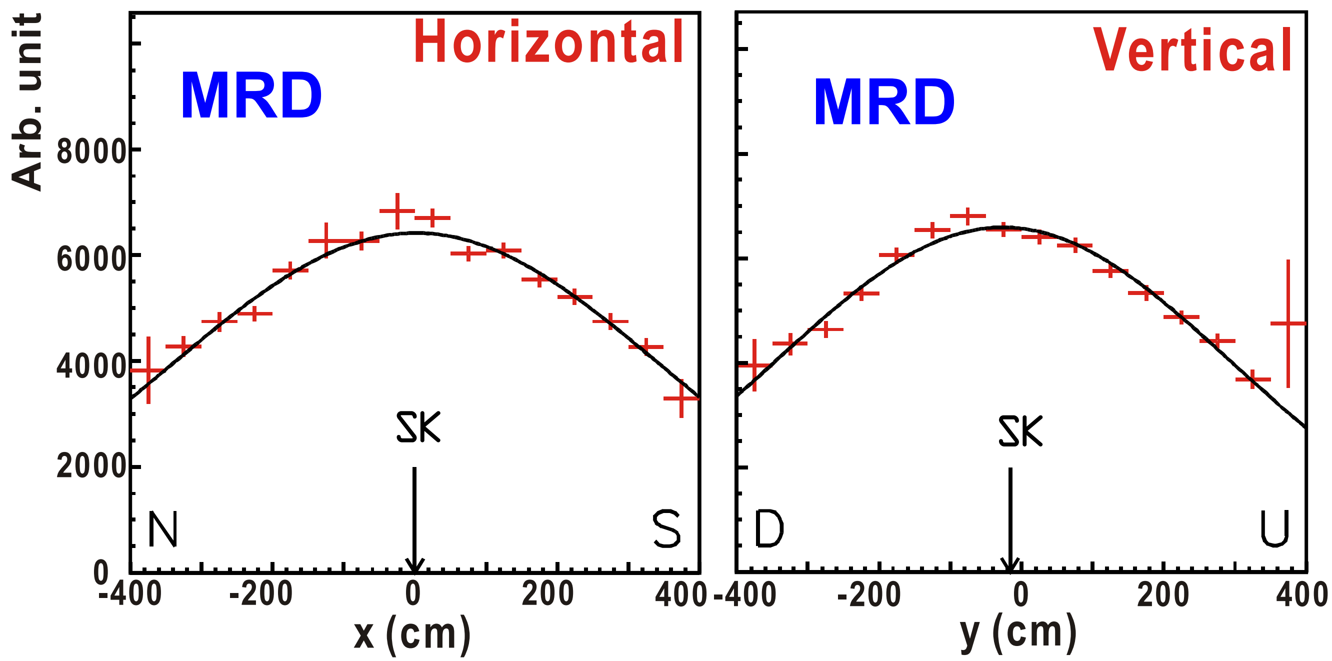

- Neutrino int. in SciFi $H_2O$ target (+Al 20%)
- Pos. resolution □ 1mm
  - ⇒ well defined fid. vol.
  - ⇒ multitrack resolution
- Fiducial mass = 5.9 ton
- Event selection: matching SCIFI & MRD track
- 1 event/1000 spill
- Study neutrino interaction, e.g. $\sigma_{inelastic}/\sigma_{elastic}$

# Protons Delivered onto the Target



# Beam Direction

**Vertex distribution of MRD events (Nov99)**




Fitted center x: 1±5cm

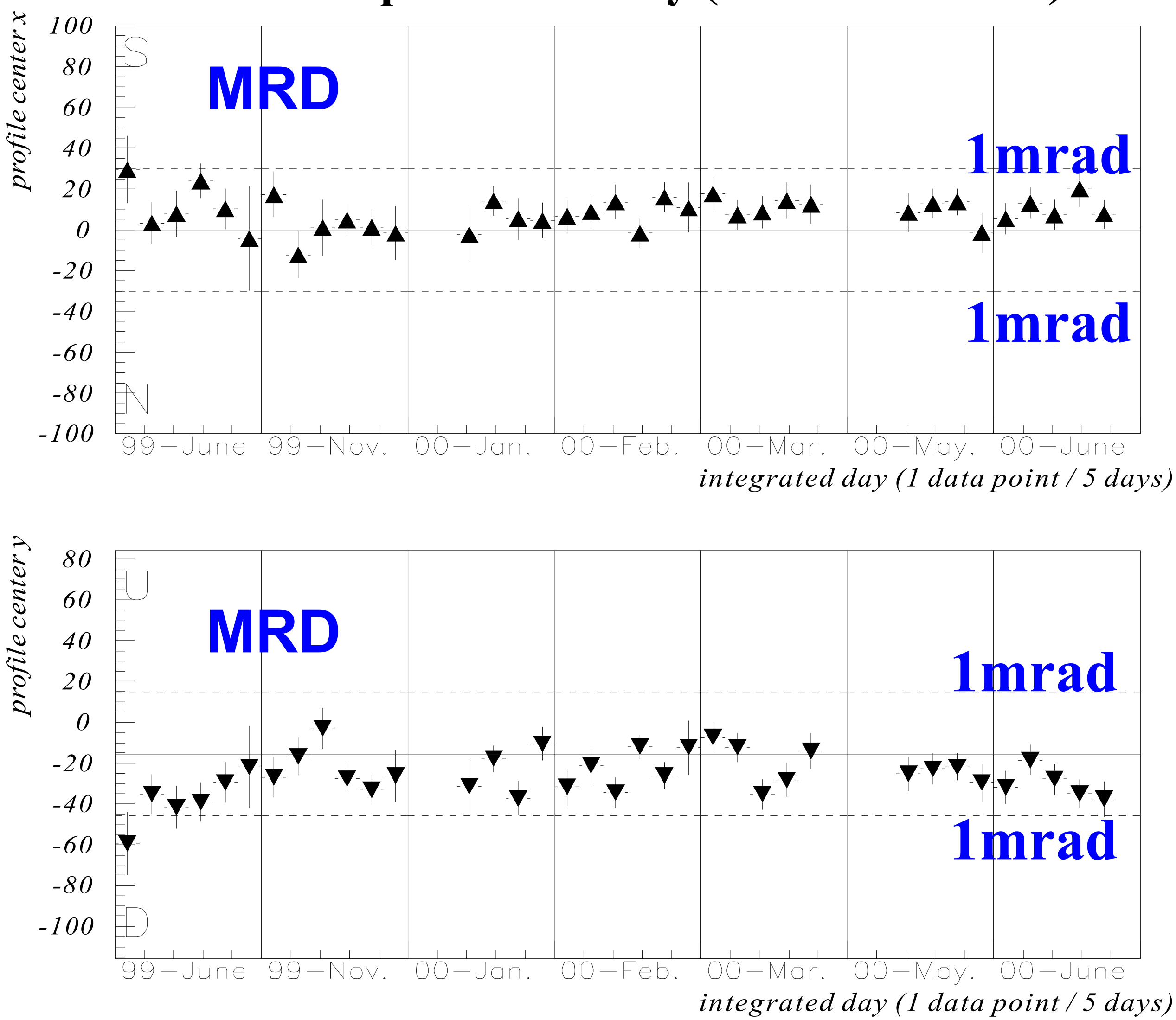
y: □10±4cm from SK dir.

(stat)

Centered within sys. err. of 20cm (**0.7mrad**)

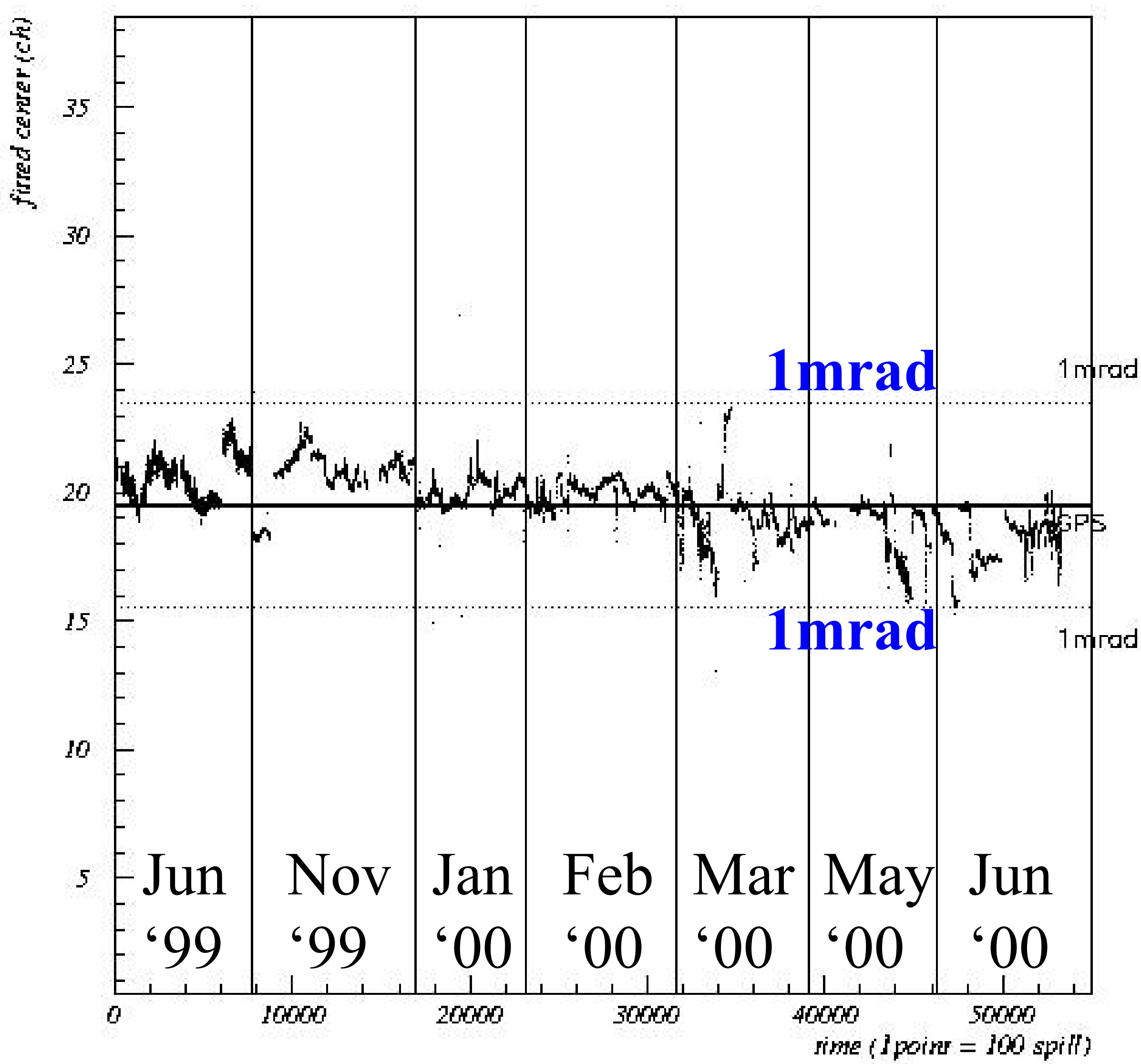
# Stability of the Profile Center

**Neutrino profile stability (99June - 00June)**



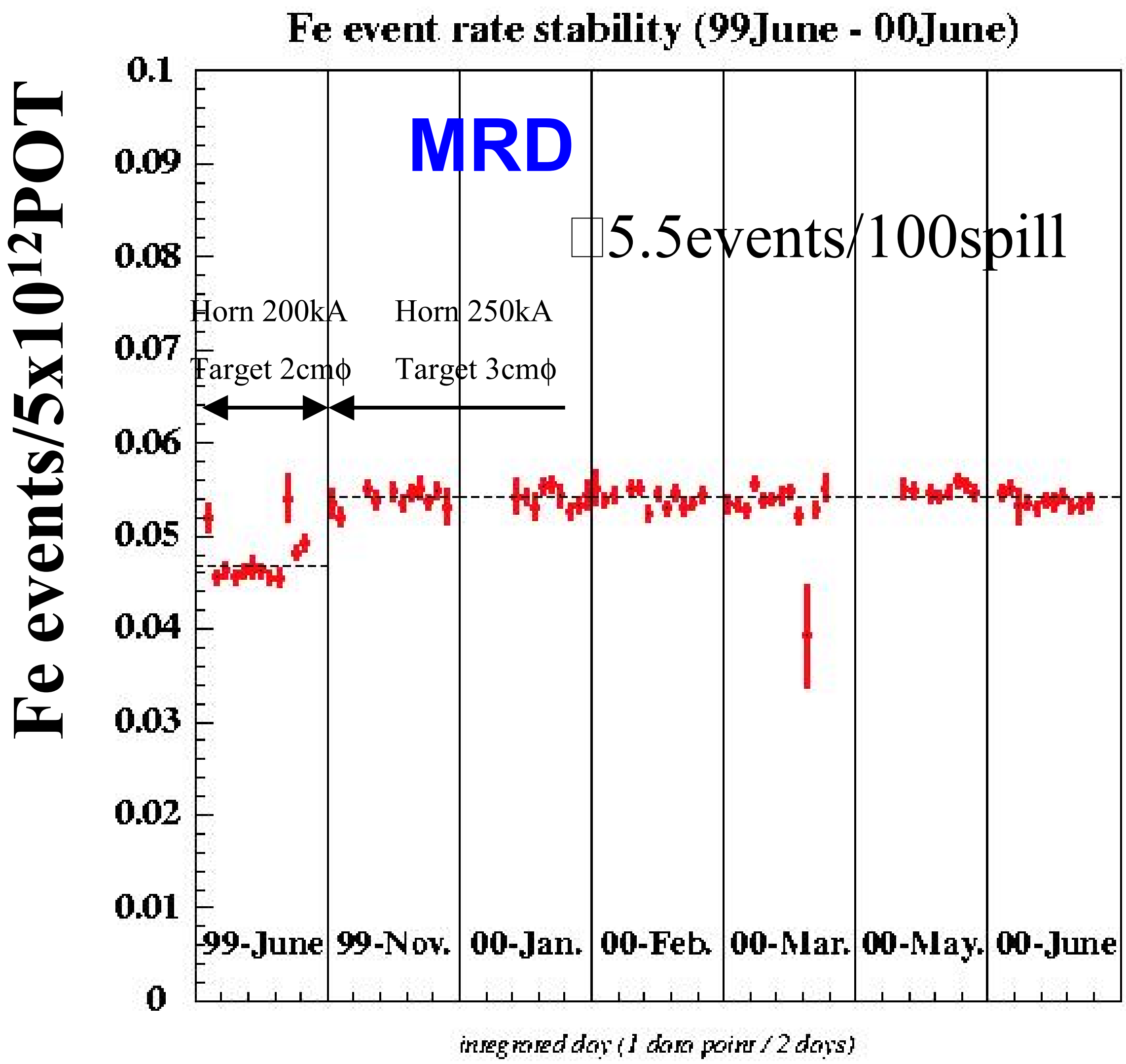

- Measured with the Muon Range Detector
- Stable to within $\pm 1$ mrad
- Well within the required 3 mrad

# Stability of the Muon Profile Center



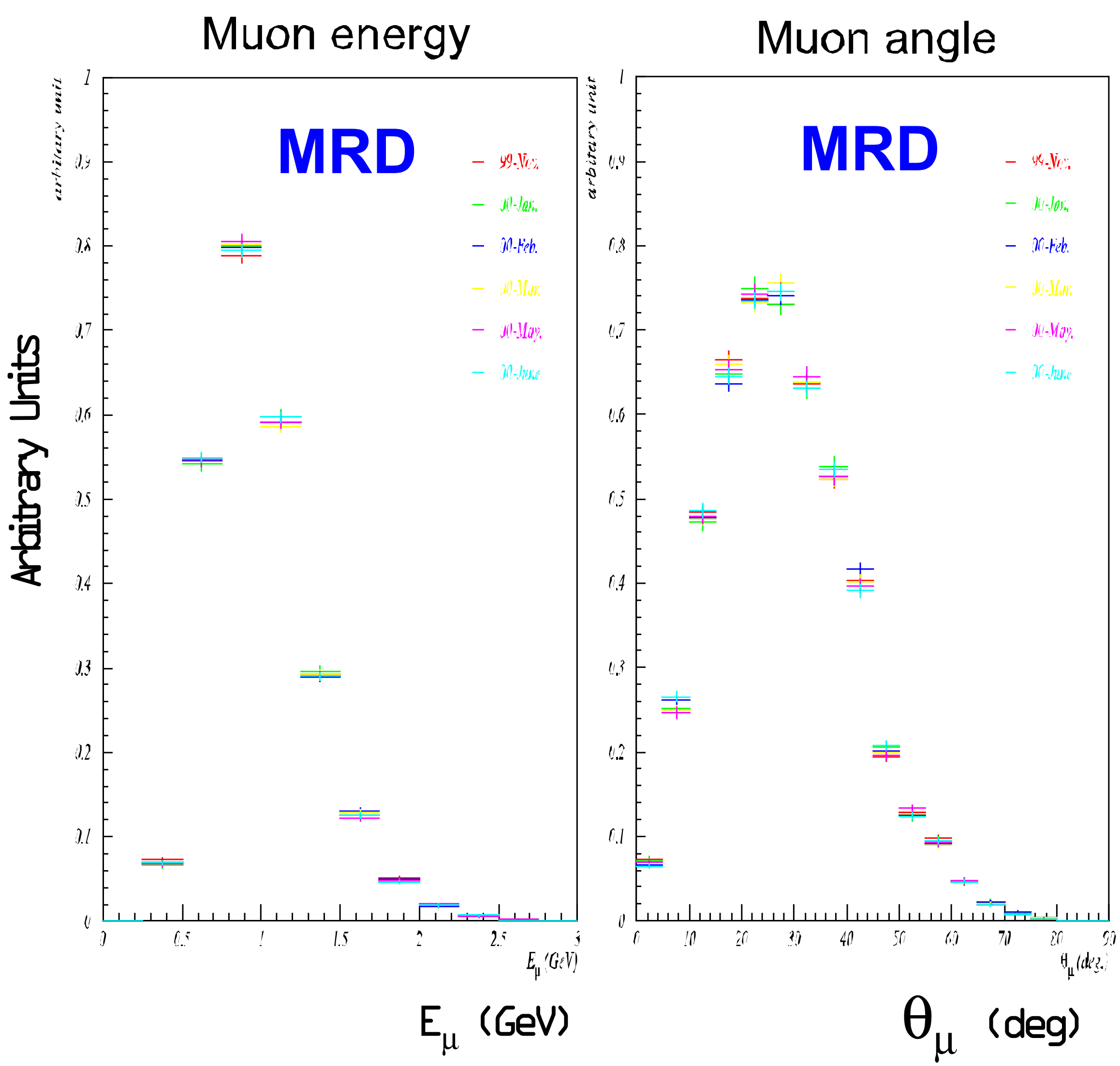

- Spill-by-spill measurement with the muon monitor
- Stable within ± 1 mrad

# Stability of the MRD Event Rate




- Measured with the MRD
- Good stability

# Stability of Muon Energy and Angle




- Measured with MRD
- Stable within statistical error

# Expected Number of SK Events

$$N_{SK}^{\text{exp}} = \frac{N_{kt}^{\text{obs}}}{\varepsilon_{kt}} \cdot R \cdot \varepsilon_{SK}$$

$$R = \frac{M_{SK}}{M_{kt}} \cdot \frac{\int \Phi_{SK}(E_\nu) \cdot \sigma_{\mathrm{H_2O}}(E_\nu) dE}{\int \Phi_{kt}(E_\nu) \cdot \sigma_{\mathrm{H_2O}}(E_\nu) dE}$$

$N_{kt}^{\text{obs}}$ : observed events in 1kt

$\varepsilon_{kt}$ : detection eff. of 1kt

$\varepsilon_{SK}$ : detection eff. of SK

$M_{SK}/M_{kt}$ : fiducial mass ratio

$$\boxed{N_{SK}^{\text{exp}} = 37.8 \pm 0.2(\text{stat.})\ {}^{+3.5}_{-3.8}(\text{syst.})}$$

from 1 kton events

c.f.: $N_{SK}^{\text{exp}} = 41.0^{+6.0}_{-6.6}$ from MRD events

: $N_{SK}^{\text{exp}} = 37.2^{+4.6}_{-5.0}$ from SCIFI events

These results are consistent with each other.

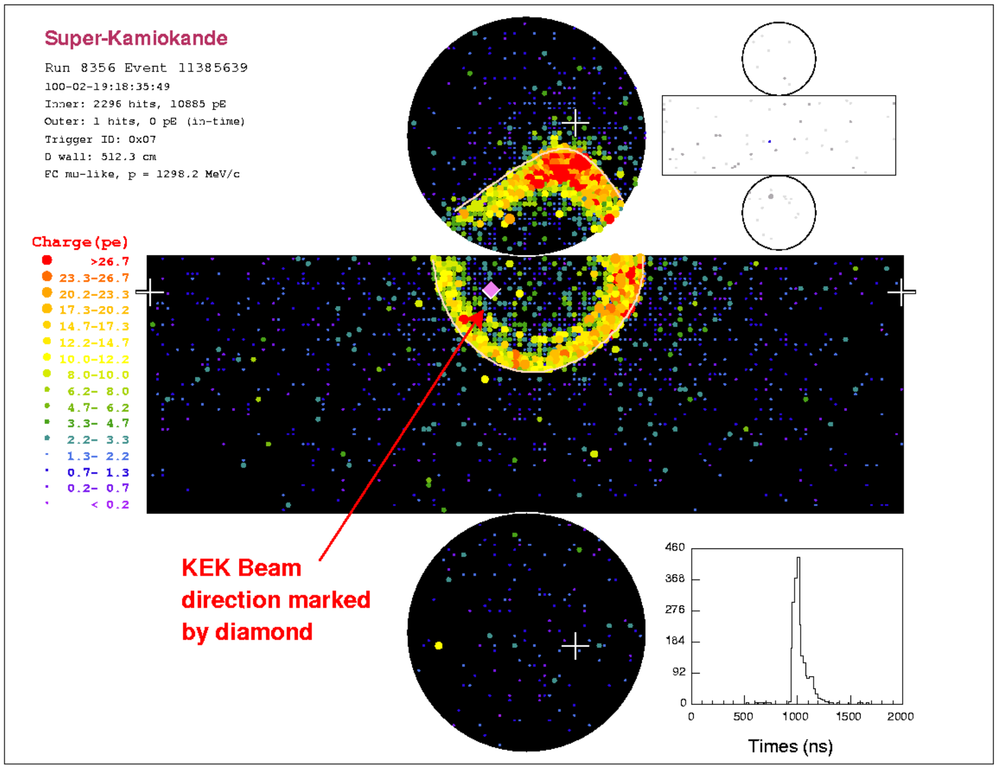
# Systematic Error

$$N_{SK}^{\exp} = 37.8 \pm 0.2(\mathrm{stat.})\ {}^{+3.5}_{-3.8}(\mathrm{syst.})$$

| | |
|---|---|
| Near/Far Ratio | ${}^{+6}_{-7}$ % |
| 1kt (mainly $\Delta V/V$) | $\pm$ 5 % |
| SK(mainly $\Delta V/V$) | $\pm$ 3 % |

**Total** ${}^{+9}_{-10}$ %

# SK Event




## K2K event selection at SK

1. No pre-activity in 30μsec
2. p.e. in 300ns window > 200
3. OD Nhit in largetst cluster<10
4. Deposite Energy > 30MeV
5. Fiducial cut (distance from wall>2m)

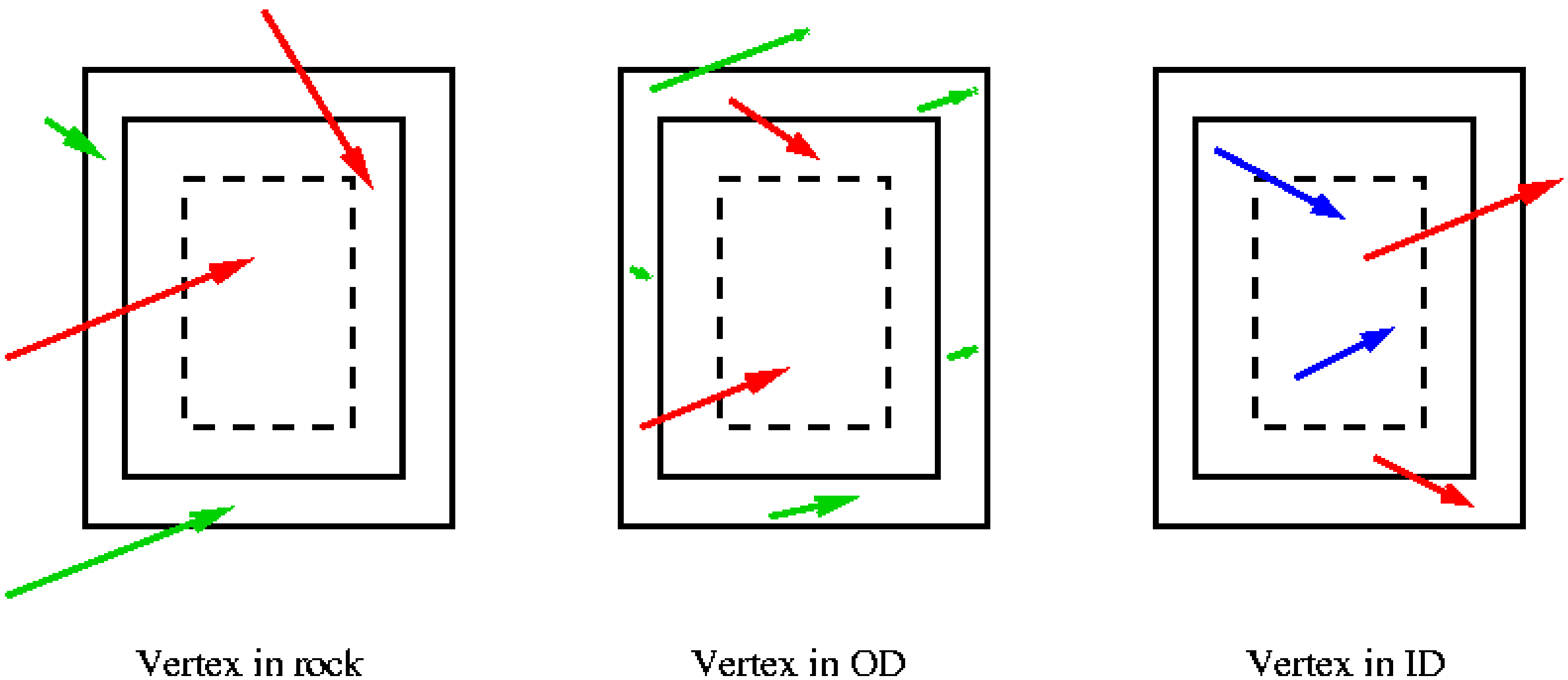
Detection efficiency

$\varepsilon$=79%

for CC:93%,

for $NC_{inel}$:68%

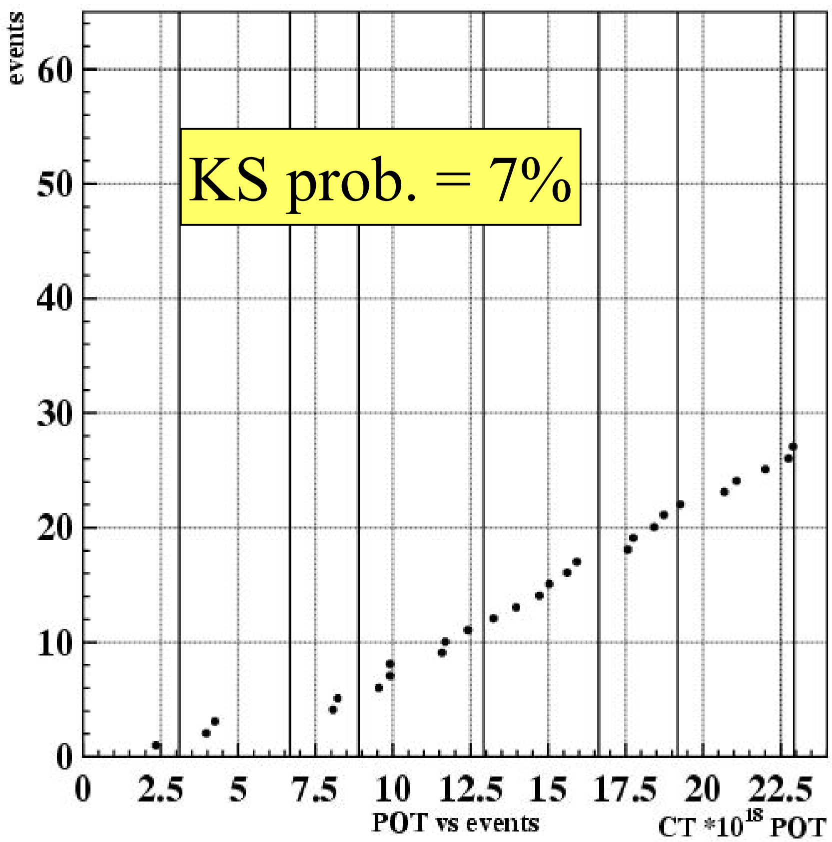
# SK Event Category



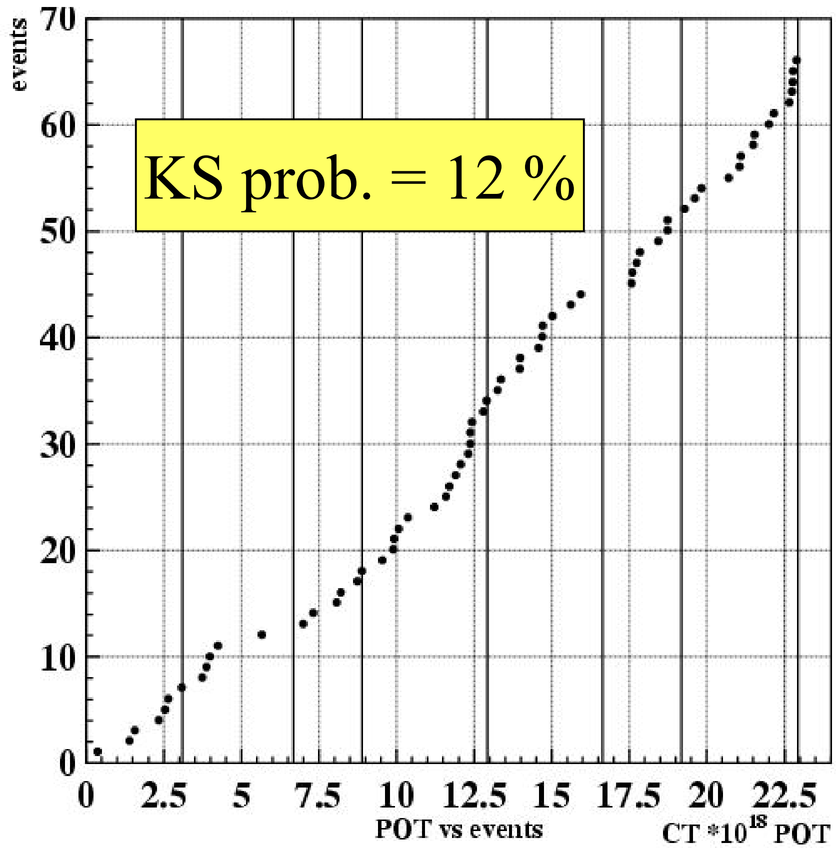

- FC (Fully Contained: Light in ID only)
  - Vertex inside the 22.5 kton fiducial volume
  - Vertex outside the fiducial volume
- OD contained (light in OD only)
- Crossing (Light in both ID and OD)

# Events vs POT

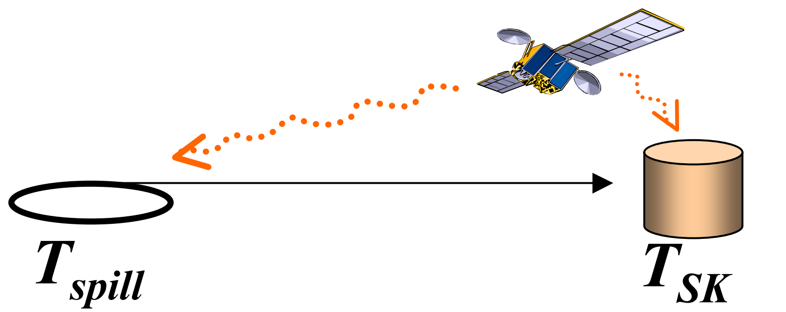
FC events in 22.5 kton fiducial volume




All events (FC + OD)



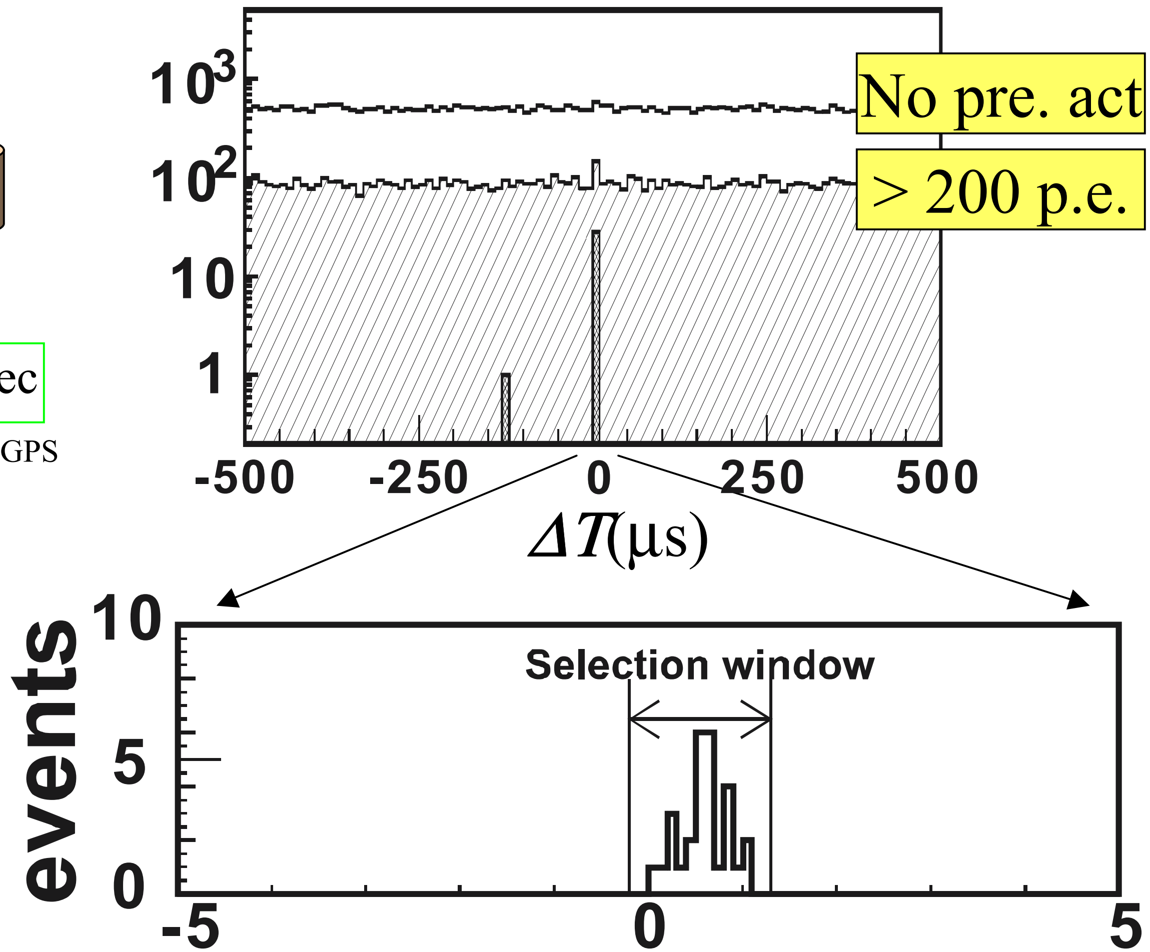
# Arrival Time Distribution




$$-0.2 \le \Delta \boldsymbol{T} \equiv \boldsymbol{T}_{SK} - \boldsymbol{T}_{Spill} - \mathrm{TOF} \le 1.3\mu\,\mathrm{sec}$$

$T_{Spill}$, $T_{SK}$: Abs. time of spill start, SK event measured with GPS

TOF: 0.83ms(Time of flight from KEK to Kamioka)



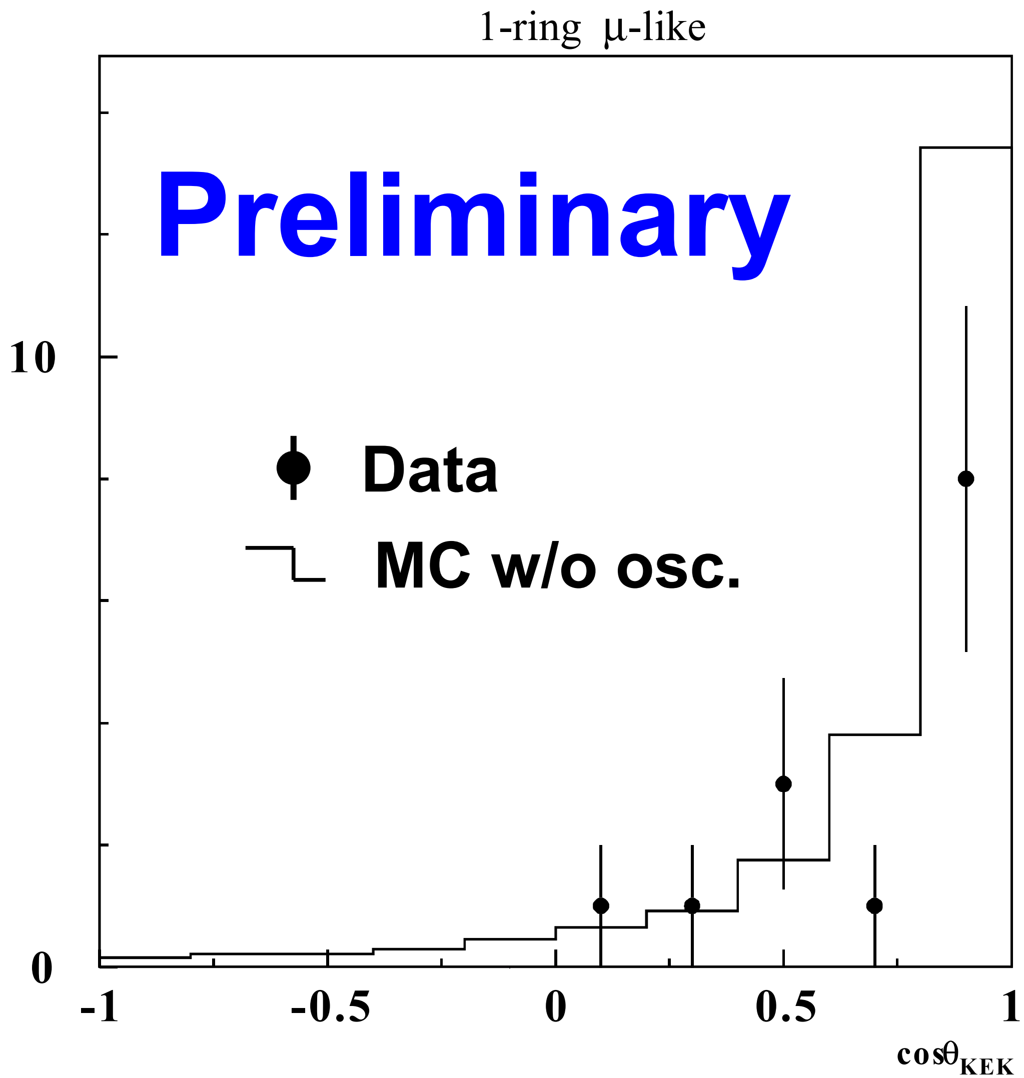

**28 observed.**

Exp'ed Atm ν BG
$<10^{-3}$ in 1.5μs win.

# Observed vs Expected at SK

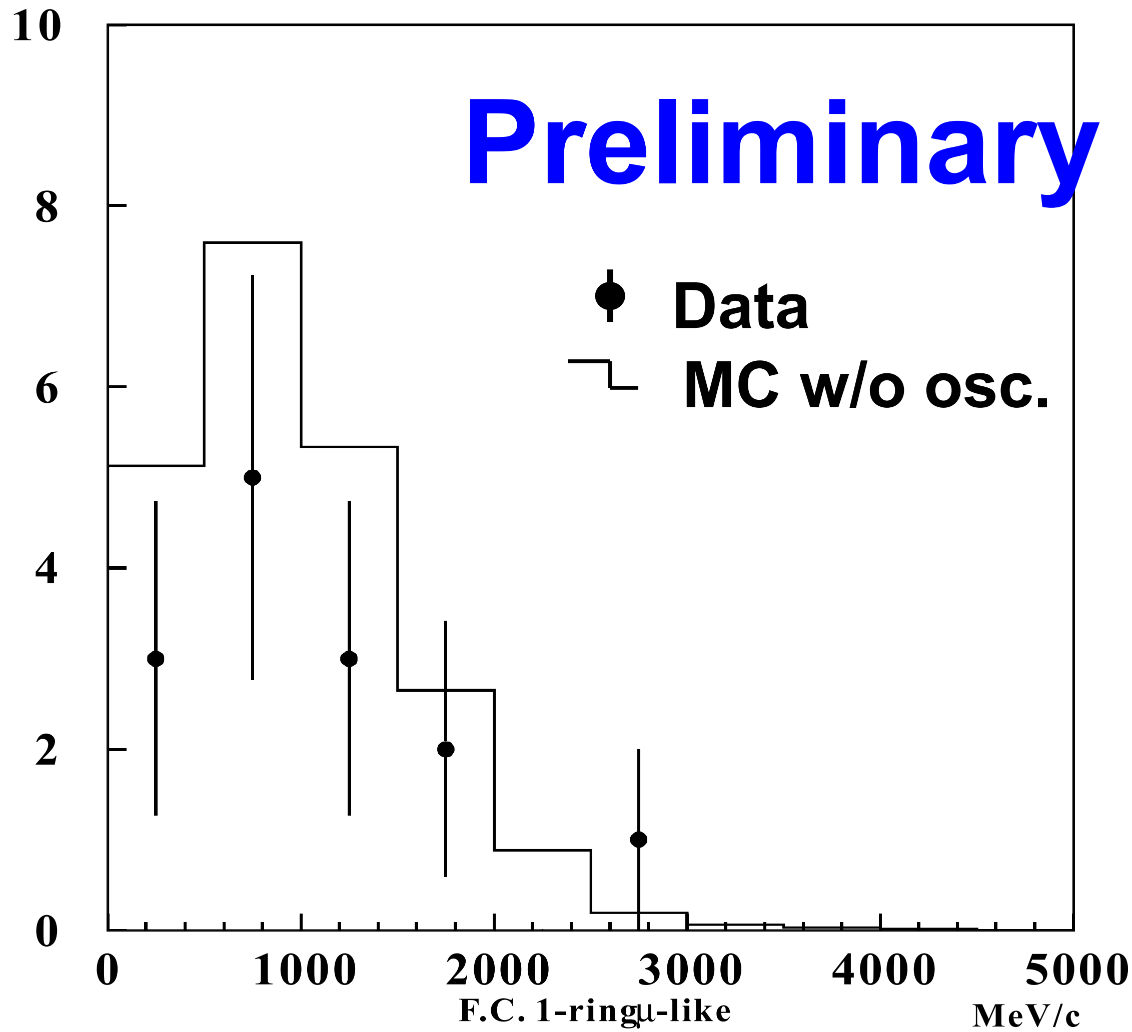
| | Obs. | No Ocsi. |
|---|---|---|
| FC 22.5kt | 28 | $37.8\ ^{+3.5}_{-3.8}$ |
| 1-ring | 15 | $22.7 \pm 3.2$ |
| $\mu$-like | 14 | $20.8 \pm 3.2$ |
| e-like | 1 | $1.9 \pm 0.4$ |
| multi ring | 13 | $15.1 \pm 2.5$ |

# $\cos\,\theta_{KEK}$ Distribution




**Need to estimate syst. err. in MC expect.**

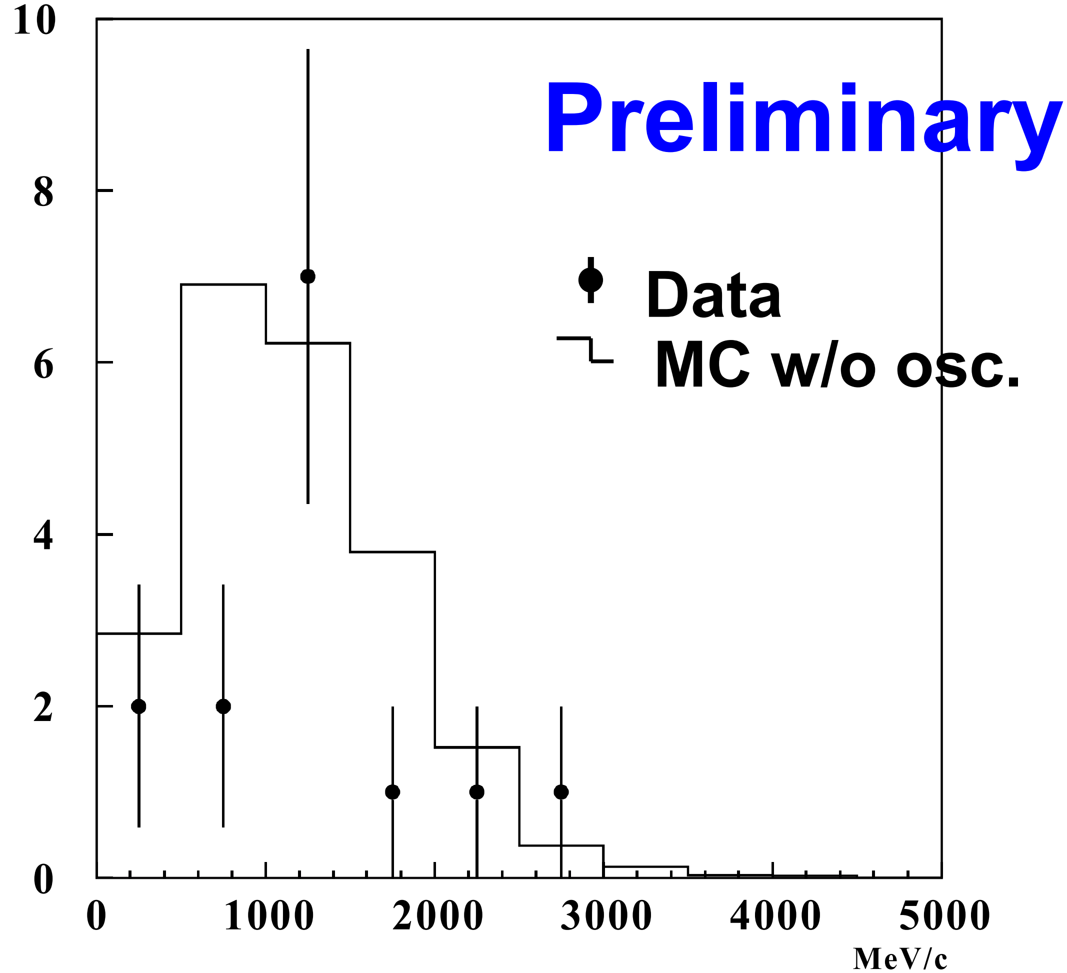
# Reconstructed μ Momentum




Need to estimate syst. err. in MC expect.

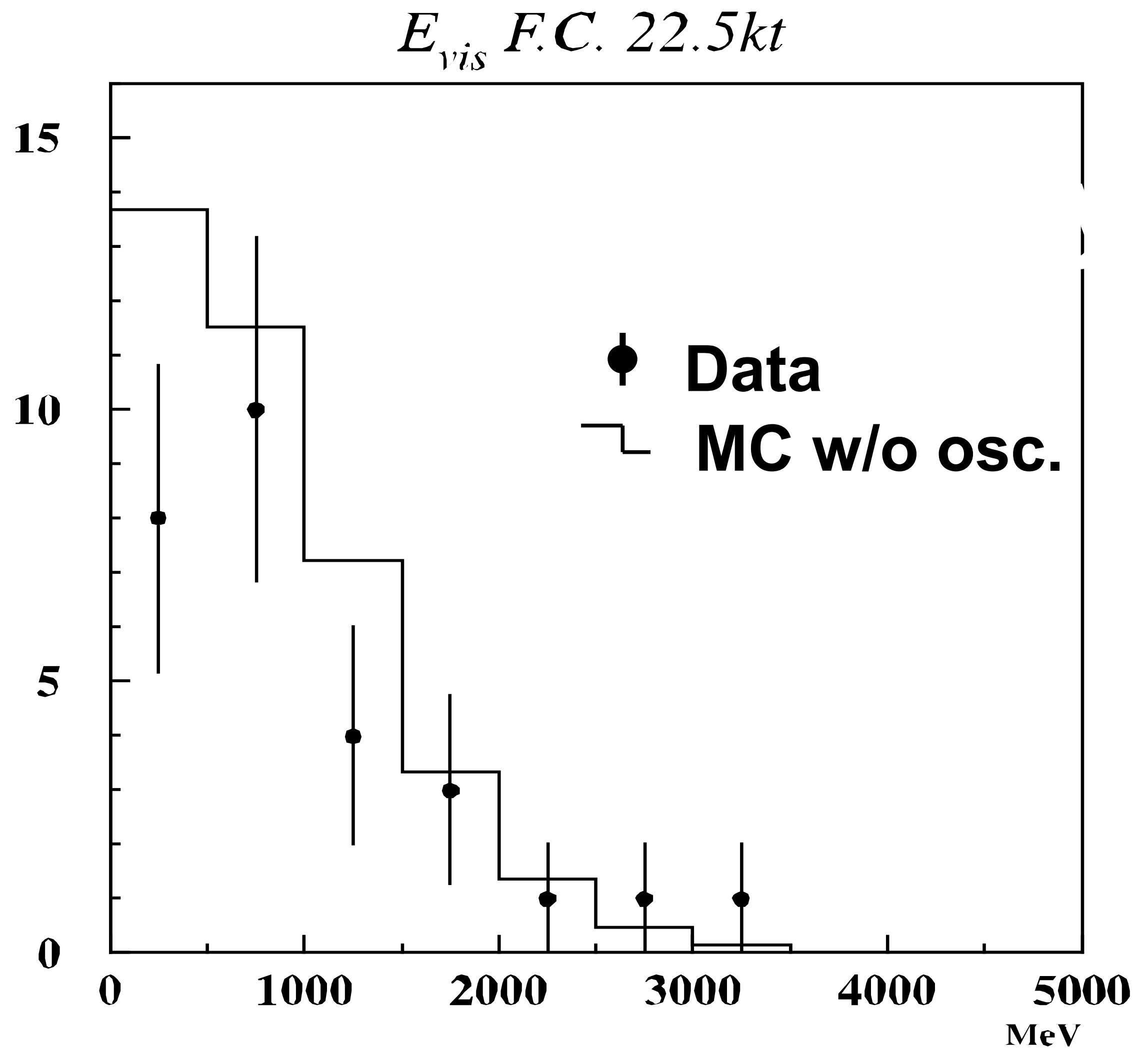
# Reconstructed $E_\nu$

Fully contained 1-ring μ-like (22.5kt)



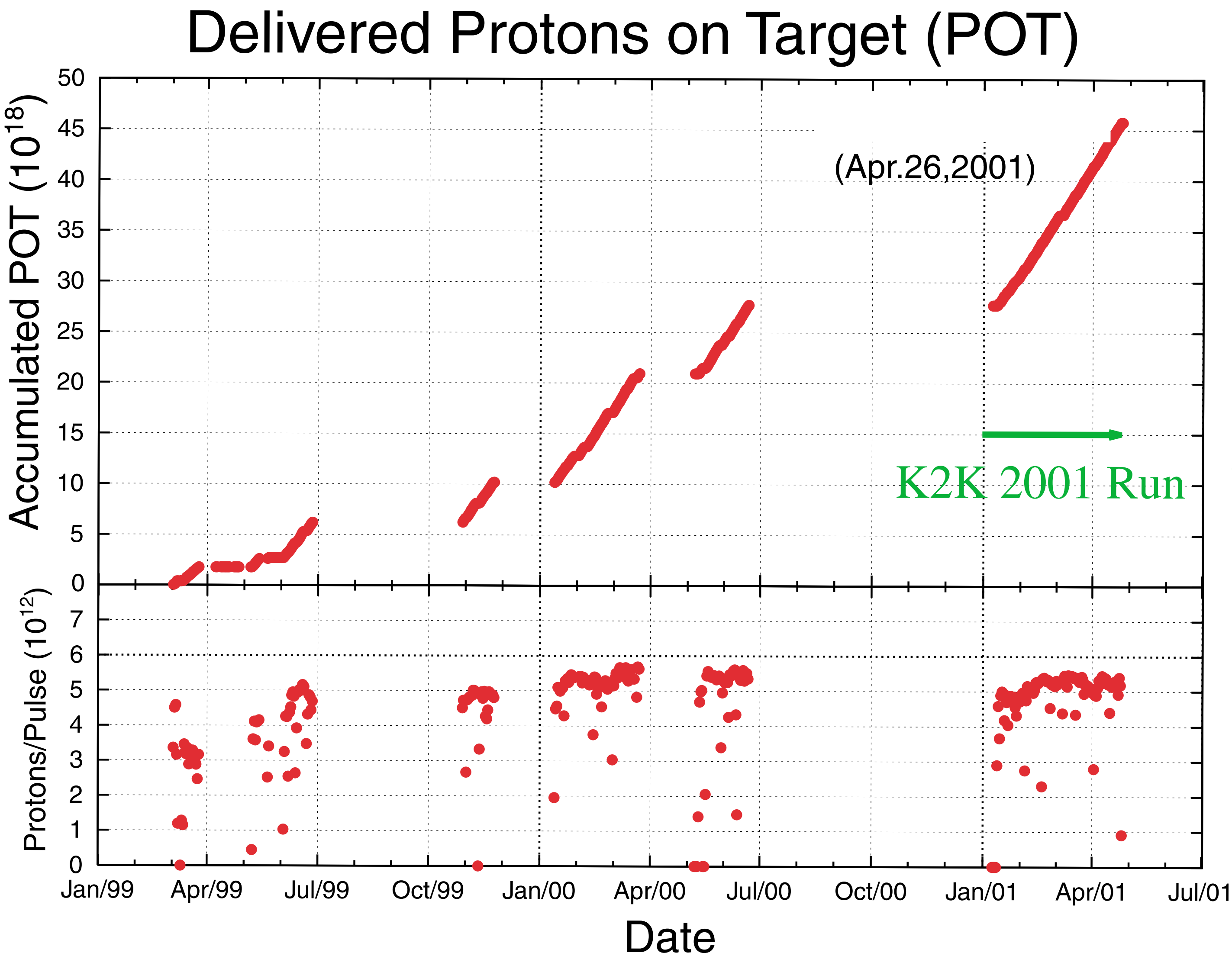

**Need to estimate syst. err. in MC expect.**

# Visible Energy




need to estimate syst. err. in MC expect.

# K2K Run in 2001




Until July 12

# Conclusions

- Methodology of a long-baseline neutrino experiment established.
  - Beam steering (direction)
  - Time synchronization between near site and far site
  - Monitoring of the neutrino beam at near site
  - Prediction of neutrino beam properties at far site from near site measurements
- $2.29 \times 10^{19}$ POT accumulated from Jun '99 to Jun '00.

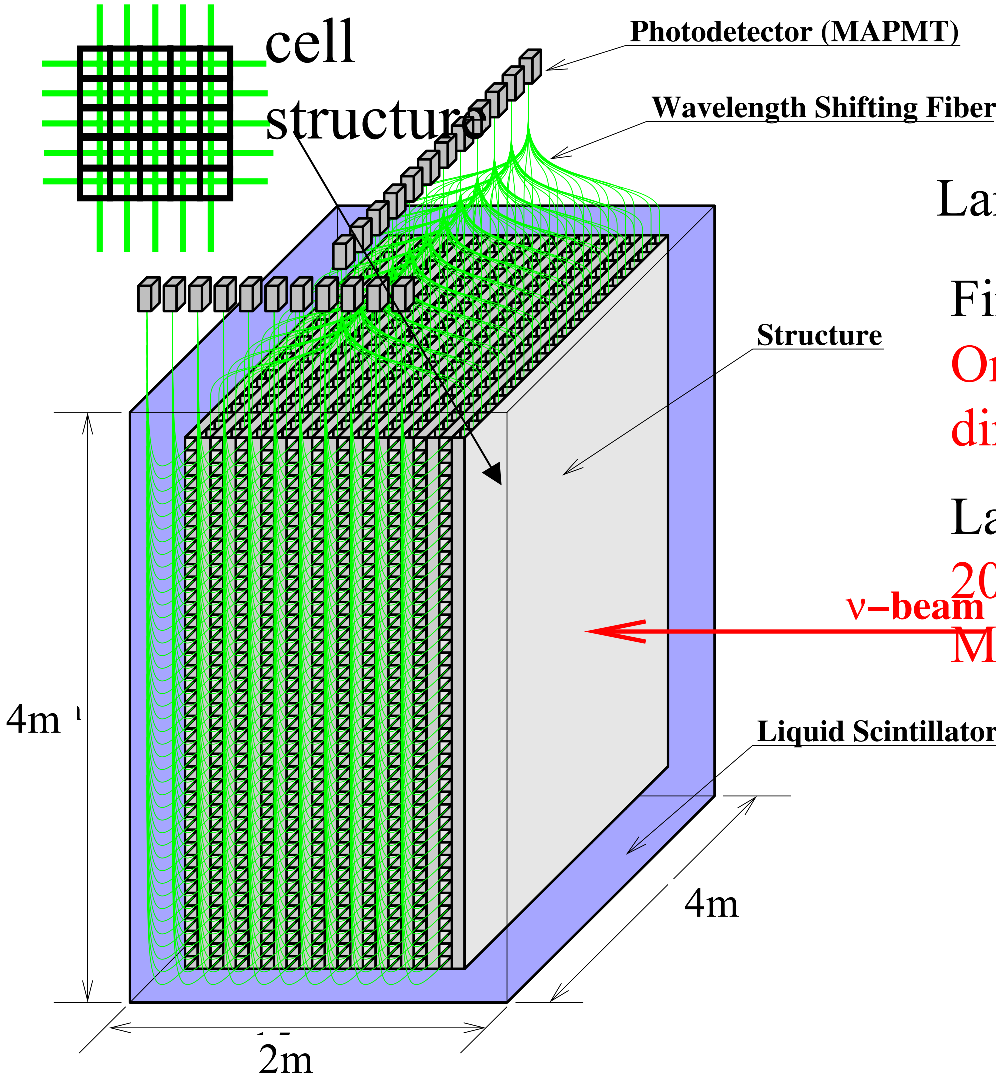
  # of fully contained events in fiducial volume @ SK
  - Observed : 28
  - Expected : $37.8^{+3.5}_{-3.8}$ (w/o osc.)
- **Deficit of ~1GeV $\nu_\mu$ after 250km flight at 90% significance**
- **Statistics doubled this summer**

# Future

- Spectrum analysis
- $\nu_e$ appearance
- Study of $\nu_\mu$ interactions at 1GeV region
- Upgrade of the near detector in summer, 2003

# Upgrade of the near detector

# Upgrade of the Near Detector
## (Segmented Liquid Scintillator with WLS Fiber Readout)




Large Volume: $4\times4\times2\mathrm{m}^3$ ~30tons

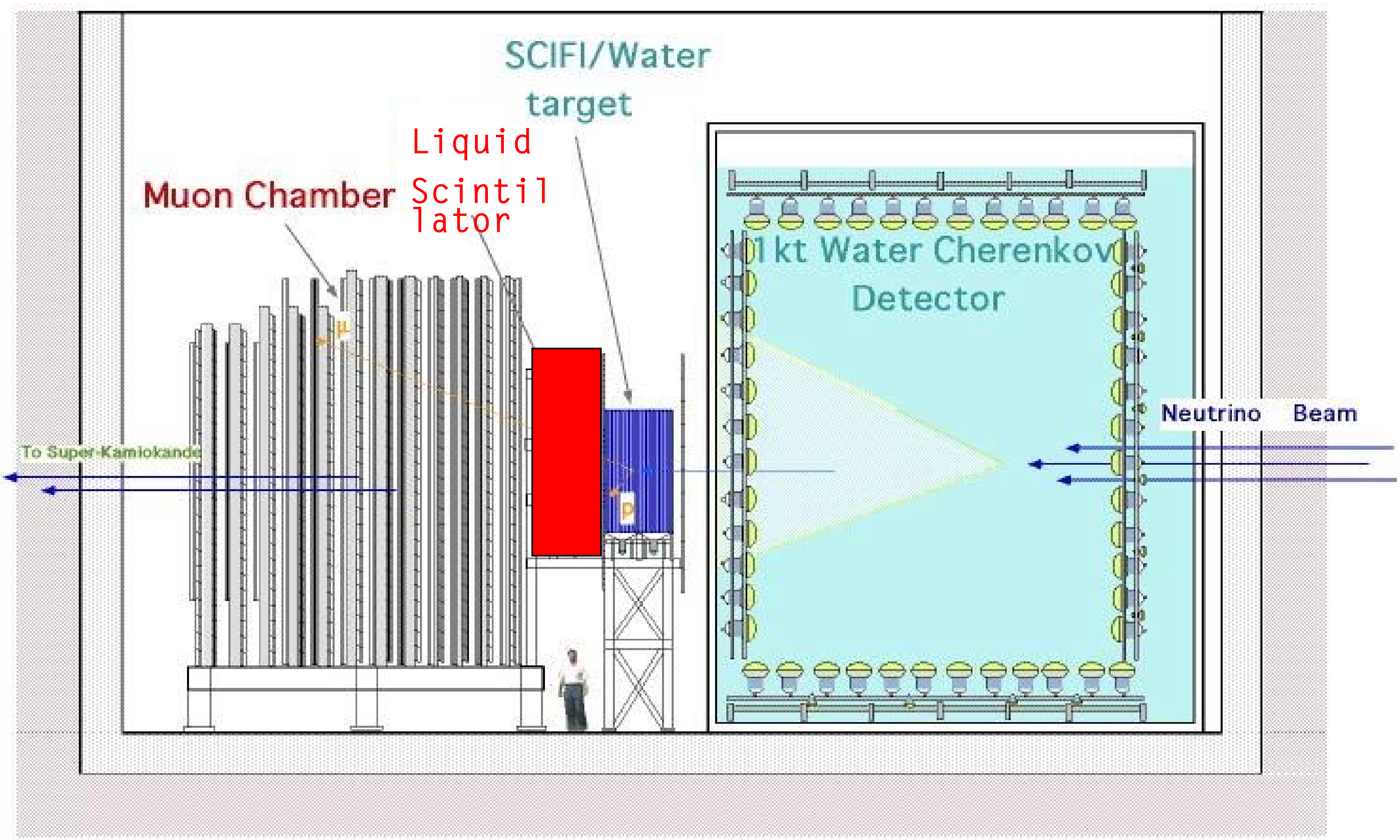
Fine segment: $20\times20\times20\mathrm{mm}^3$
One cell is read-out to both X and Y directions by X,Y fibers.

Large Light Yield:
20~30 photo-electrons/cell for MIP

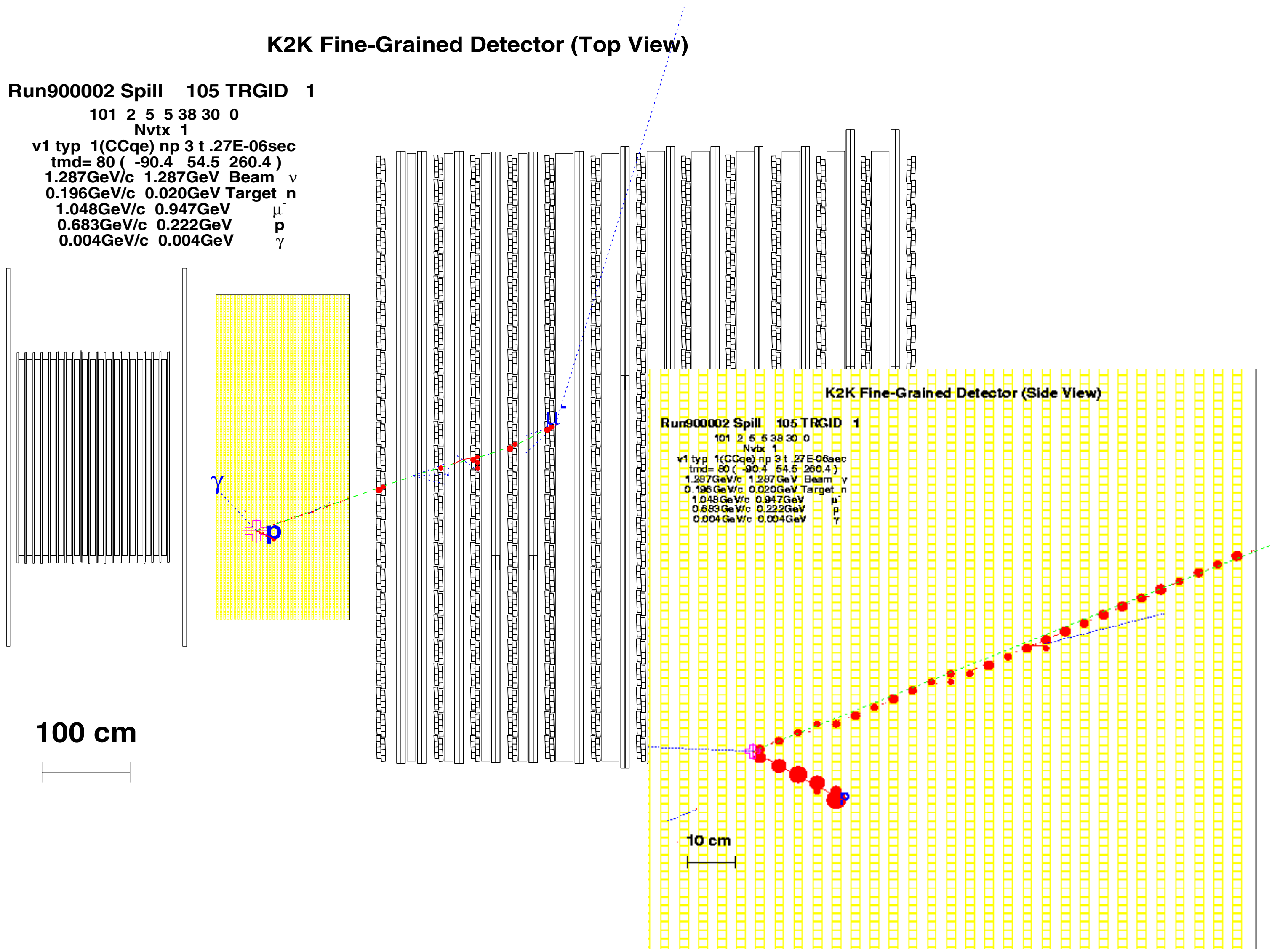
Particle ID:
p/π : dE/dx
μ/π : range

#channels : □40,000

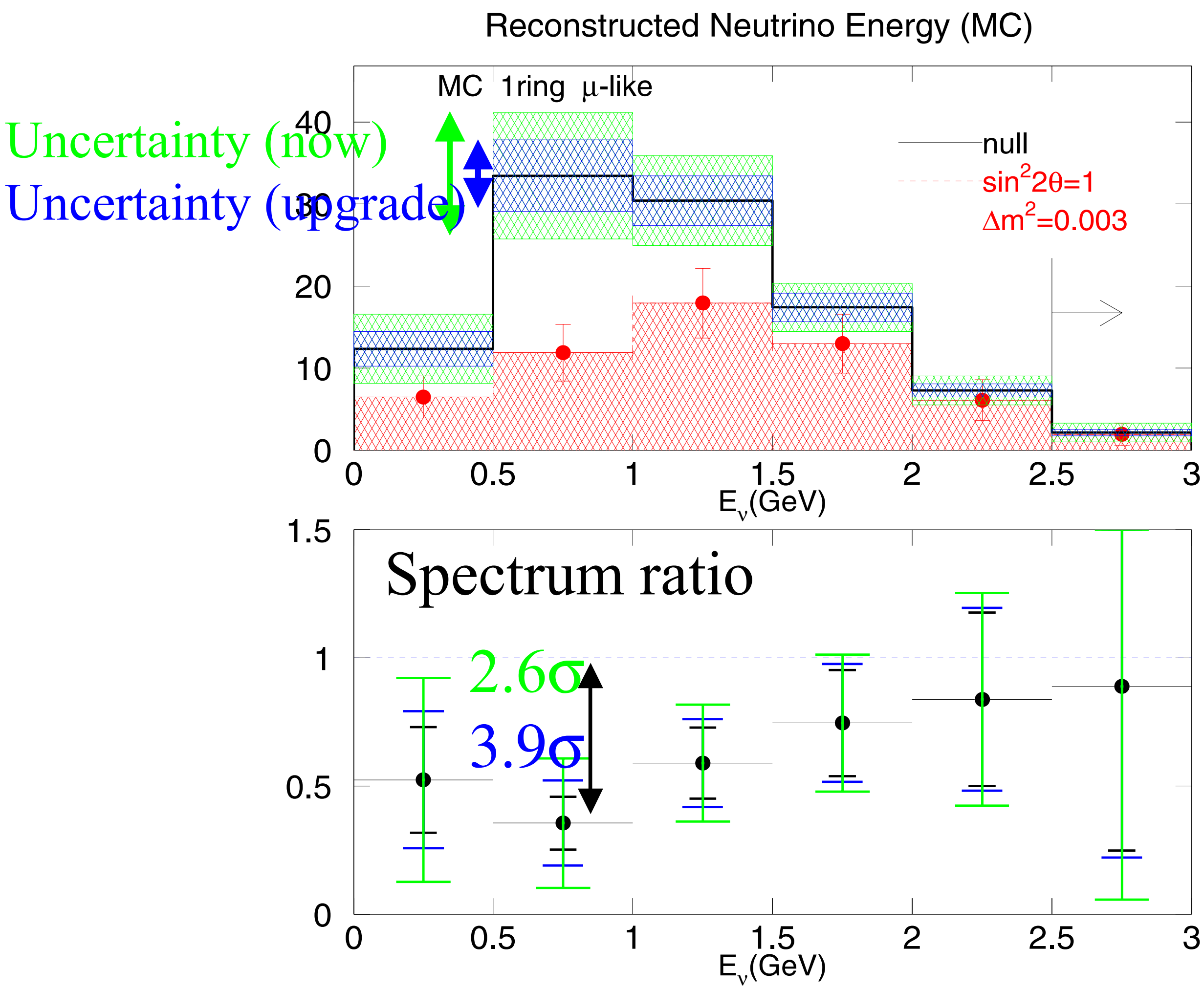
# Upgraded Near Detector



# Event Simulation



# Neutrino Energy spectrum and the ratio w/ and w/o oscillation

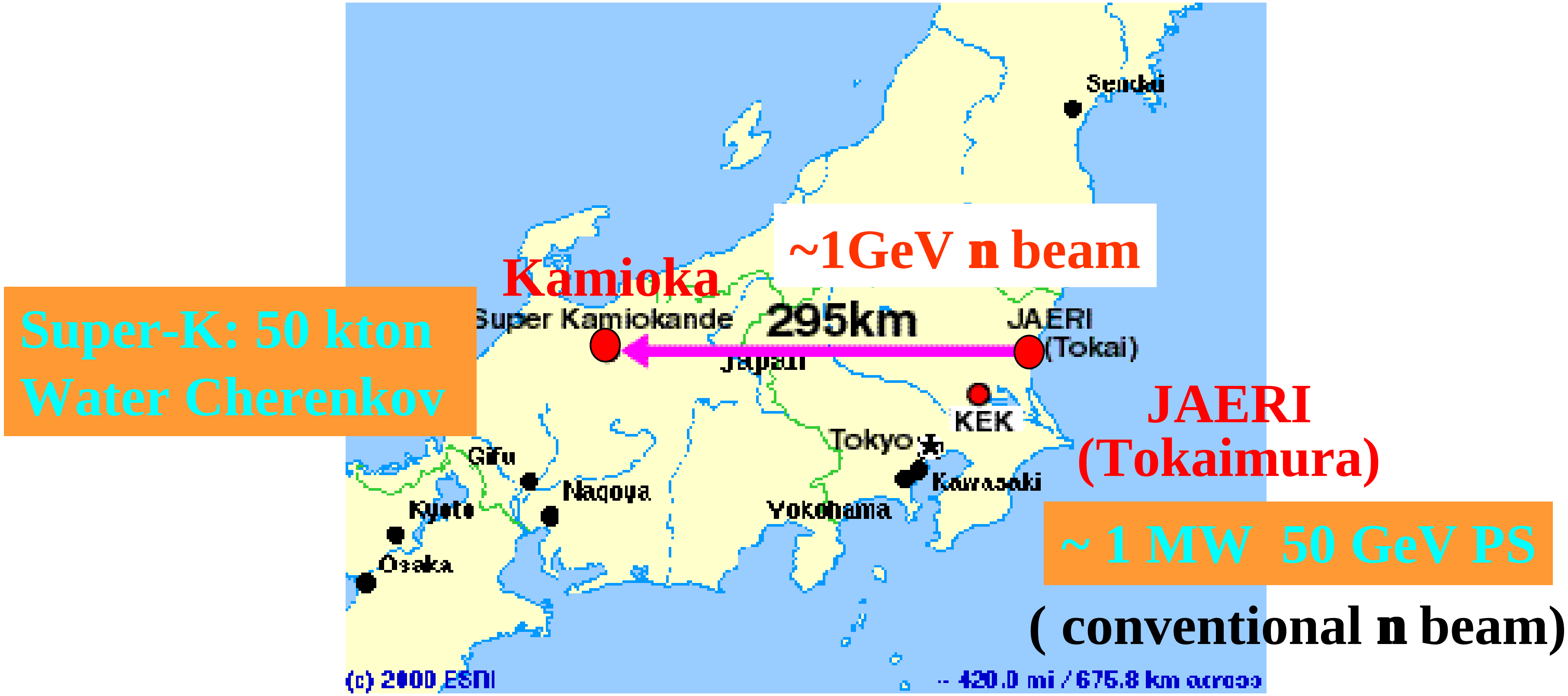


# JHF-to-SK Neutrino Project

http://neutrino.kek.jp/jhfnu/

Letter of Intent: hep-ex/0106019

# Overview



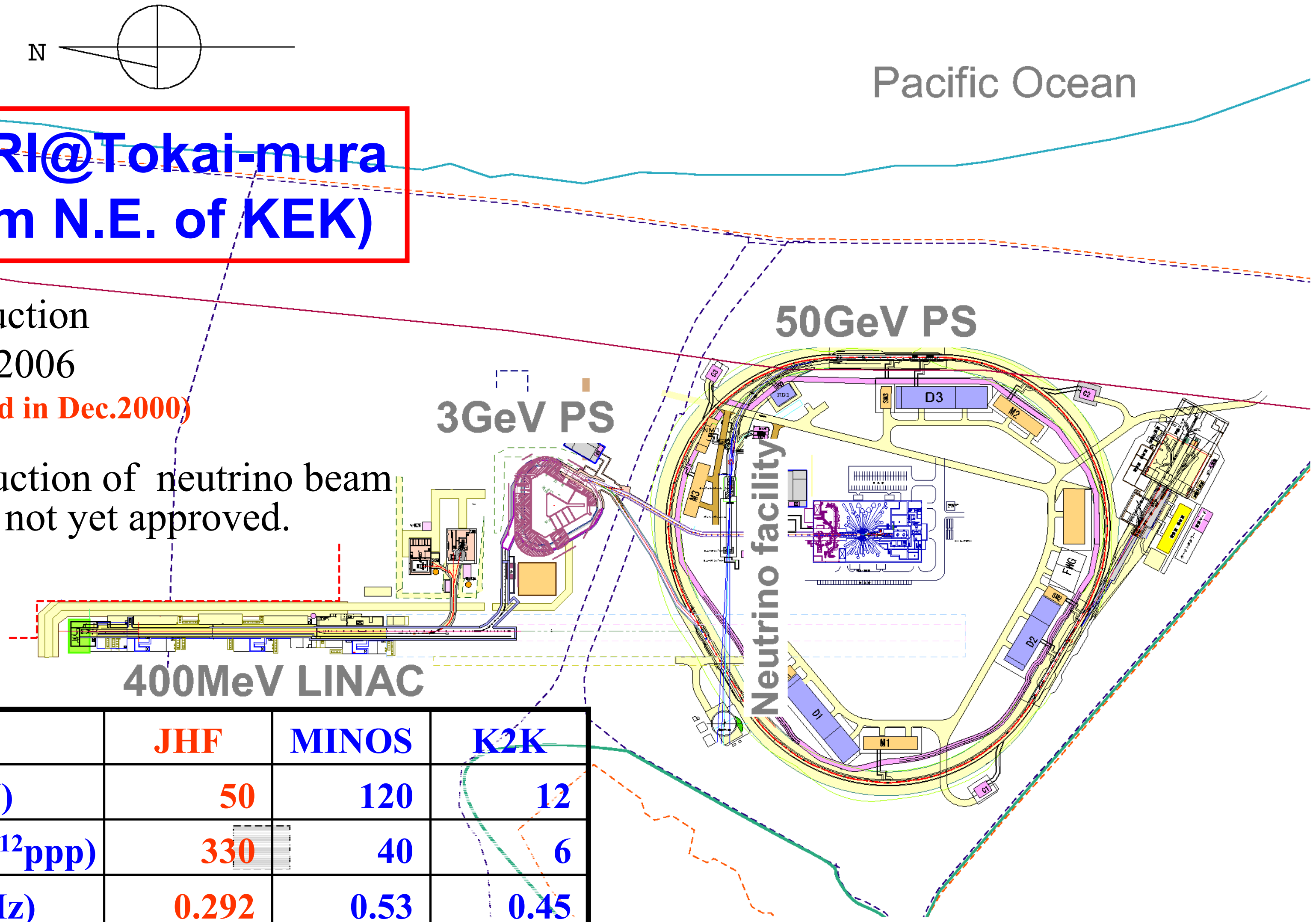

- **nm. nx** disappearance $\delta(\Delta m_{23}^2) \sim 10^{-4}\ \mathrm{eV}^2$, $\delta(\sin^2 2\theta_{23}) \sim 0.01$
- **nm. ne** appearance $\sin^2 2\theta_{13} \sim 0.01$
- NC measurement $\nu_\mu \to \nu_\tau / \nu_\mu \to \nu_s$

# JHK Accelerator Complex

**JAERI@Tokai-mura (60km N.E. of KEK)**

Construction
2001 - 2006
(Approved in Dec.2000)

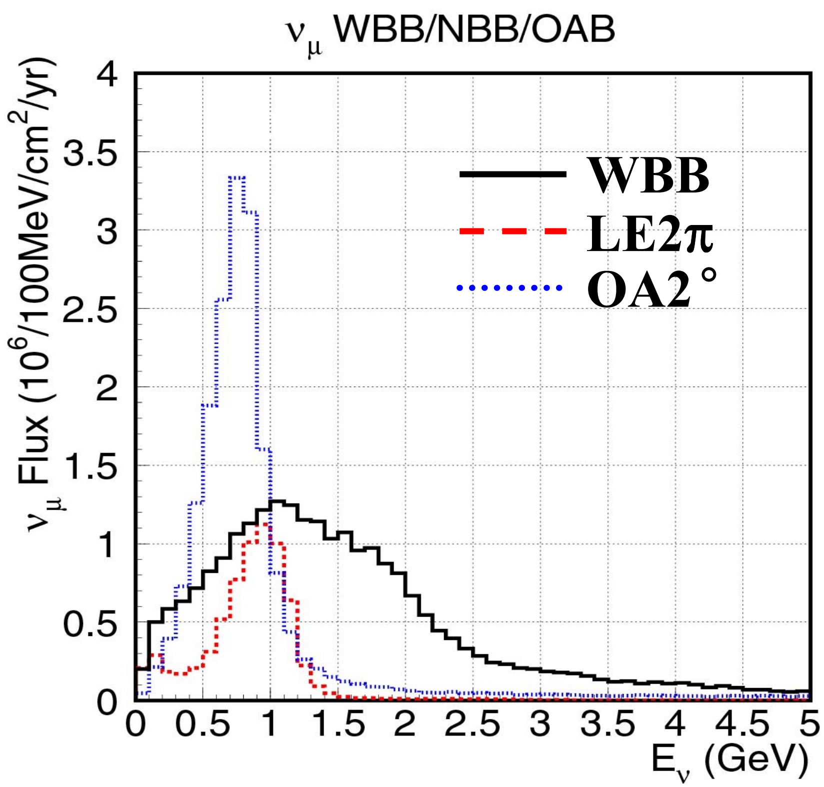
Construction of neutrino beam lines is not yet approved.

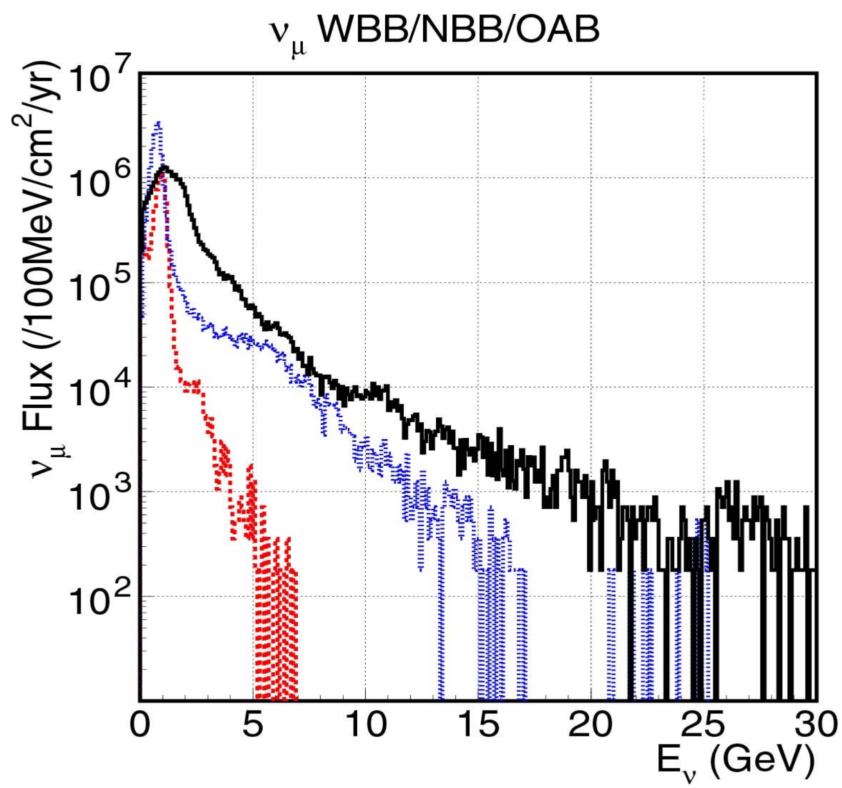



| | JHF | MINOS | K2K |
|---|---|---|---|
| E(GeV) | 50 | 120 | 12 |
| Int.($10^{12}$ppp) | 330 | 40 | 6 |
| Rate(Hz) | 0.292 | 0.53 | 0.45 |
| Power(MW) | 0.77 | 0.41 | 0.0052 |

# Comparison of Three Beams

Target: Cu. 1cm$^{\phi}$, 30cm rod
SK size: 🎙500m

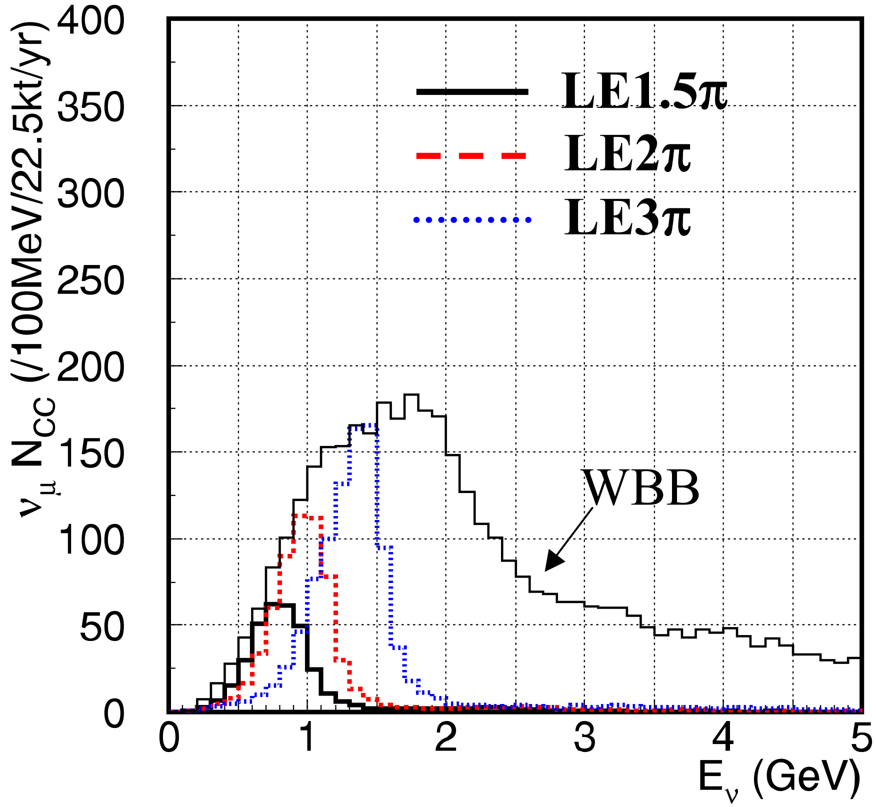


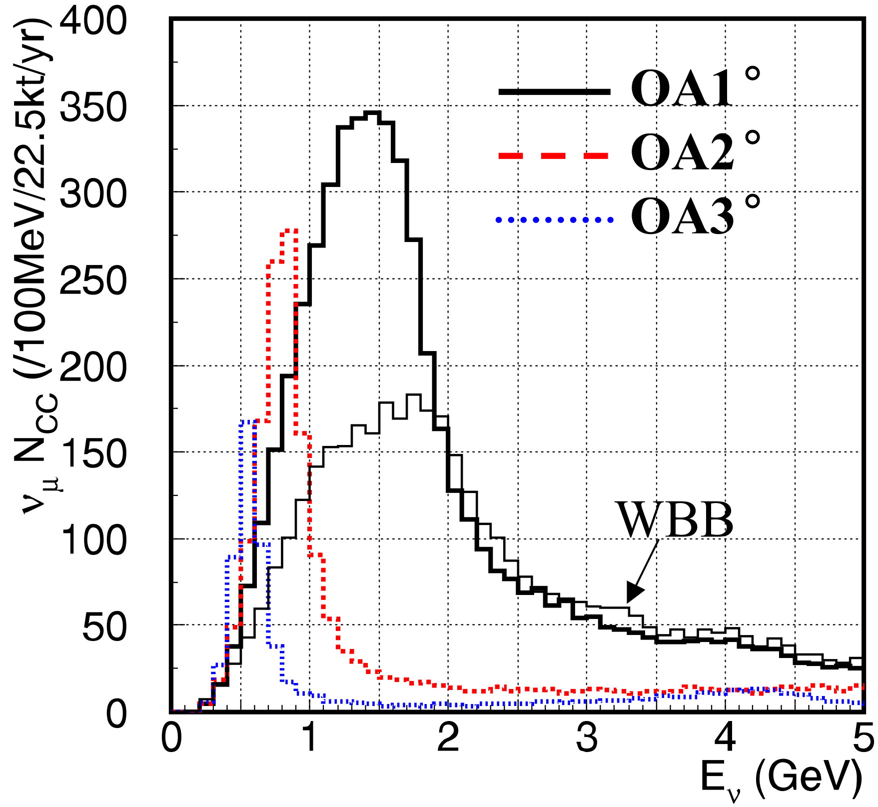




Peak @ 800MeV~1GeV
Sharp peak for NBB/OAB
OAB produce very intense "NBB"

OAB/WBB long HE tail

# Number of CC Events with Various Beams




WBB:**5200** CC int./22.5kt/yr

NBB: **620** CC int./22.5kt/yr (2GeV/c π tune)

OAB: **2200** CC int./22.5kt/yr (2degree)

# MNS Matrix and Parameters

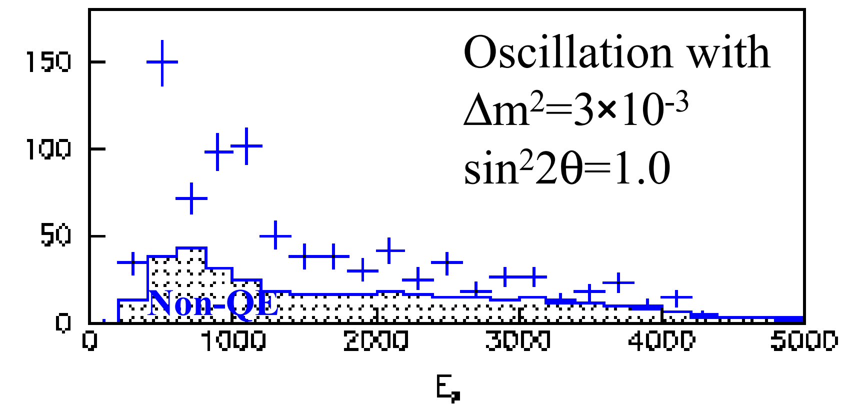
- MNS mixing matrix

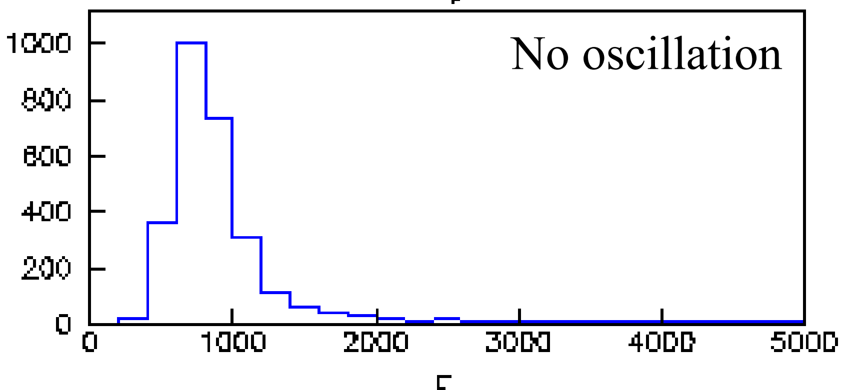
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- three mixing parameters $\theta_{12}, \theta_{13}, \theta_{23}$
- ***a cp*** violating phase $\delta$
- mass-squared differences $\Delta m_{21}^2, \Delta m_{32}^2$

# $\nu_\mu$ Disappearance

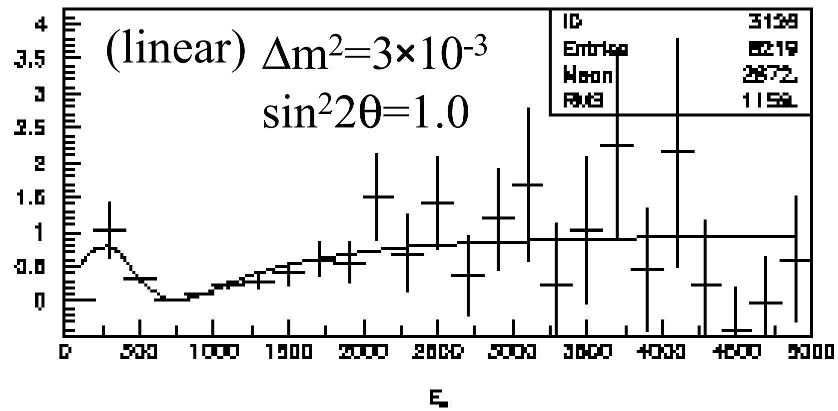
## 1ring FC $\mu$-like

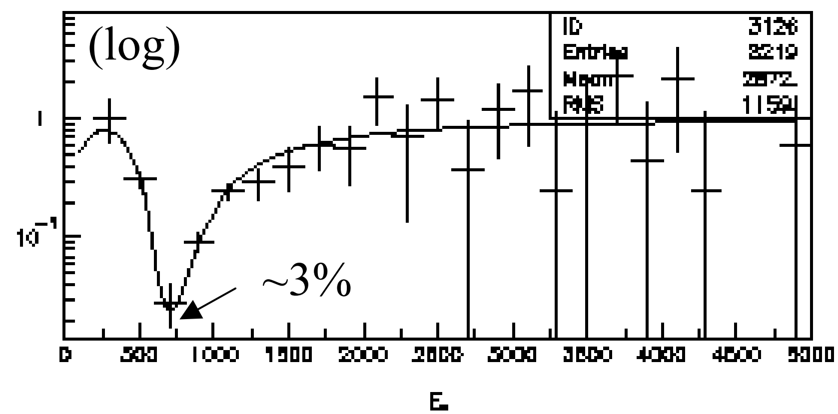



**Reconstructed E$\nu$ (MeV)**

## Ratio after BG subtraction

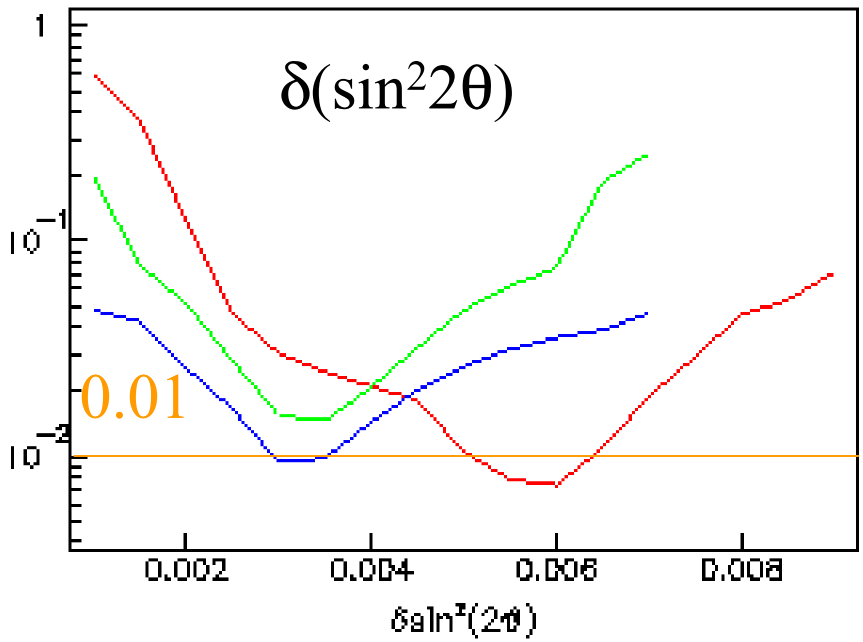


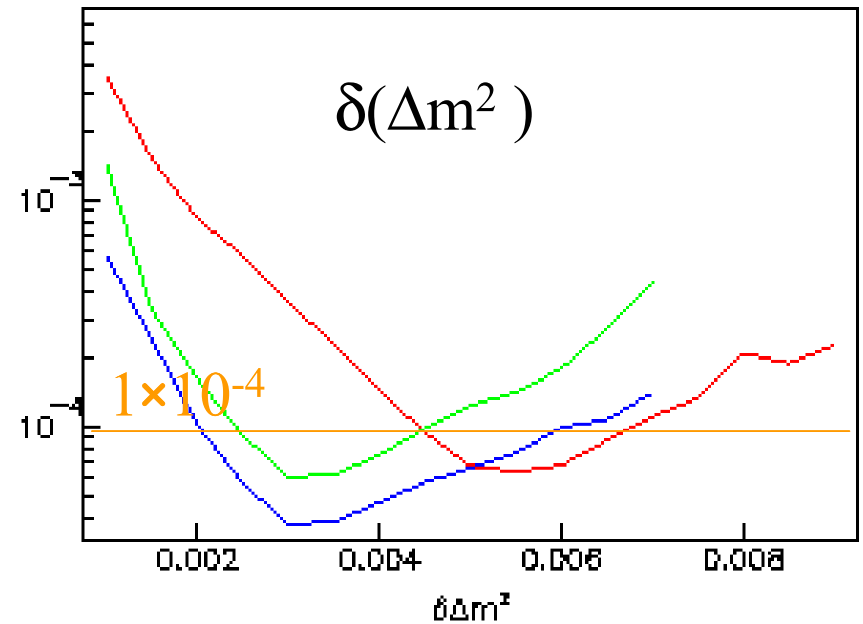




Fit with $1-\sin^2 2\theta \cdot \sin^2(1.27\Delta m^2 L/E)$

# Precision of the Parameters

NBB-3GeVπ, OAB-2degree, NBB-1.5GeVπ



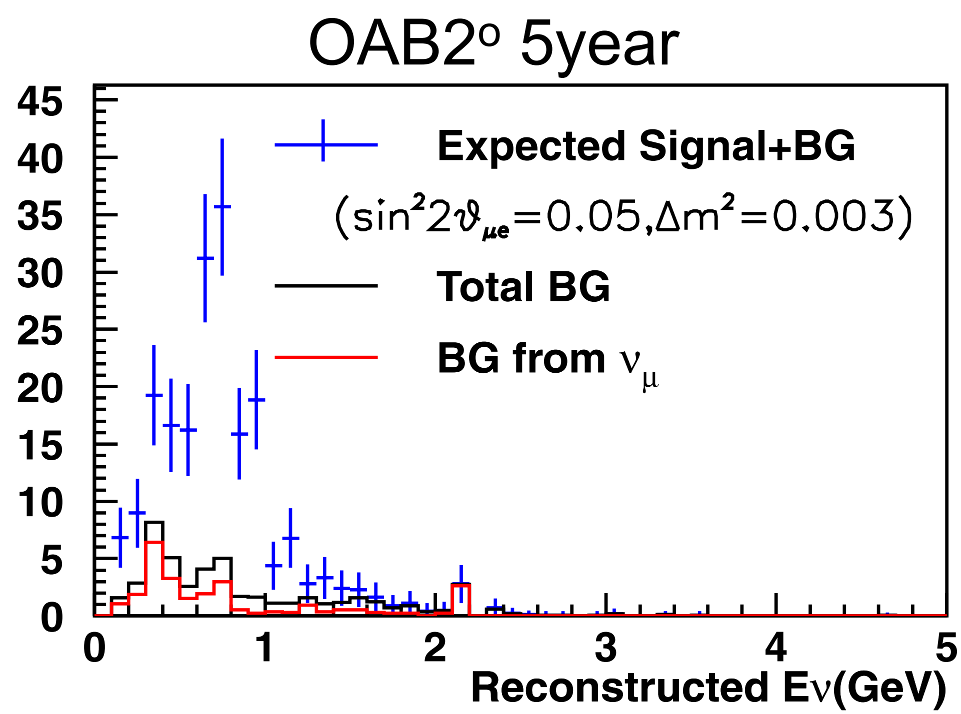




$\delta(\sin^2 2\theta)$□0.01 in 5 years

$\delta(\Delta m^2)$ □<1×$10^{-4}$ in 5 years

# $\nu_e$ Appearance: Expected Signal and Background

- Reconstruct $E_\nu$ as Quasi-Elastic interaction
- Apply Energy Cut
  - 0.4GeV< E <1.2GeV (OAB2°)



# $\nu_e$ Appearance: Sensitivities

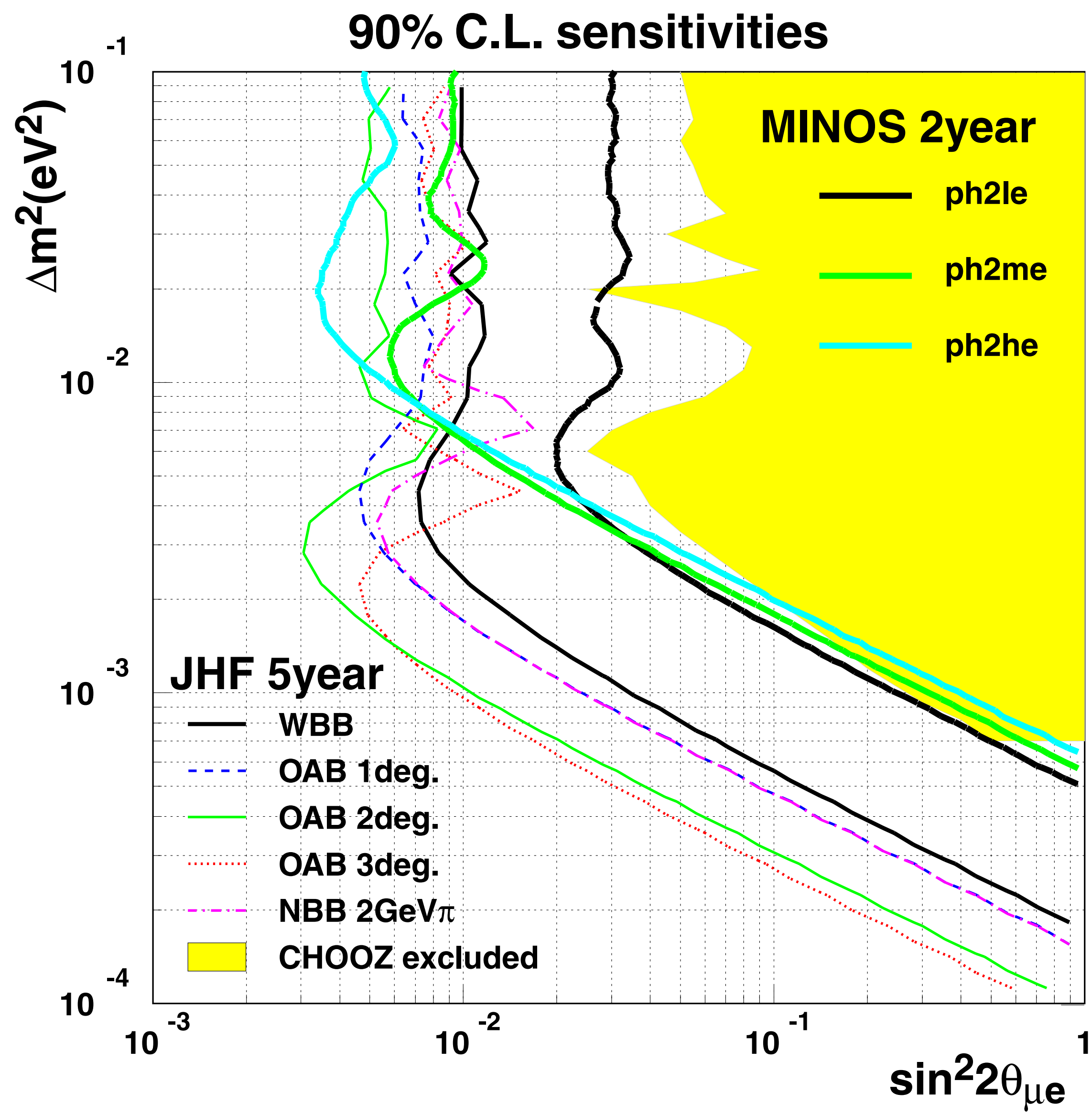
In the SK allowed region

$1.5\times10^{-3}<\Delta m^2<5\times10^{-3}$ eV$^2$:

$\sin^2 2\theta_{\mu e}$□0.005

or

$\sin^2 2\theta_{13}$□0.01

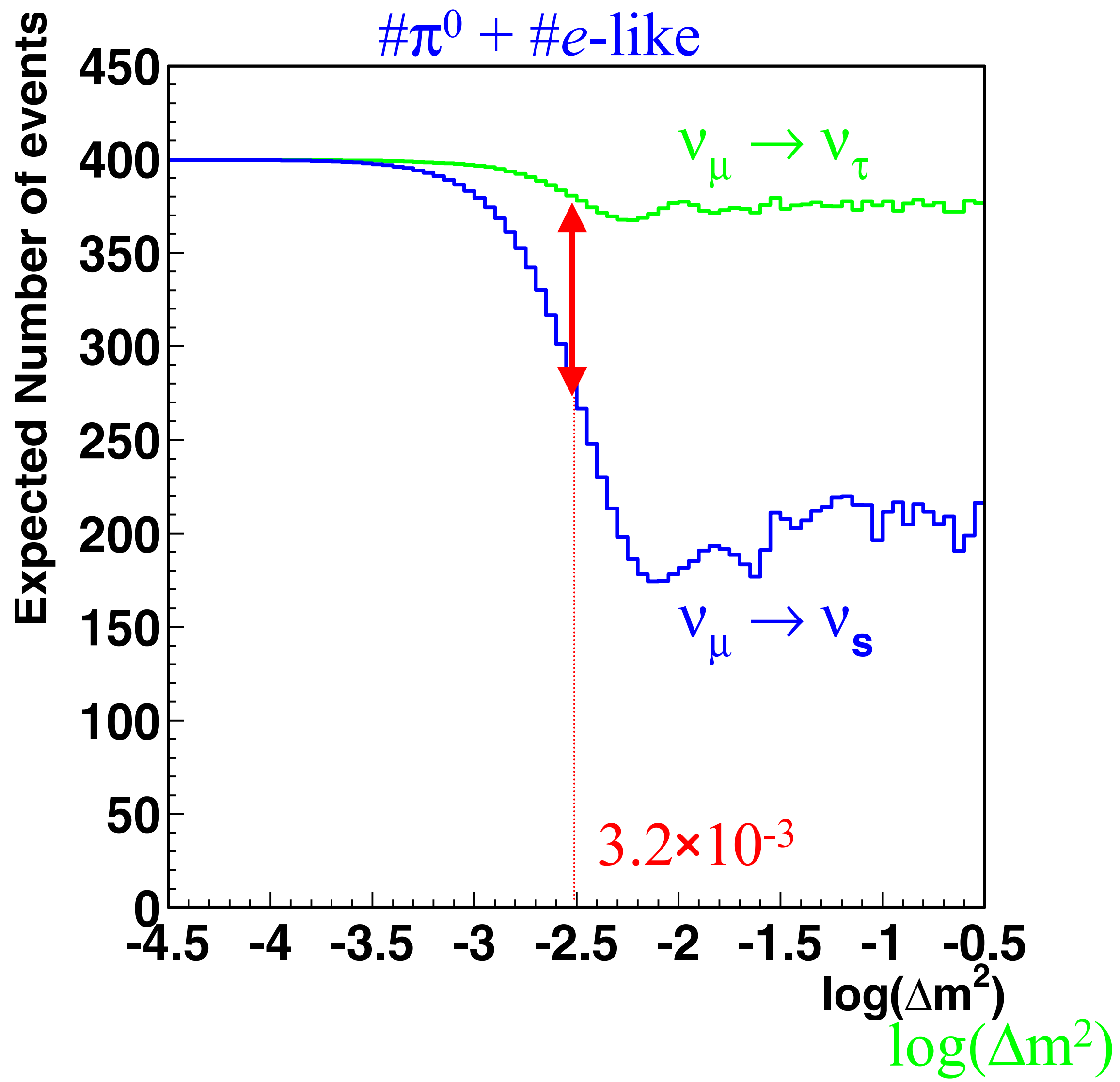


# NC Measurement

# of NC events

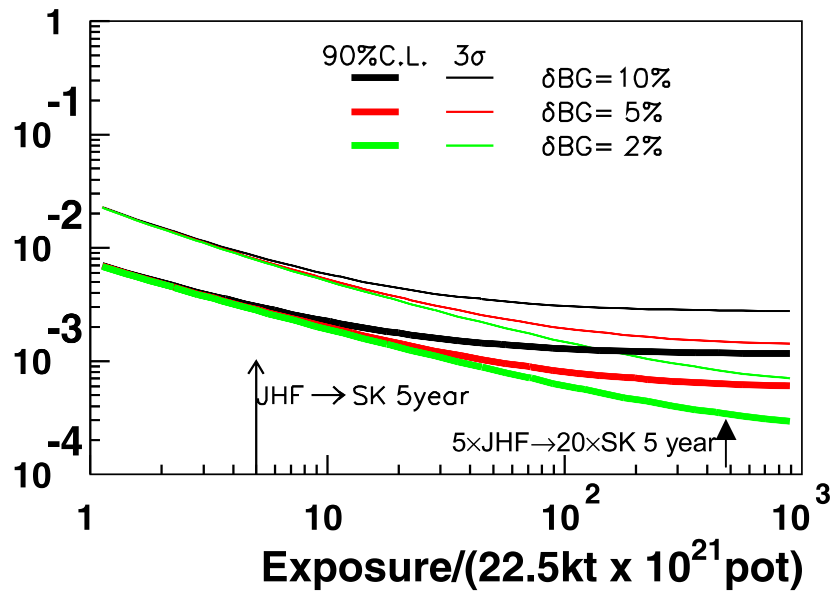
$$N_{NC} \propto P_{\mu\rightarrow active} = 1 - P_{\mu\rightarrow sterile}$$

- NC/CC sensitive to $\nu_s$
- NC Enriched Sample



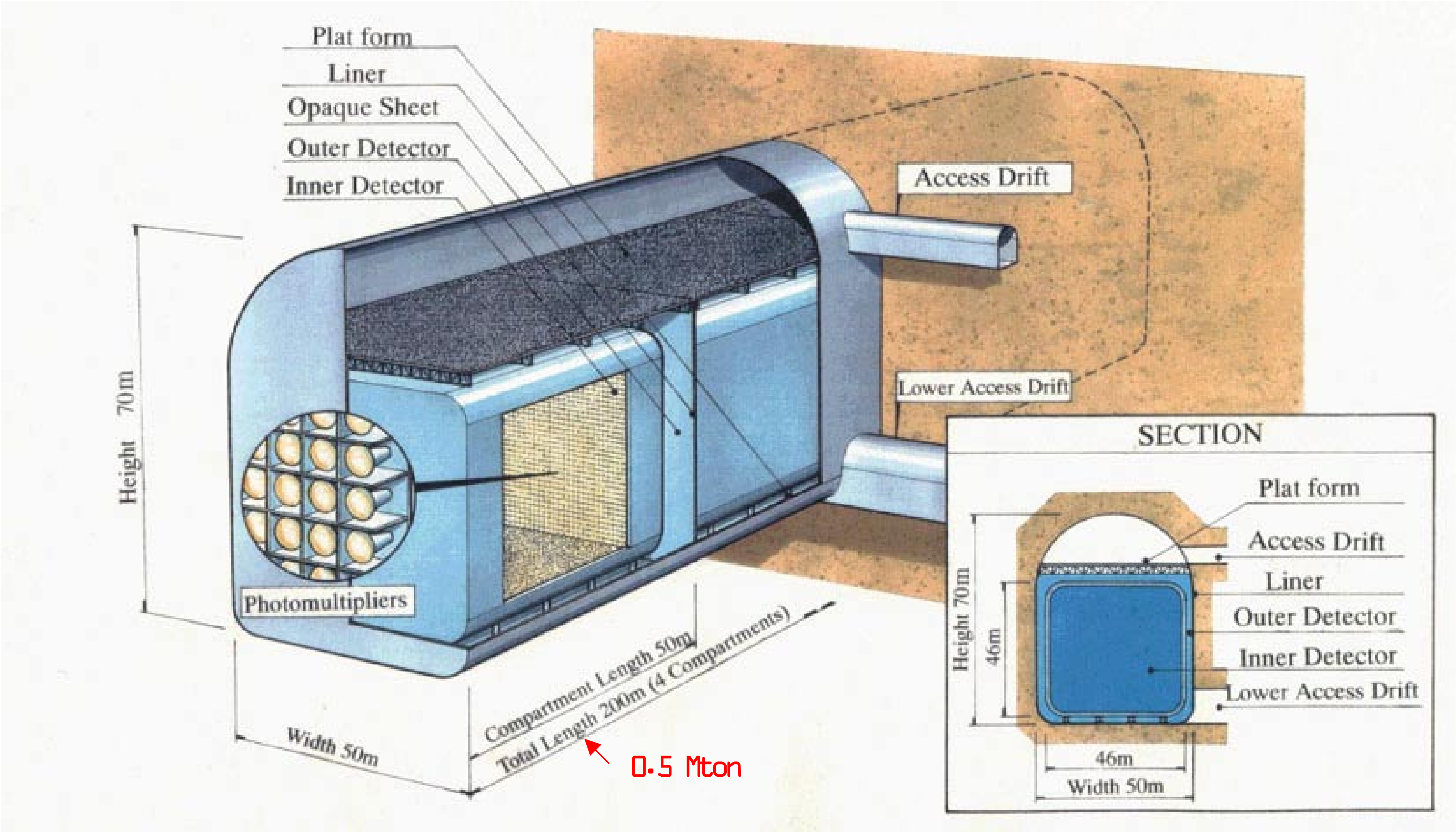
# JHF-to-SK ν Second Phase

- Hyper-Kamiokande: 1 Mton water Cherenkov detector
- JHF beam power upgrade: 4MW
  - ⇒ ×200 statistics
- Goal of the 2nd phase
  - – $\sin^2 2\theta_{13}$ sensitivity below $10^{-3}$ (if $\theta_{13}$ not discovered in the $1^{st}$ phase)




  - – CP phase δ to 10 – 20 degrees (if the solution to the solar neutrino problem is MSW-LMA)
  - – Proton decay ($p \to K\nu$, $e^+\pi^0$)

# Hyper-Kamiokande: A Next-Generation Nucleon Decay Detector at Kamioka

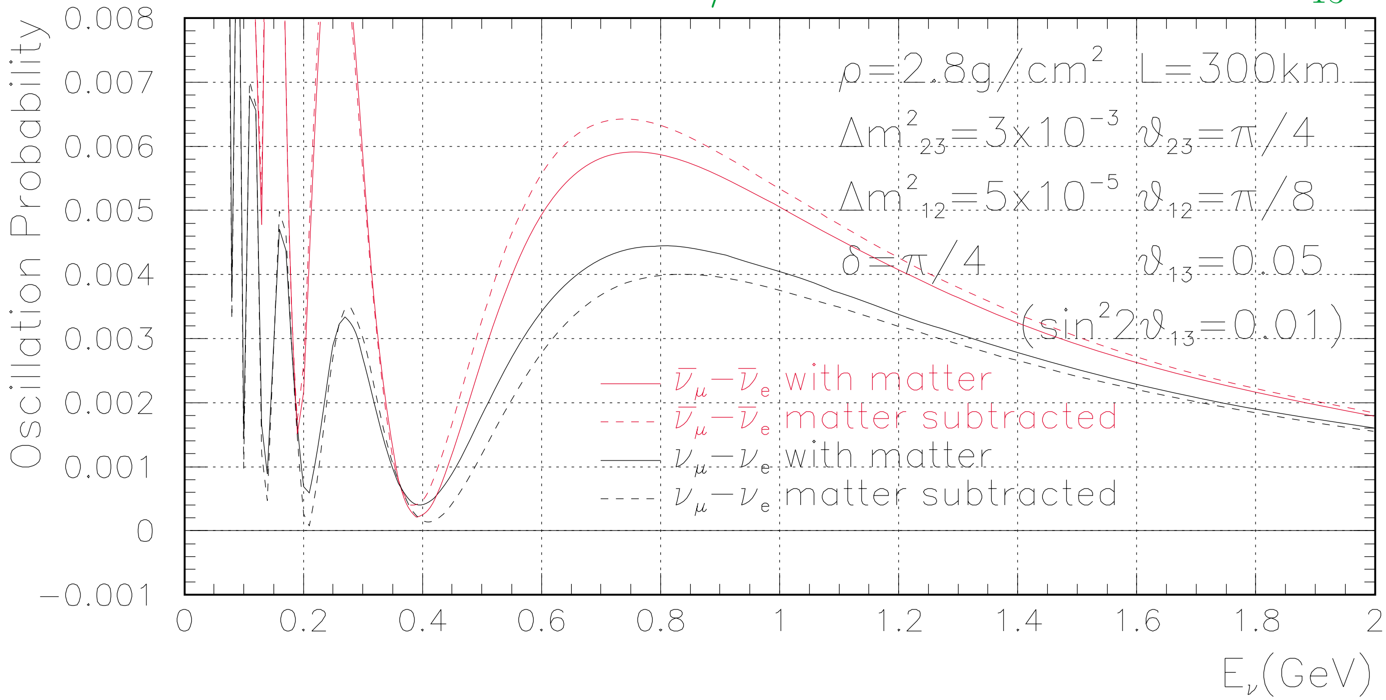



1 Mton: Total Length 400m (8 Compartments)

# CP Violation

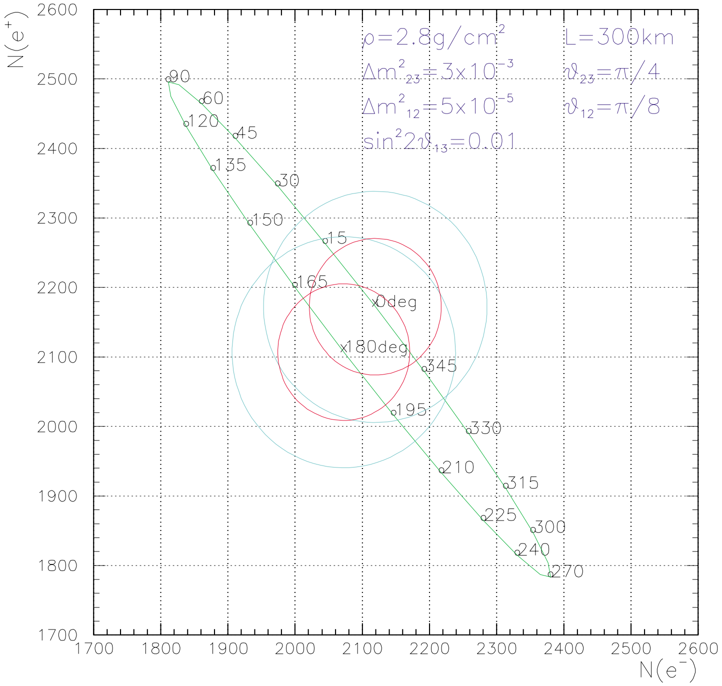
$$A_{CP} = \frac{Prob(\nu_\mu \to \nu_e) - Prob(\bar{\nu}_\mu \to \bar{\nu}_e)}{Prob(\nu_\mu \to \nu_e) + Prob(\bar{\nu}_\mu \to \bar{\nu}_e)}$$
$$= \frac{1.27 \Delta m^2_{12} L}{E} \cdot \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot sin\delta$$

Central values of LMA and 1/10 of reactor limit in $\sin^2 2\theta_{13}$



# CP Sensitivity

## CP sensitivity




- Ocillation maximum and low neutrino energy
  Signal enhancement relative to the backgrounds.
- Double ratio: **cancellation of systematic errors**

$$\frac{P_{\nu_\mu\to\nu_e}(far)}{P_{\nu_\mu}(near)} / \frac{P_{\bar{\nu}_\mu\to\bar{\nu}_e}(far)}{P_{\bar{\nu}_\mu}(near)}$$

- CP phase $\delta$ can be measured down to 10-20 degrees.