Latest Results of K2K

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Contents

Neutrino Oscillation

Neutrino Mixing

$$|\nu_l\rangle = \Sigma V_{li} |\nu_i\rangle$$

Weak eigenstates — Mass eigenstates

Maki-Nakagawa-Sakata Matrix

$$V = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix}$$

Oscillation Probability

$$P_{l\to m} = \left| \langle \nu_m(t) | \nu_l(0) \rangle \right|^2$$

$$= \delta_{ml} - 2\sum_{i<j} \mathrm{Re}\left[\left(V^*_{mi} V_{li}\right) \cdot \left(V_{mj} V^*_{lj}\right) \cdot \left\{ 1 - \exp\left(-i \frac{\Delta m^2_{ij}}{2E} L \right) \right\} \right]$$

L : flight length, E : neutrino energy, $\Delta m^2_{ij} \equiv m_i^2 - m_j^2$

mass eigenvalues

$$P_{l\to m} \neq \delta_{ml} \Leftrightarrow \Delta m_{ij} \neq 0$$

Motivation

Evidence of osc. in atm. ν observation by SK

$\Delta m^2 = 2\sim5 \text{ x } 10^{-3} \text{ eV}^2$
$\sin^2 2\theta > 0.88$
almost $\nu_\mu \rightarrow \nu_\tau$

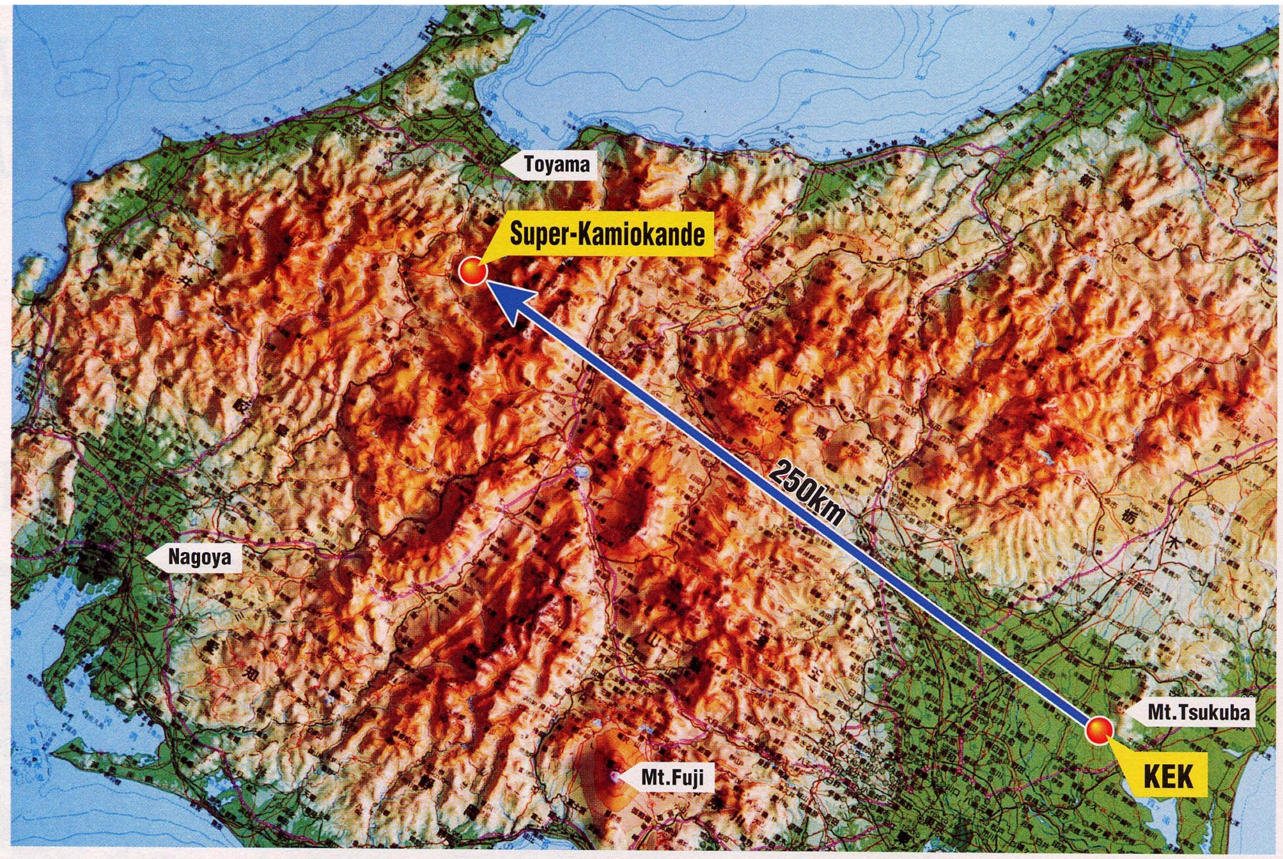
Neutrino Oscillation(2flavors)

$$p = \sin^2 2\theta \cdot \sin^2(1.27\Delta m^2 L / E_\nu)$$

K2K: **Establish non zero neutrino mass**
well defined flight length (=250 km)
well defined artificial pure ν_μ beam

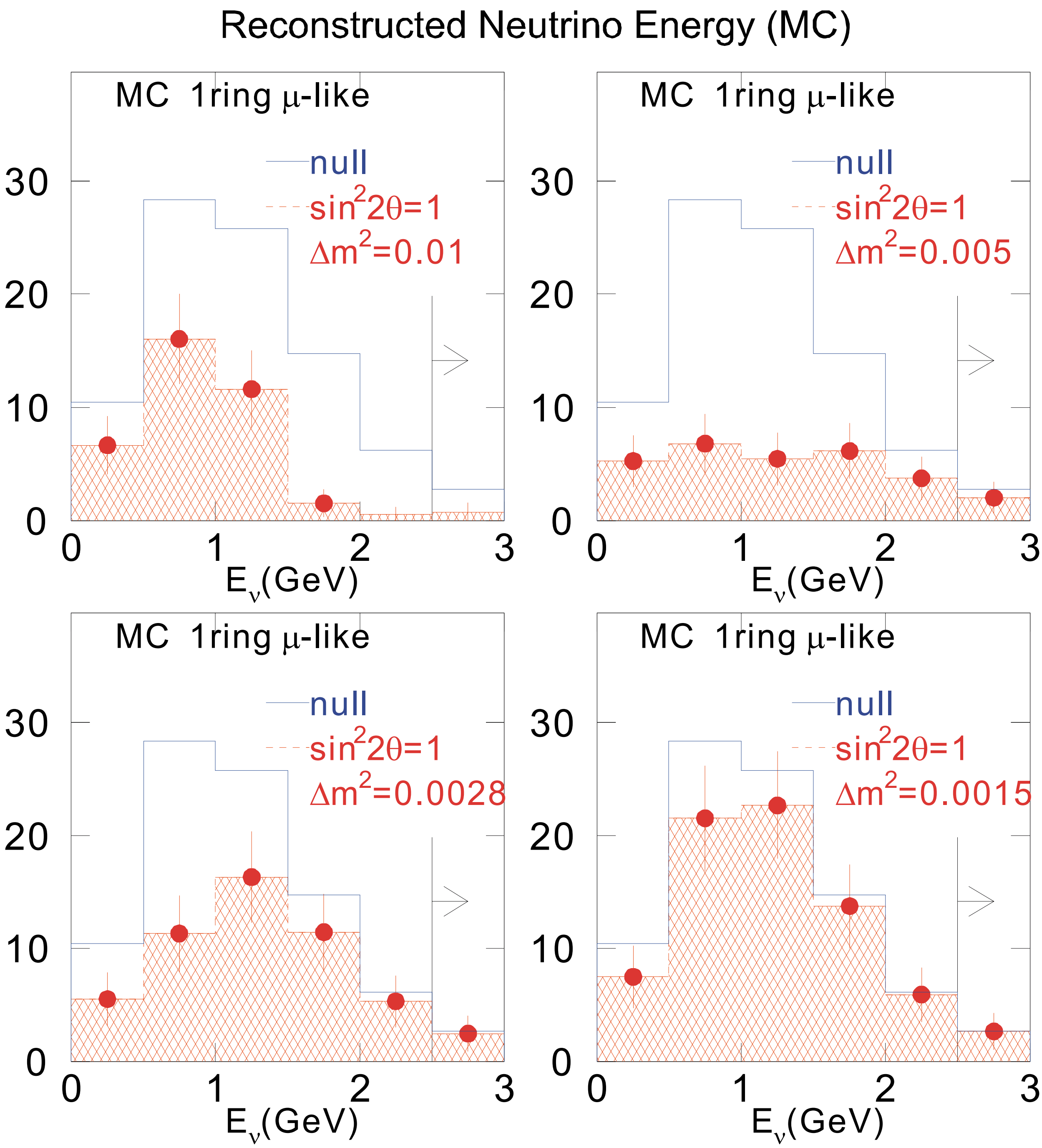
	L	E	E/L	ν_μ/ν_e
Atm ν	10～10^4km	<5GeV	0.5～$5\text{x}10^{-4}$	2/1
K2K	250km	～1GeV	$4\text{x}10^{-3}$	99/1

K2K Overview



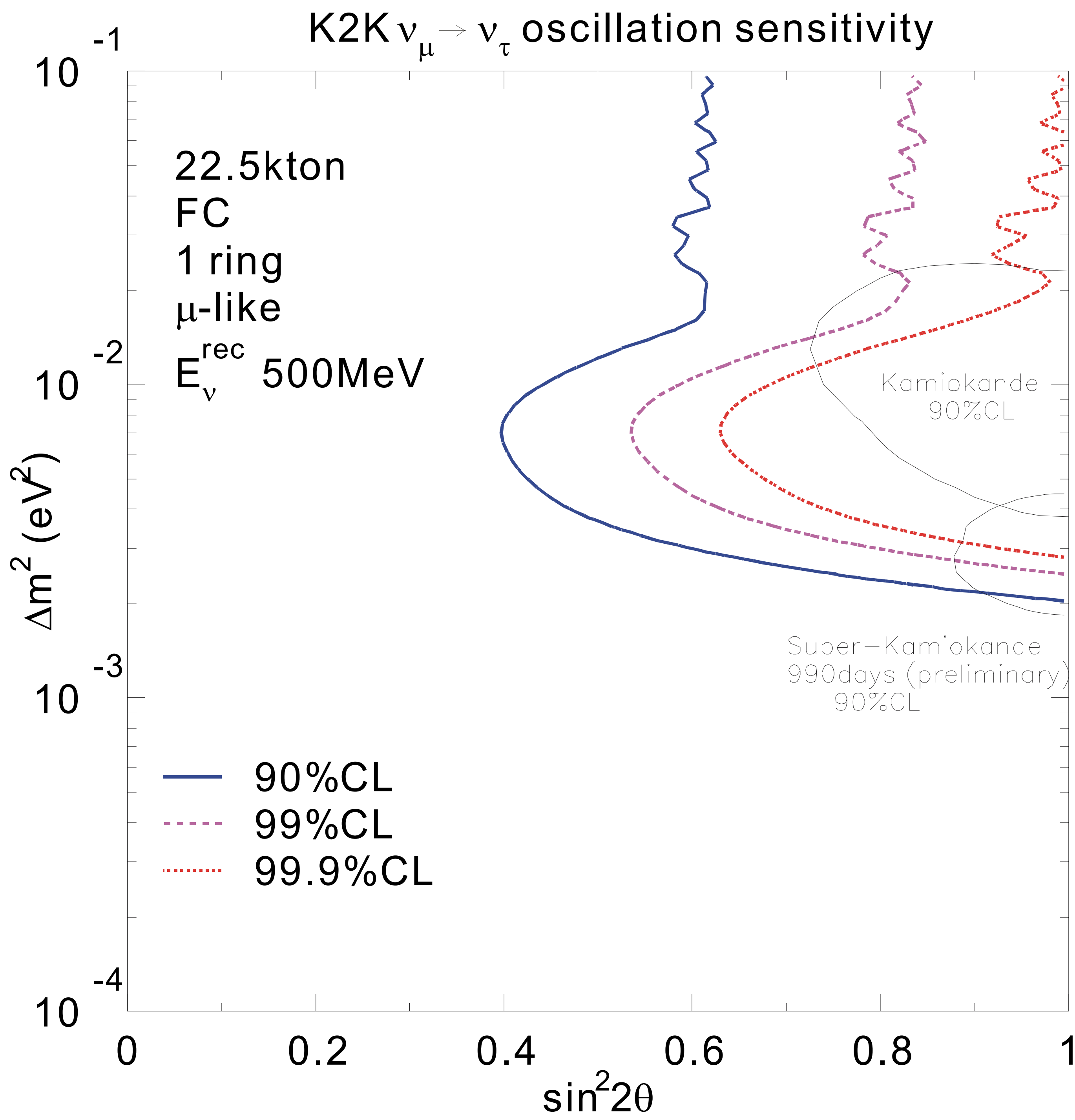
- almost pure ν_μ(99%) beam w/ <E_ν> ~ **1.3GeV**
- Far detector: Super Kamiokande(SK)@**250km**
- Most sensitive at $\Delta m^2 \sim 7\text{x}10^{-3}\ \text{eV}^2$
- ν_μ disappearance and ν_e appearance

Expected Signal



Sensitive Region

10^{20} POT (～5year)

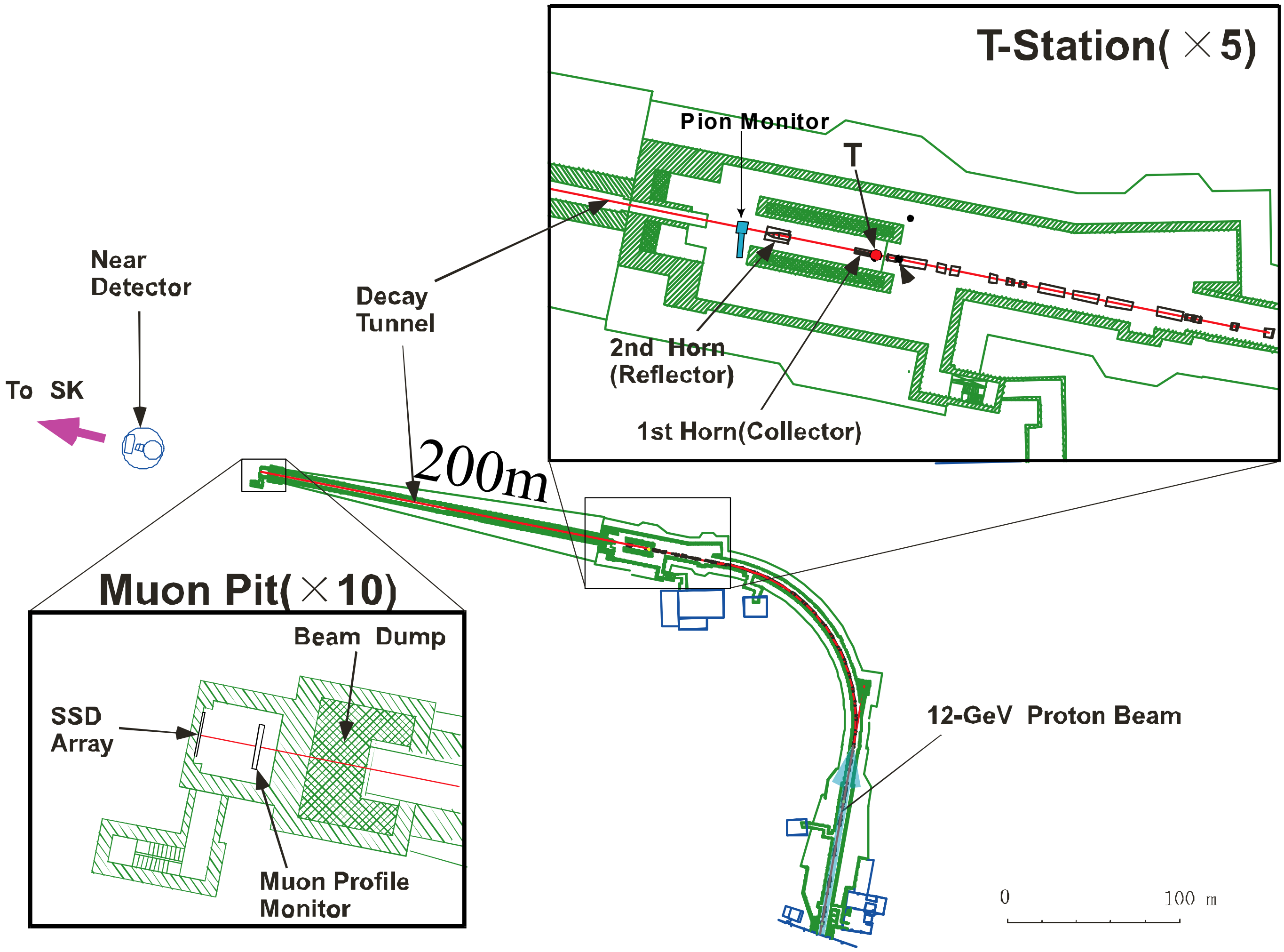


Experimental Setup

Neutrino Beam Production

$p+\mathrm{Al} \rightarrow \pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$

$\mu^{+} \rightarrow e^{+}+\nu_{e}+\bar{\nu}_{\mu}(1\%)$

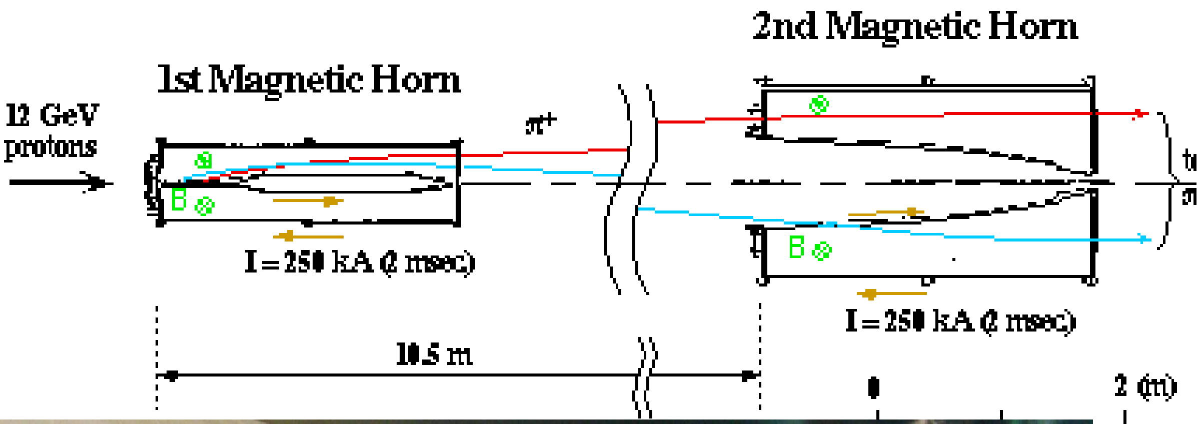


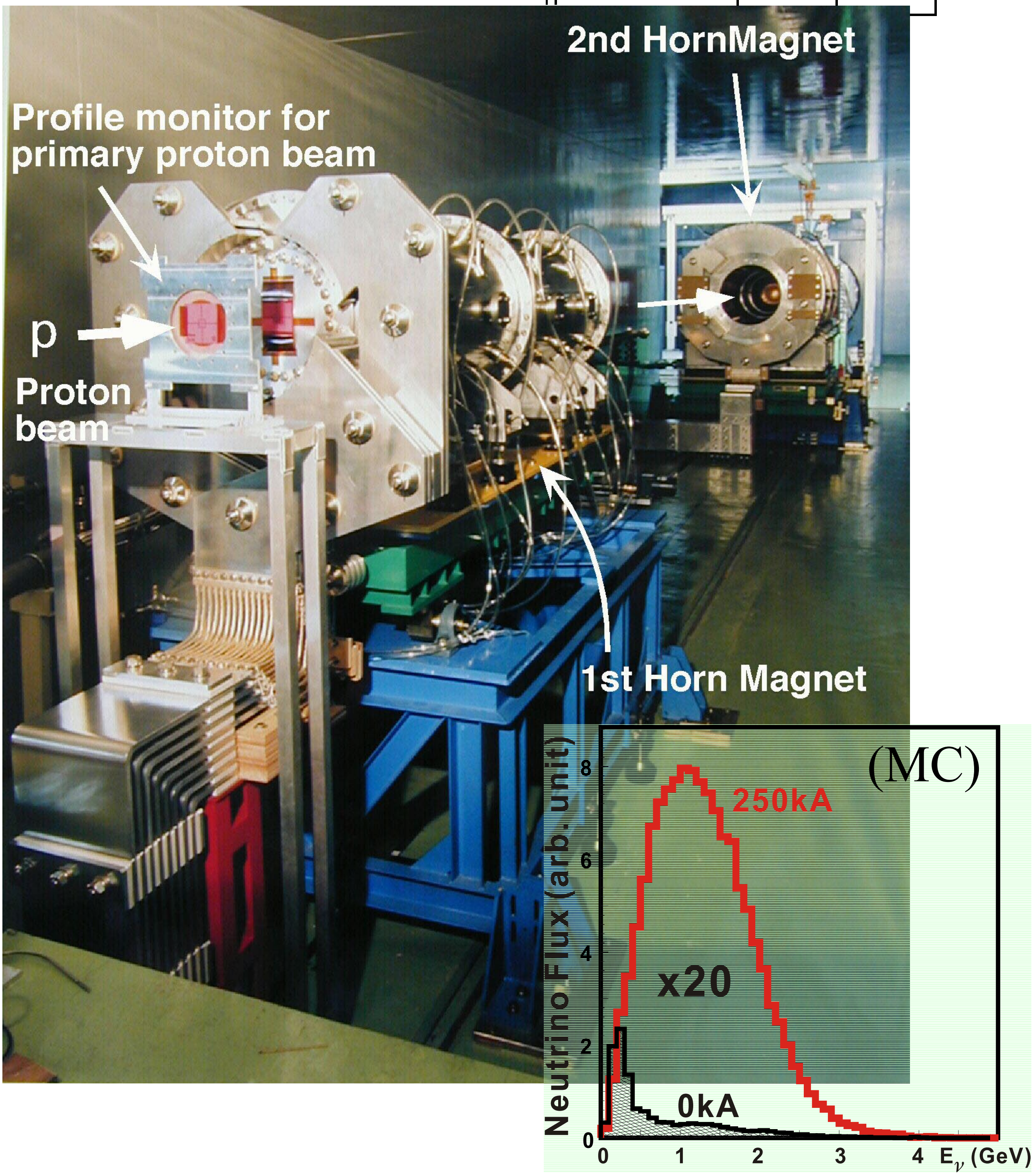
PS: 13GeV/c proton
1.1μsec spill/2.2sec
6×10^{12}protons/spill (design)

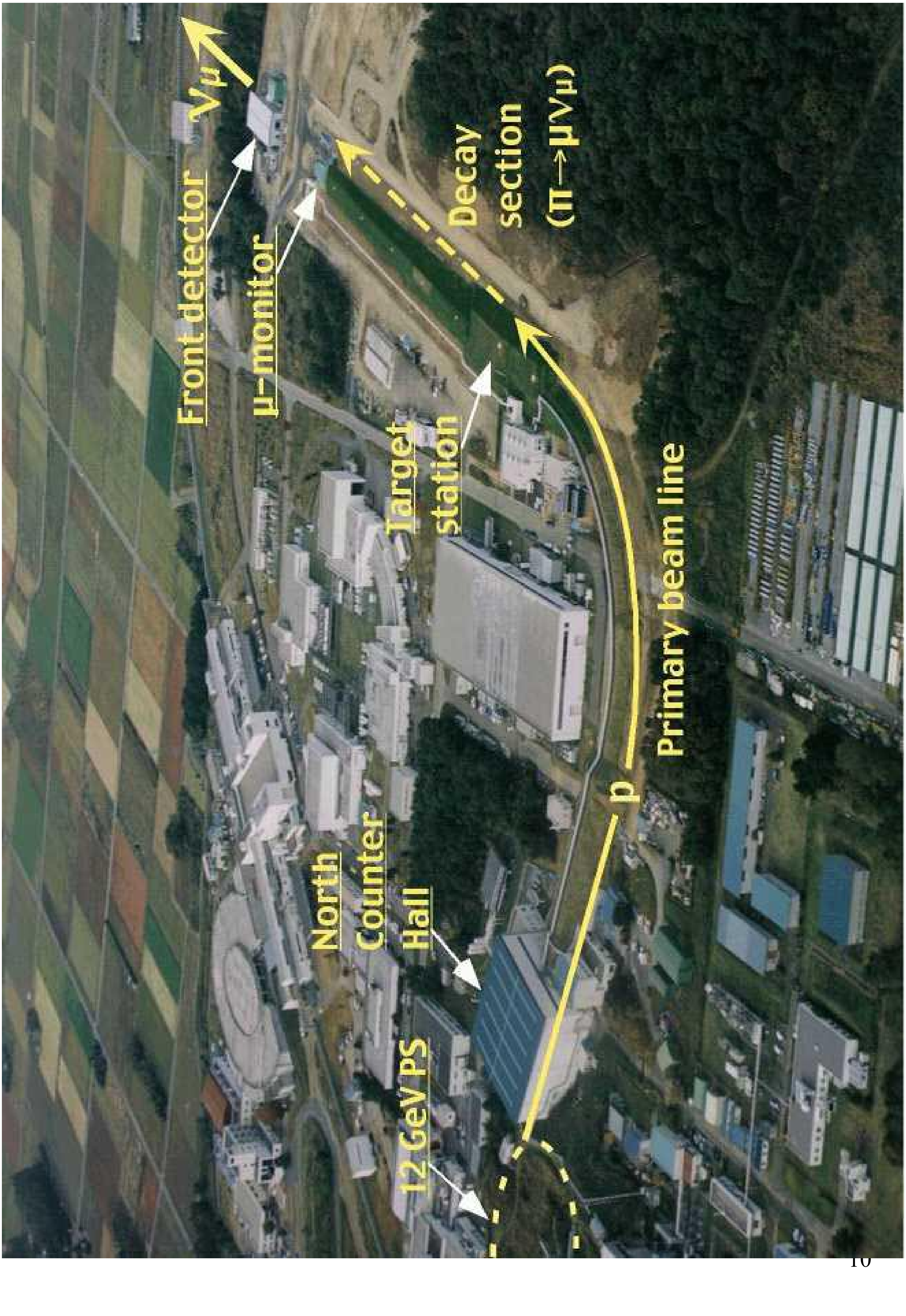
Beam line: aligned toward SK using GPS
(global positioning system)
GPS< 0.01mrad, civil const<0.1mrad

Decay pipe: 200m

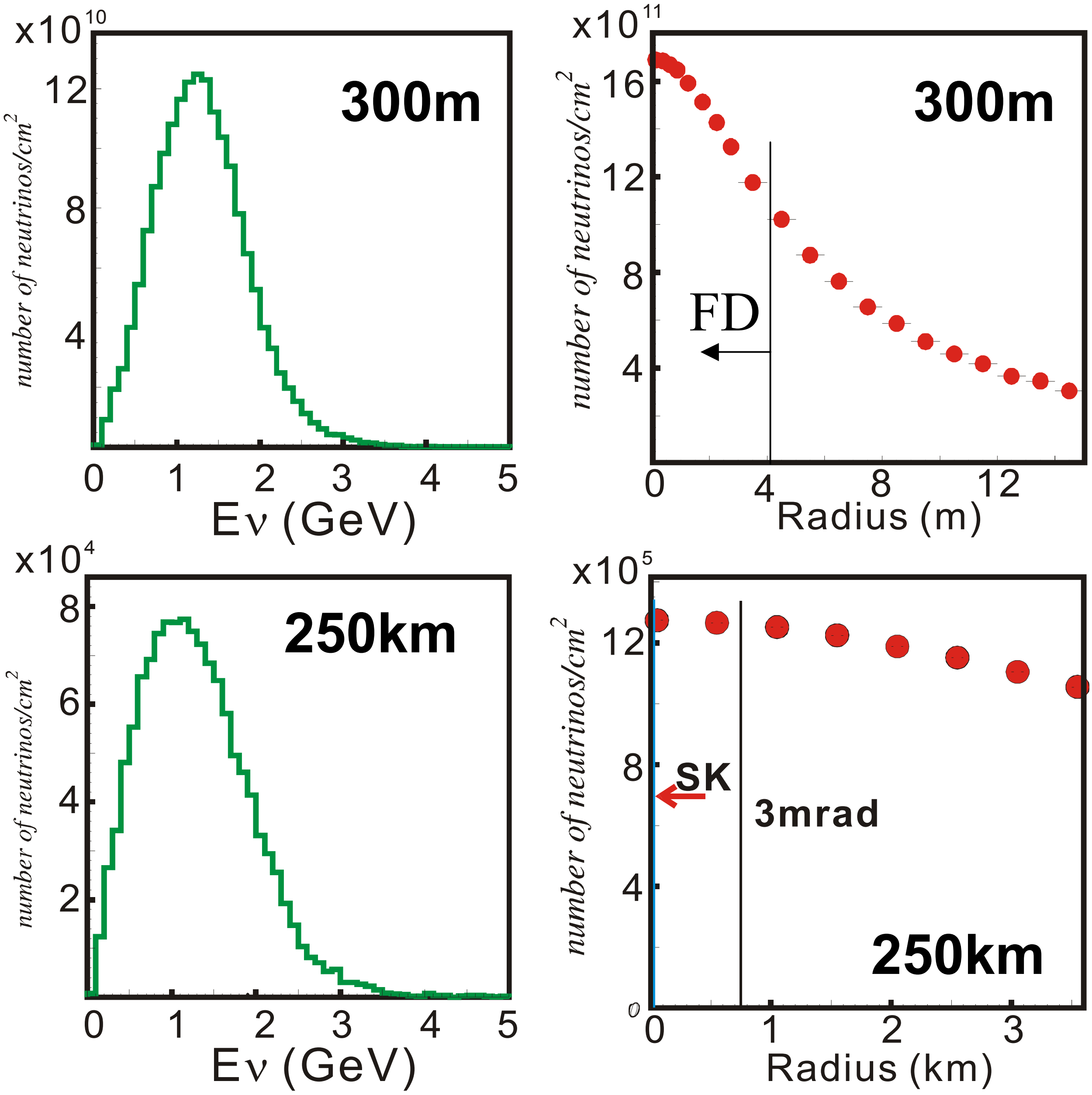
Target and Horns






Front detector
μ-monitor
ν_μ
Decay
section
($\pi \to \mu\nu_\mu$)
Target
station
Primary beam line
p
North
Counter
Hall
12 GeV PS

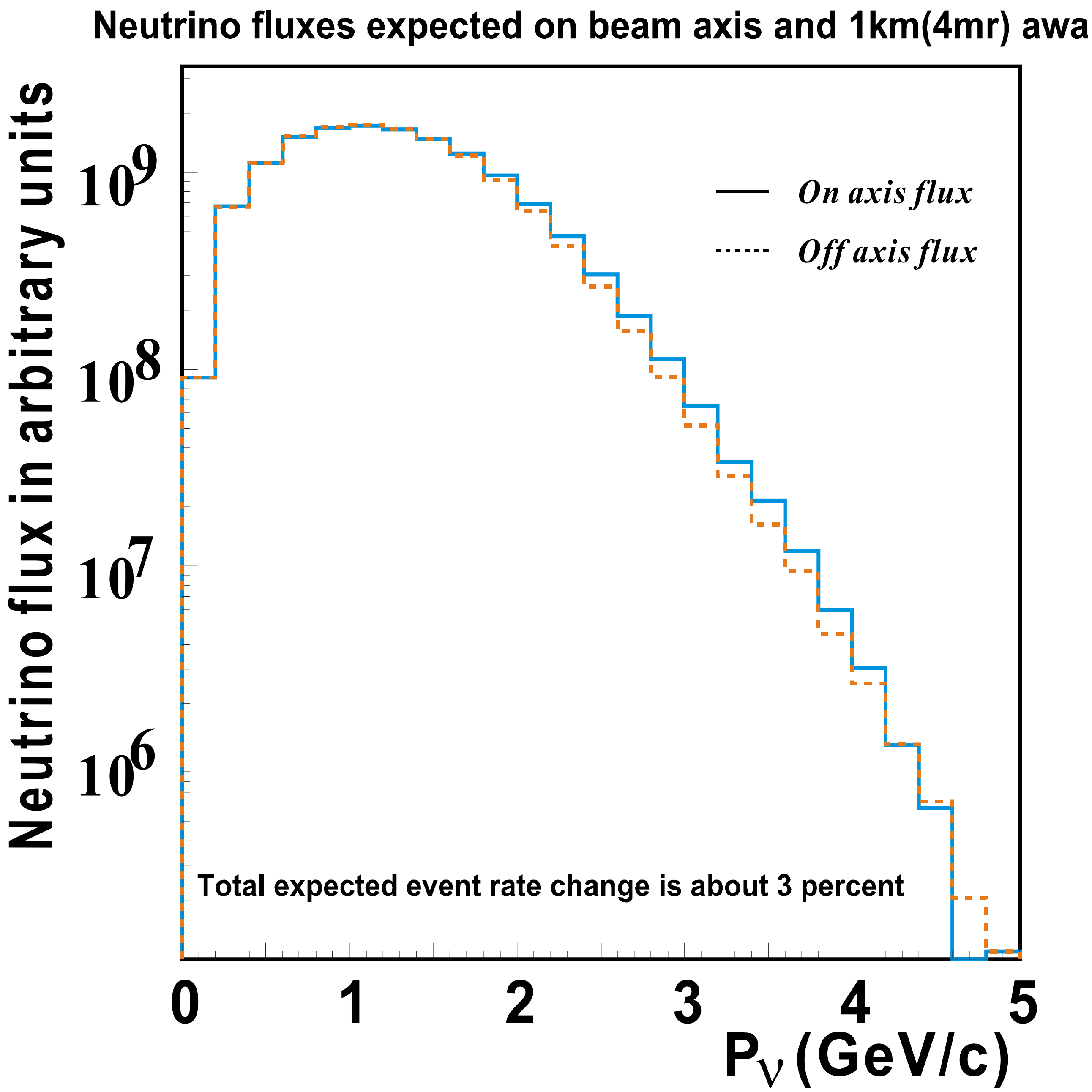
Neutrino Spectra and Radial Distributions at 300m/250km (MC)



Almost const flux < 3mr(750m) @ SK

Near/Far spectra differ

Spectrum Distortion at Off axis **(MC)**



Roles of Detectors in KEK

- Neutrino beam direction
  - Front neutrino detector (FD) (direct)
  - Muon monitor (indirect, fast)
- Absolute neutrino flux
  - FD
- Spectrum extrapolation from near(KEK) to far(250km)
  - Pion monitor
- Neutrino spectrum
  - FD
  - Pion monitor
- Study neutrino interaction
  - Future

⇒ **Expected # of SK events**

Pion Monitor

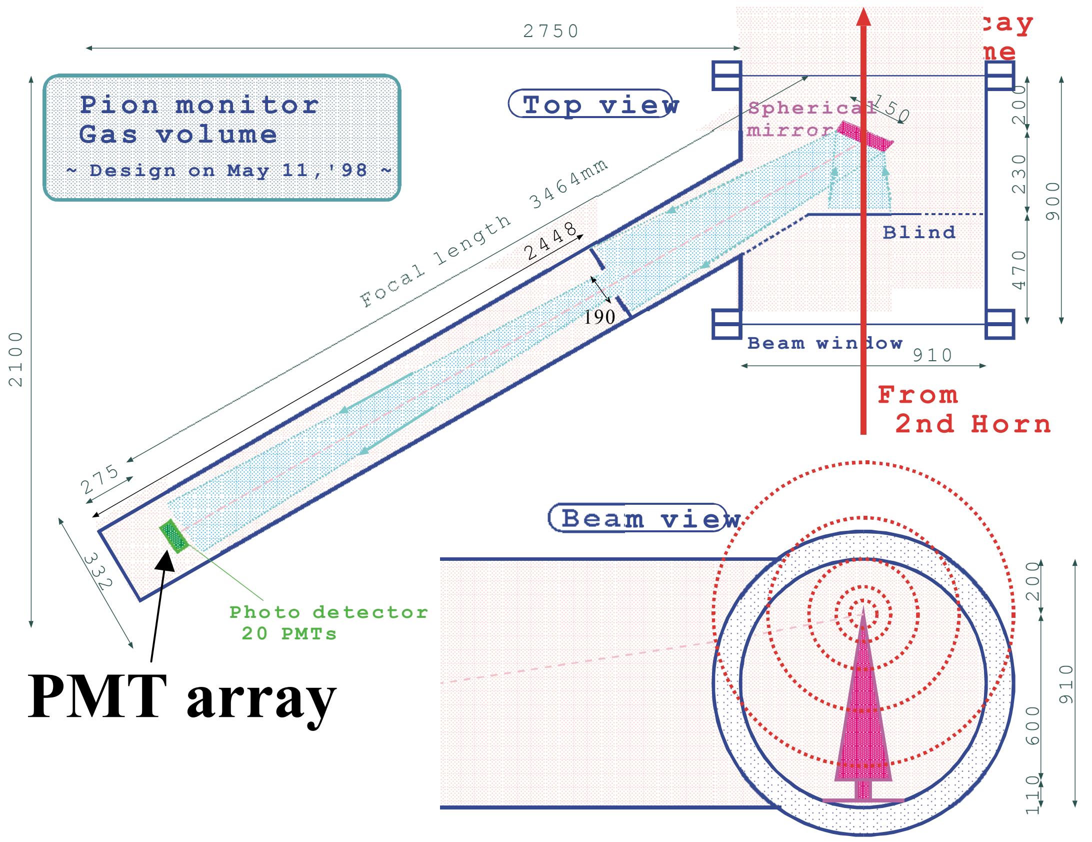
Purpose:Measure momentum and angular distribution of pions, $N(p_\pi, \theta_\pi)$

$N(p_\pi, \theta_\pi) \rightarrow$ Neutrino flux $\Phi(E_\nu)$ at any distance using **only decay kinematics**

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

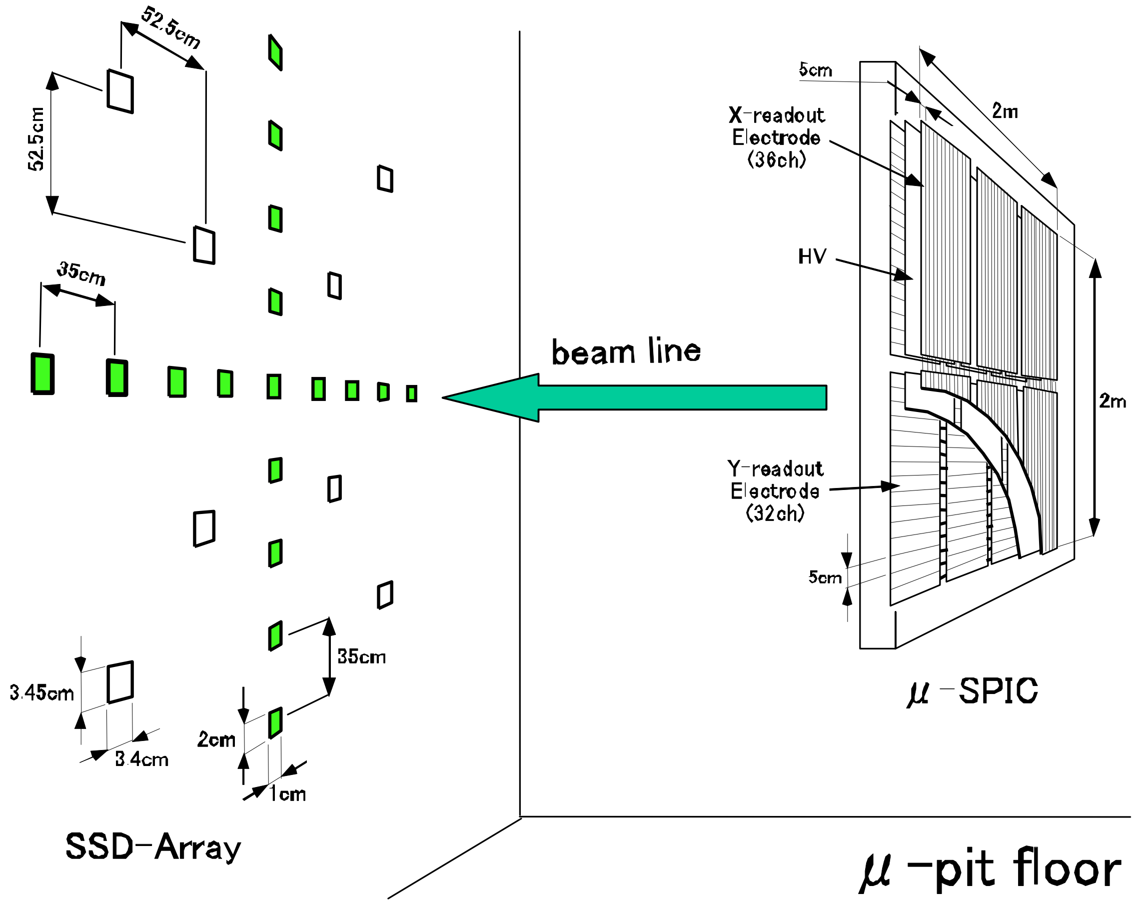
as a result of pion monitor

Gas Cherenkov detector



to avoid signal from 12GeV protons
$\rightarrow$ insensitive to p_π<2GeV (E_ν<1GeV)

Muon Monitors

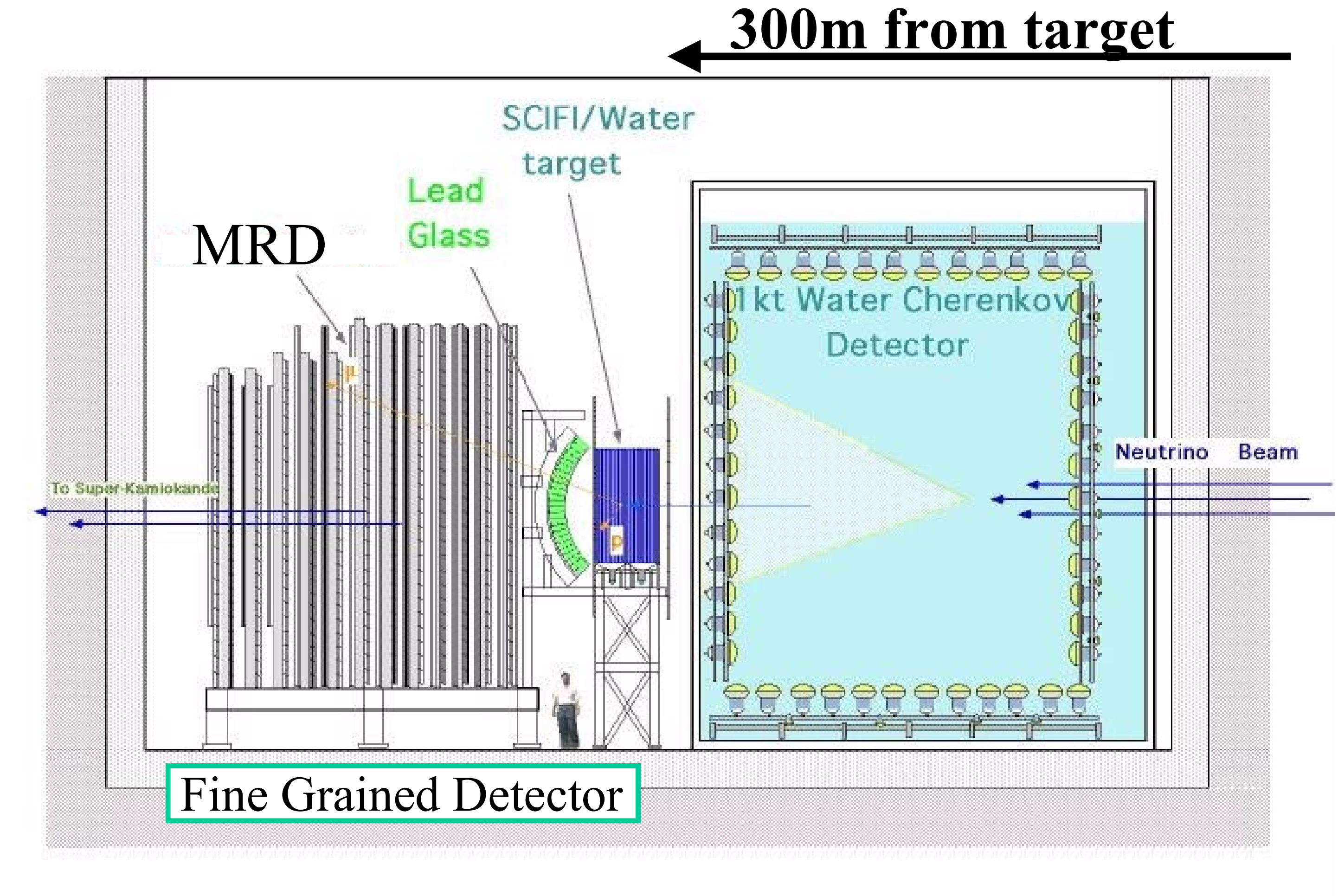


Segmented Ionization Chamber
Silicon pad detector array

Behind beam dump
→Only sensitive to initially high energy μ (>5.5GeV)

Provide **fast (spill-by-spill)** monitoring of
Intensity → targeting/horn stability
Profile → beam direction

Front NeutrinoDetector(FD)



Purpose

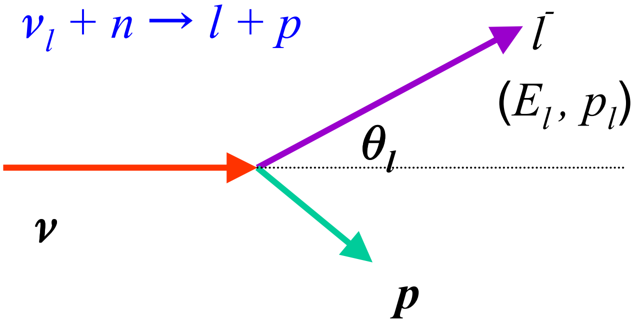
1. ν_μ absolute flux
2. ν_μ directrion(profile)
3. ν_e contamination

- 1kt water Cherenkov detector
- Scintillation Fiber Tracker(SFT): SF sheets+water(6cm)
- Electromagnetic calorimeter : lead glass
- Muon rande detector (MRD) : drift chamber+iron plates

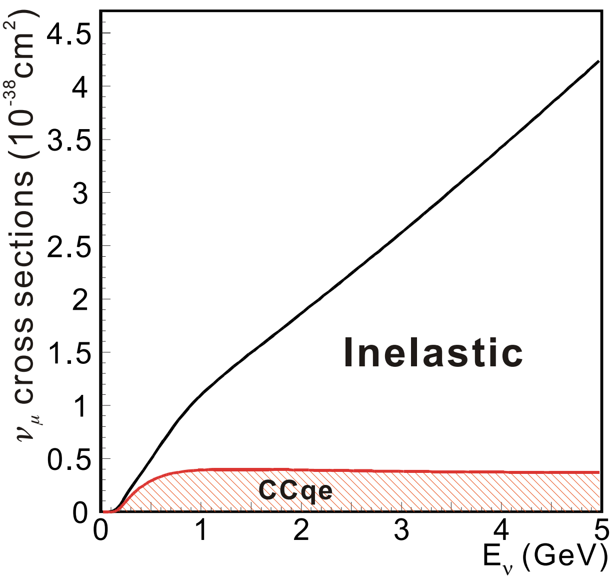
Neutrino Energy Reconstruction (GeV region)

Assume CC quasi elastic (CCqe) reaction

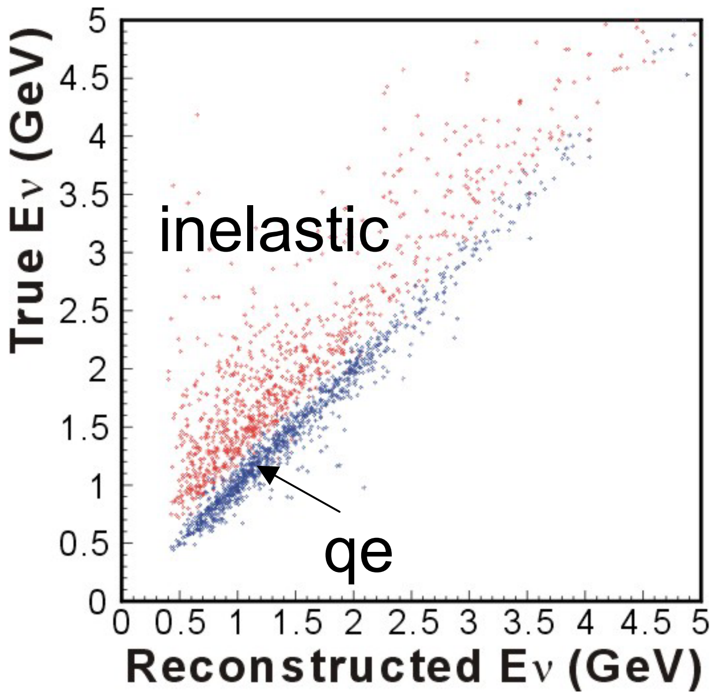
$\nu_l + n \rightarrow l + p$



$$E_\nu = \frac{m_N E_l - m_l^2/2}{m_N - E_l + p_l \cos\theta_l}$$



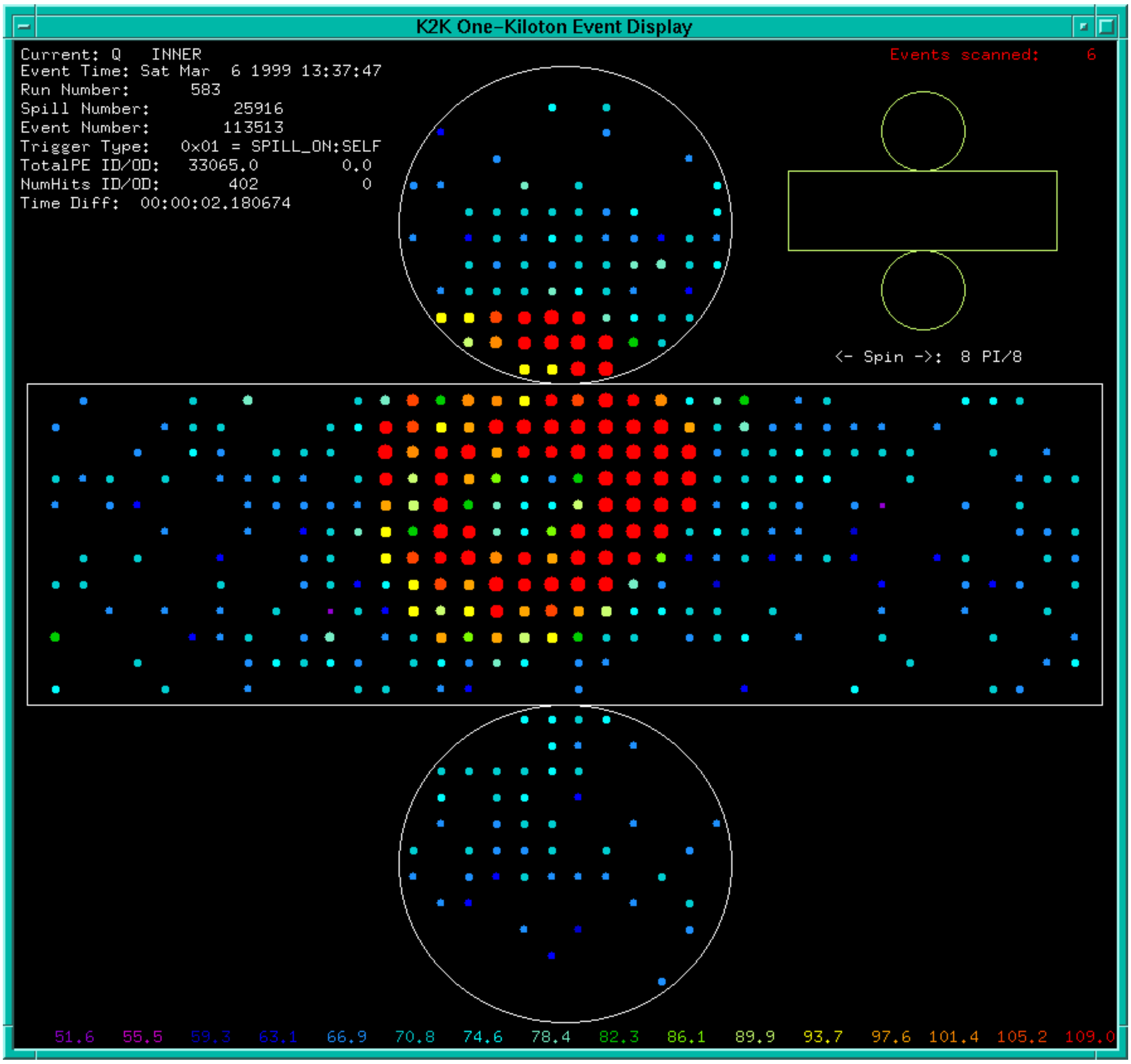
Water Cherenkov 1ring μ-like sample



Inelastic scattering w/ invisible pion(s) give wrong energy

Event categories

1kt Event



H_2O target (same as SK)

Same detection principle as SK

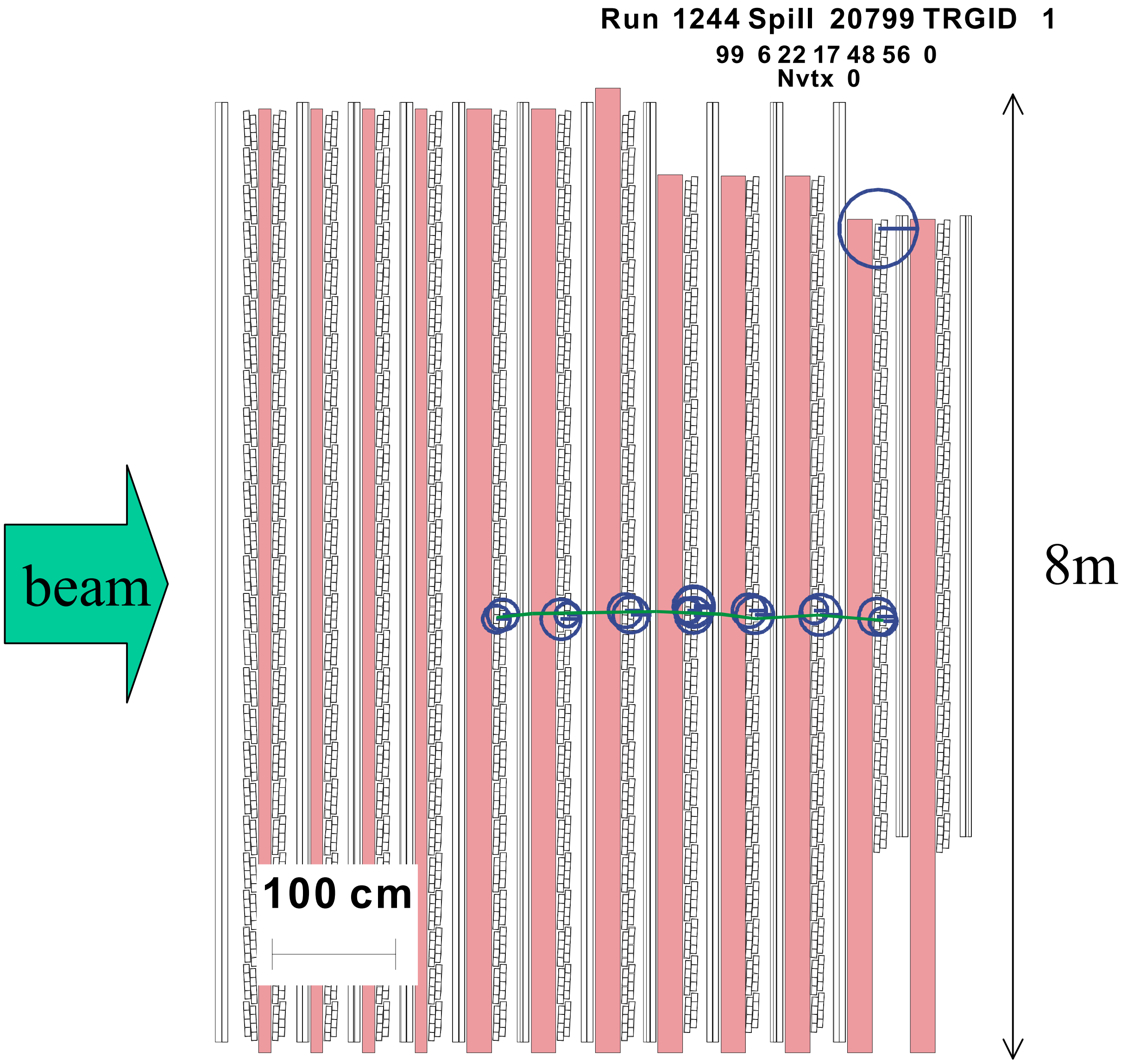
→ **expect least syst. err. for SK exp'ed**

Fid. mass **25ton**

Event selection: Qtot>1000p.e.

～2events/100spill

Fe Event

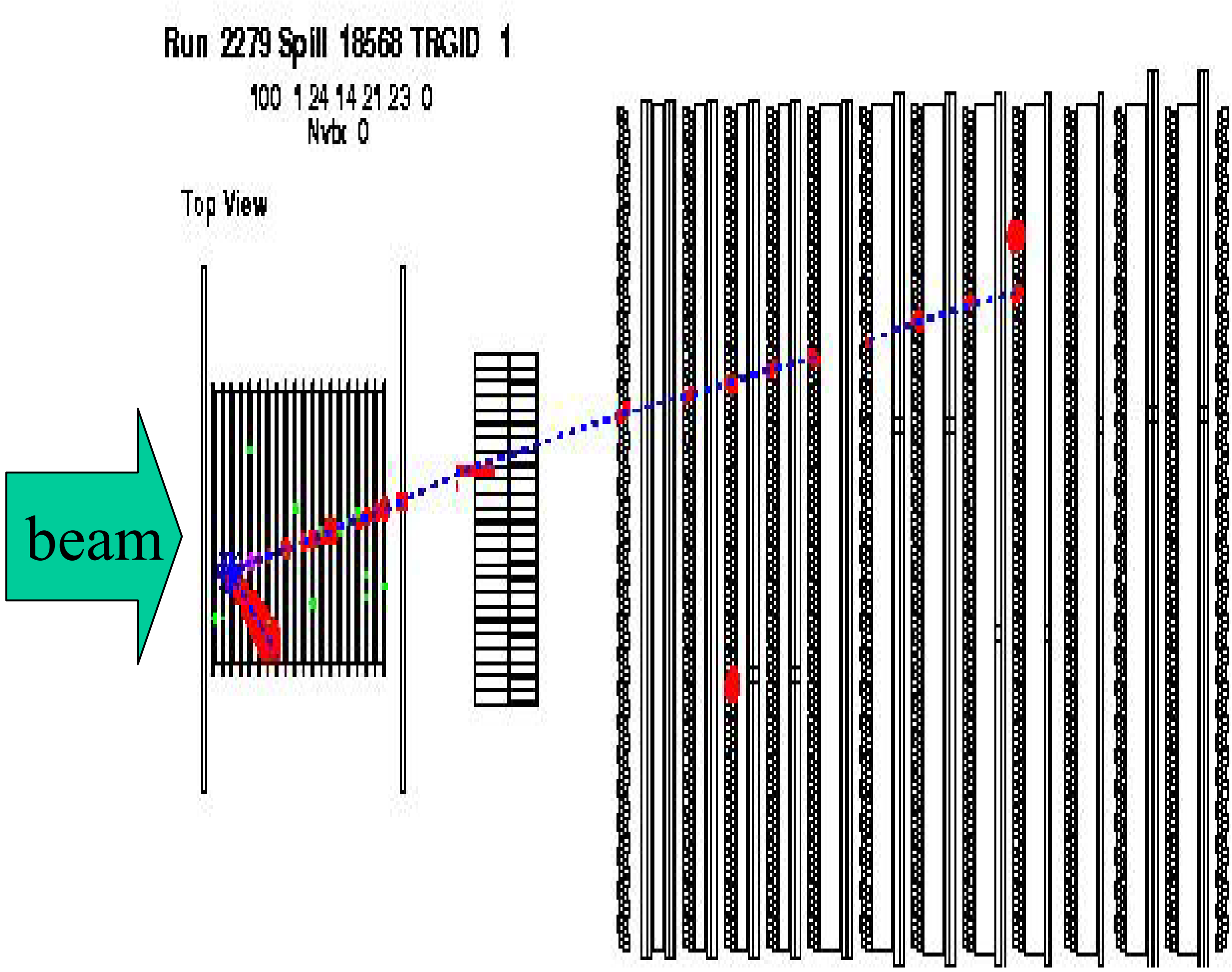


Neutrino int. in MRD **iron** plates

CC inclusive (insensitive to NC)
Large area coverage (8m) → profile(vtx dist.)
Large mass → high rate (～5/100spill)

Good for neutrino dir. and int. monitor

SFT event



Neutrino int. in SFT **H_2O** target(+Al 20%)

Pos. resolution **~1mm**

→ well defined fid. vol.

→ multi track resolution

Fid. mass = **5.8ton**

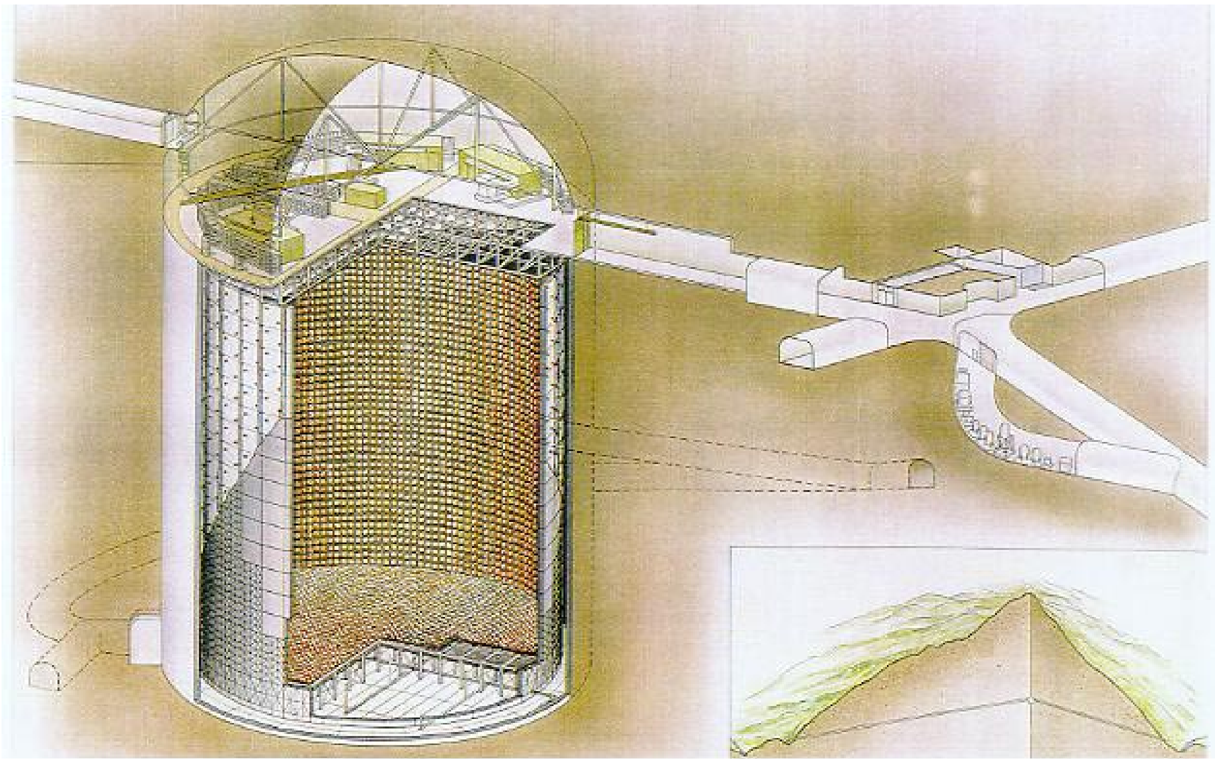
Event selection: matching SFT&MUC track

1event/1000spill

Study neutrino interaction, e.g. $\sigma_{\text{inelastic}}/\sigma_{\text{elastic}}$

Far Detector

Super-Kamiokande
@Kamioka (250km from KEK)



- 1000m underground @ Kamioka
- ~40m$^{\phi}$, ~40m high
- 50,000t Pure water as target
- 11146 PMTs in inner tank
- 22.5kt Fiducial Volume
- Outer detector (OD) :active VETO

Strategy

For now,

1. count # of events @ SK

$$\boxed{N_{SK}^{\text{obs}}}$$

2. calc. expected # of events @ SK

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

N_{FD}^{obs} :observed # of events in one of FDs

R: Near/far ratio from MC

(guaranteed by Pi mon)

ε : detection efficiency

3. compare N_{SK}^{obs} and N_{SK}^{exp}

use 1kt events as a reference

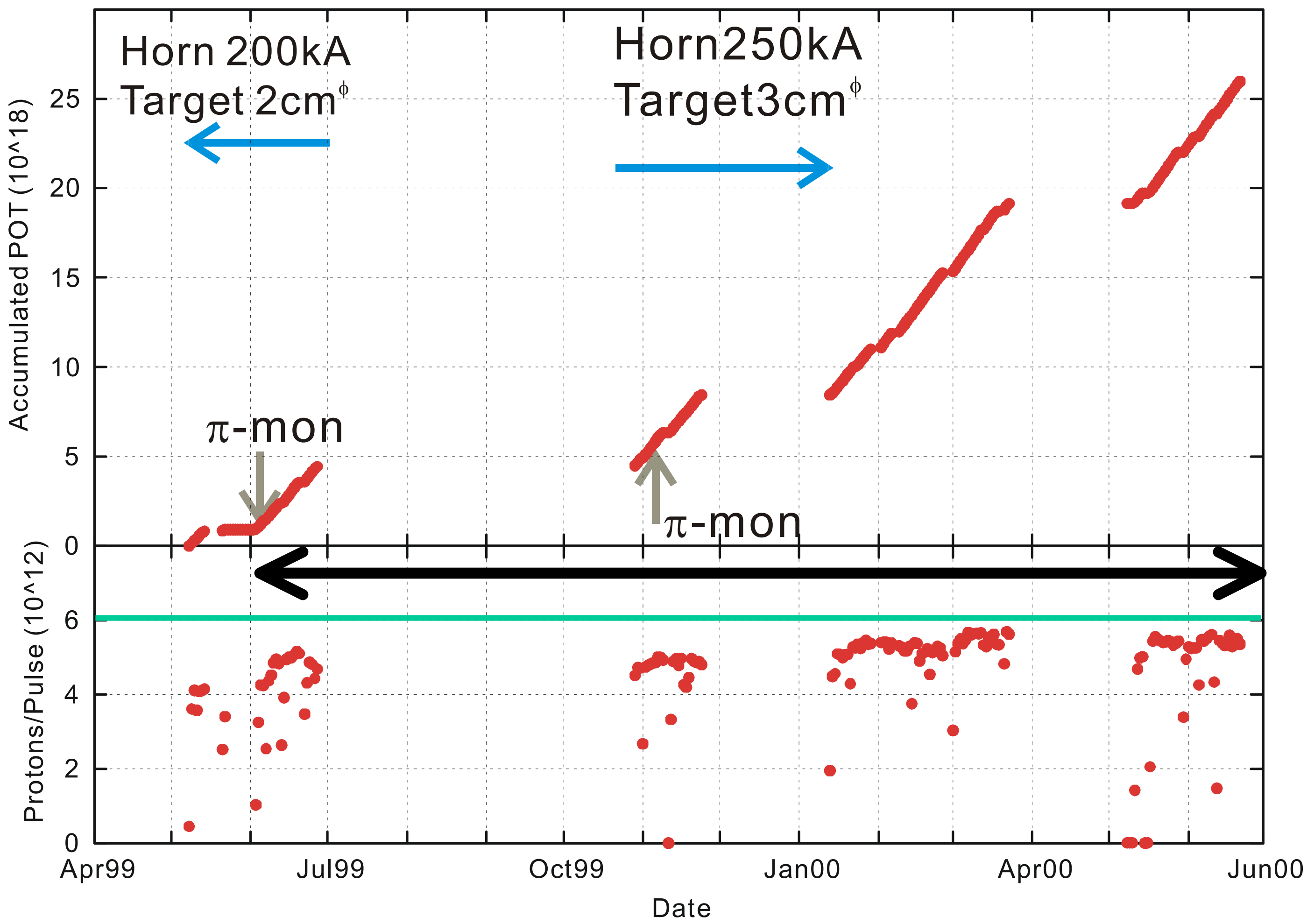
check consistency btw. kt/Fe/SFT events

*eventually,…

$$N_{SK}^{\text{obs}}(\mathrm{E}_\nu) \text{ and } N_{SK}^{\text{exp}}(\mathrm{E}_\nu)$$

Results

Delivered Beam



- Design Proton Int. 6×10^{12} protons/pulse almost achieved (5.5×10^{12})
- ~2.6×10^{19}POT delivered by the end of Jun. '00
- SK Live = **2.29×10^{19}** POT(Jun99-Jun00)

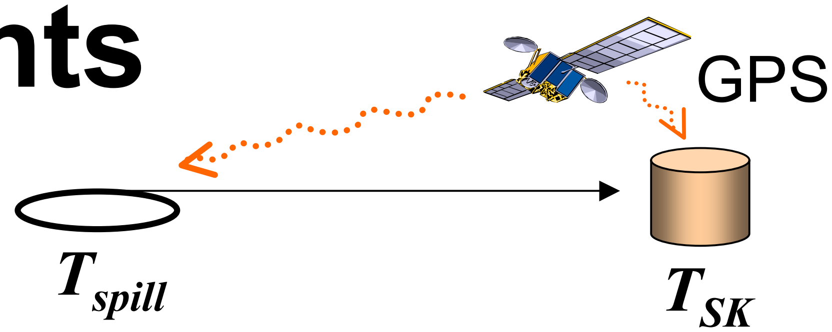
K2K event selection in SK

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

ε=79%

(93% for CC)

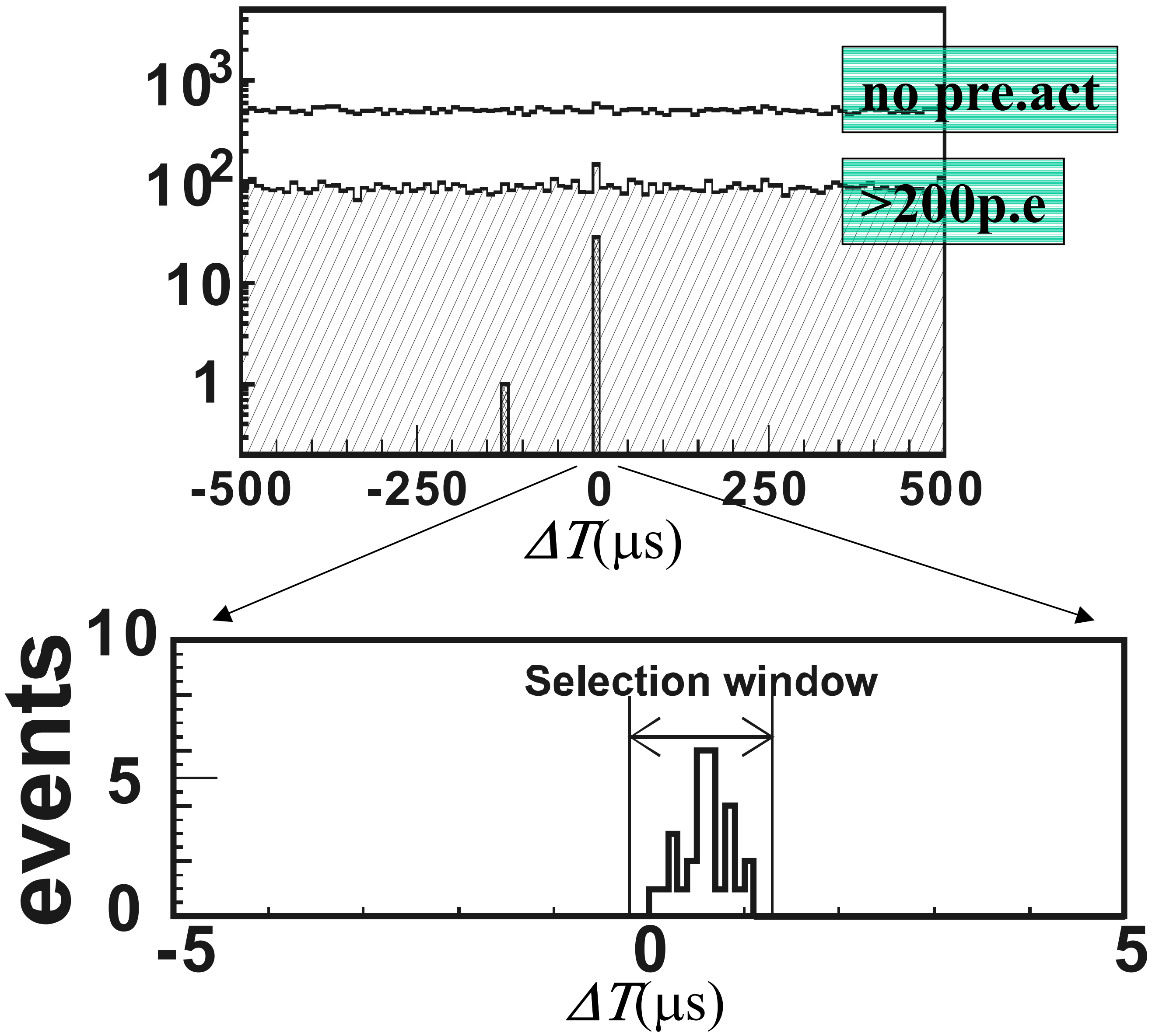
SK Events



$$-0.2 \le \Delta T \equiv T_{SK} - T_{Spill} - \text{TOF} \le 1.3\,\mu\,\text{sec}$$

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

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

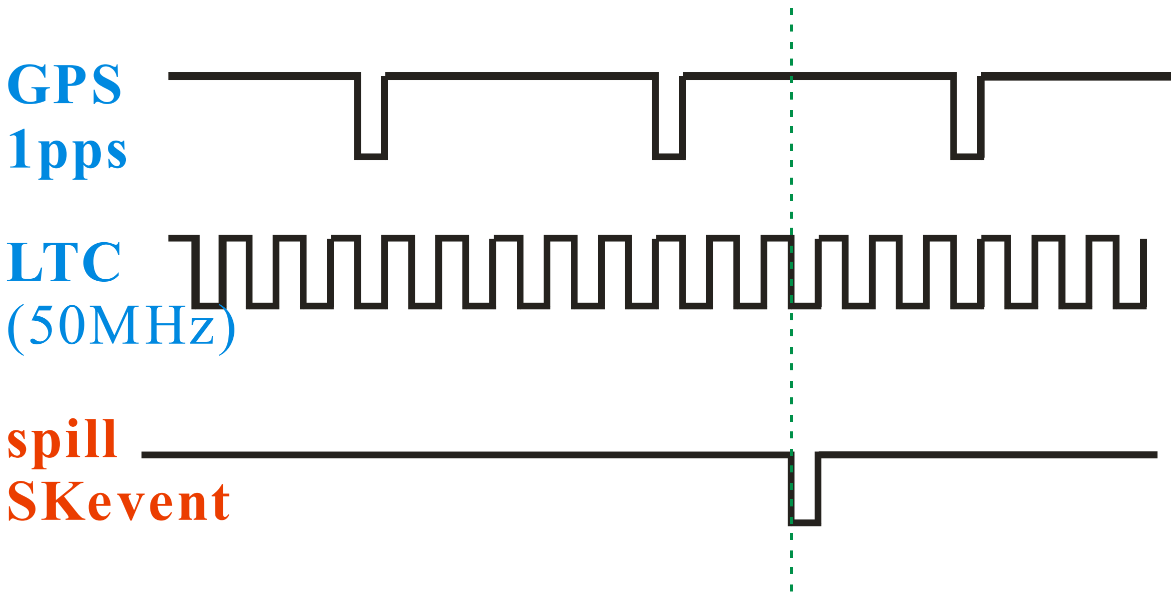


28 observed.

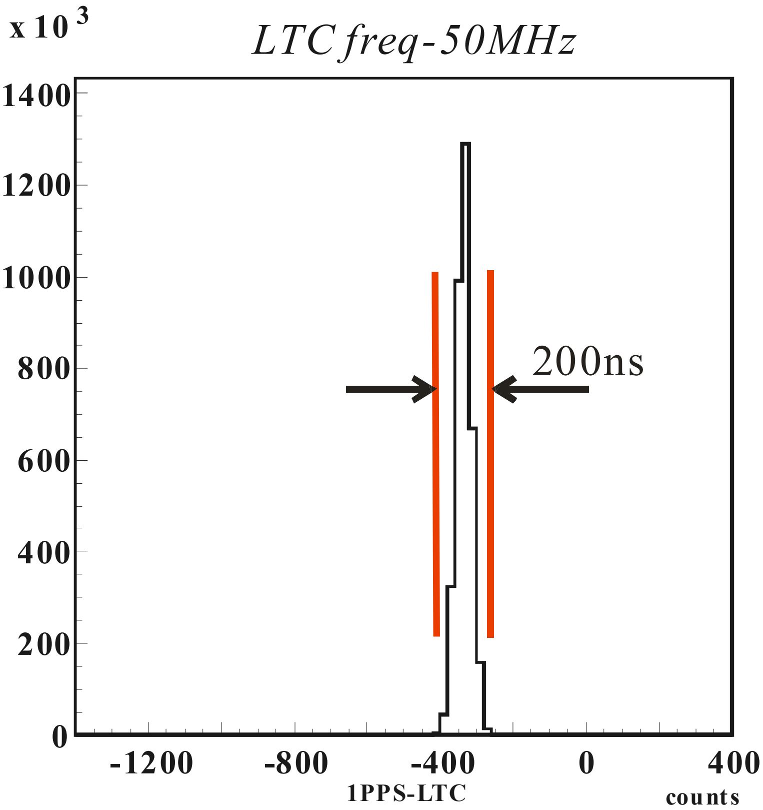
Exp'ed Atm ν BG

$<10^{-3}$ in 1.5μs win.

GPS Time Stamping

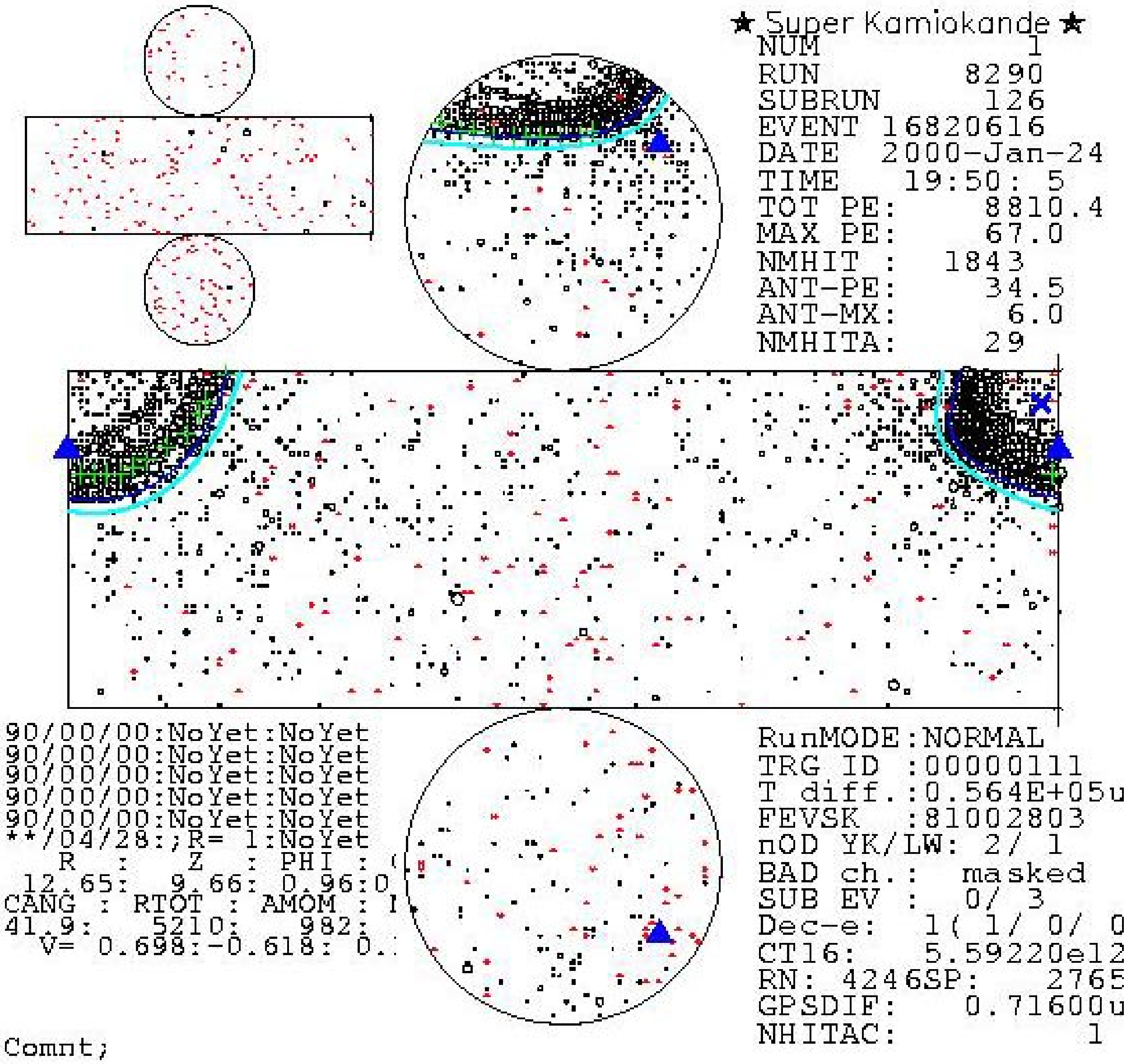


GPS 1pps interpolated with local time clock(LTC

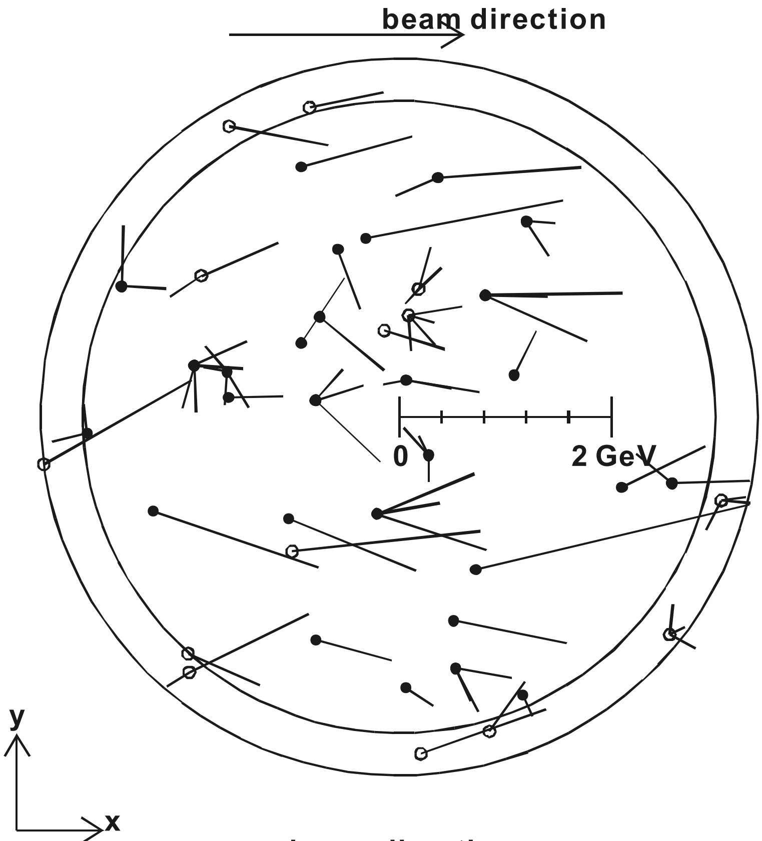


Stable within ~200ns

Typical SK Events

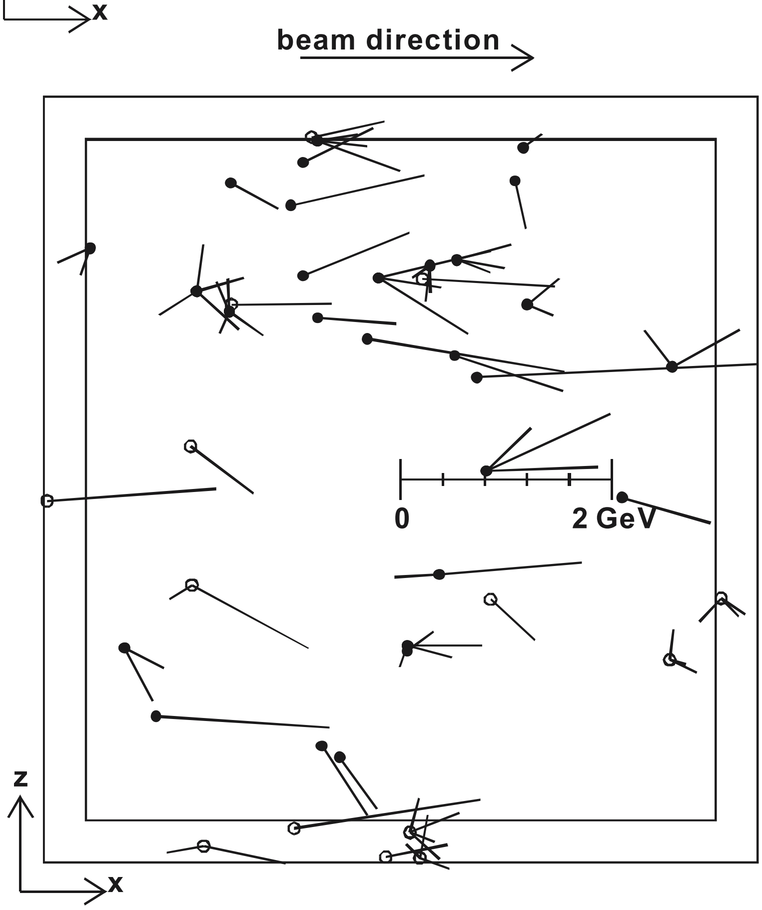


Vertex and Direction



top view

fully contained



side view

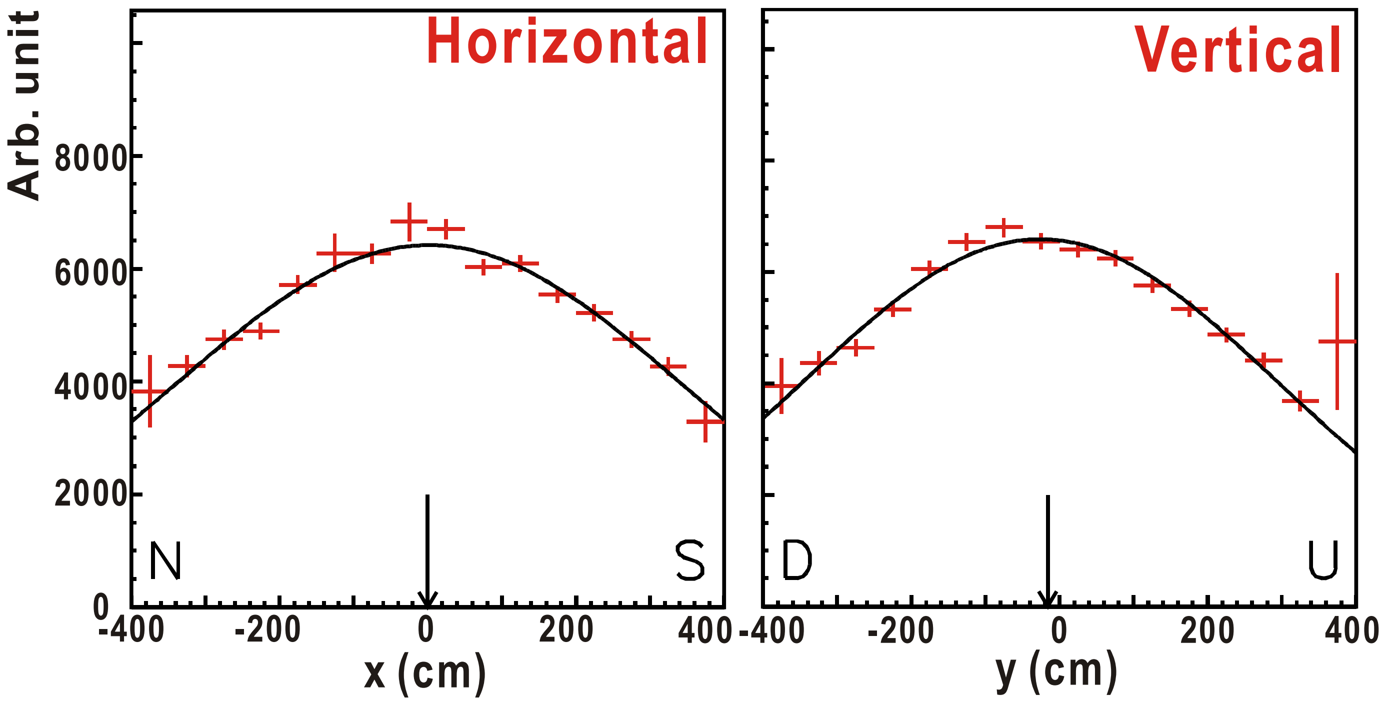
Measurements @ KEK

- Beam Direction
- Rate
- Spectrum Stability
- Spectrum extrapolation
- Neutrino spectrum
  - CC μ energy spectrum
  - CC μ angle

Stability of beam quality is of great impotance.

Beam Direction

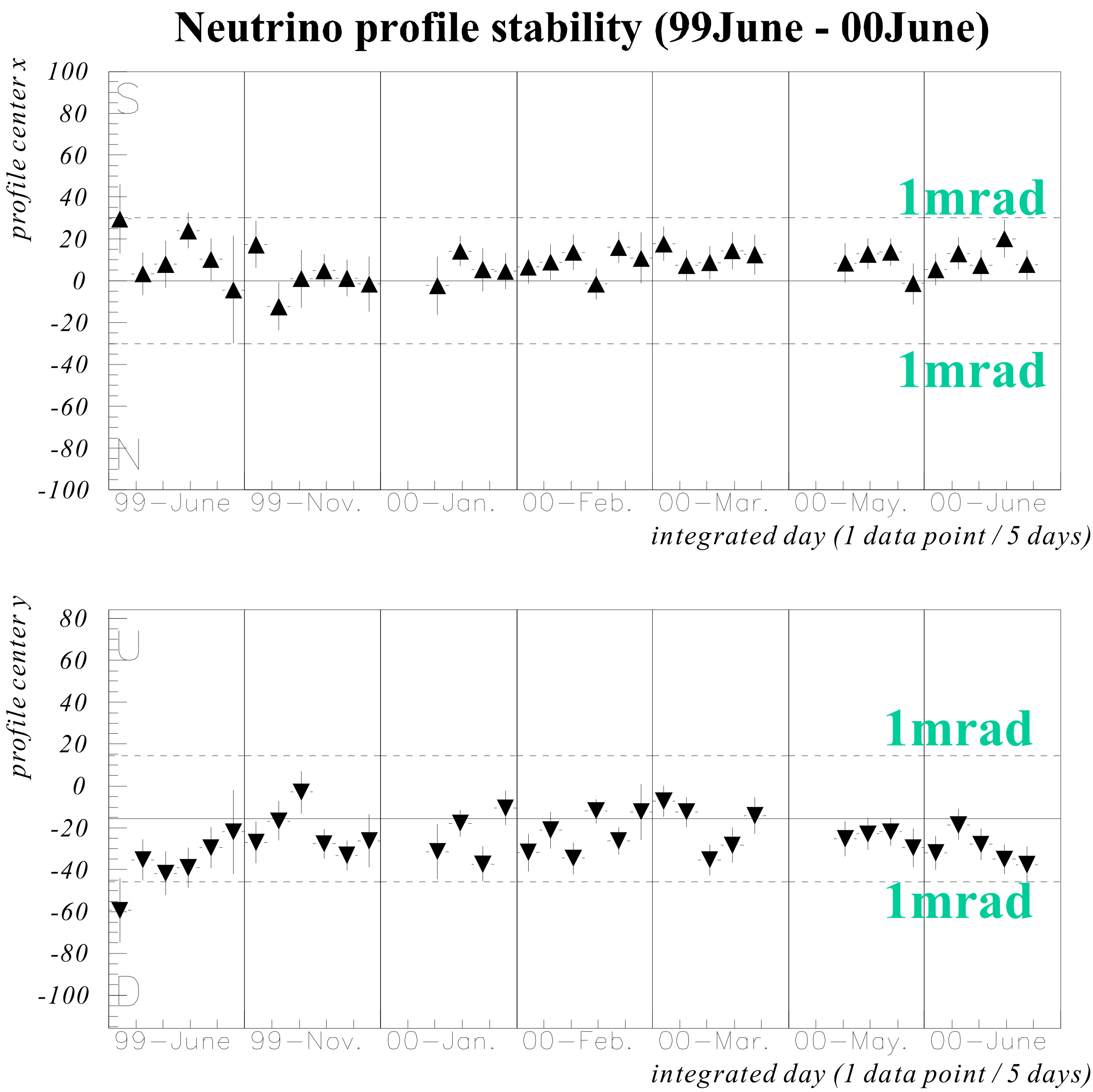
Vertex distribution of Fe events (Nov99)



Fitted center x: 1±5cm
y: −10±4cm (stat) from SK dir.

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

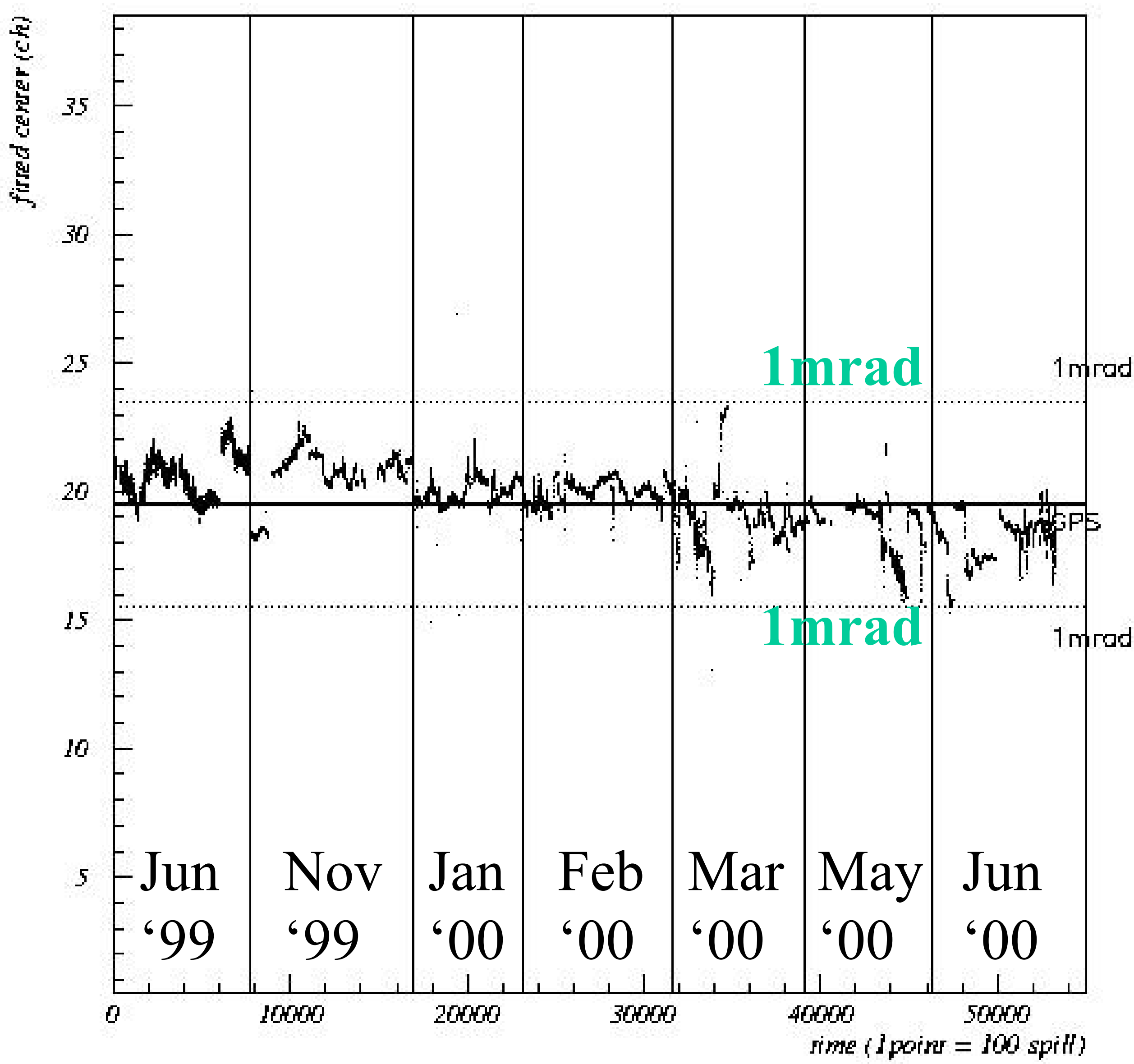
Stability of Profile Center (Fe event)



Stable within ±1mrad.

Stability of Muon Profile Center @ Muon Monitor

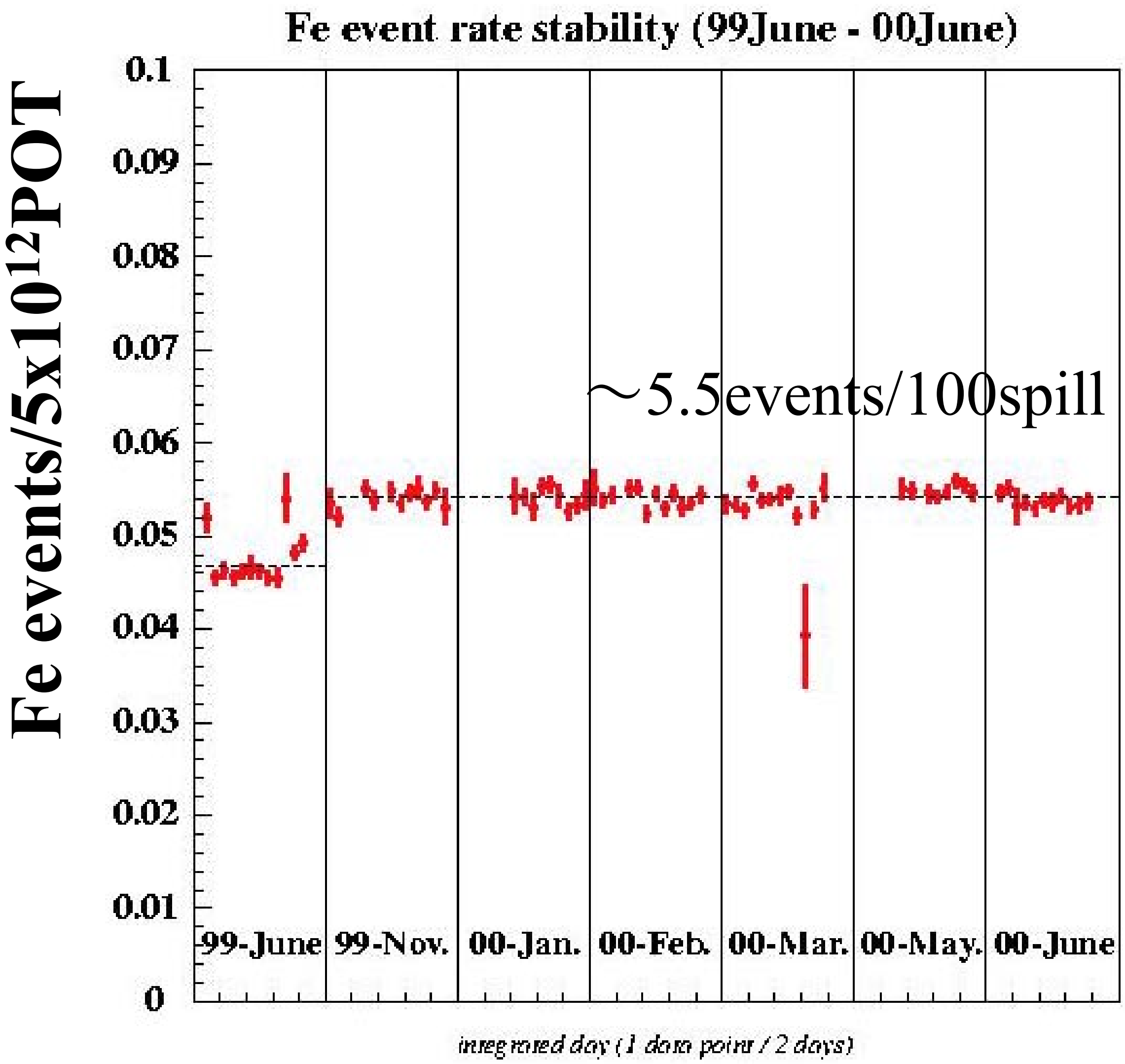
Fast (spill-by-spill) but indirect monitor



Stable within ±1mrad

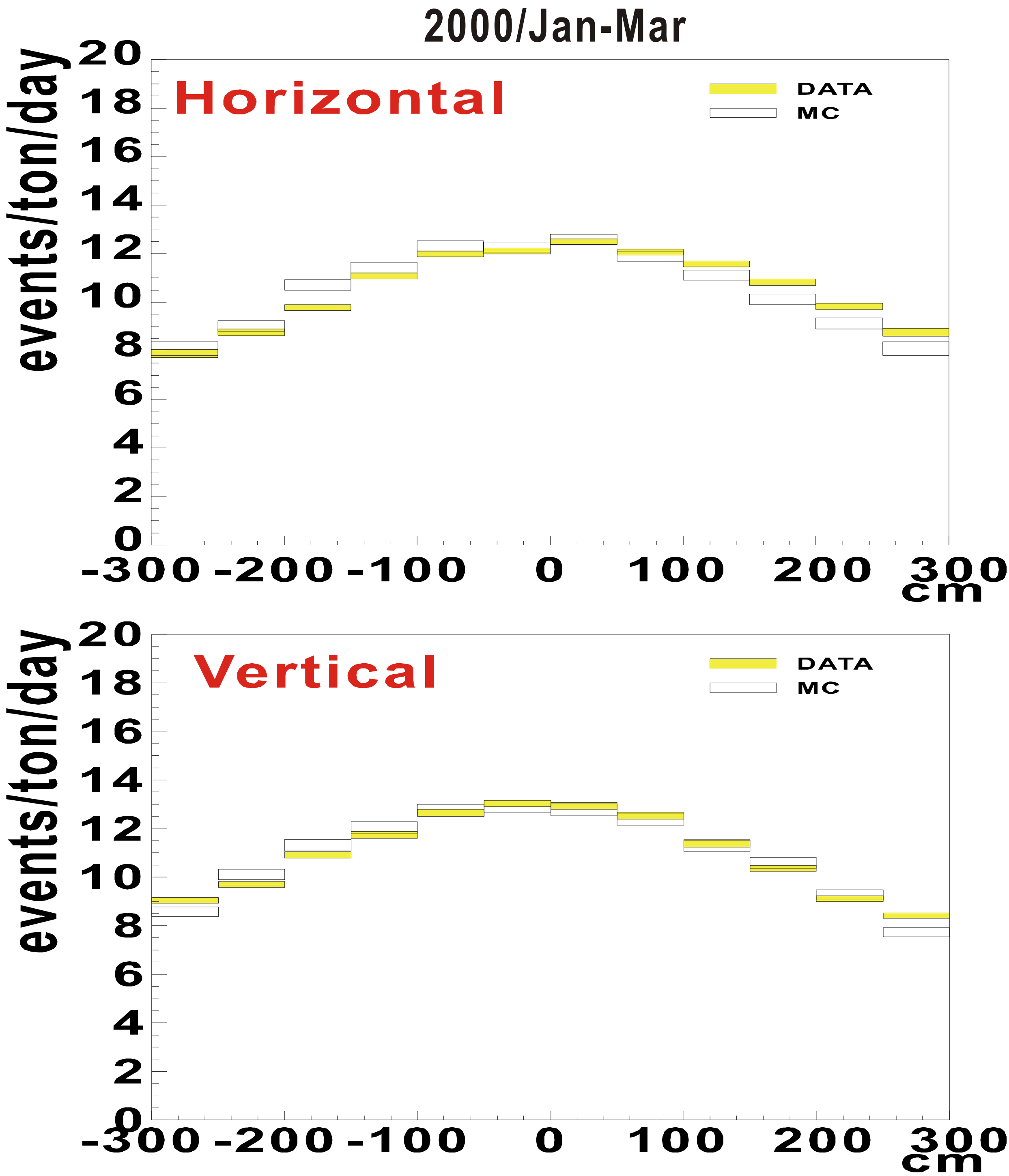
Measurements of FDs

Event rate



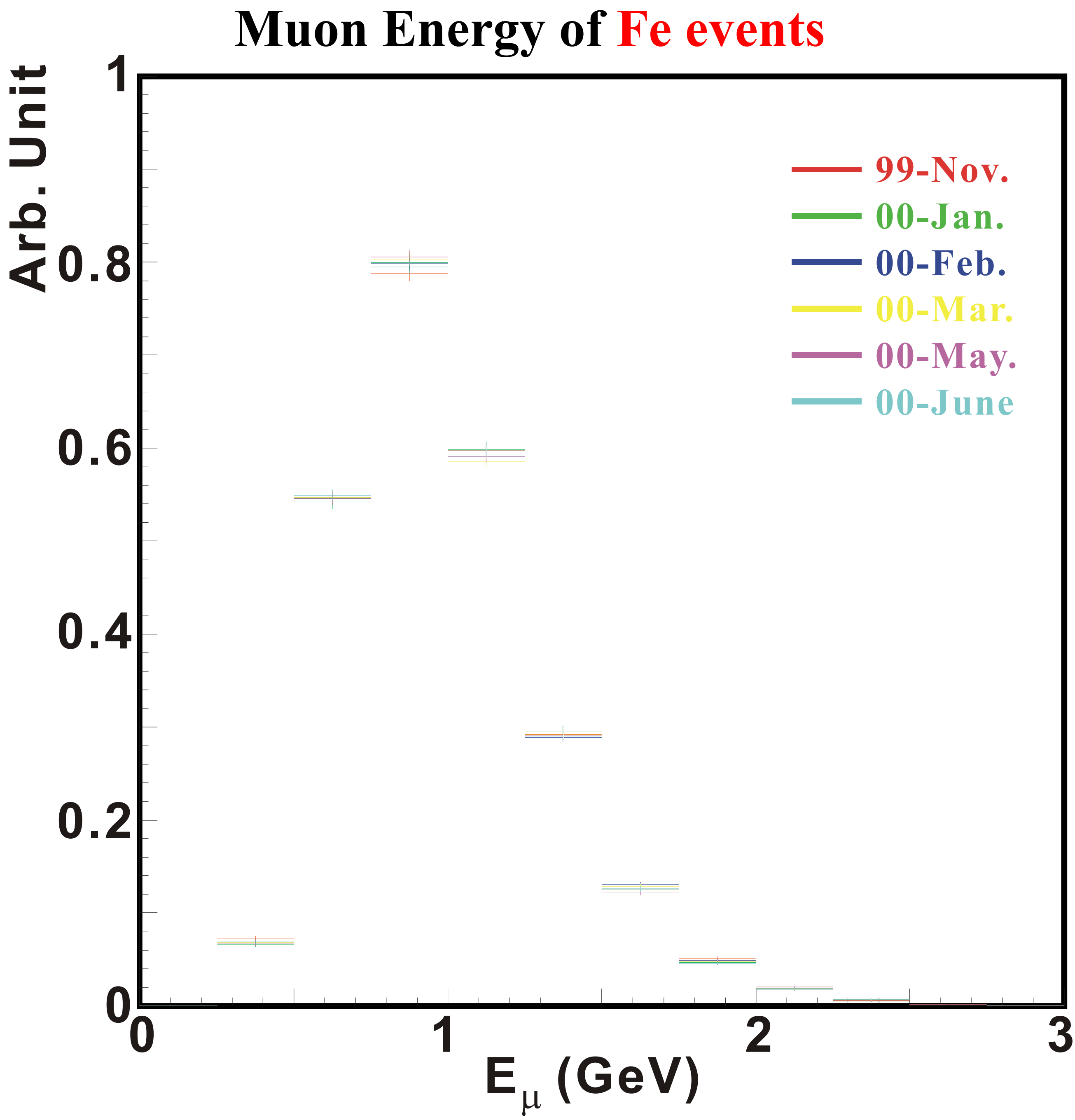
Stable.

Vertex dist. of 1kt events



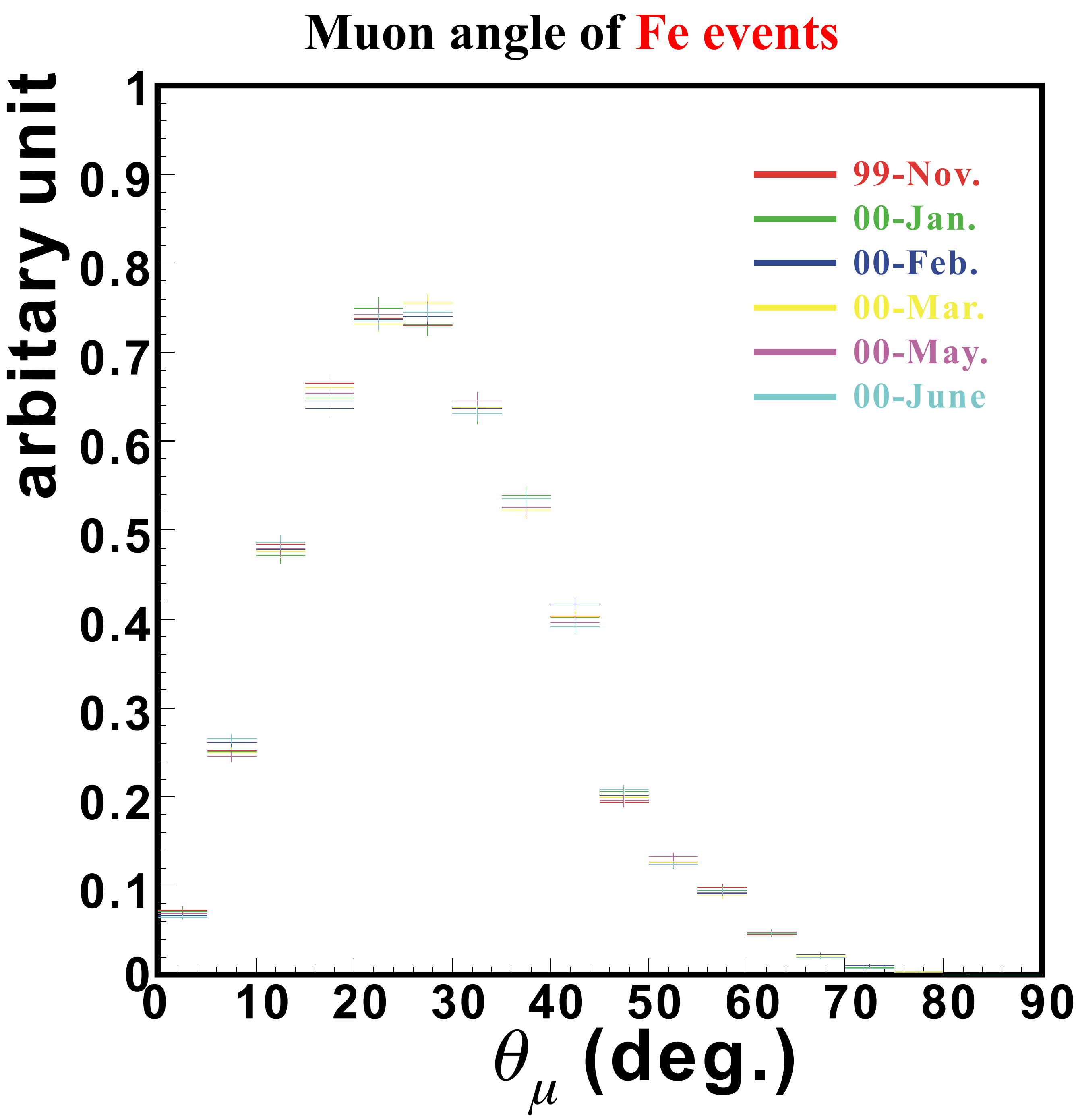
Agree with MC well.

Stability of Spectrum



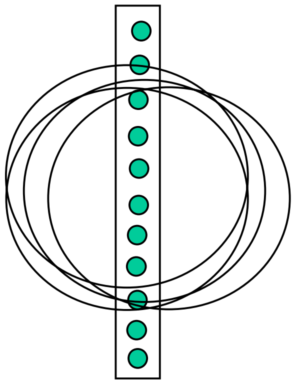
Stable within stat. error.

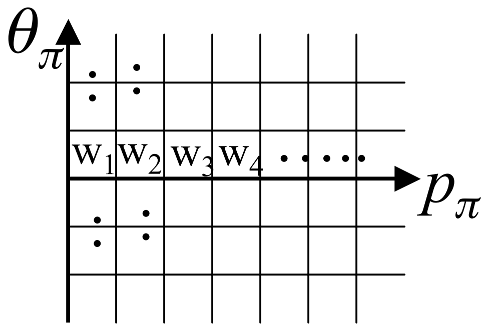
Stability of muon angle



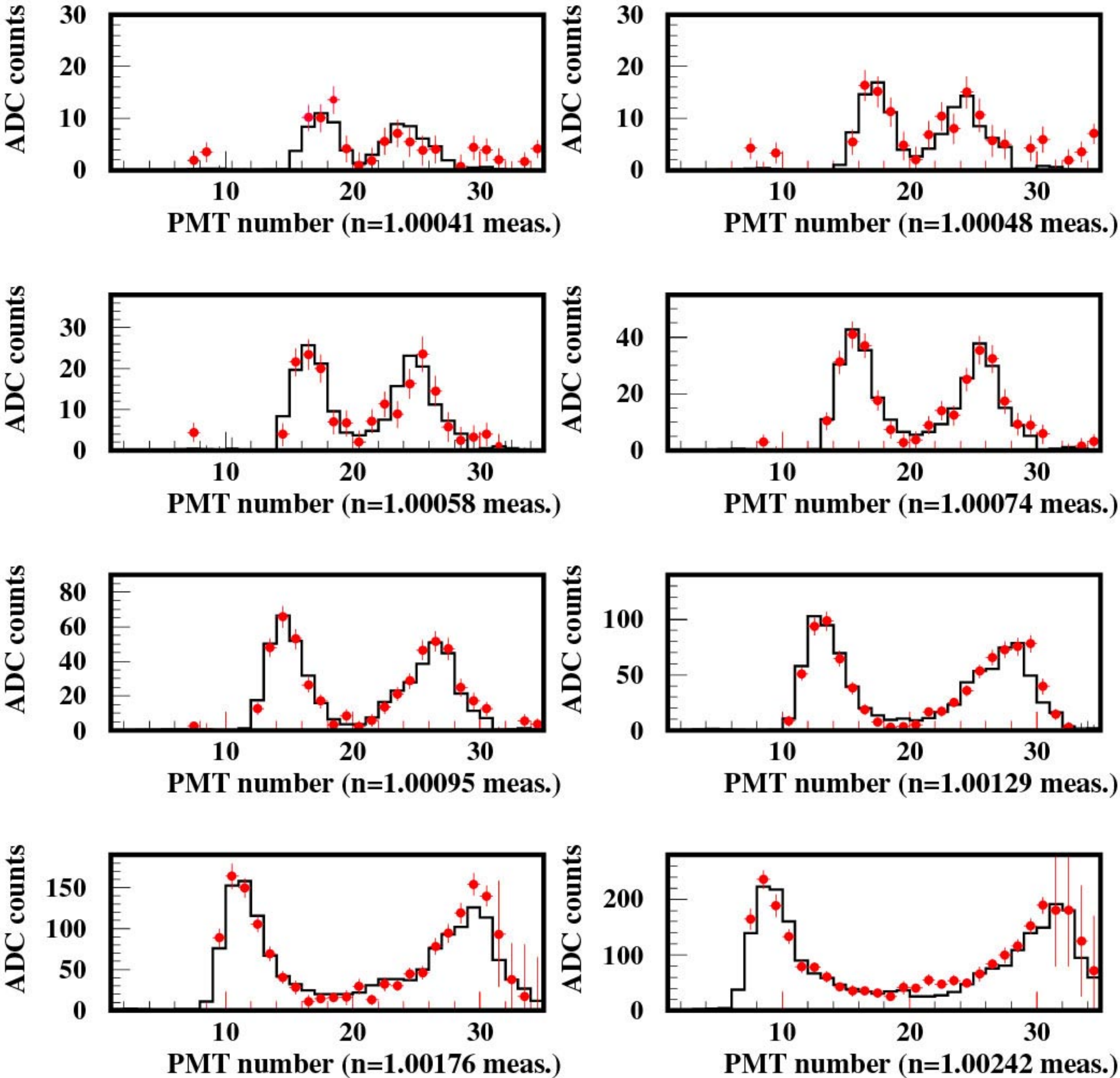
Stable within stat. error.

Pion Monitor Results



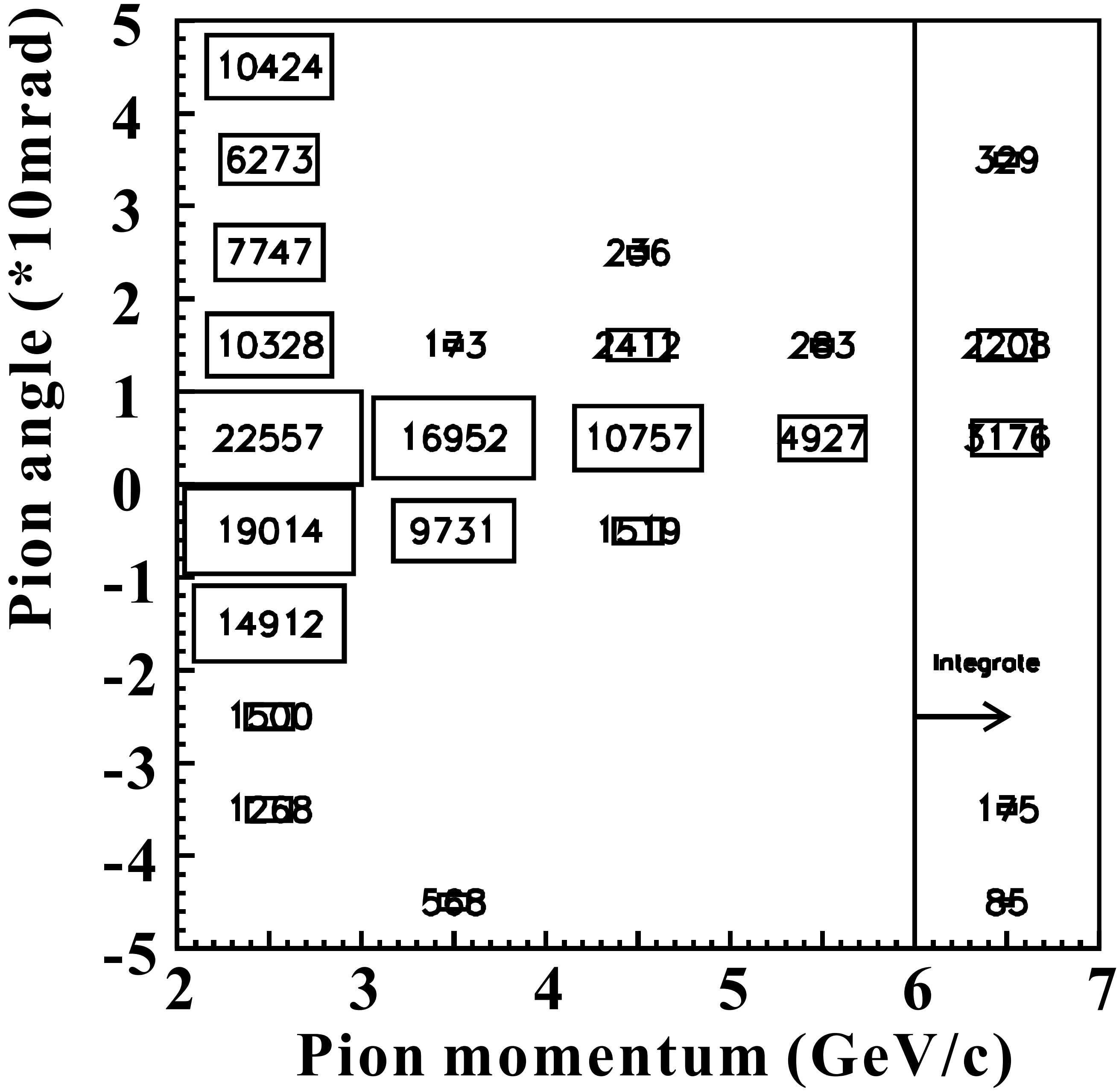


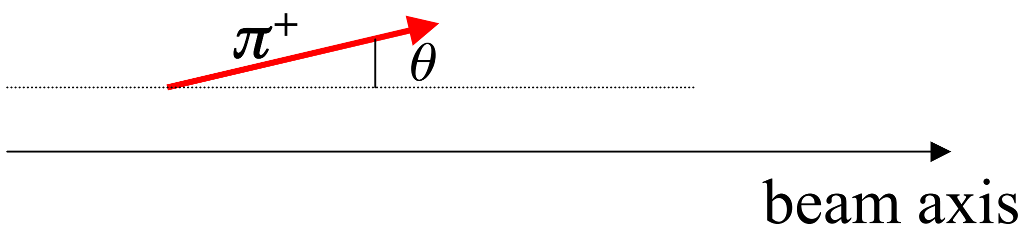
Pion Monitor Fitting (November)



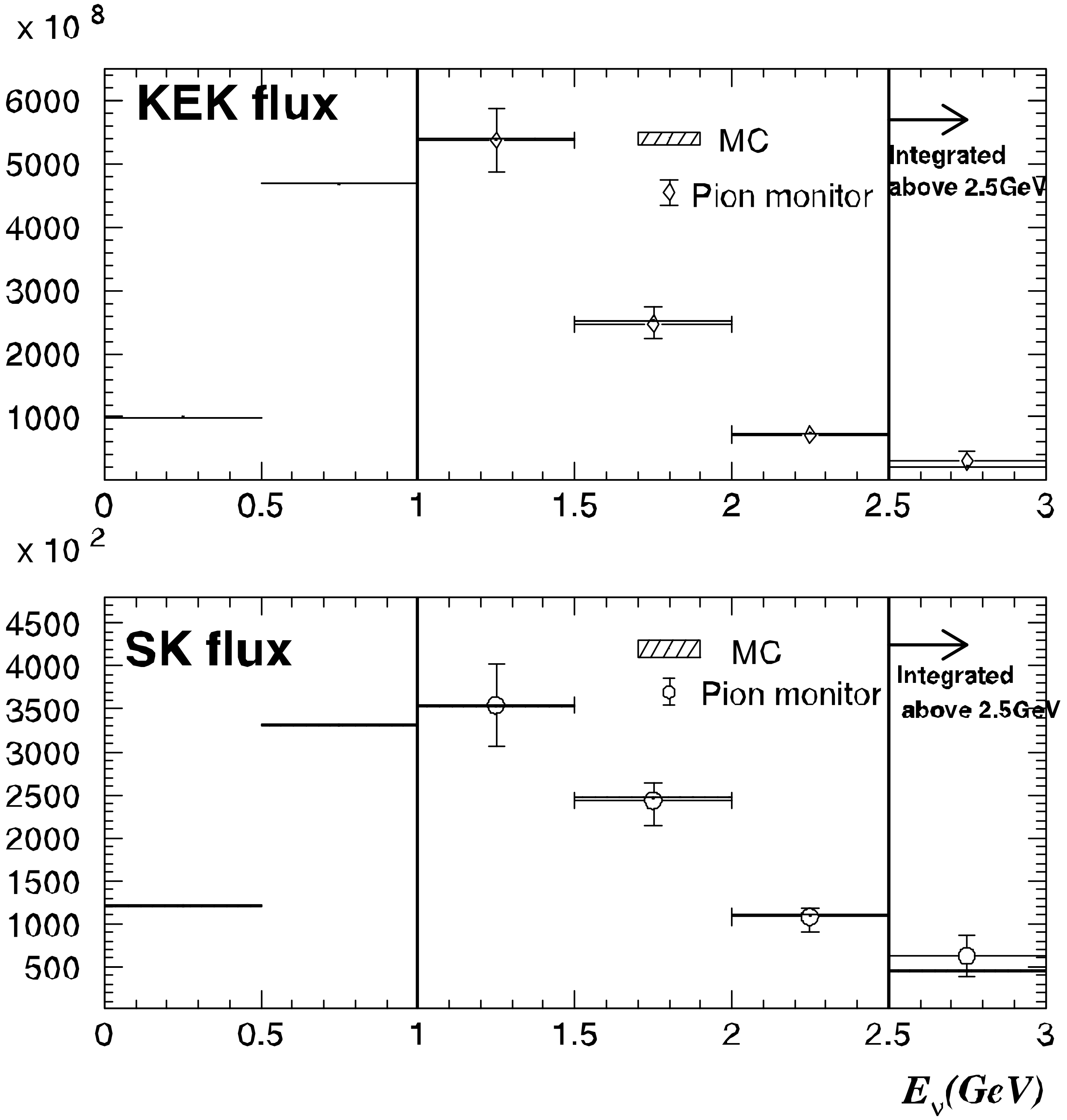
Pion Monitor Result

Relative Pion Distribution in p_π-θ_π plane





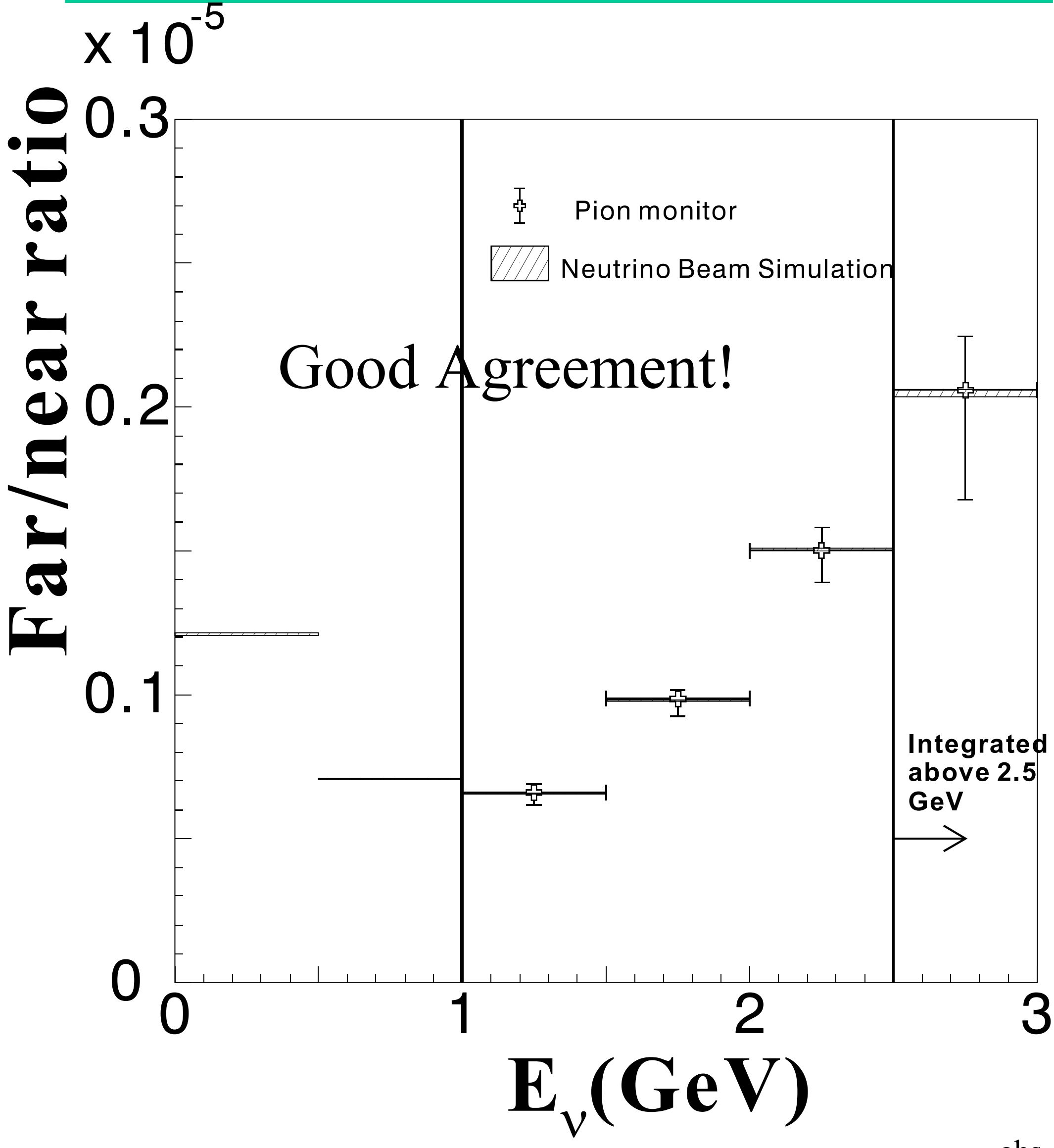
ν_μ spectra from Pion Monitor Measurement



Agree with MC very well.

Flux Ratio from Pion Monitor

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



For integrated far/near ratio ***R*** in $N_{SK}^{\exp}=\frac{N_{FD}^{\text{obs}}}{\varepsilon_{FD}}\cdot R\cdot\varepsilon_{SK}$

use MC for central value

syst. error $\Delta R=^{+6\%}_{-7\%}$ from Pi. mon.

(for 1kt)

Expected # of SK events from 1kt detector

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

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

N_{kt}^{obs} : 61585 (in 25t f.v.)

ε_{kt} : 0.72 (detection eff. of 1kt)

L_{SK}/L_{kt} : Live POT ratio (～1.2)

M_{SK}/M_{kt} : Fiducial mass ratio

ε_{SK} : 0.79 (detection eff. of SK)

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

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

: $N_{SK}^{\text{exp}} = 37.2^{+4.6}_{-5.0}$ (tot.) from SFT events

Consistent with each other.

Systematic Error for N_{SK}

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

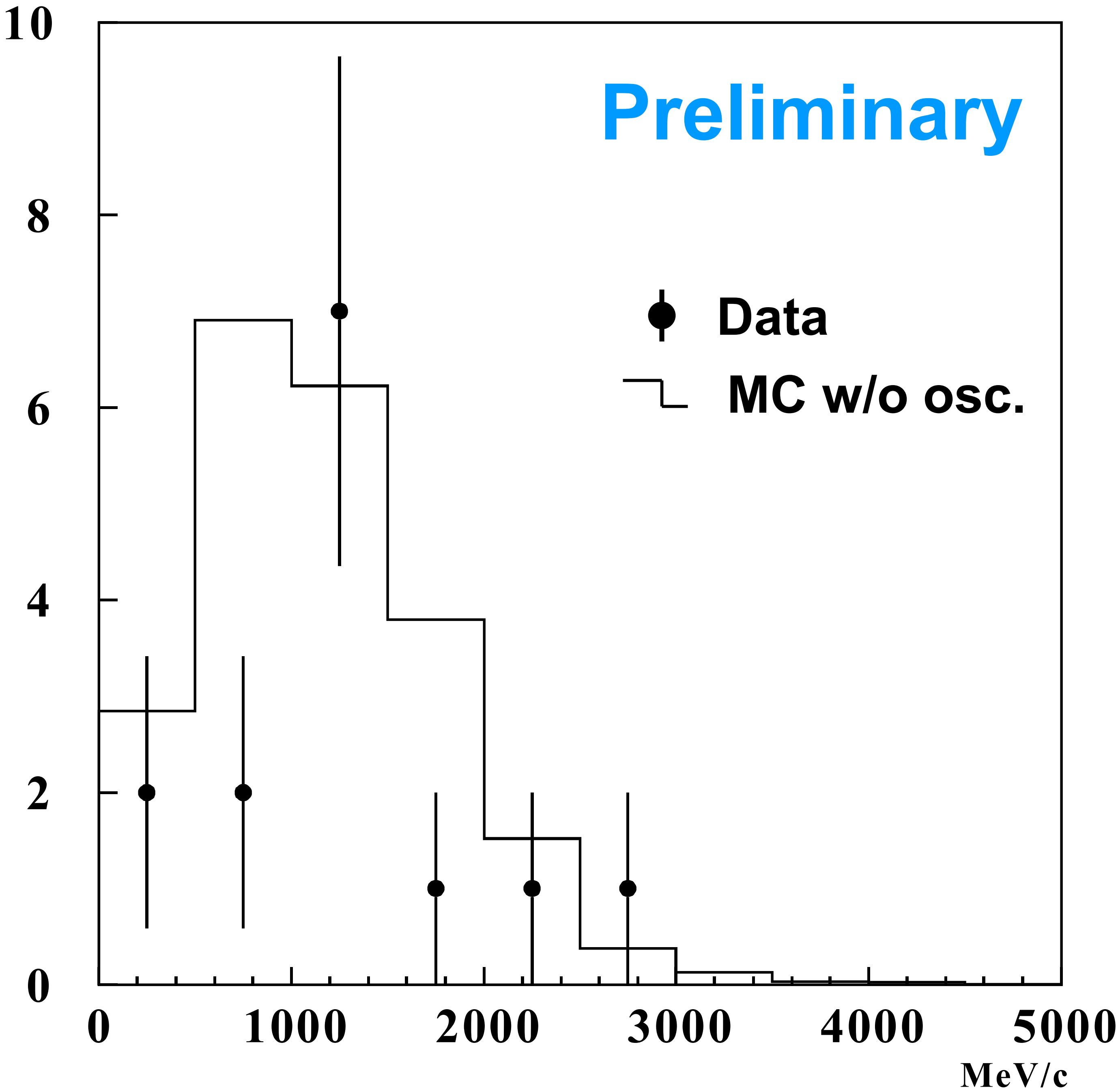
Near/Far Ratio	${}^{+6}_{-7}\%$
1kt ΔV/V	$\pm 4\%$
Multi Event	$\pm 3\%$
Spectrum(eff.)	$\pm 2\%$
SK(mainly ΔV/V)	$\pm 3\%$
Total	${}^{+9}_{-10}\%$

of observed and expected events @ SK

	Obs.	No Ocsi.
FC 22.5kt	28	$37.8\ ^{+3.5}_{-3.8}$
1-ring	15	22.9 ± 3.2
μ-like	14	20.9 ± 3.2
e-like	1	2.0 ± 0.4
multi ring	13	14.9 ± 2.4

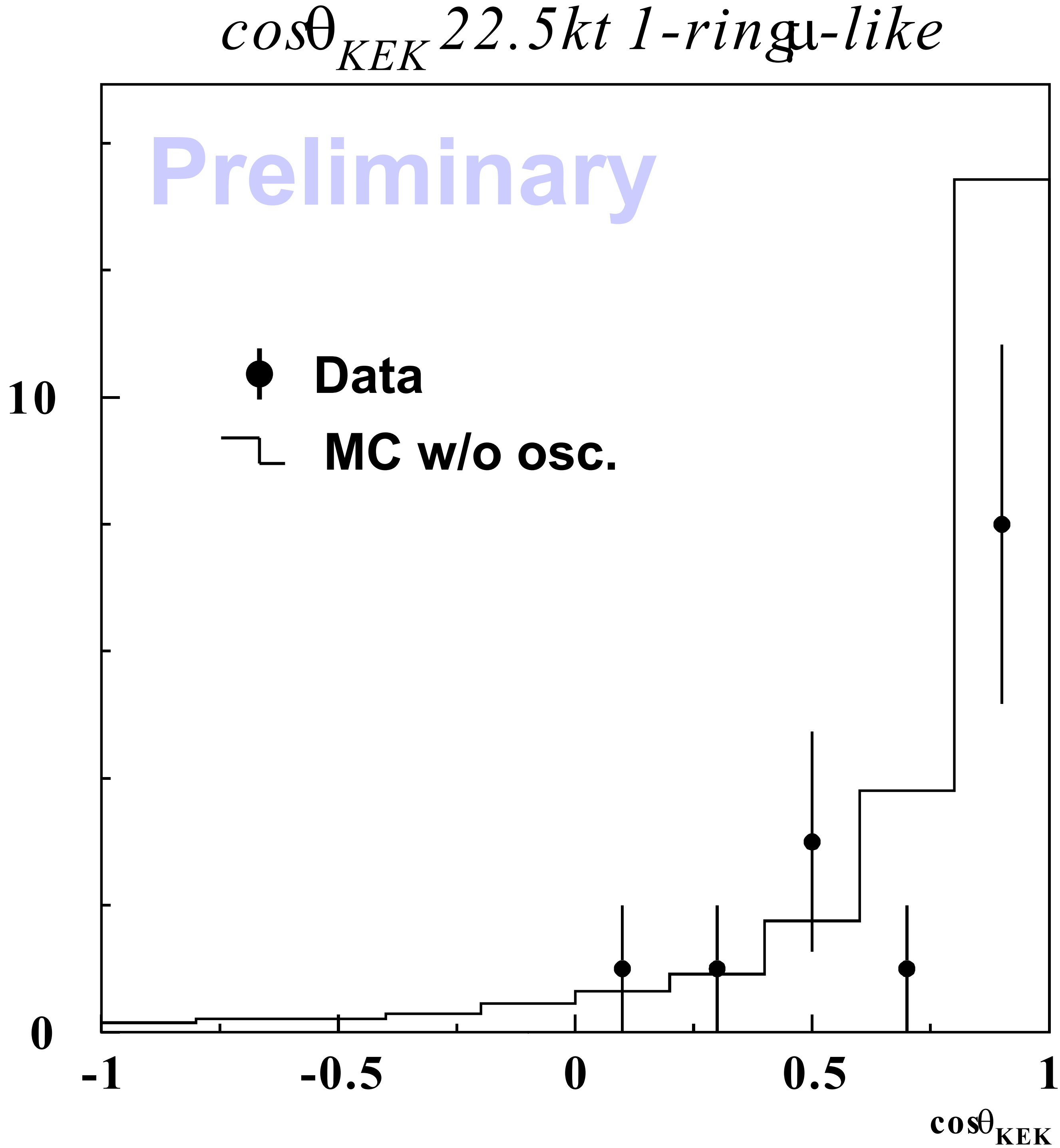
Reconstructed E_ν

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



Need to estimate syst. err. in MC expect.

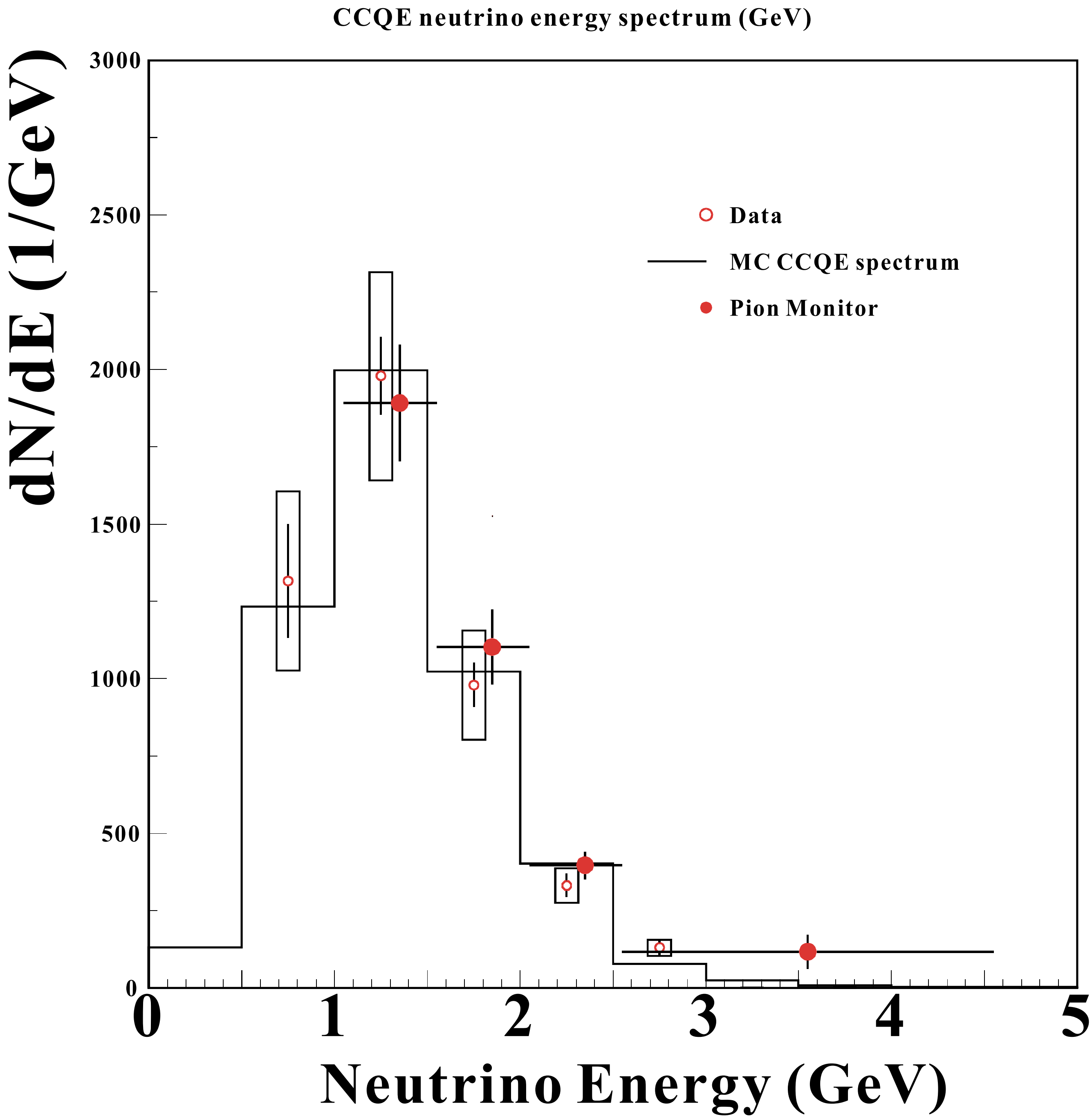
Angle Distribution



Need to estimate syst. err. in MC expect.

Toward Spectrum Analysis

Detailed Study of FD data needed.



Data agree with MC fairly well.

Need more detailed analysis of FD data to extract spectrum information.

Conclusions

- Accumulated $2.29\text{x}10^{19}$POT @ SK from Jun '99 to Jun '00.
- Neutrino beam is well under control
  - Direction: always directed to SK within 1mrad
  - Spectrum: stable within stat. error
  - Intensity: stable within stat. error
  - Pi mon proved MC spectra ratio
- # of fully contained events in fiducial volume @ SK

  Observed: 28

  $\text{Expected} : 37.8^{+3.5}_{-3.8}$ (w/o osc.)
- **Deficit of 90% significance observed.**
- Todo
  - reduce systematic errors ($\Delta V/V$, σ_{Fe},....)
  - spectrum analysis
    - need more stat
    - need more study on FD data
  - ν_e appearance search
- Experiment resumed Jan. 2001

Expected Allowed Region

10^{20} POT ~ 5 years