Latest Results of K2K

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Contents

Motivation

Evidence of osc. in atm. ν observation by SK

$\Delta m^2 = 2 \sim 5 \times 10^{-3}$ eV^2
$\sin^2 2\theta > 0.88$
almost $\nu_\mu \rightarrow \nu_\tau$

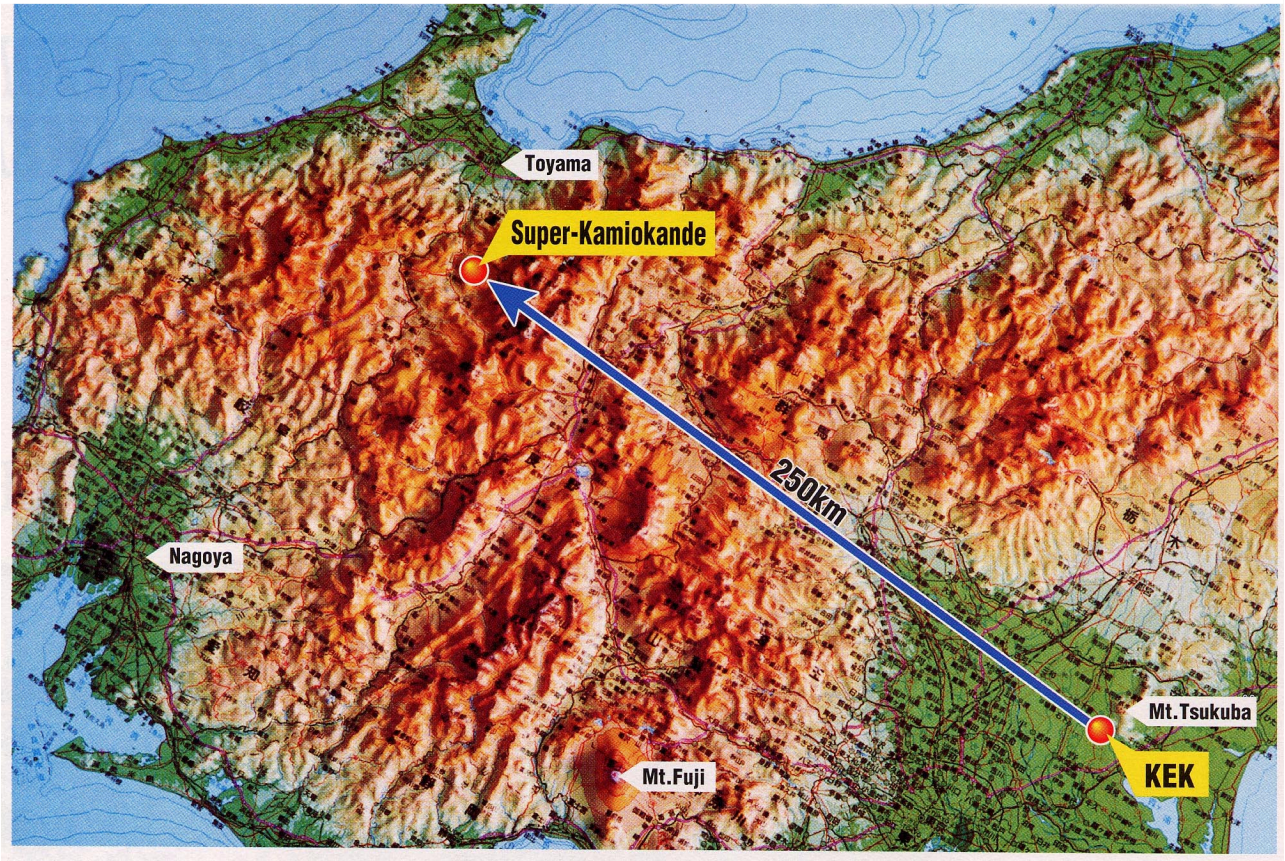
Neutrino Oscillation(2flavors)

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

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	$10 \sim 10^4$km	<5GeV	$0.5 \sim 5 \times 10^{-4}$	2/1
K2K	250km	~1GeV	4×10^{-3}	99/1

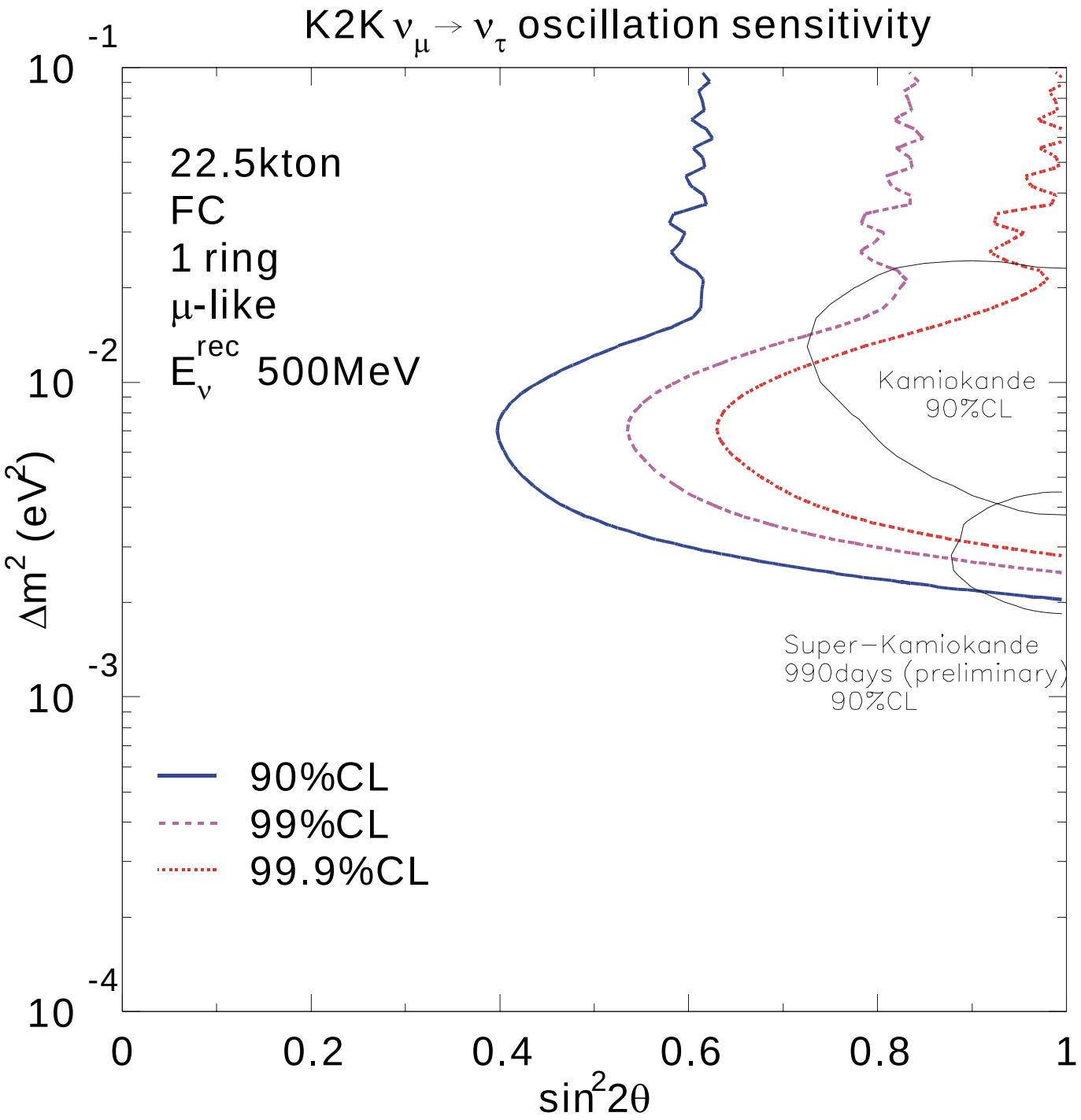
K2K Overview



- almost pure ν_μ(99%) beam w/ $\langle E_\nu \rangle \sim$ **1.3GeV**
- Far detector: Super Kamiokande(SK)@**250km**
- Most sensitive at $\Delta m^2 \sim 7\times10^{-3}$ **eV**^{2}
- ν_μ disappearance and ν_e appearance

Sensitive Region

10^{20} POT (～5year)

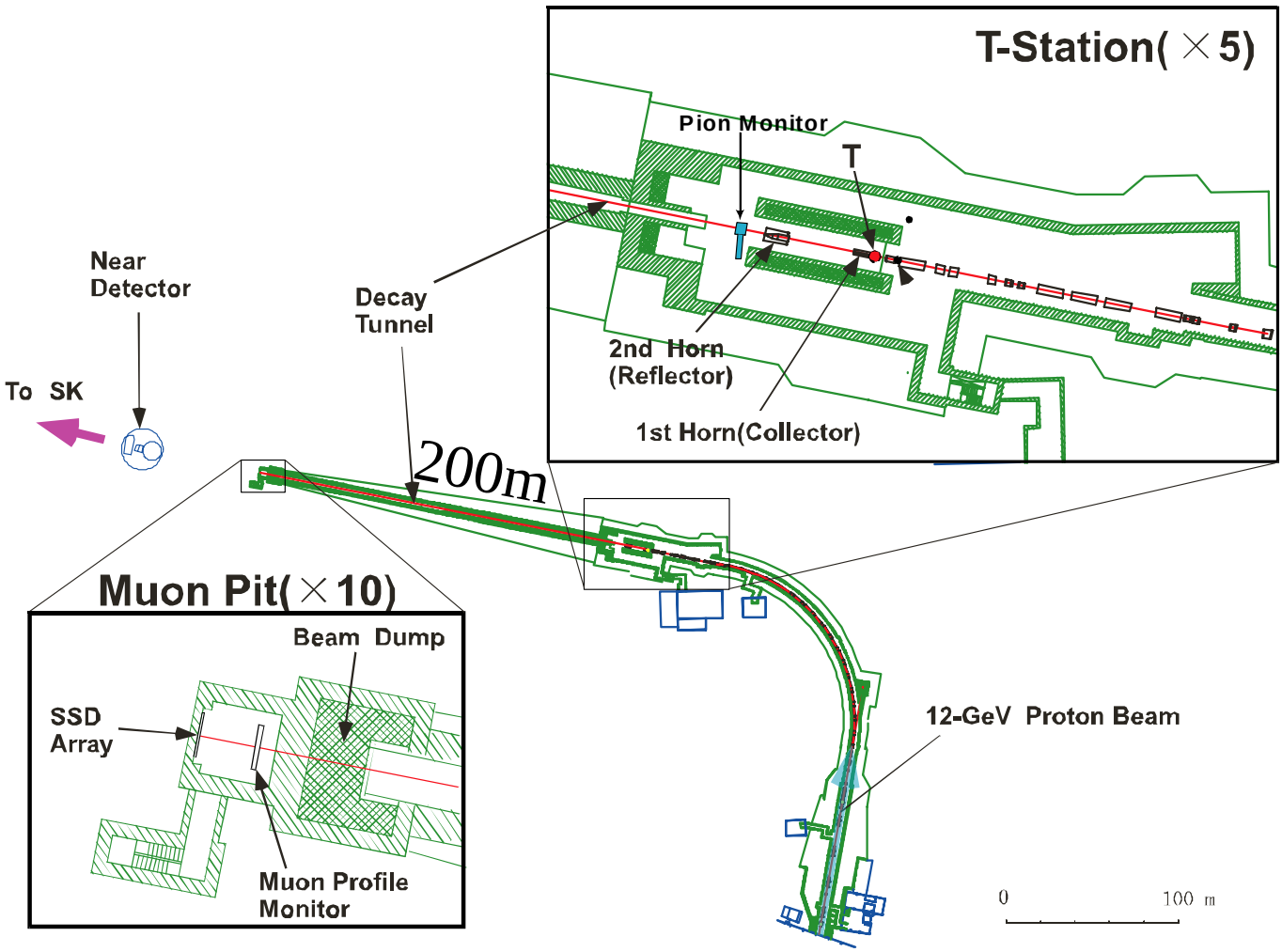


Experimental Setup

Neutrino Beam Production

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

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

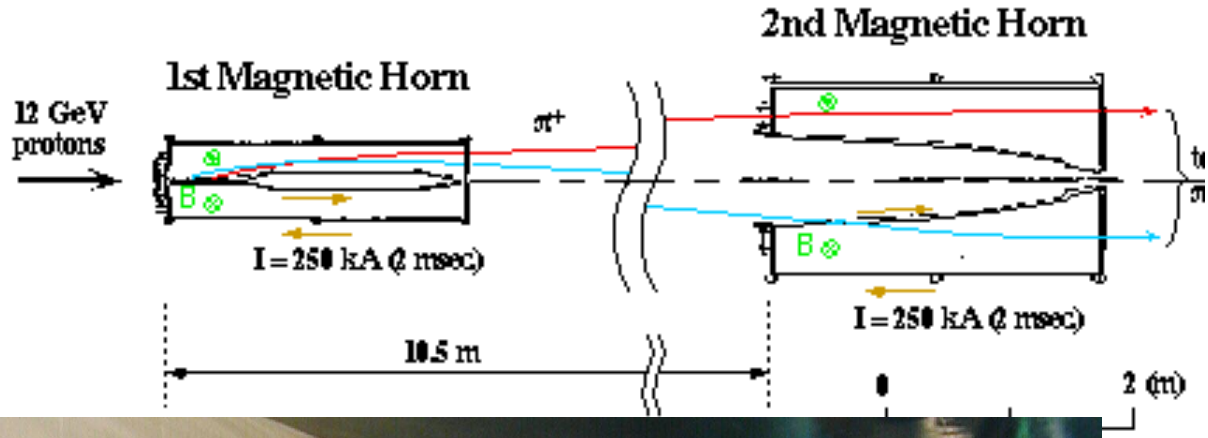


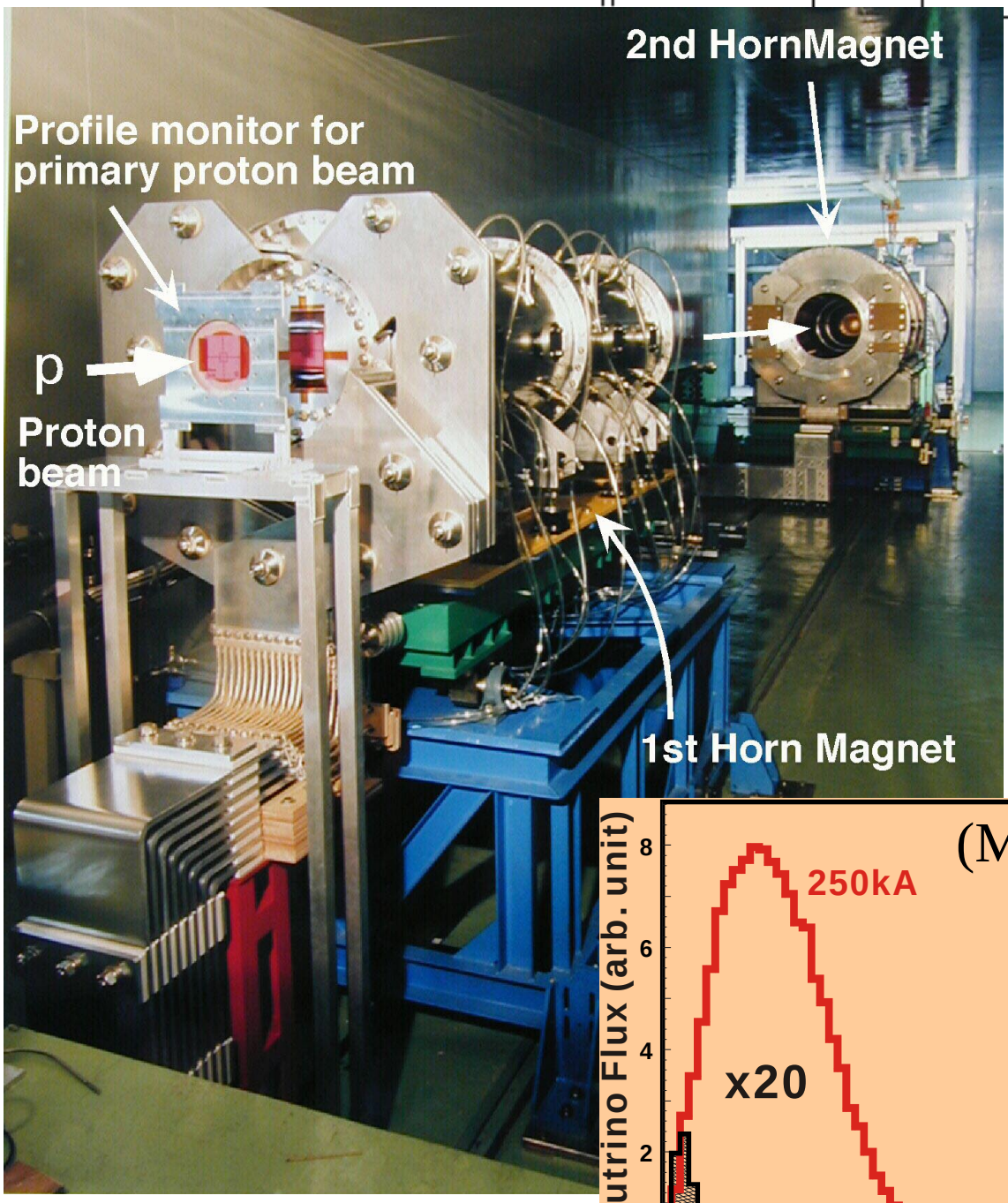
PS: 13GeV/c proton
1.1μsec spill/2.2sec
6×10^{12}protons/spill (design)

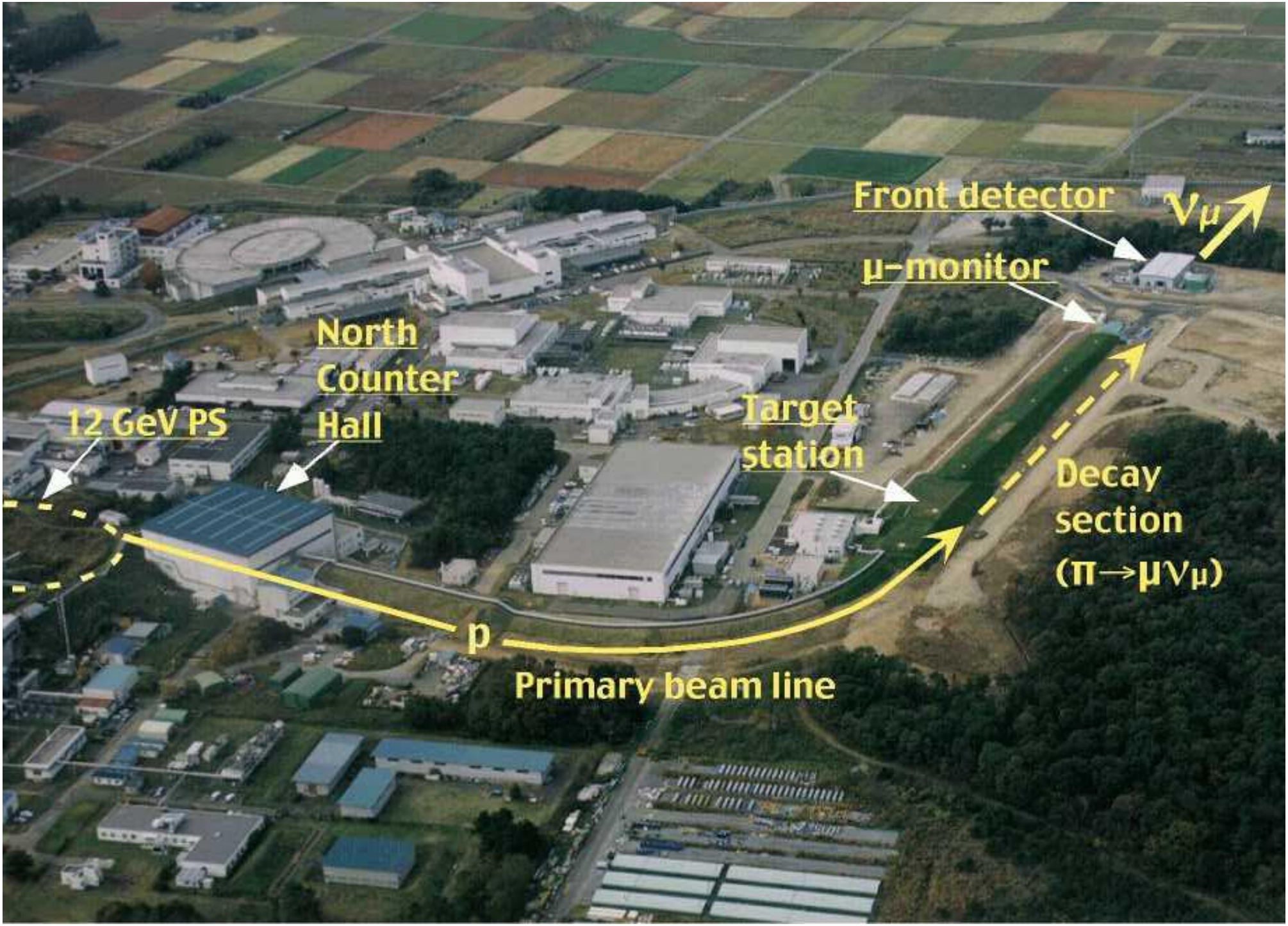
Beam line: aligned toward SK using GPS (global positioning system)
GPS< 0.01mrad, civil const<0.1mrad

Decay pipe: 200m

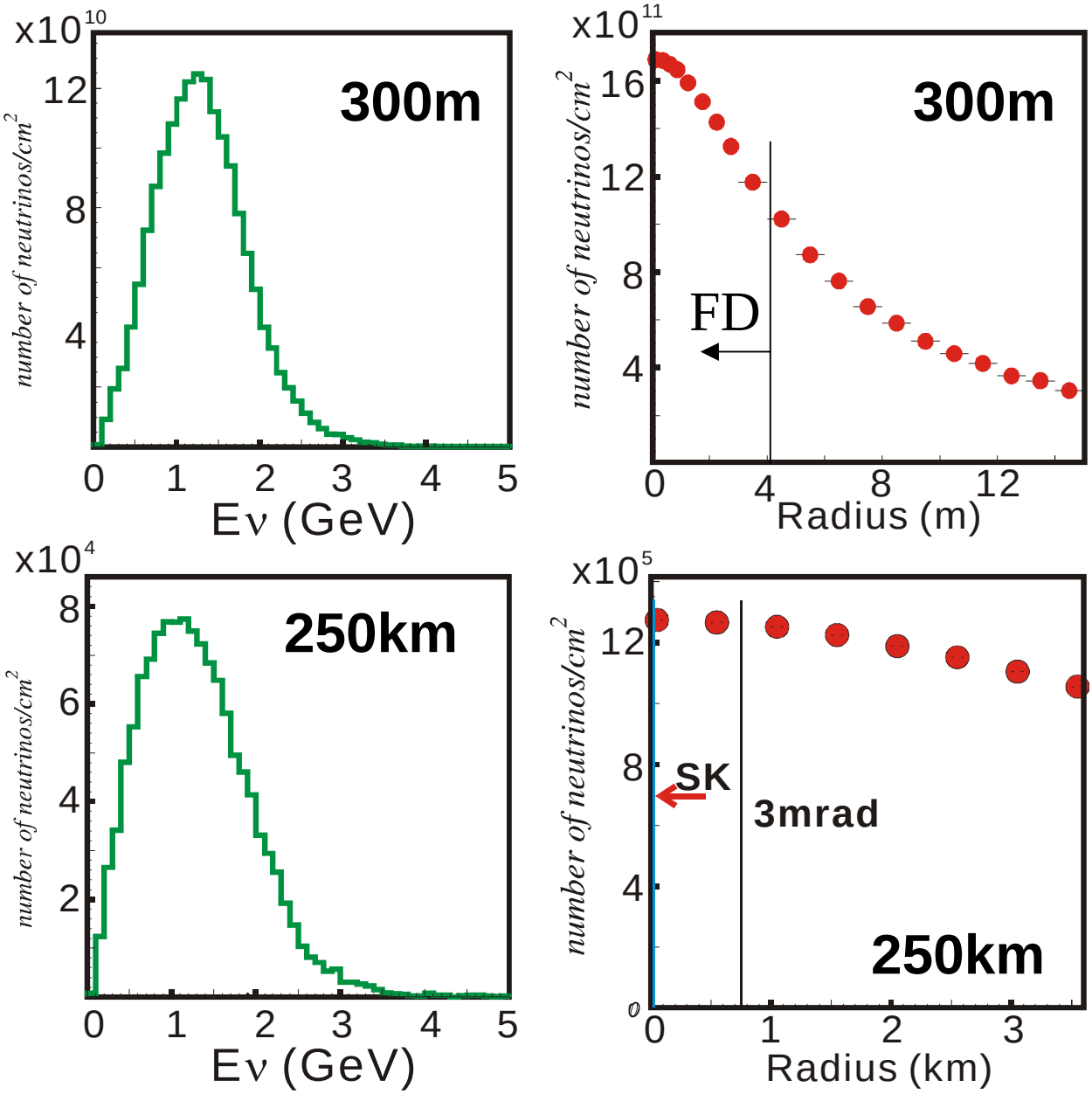
Target and Horns






Front detector
ν_μ
μ-monitor
North
Counter
Hall
12 GeV PS
Target
station
Decay
section
(π→μνμ)
p
Primary beam line

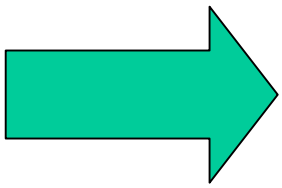
Neutrino Spectra and Radial Distributions at 300m/250km (MC)



Almost const flux < 1km(4mr) @ SK
Near/Far spectra differ

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, $N(p_\pi, \theta_\pi)$

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

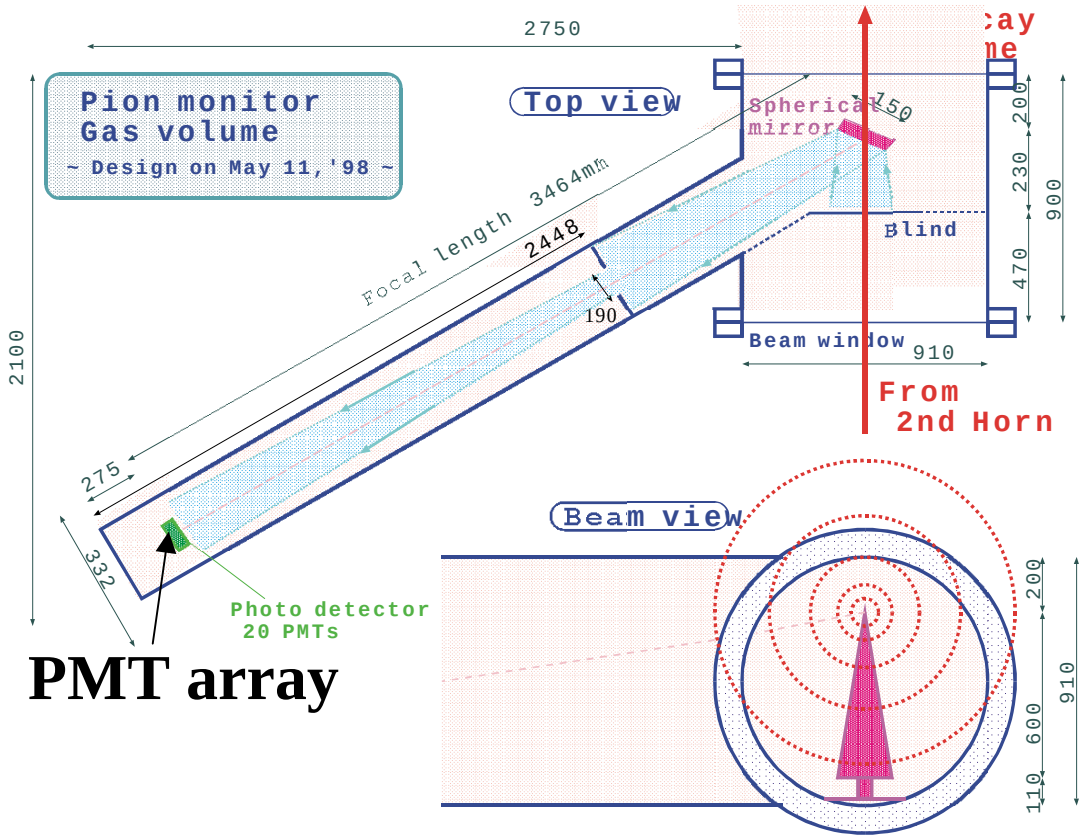
$$R(E_\nu) \equiv \Phi_{SK}(E_\nu)/\Phi_{FD}(E_\nu)$$

as a result of pion monitor

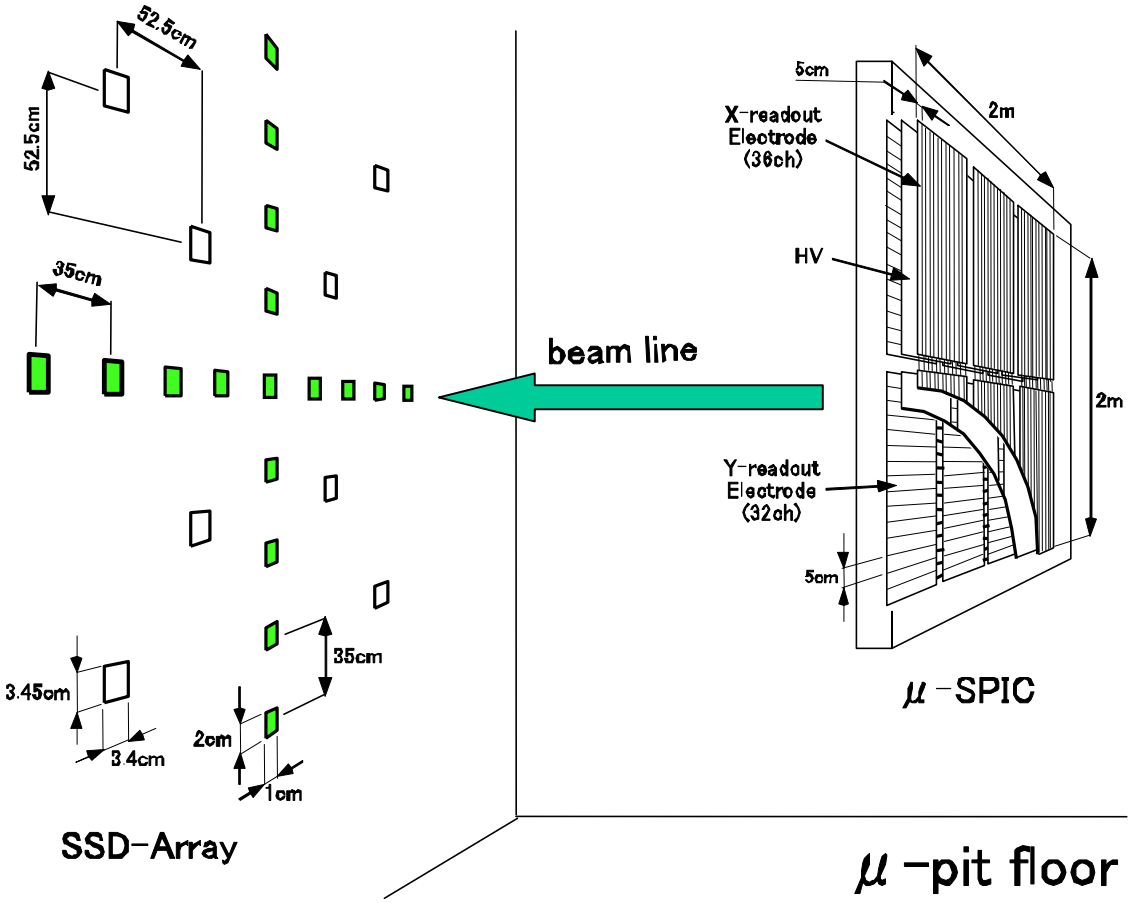
Gas Cherenkov detector

to avoid signal from 12GeV protons

→ insensitive to p_π <2GeV (E_ν<1GeV)



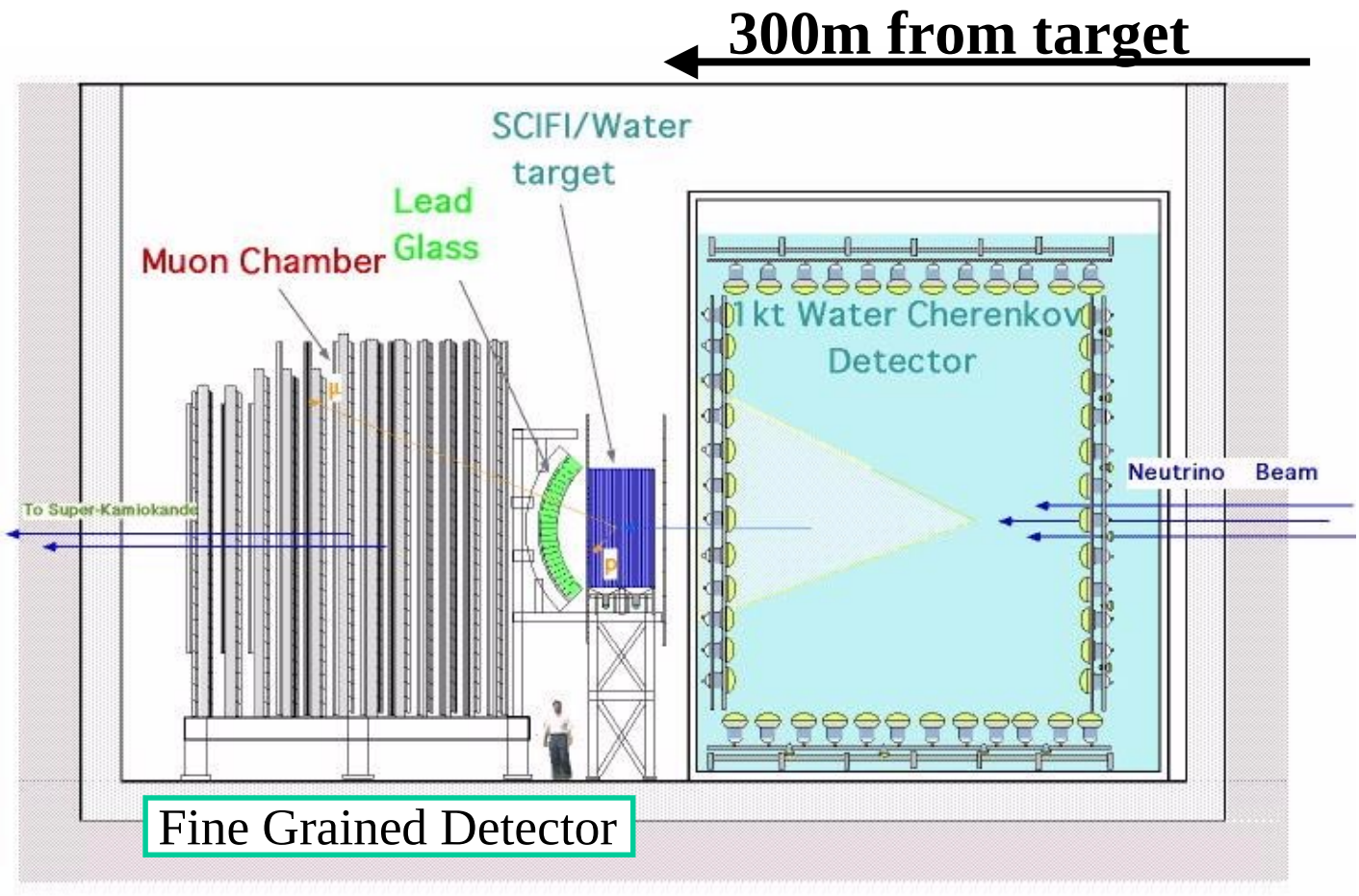
Muon Monitors



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)



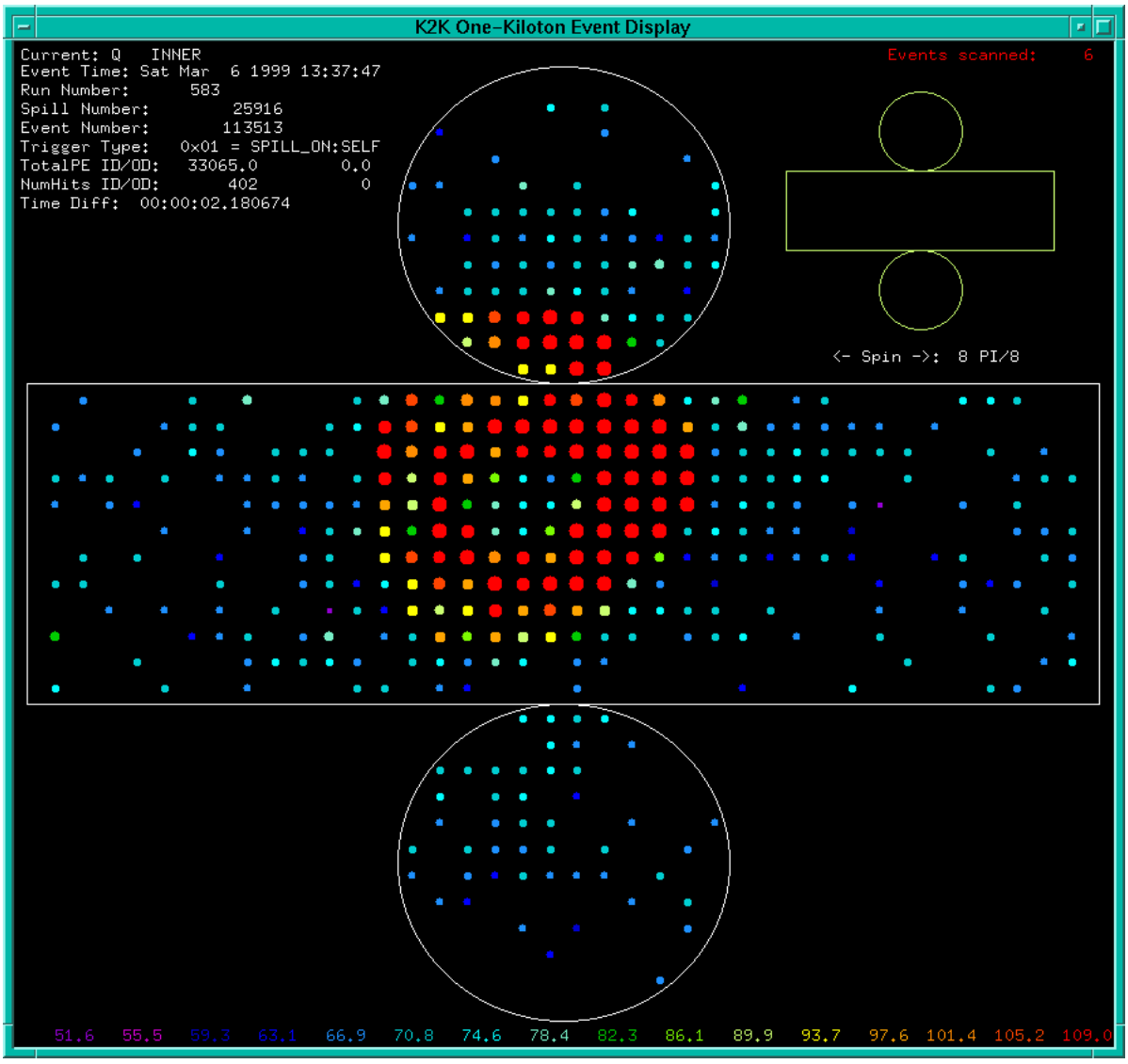
Purpose

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 chamber (MUC) : drift chamber+iron plates

Event categories

1kt Event



H_2O target (same as SK)

Same detection principle as SK

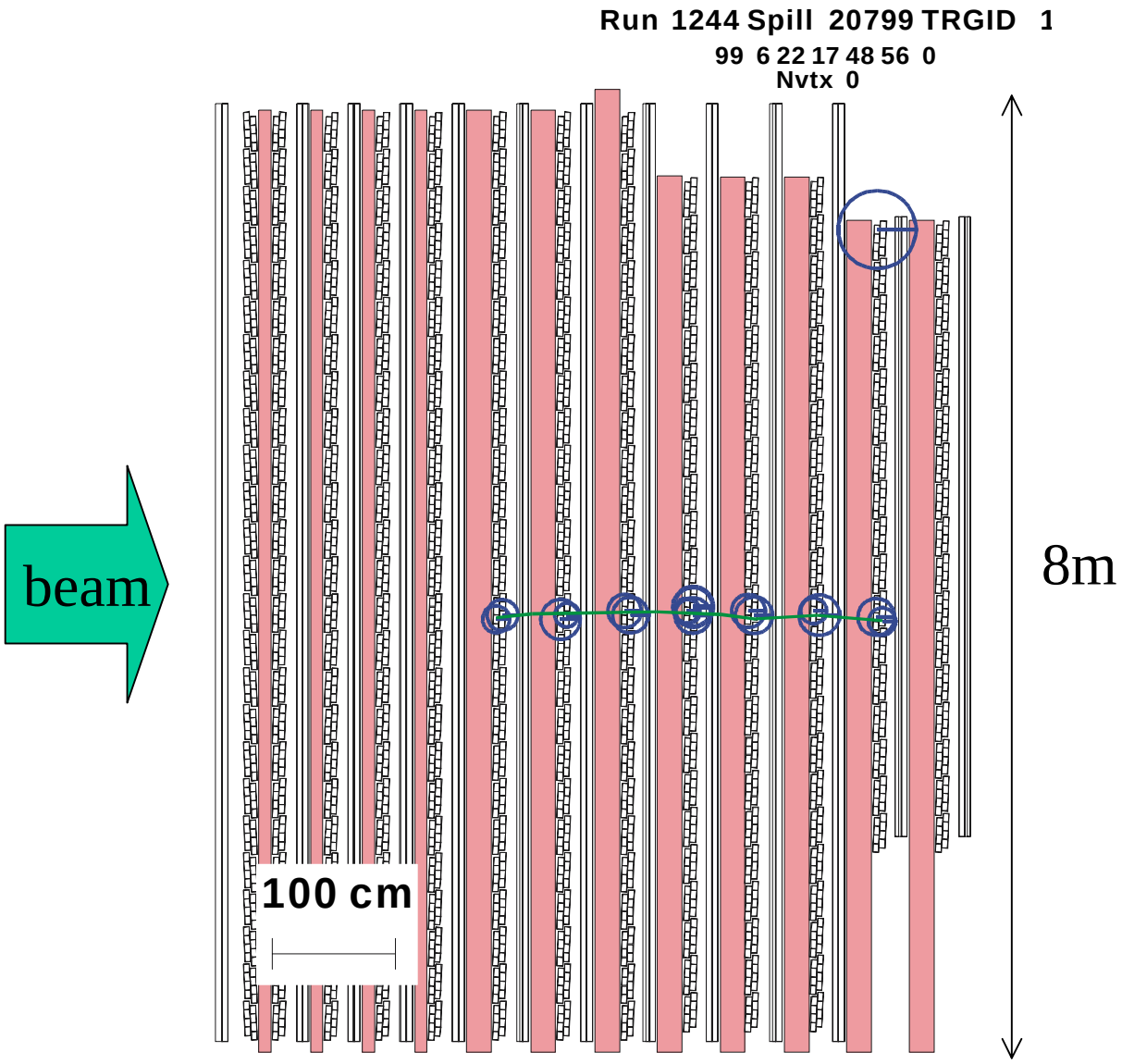
→ **expect least syst. err. for SK exp'ed**

Fid. mass **50.3ton**

Event selection: Qtot>1000p.e.

～2events/100spill

Fe Event



Neutrino int. in MUC **iron** plates

CC inclusive (insensitive to NC)

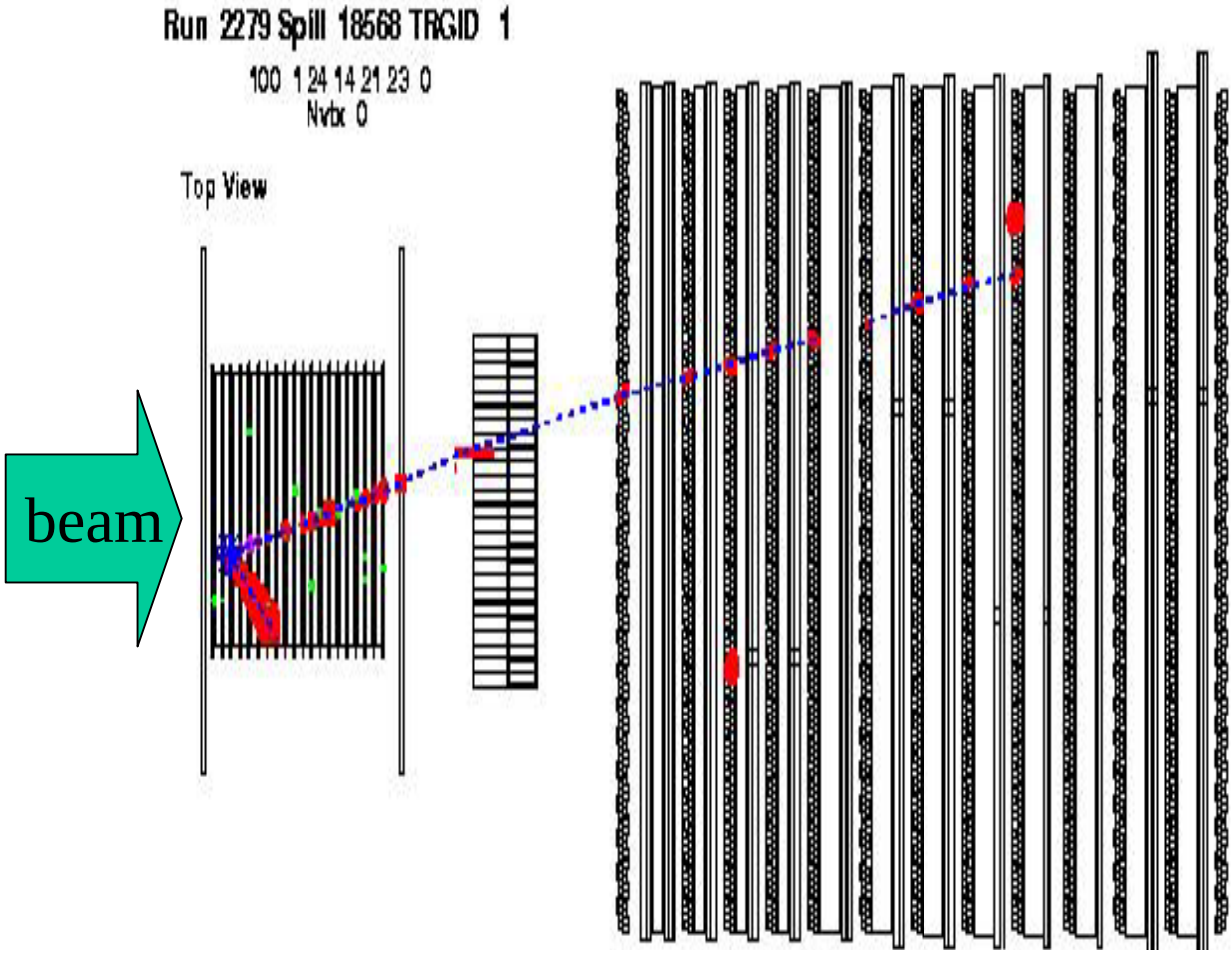
Large area coverage (8m) → profile(vtx dist.)

Large mass (fid. mass=**312 ton**)

→ 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 = **4.9 ton**

Event selection: matching SFT&MUC track

1event/1000spill

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

Strategy

For now,

1. count # of events @ SK

$$N_{SK}^{obs}$$

2. calc. expected # of events @ SK

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

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

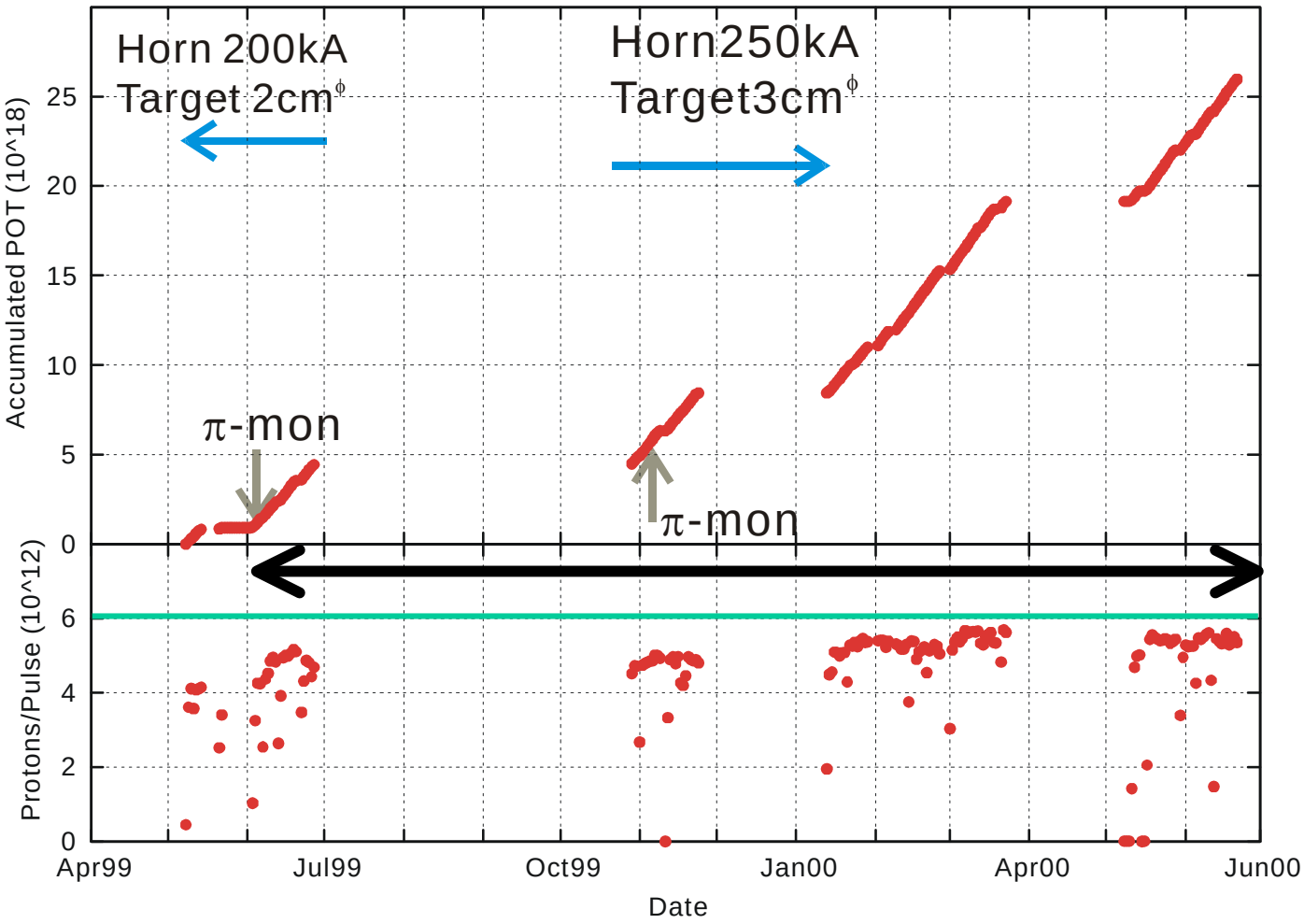
check consistency btw. kt/Fe/SFT events

*eventually,…

$$N_{SK}^{obs}(E_\nu) \text{ and } N_{SK}^{exp}(E_\nu)$$

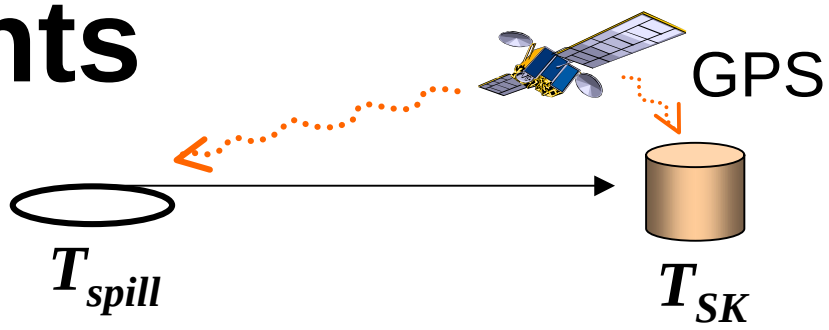
Results

Delivered Beam



- Design Proton Int. 6x10^{12} protons/pulse almost achieved (5.5x10^{12})
- ～2.6x10^{19}POT delivered by the end of Jun. ‘00
- SK Live = **2.29x10^{19}** POT(Jun99-Jun00)

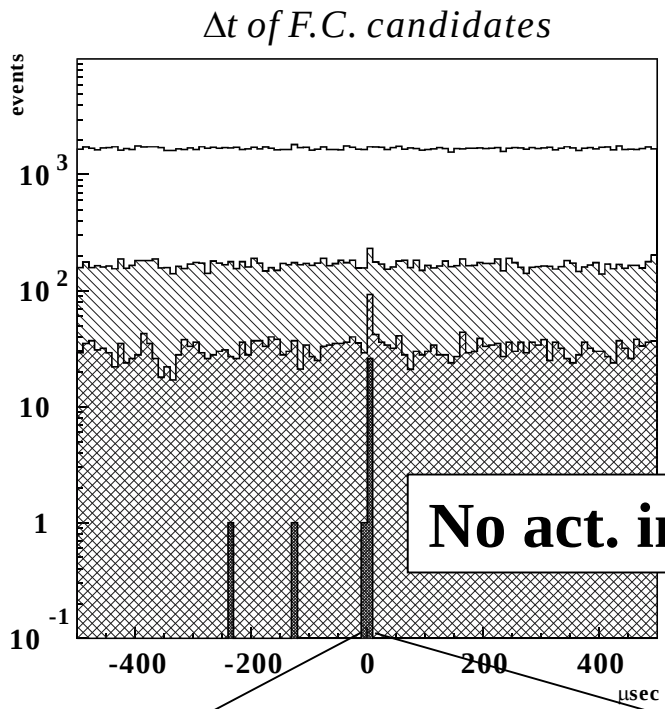
SK Events



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

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

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

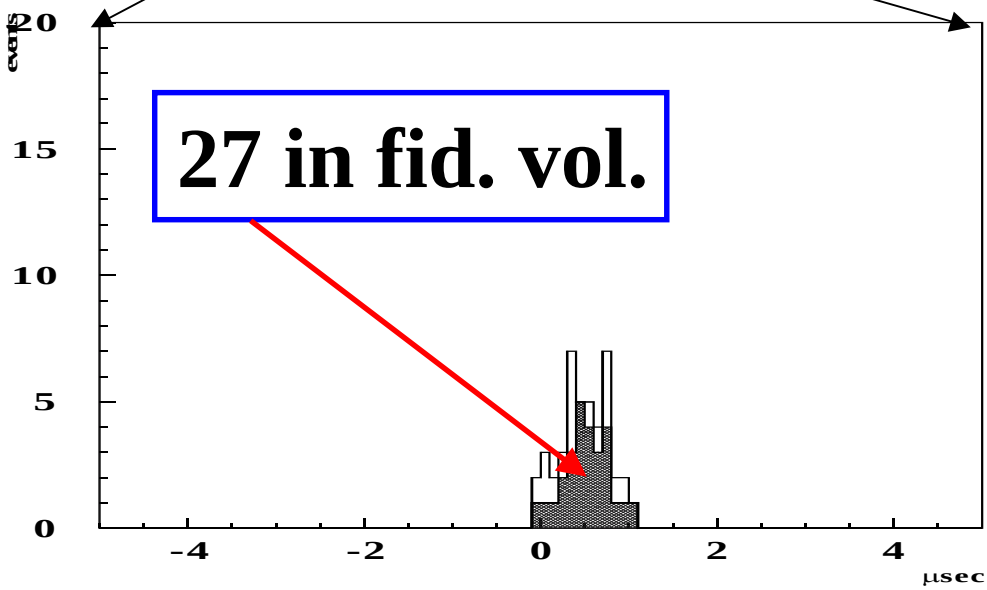


No Decay-e

HE Trig.

Qtot cut

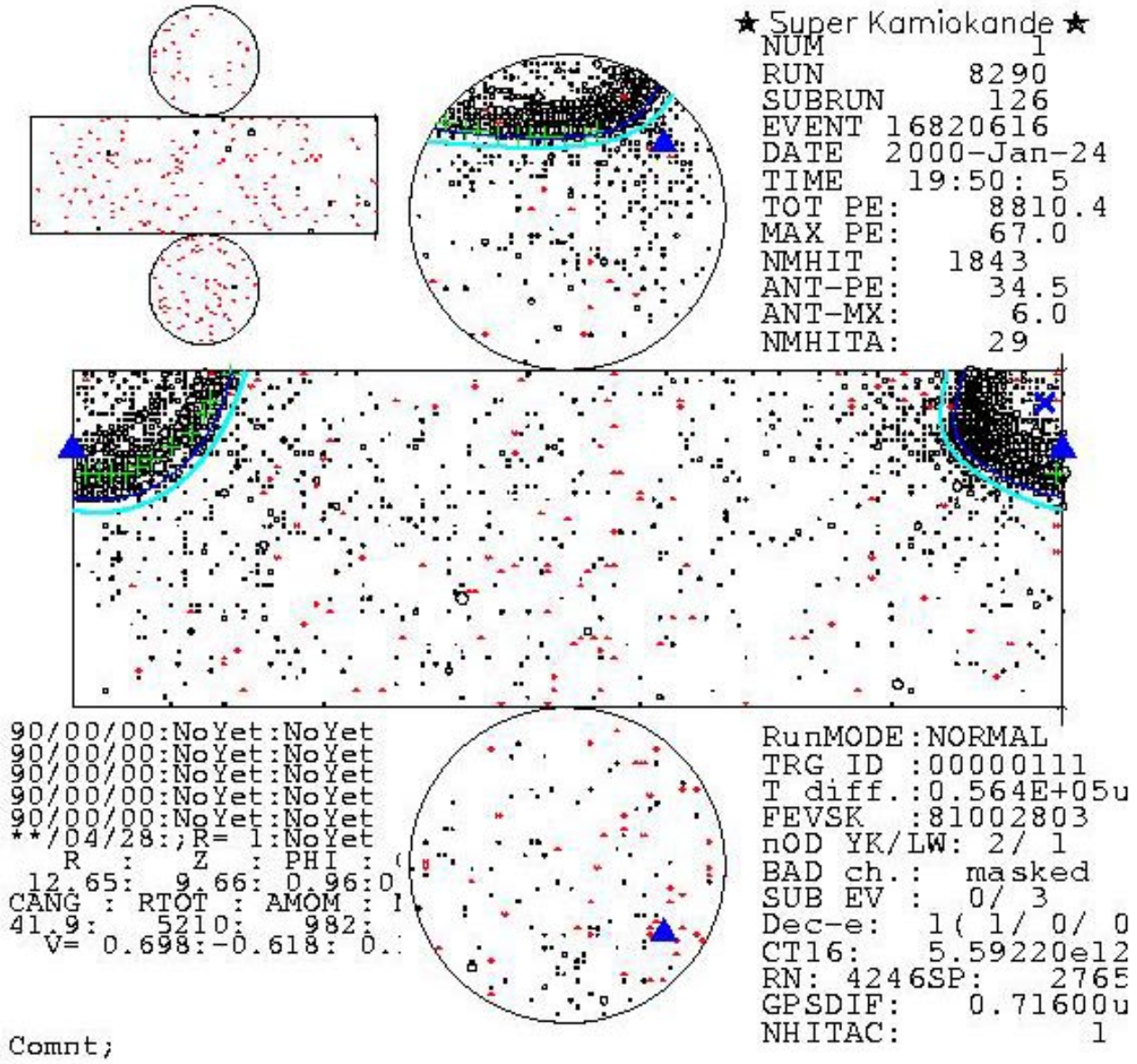
No act. in OD(fully contained)



27 in fid. vol.

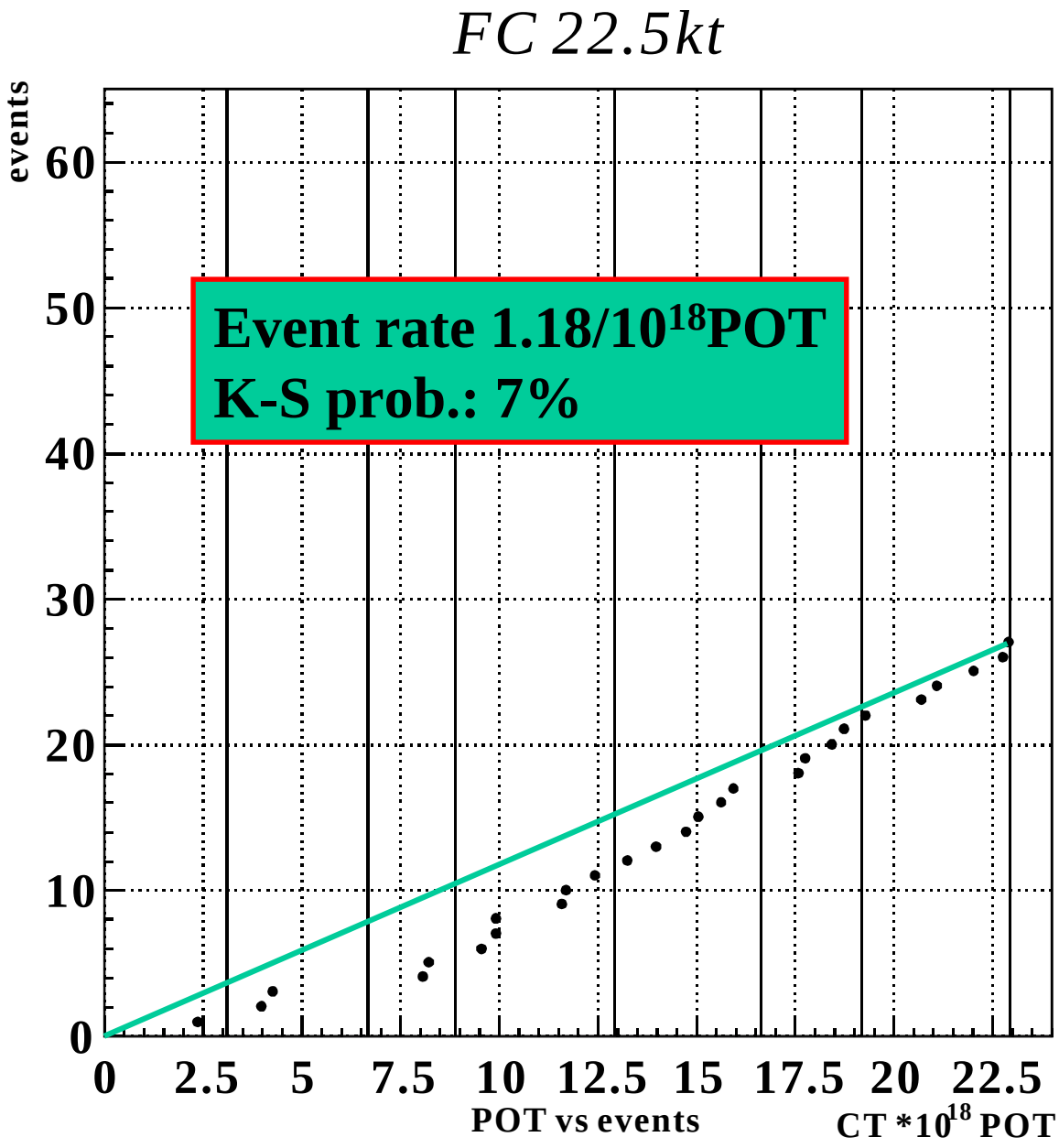
Exp'ed Atm ν BG $<10^{-3}$ in 1.5μs win.

Typical SK Events

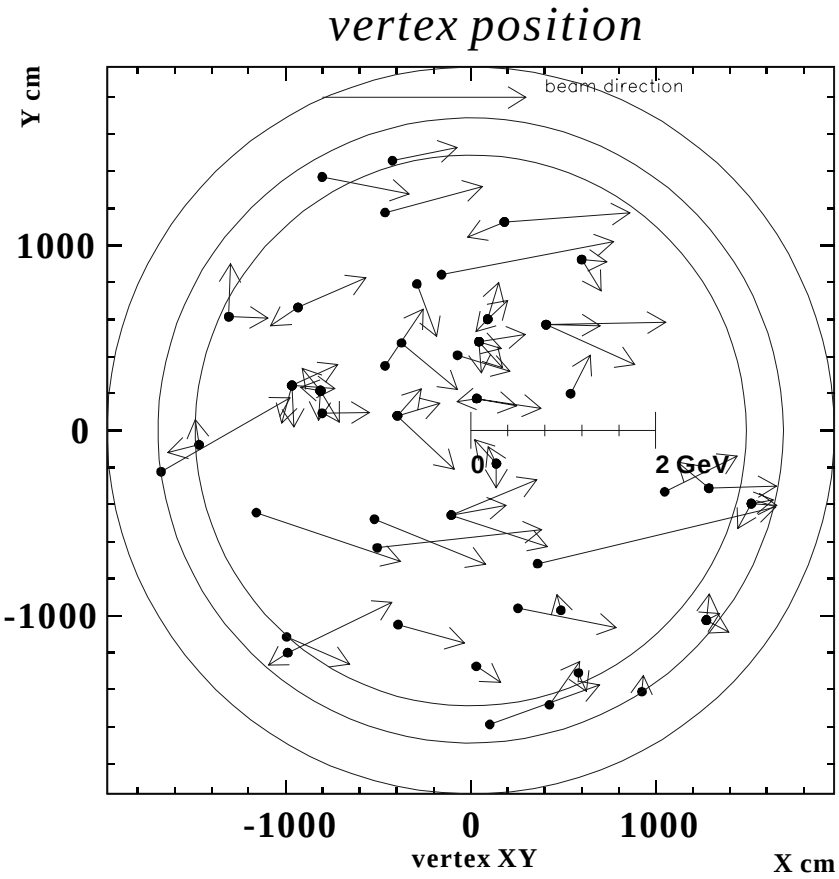


Event POT Distribution

fully contained, vertex in fiducial volume

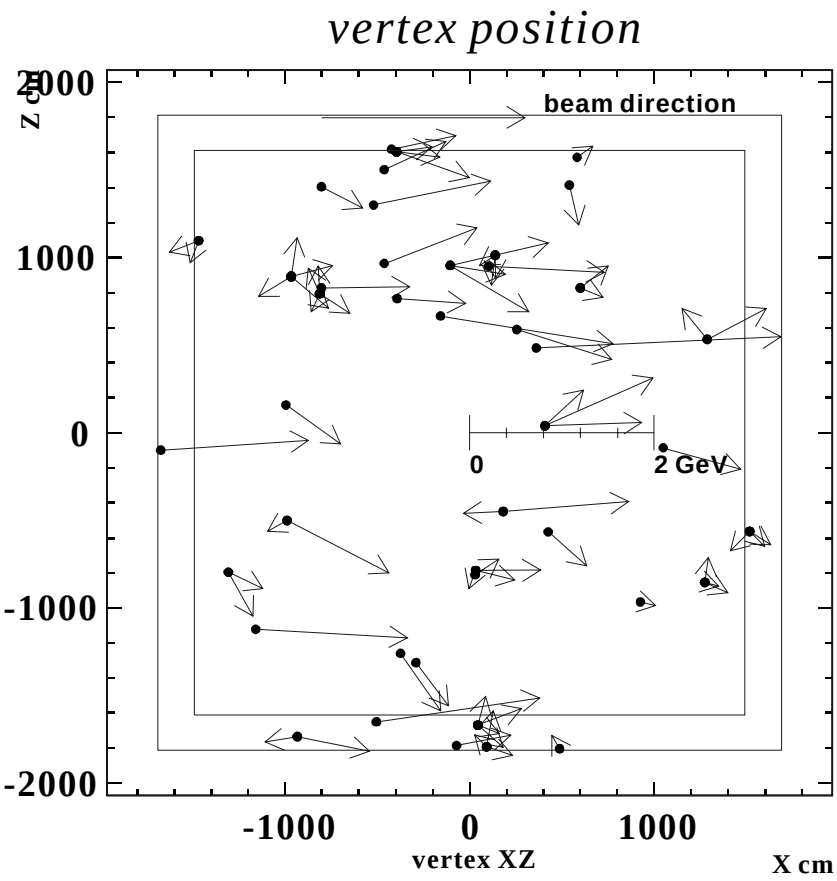


Vertex and Direction



top view

fully contained



side view

Measurements @ KEK

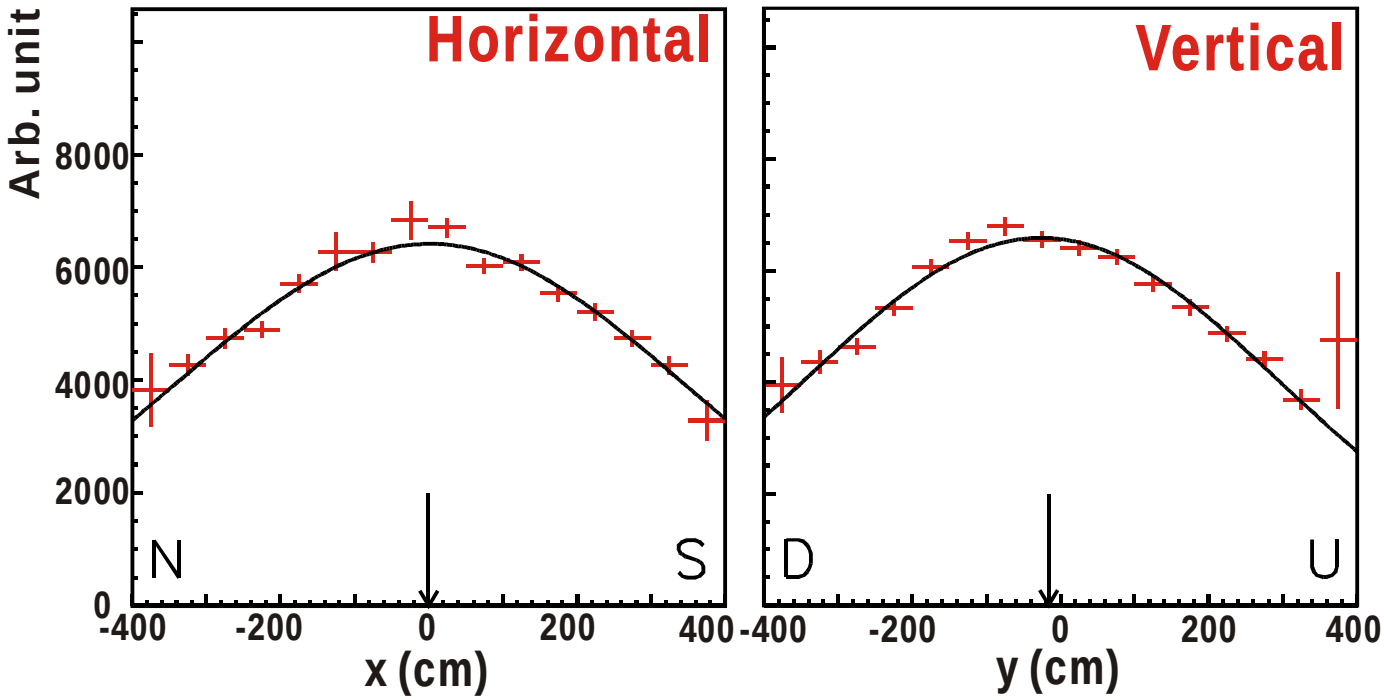
- Beam Direction
- Absolute neutrino flux
- Spectrum extrapolation
- Neutrino spectrum
  - CC μ energy spectrum
  - CC μ angle

Stability of beam quality is of great impotance.

(pi mon is not full-time det.)

Beam Direction

Vertex distribution of Fe events (Nov99)

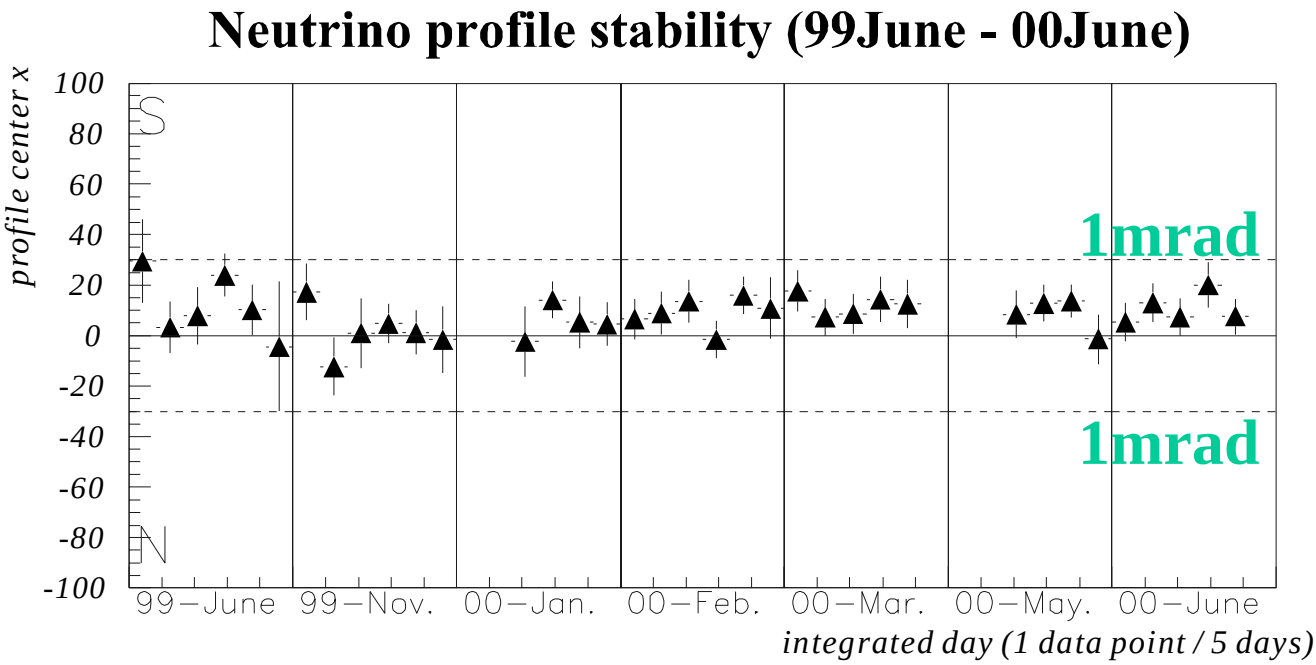


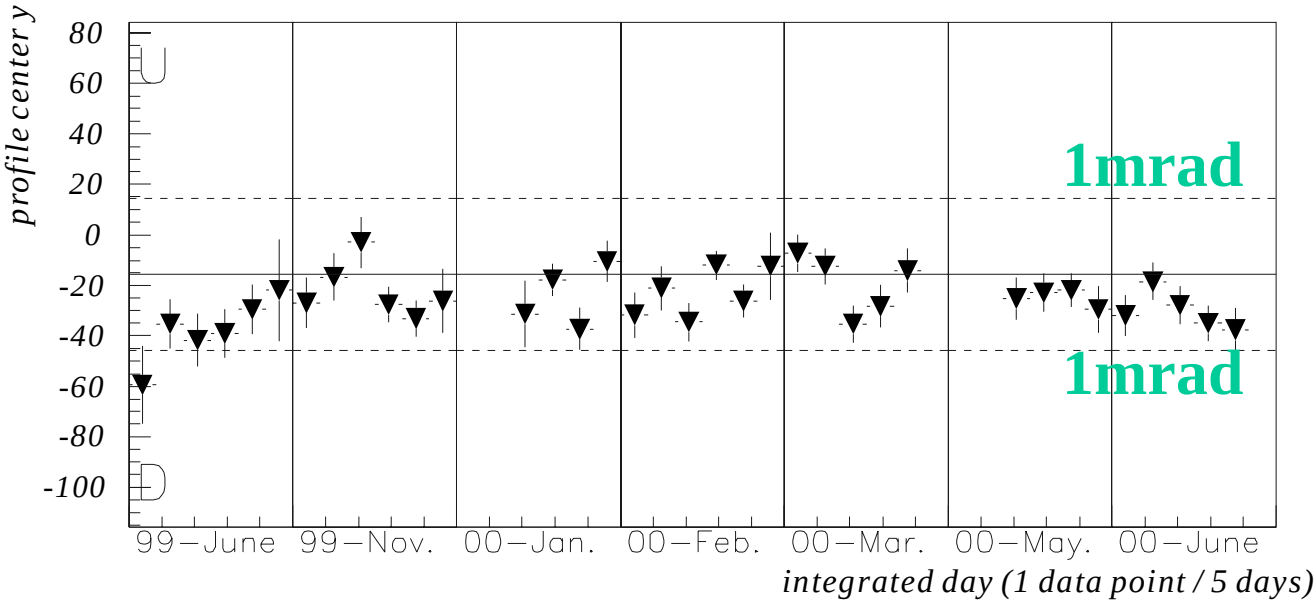
Fitted center x: 1 ± 5cm

y: -10 ± 4cm (stat) from SK dir.

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

Stability of Profile Center (Fe event)

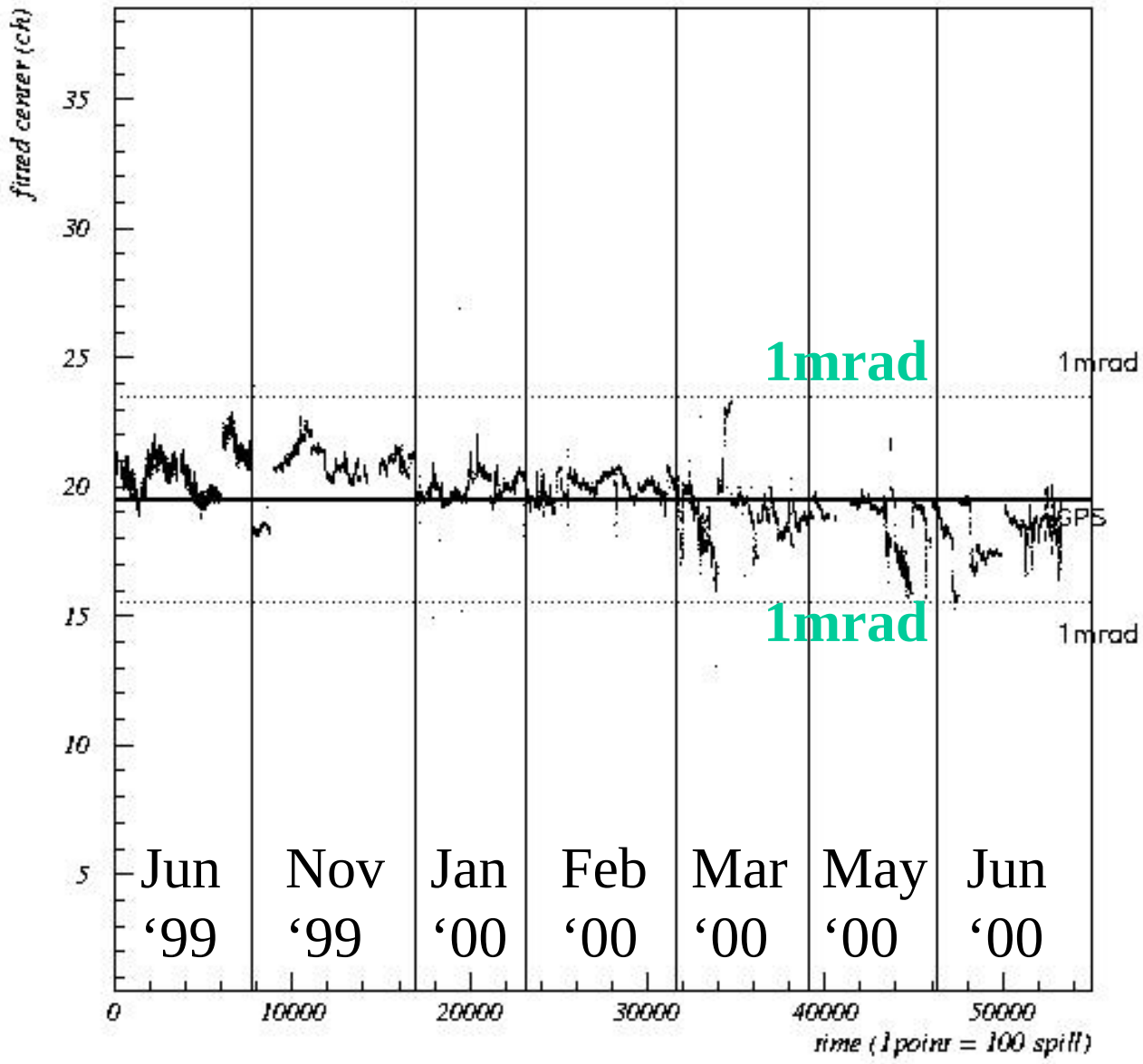




Stable within ±1mrad.

Stability of Muon Profile Center @ Muon Monitor

Fast (spill-by-spill) but indirect monitor



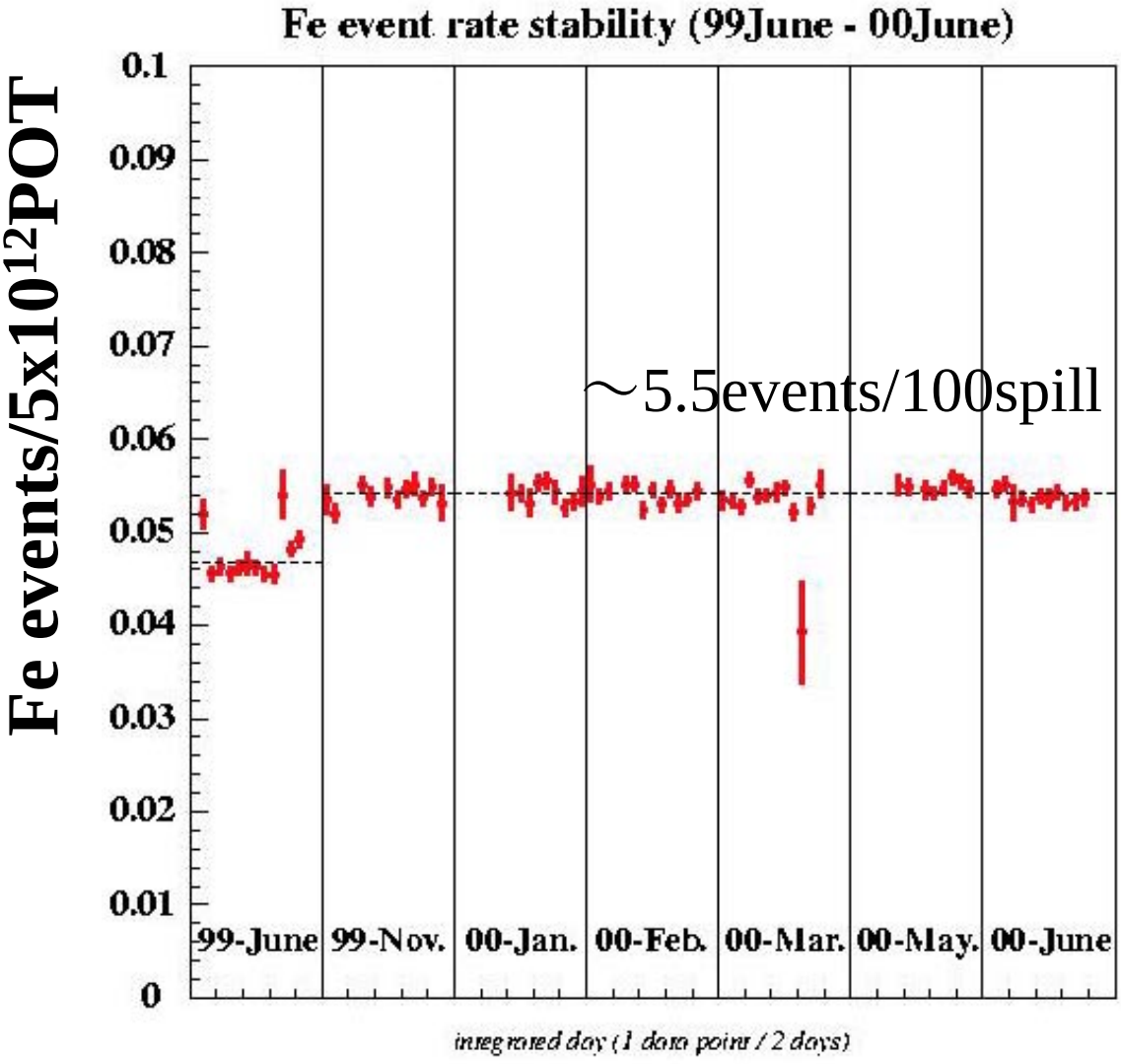
Stable within ±1mrad

Absolute neutrino flux

Count # of neutrino events in FDs

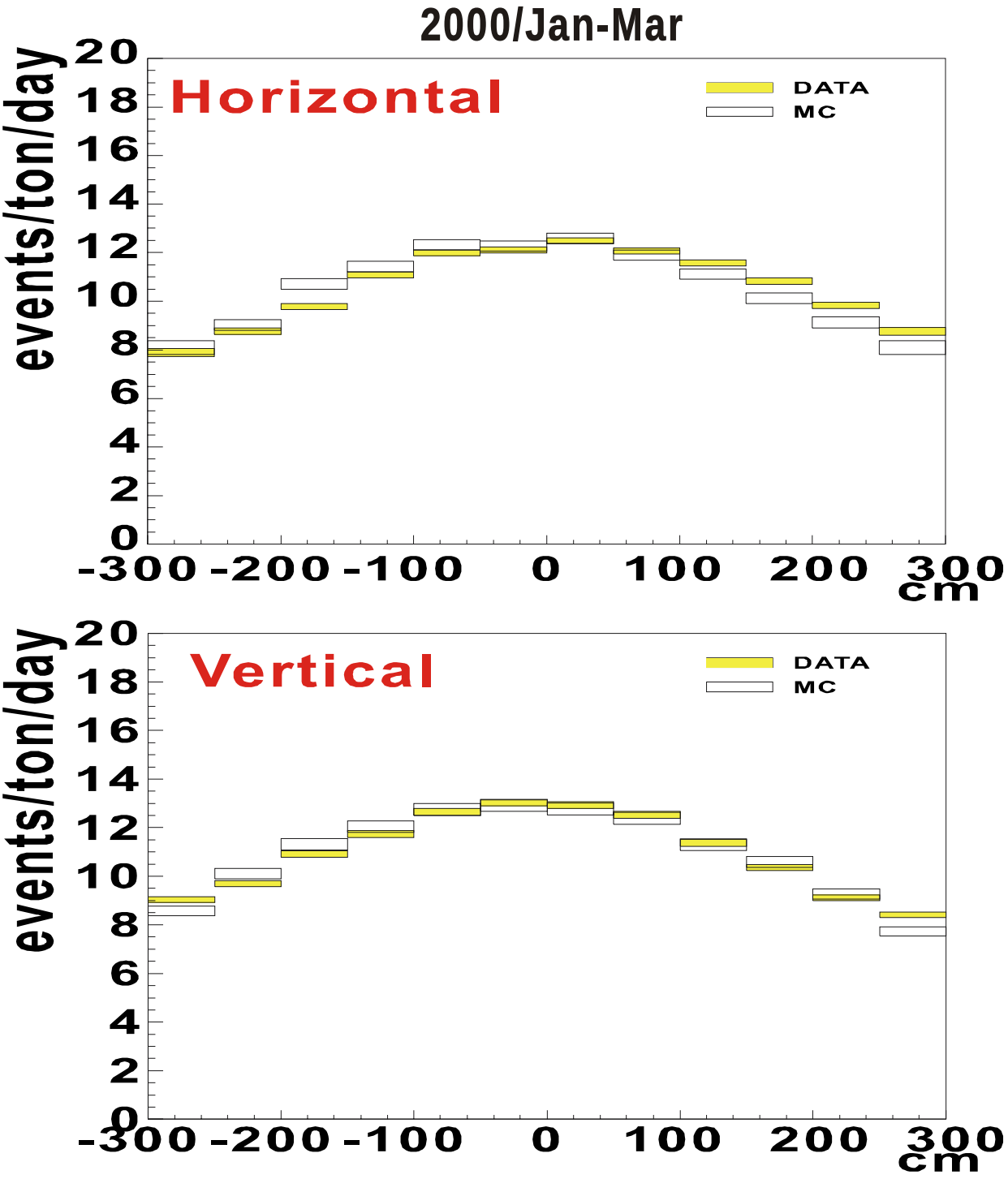
	1kt	Fe	SFT
N_{FD}	64k	223k	2,953
Live POT(10^{18})	19.1	21.0	18.2

Event rate stablity



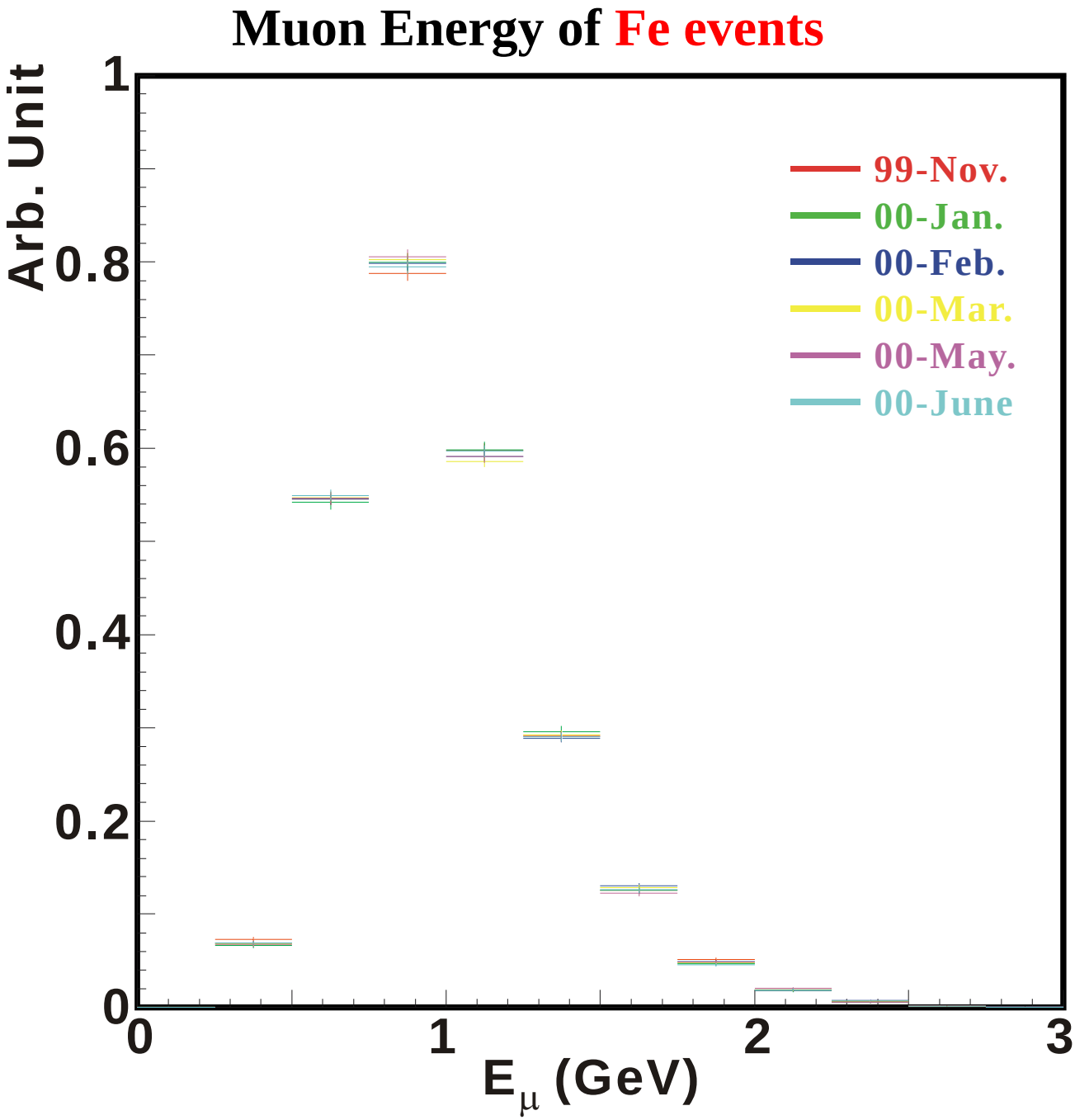
very stable

Vertex dist. of 1kt events



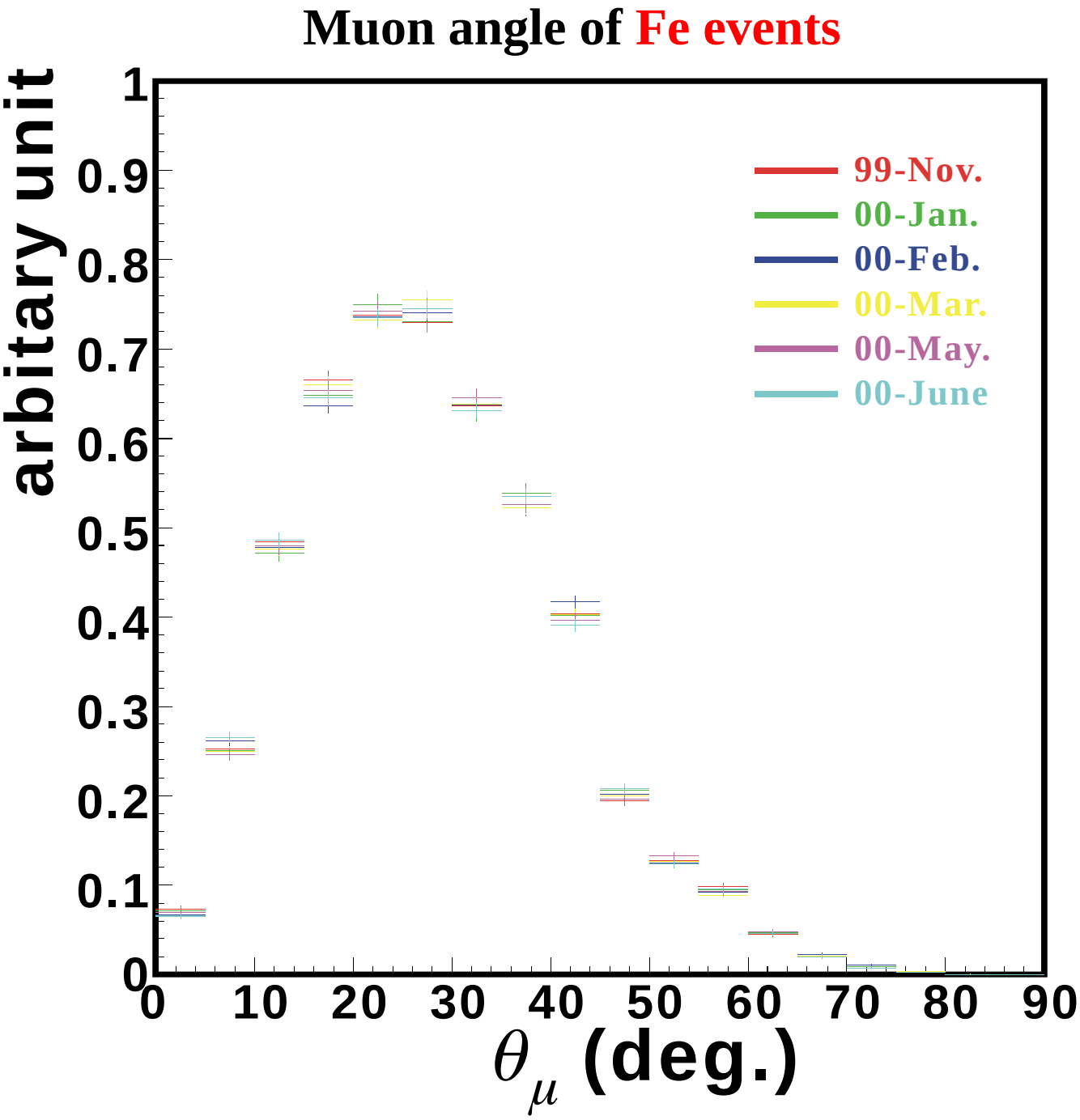
Agree with MC well.

Stability of Spectrum



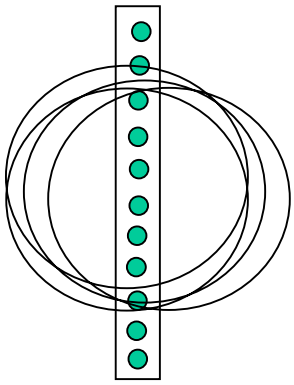
Stable within stat. error

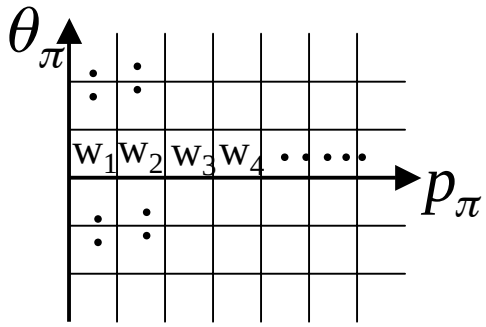
Stability of muon angle



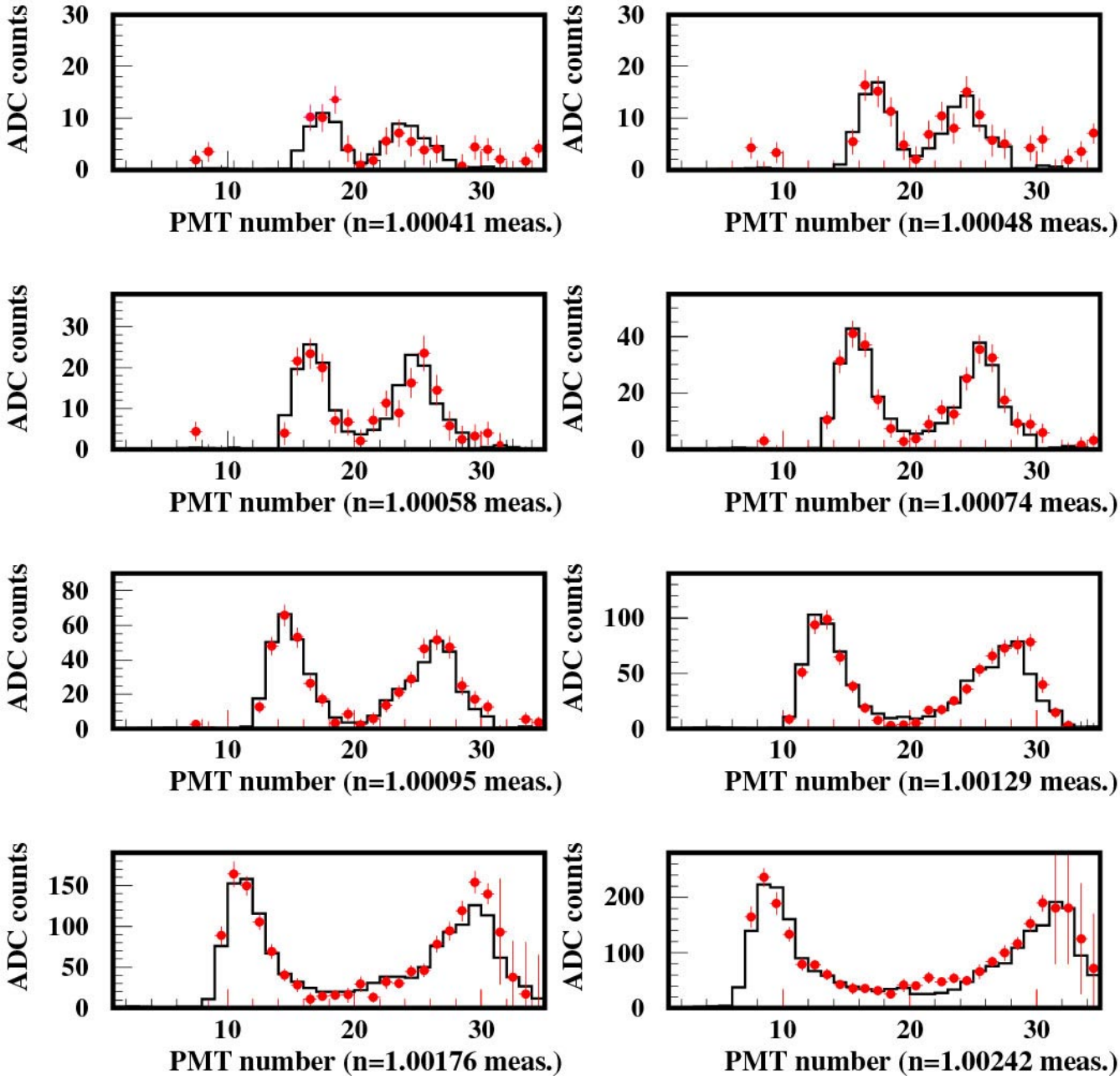
Stable within stat. error

Pion Monitor Results

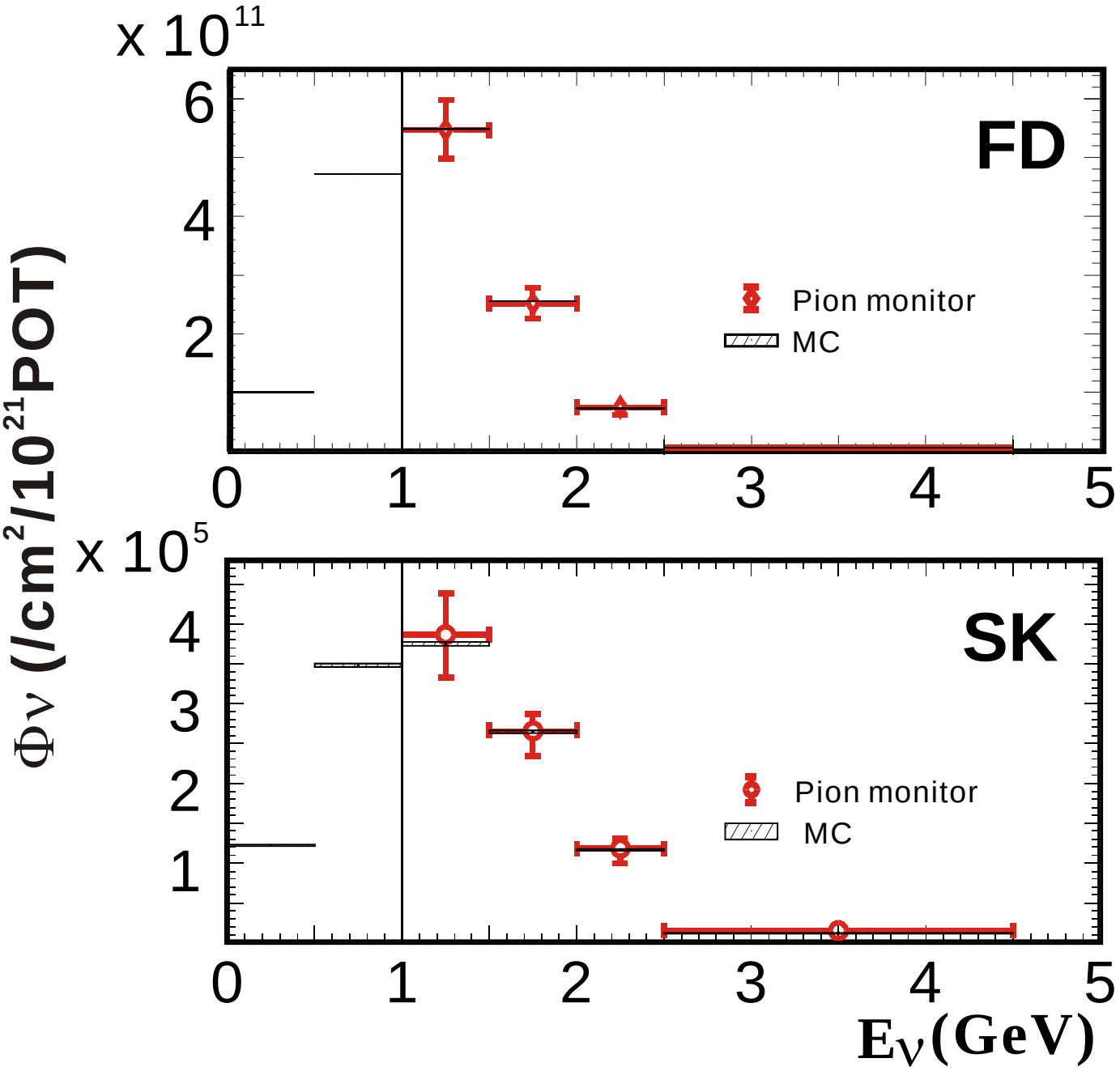




Pion Monitor Fitting (November)



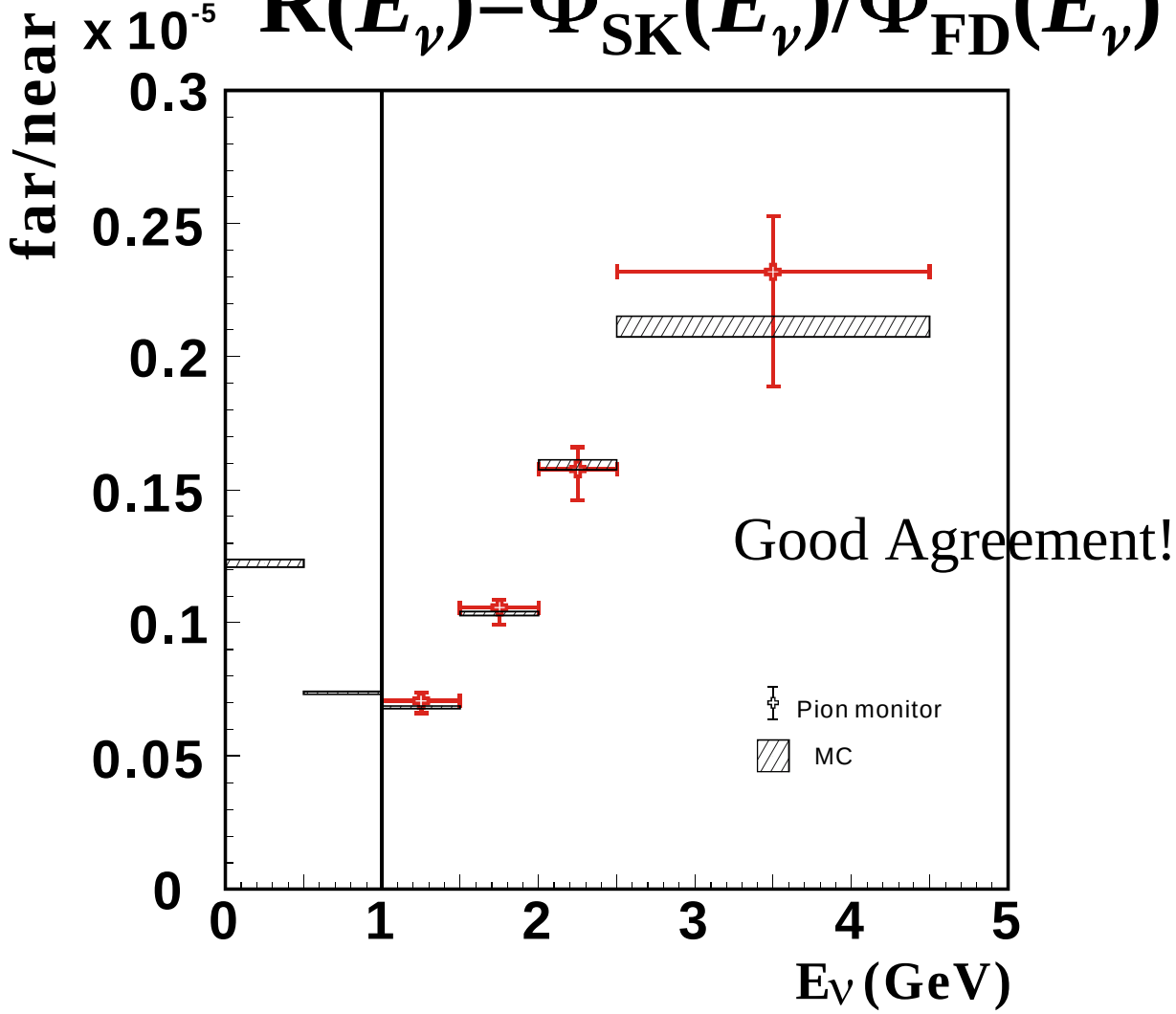
ν_μ spectra from Pion Monitor Measurement



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

use MC for central value

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

(for 1kt)

Expected # of SK events from 1kt detector

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

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

N_{kt}^{obs}	:	$\sim$64k
ε_{kt}	:	0.71 (detection eff. of 1kt)
L_{SK}/L_{kt}	:	Live POT ratio ($\sim$1.2)
M_{SK}/M_{kt}	:	Fiducial mass ratio
ε_{SK}	:	0.81 (detection eff. of SK)

$$N_{SK}^{\exp} = 40.3 \pm 0.2(\mathrm{stat.}) \, {}^{+4.7}_{-4.6}(\mathrm{syst.})$$

c.f. : $N_{SK}^{\exp} = 41.4^{+6.2}_{-6.4}(\mathrm{tot.})$ from Fe events

: $N_{SK}^{\exp} = 40.0^{+5.2}_{-5.5}(\mathrm{tot.})$ from SFT events

Consistent with each other.

of observed and expected events @ SK

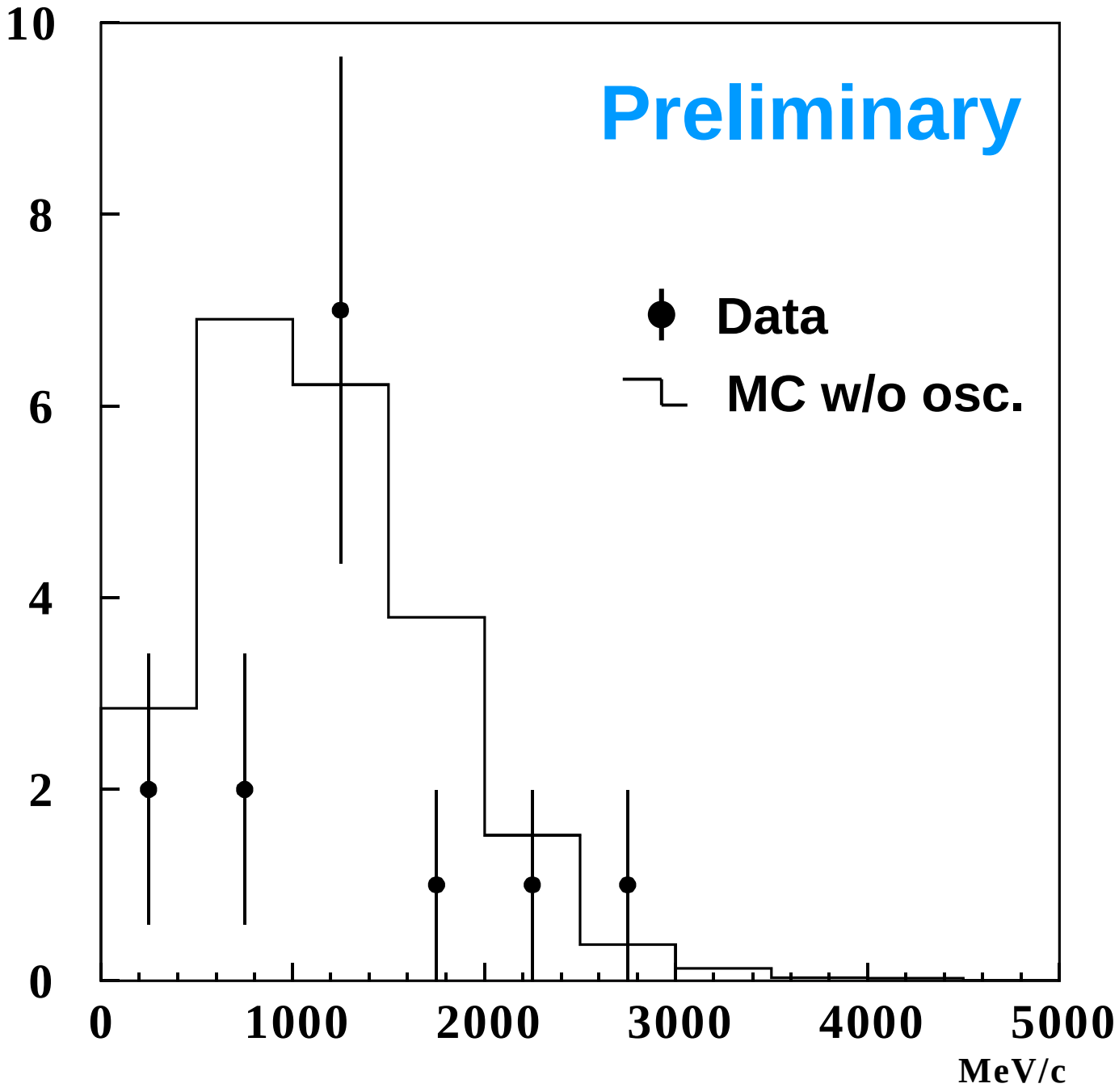
	Obs.	Exp.
FC 22.5kt	27	$40.3\ ^{+4.7}_{-4.6}$
1-ring	15	24.3 ± 3.6
μ-like	14	21.9 ± 3.5
e-like	1	2.4 ± 0.5
multi ring	12	16.0 ± 2.7

Systematic Error for N_{SK}

	1kt	Fe	SFT
(SK expected)	$40.3^{+4.7}_{-4.6}$	$41.4^{+6.2}_{-6.4}$	$40.0^{+5.2}_{-5.5}$
ΔV/V	6%	<2%	3%
Multi event	3%		
Background	1%		1%
Flux	+1.3% −1.7%	3%	3-4%
Detection Efficiency		3%	5%
NC/CC(±30%)	+0.8% −0.9%	6%	6%
Cross section		10%	3%
ΔV/V(SK)	3%	3%	3%
ΔR(Flux ratio)	+6% −7%	+6% −7%	+7% −9%
Total	+10% −11%	15%	13%

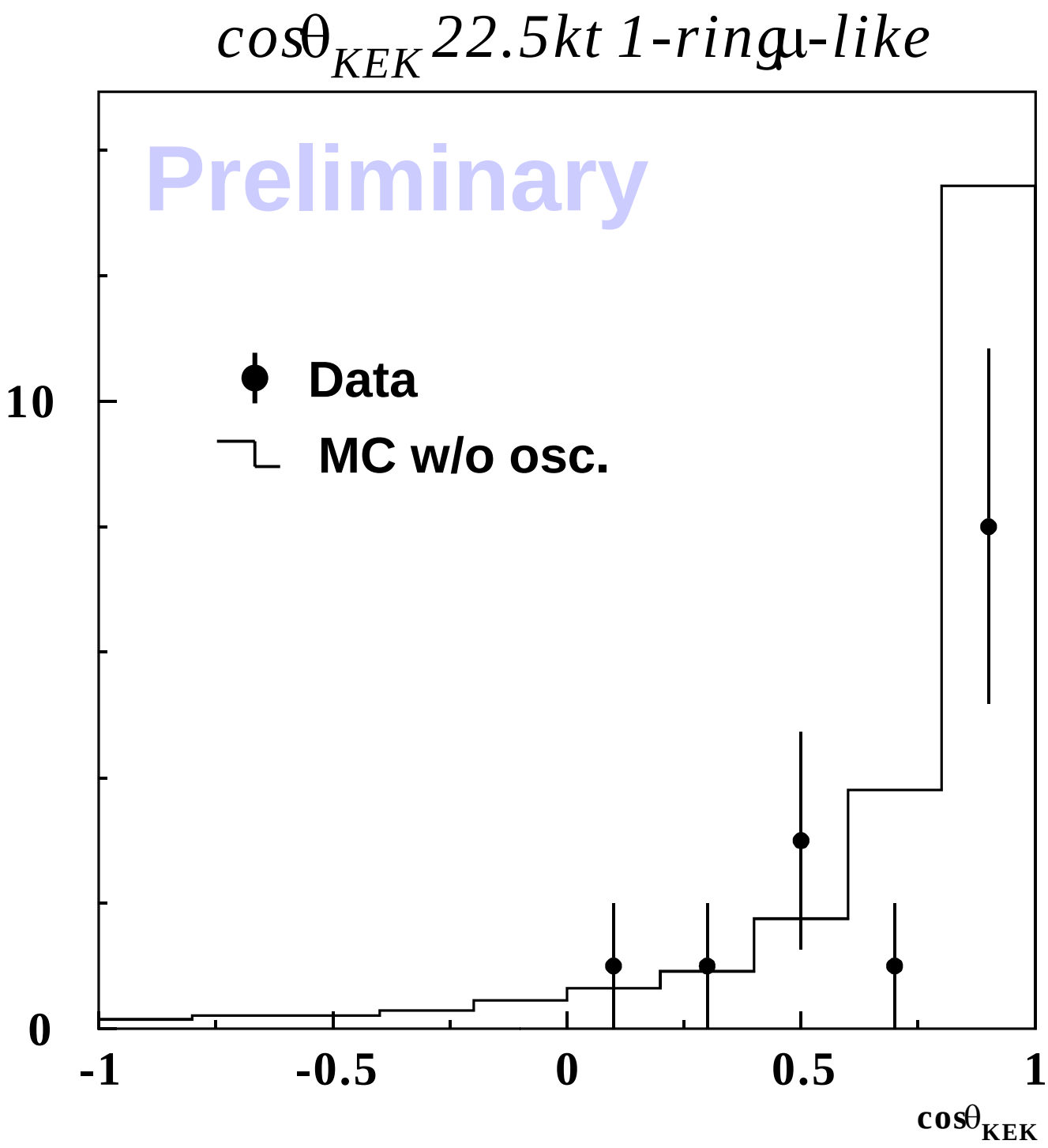
Reconstructed E_ν

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



Need to estimate syst. err. in MC expect.

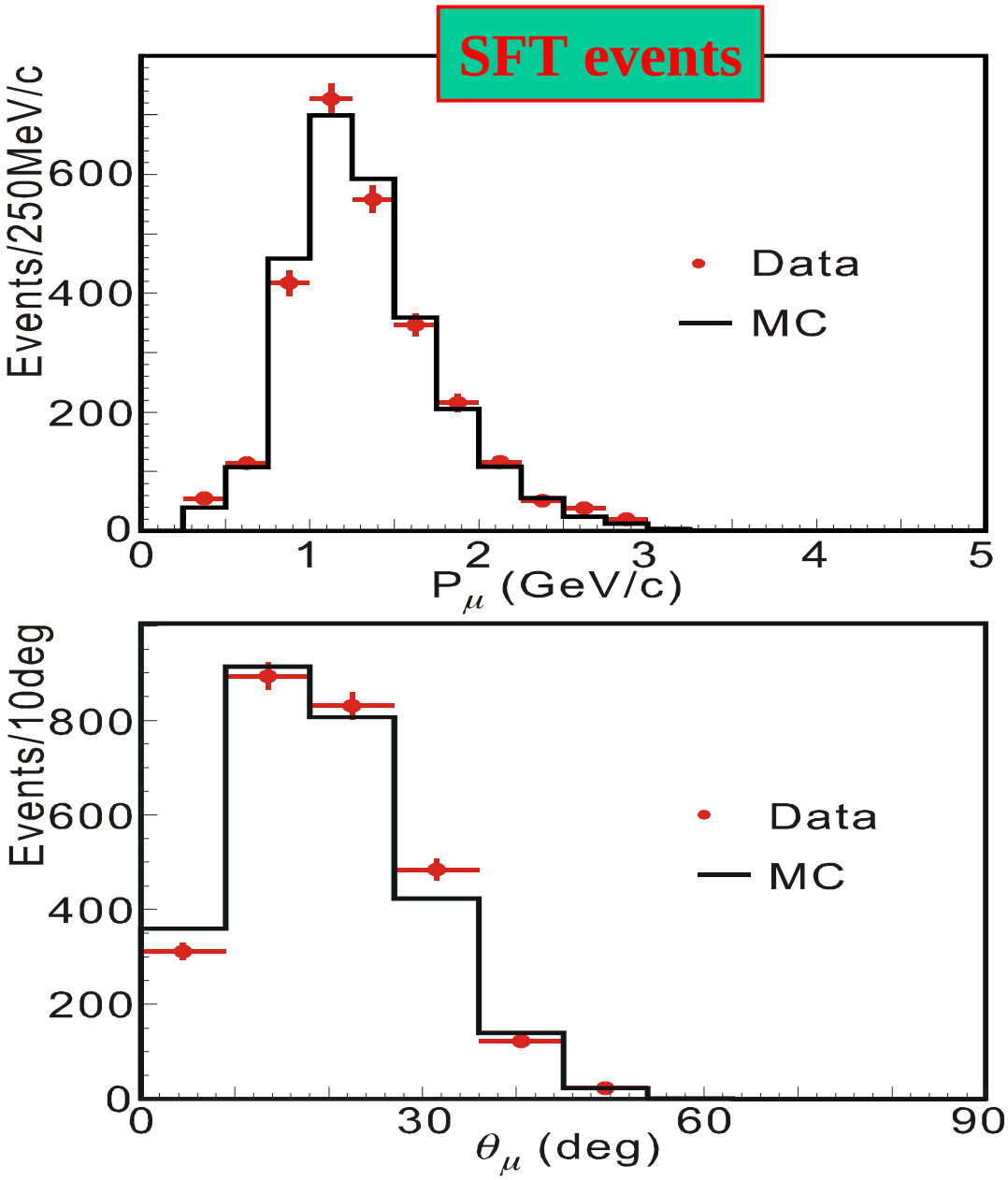
Angle Distribution



Need to estimate syst. err. in MC expect.

μ distributions in ν_μ CC int.

Neutrino spectrum



Data agree with MC fairly well.

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

Conclusions

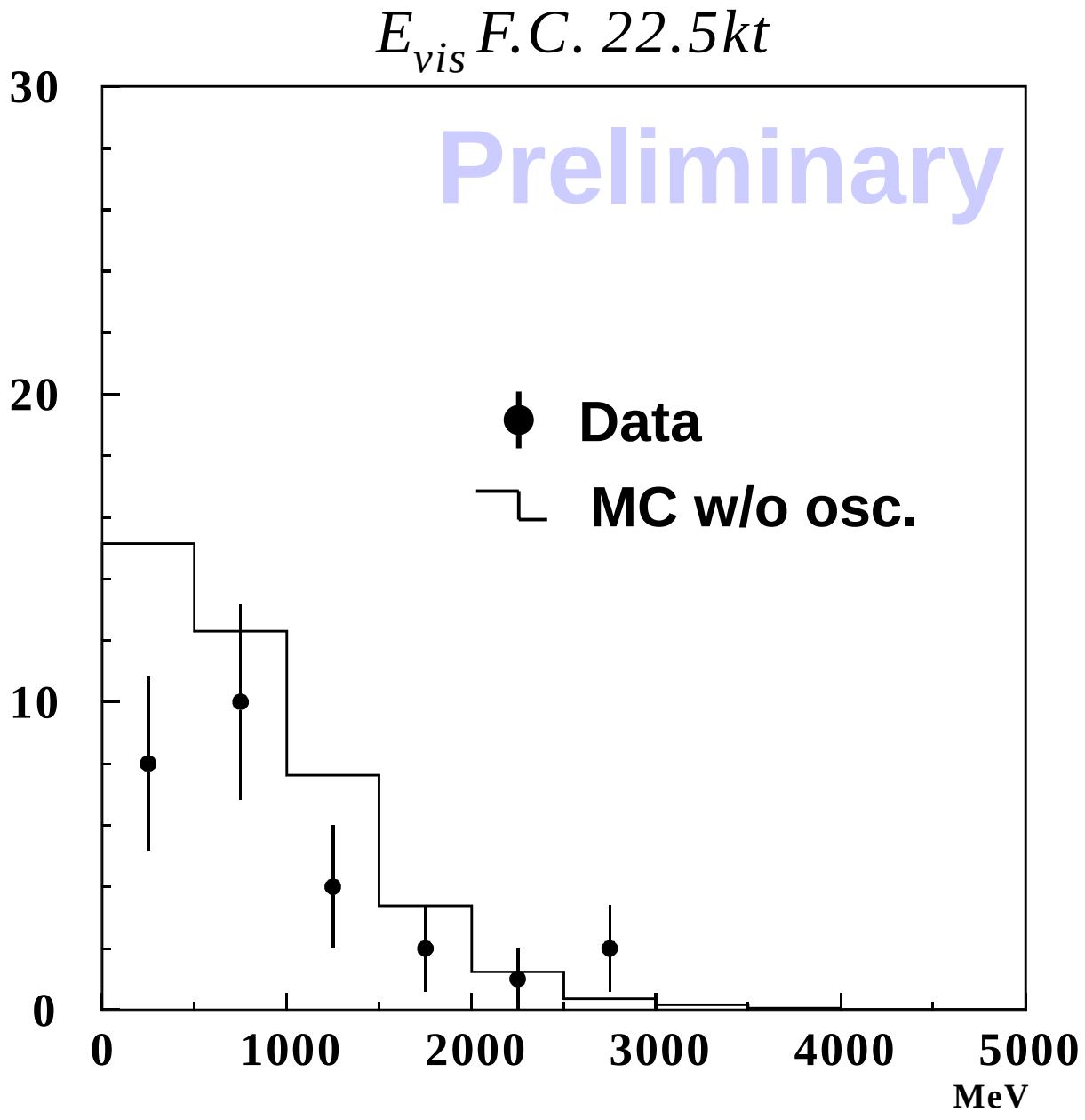
- Accumulated 2.29x10^{19}POT @ SK from Jun '99 to Jun '00.
- Neutrino beam is well under control
  - Direction: always directed to SK within 1mrad
  - Spectrum: stable within stat. error
  - Intensity: stable within stat. error
  - Pi mon proved MC spectra ratio
- # of fully contained events in fiducial volume @ SK

  Observed: 27

  Expected : $40.3^{+4.7}_{-4.6}$ (w/o osc.)
- **Observation is 2 σ smaller than expected.**
- 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 will resume Jan. 2001

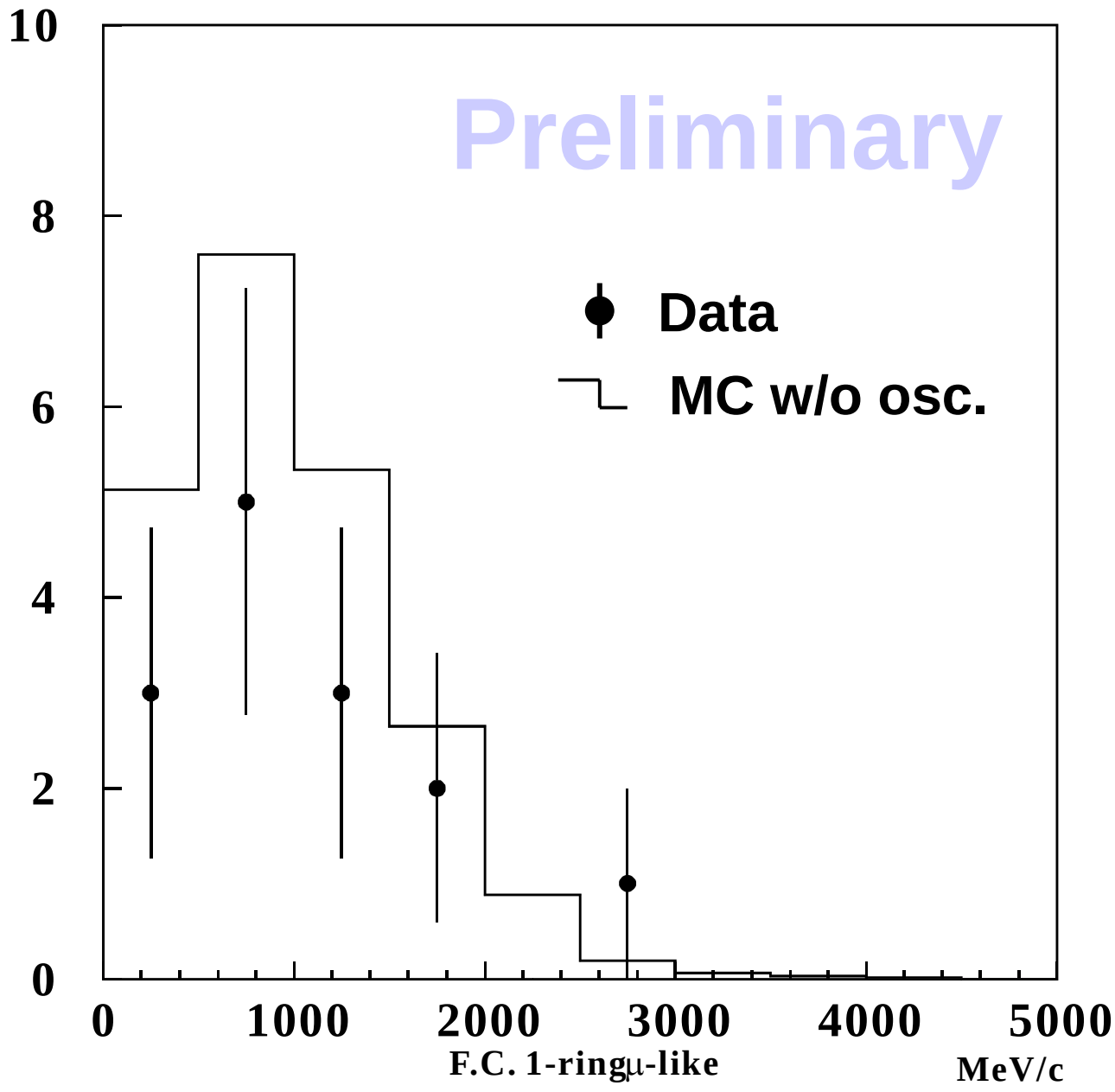
予備

Visible Energy Distribution



need to estimate syst. err. in MC expect.

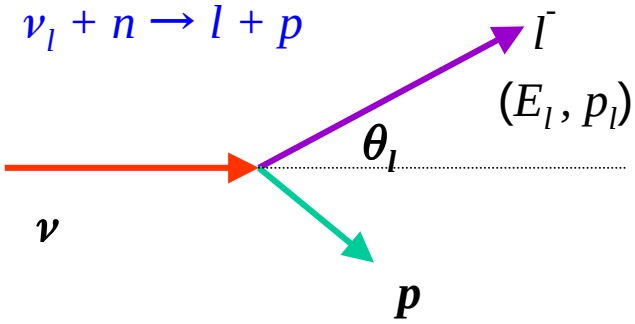
Reconstructed μ momentum



need to estimate syst. err. in MC expect.

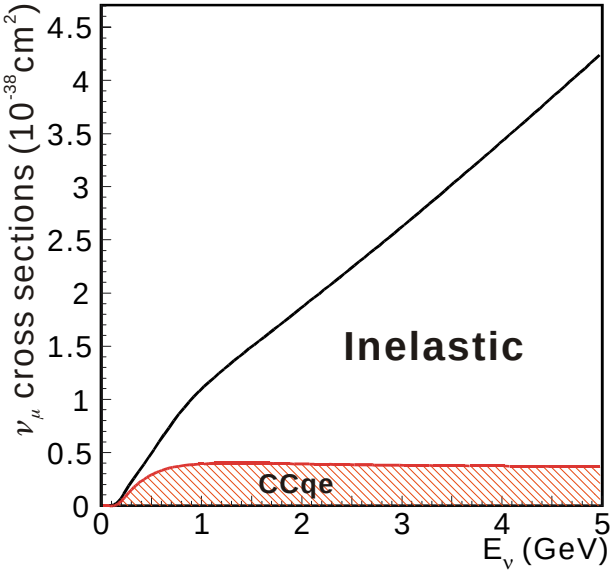
Neutrino Energy Reconstruction (GeV region)

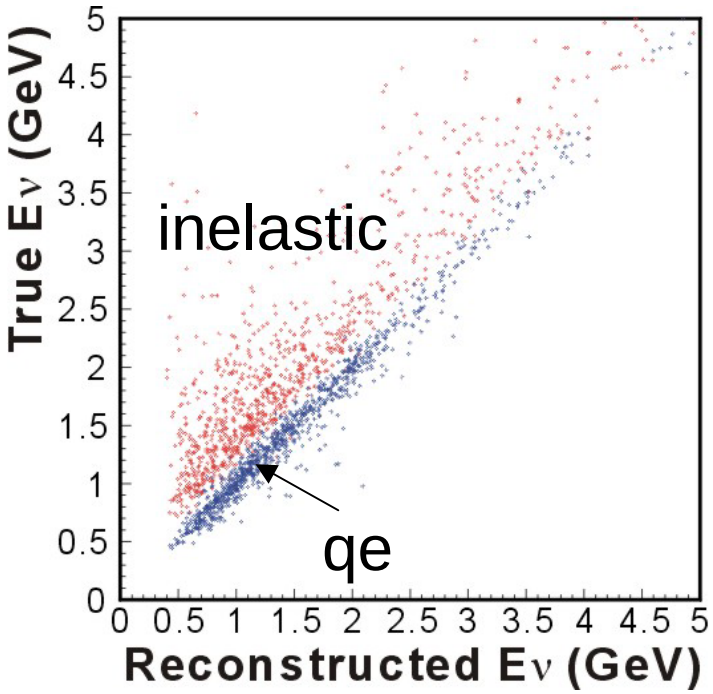
Assume CC quasi elastic (CCqe) reaction



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

Water Cherenkov 1ring μ-like sample

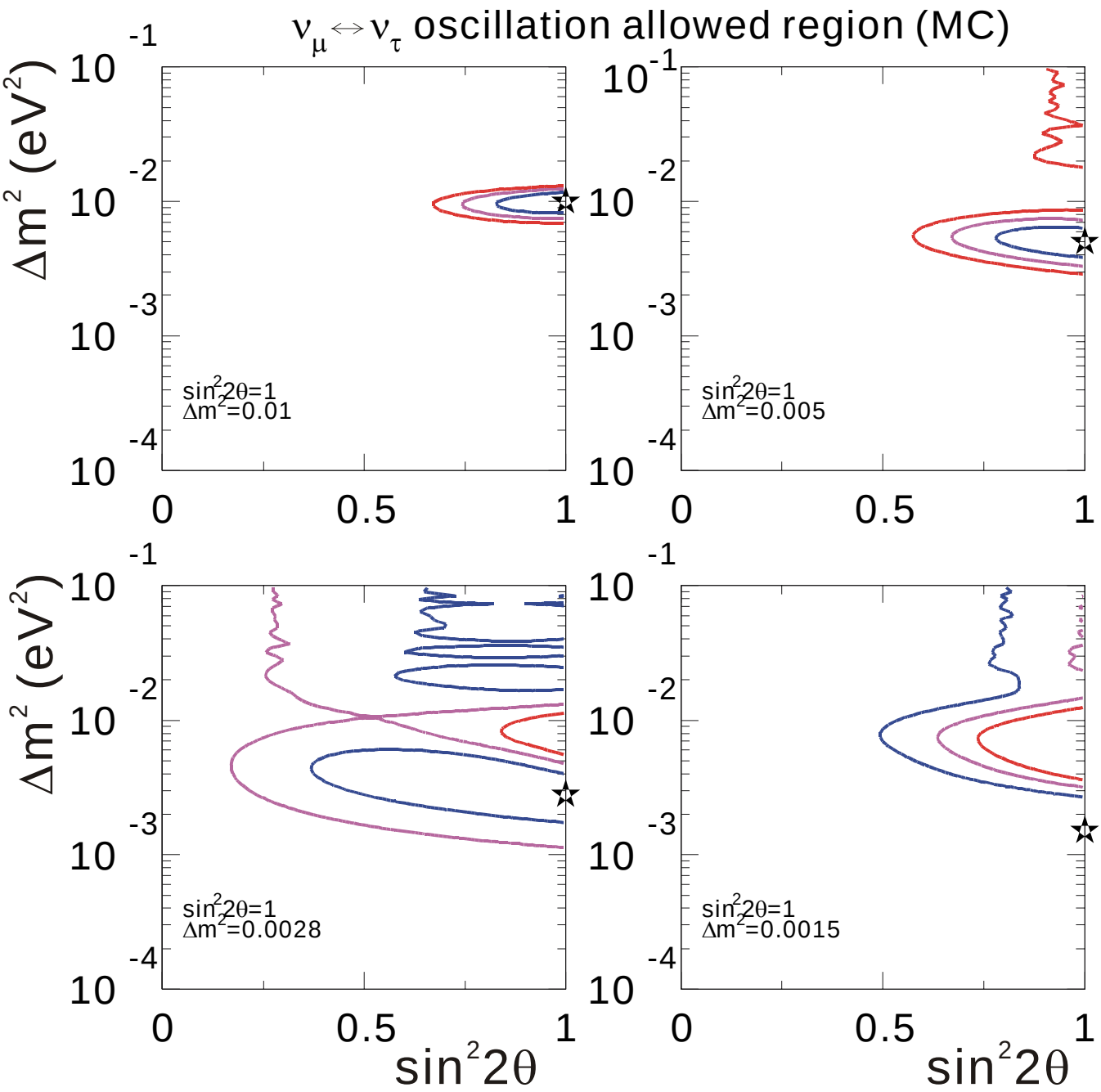




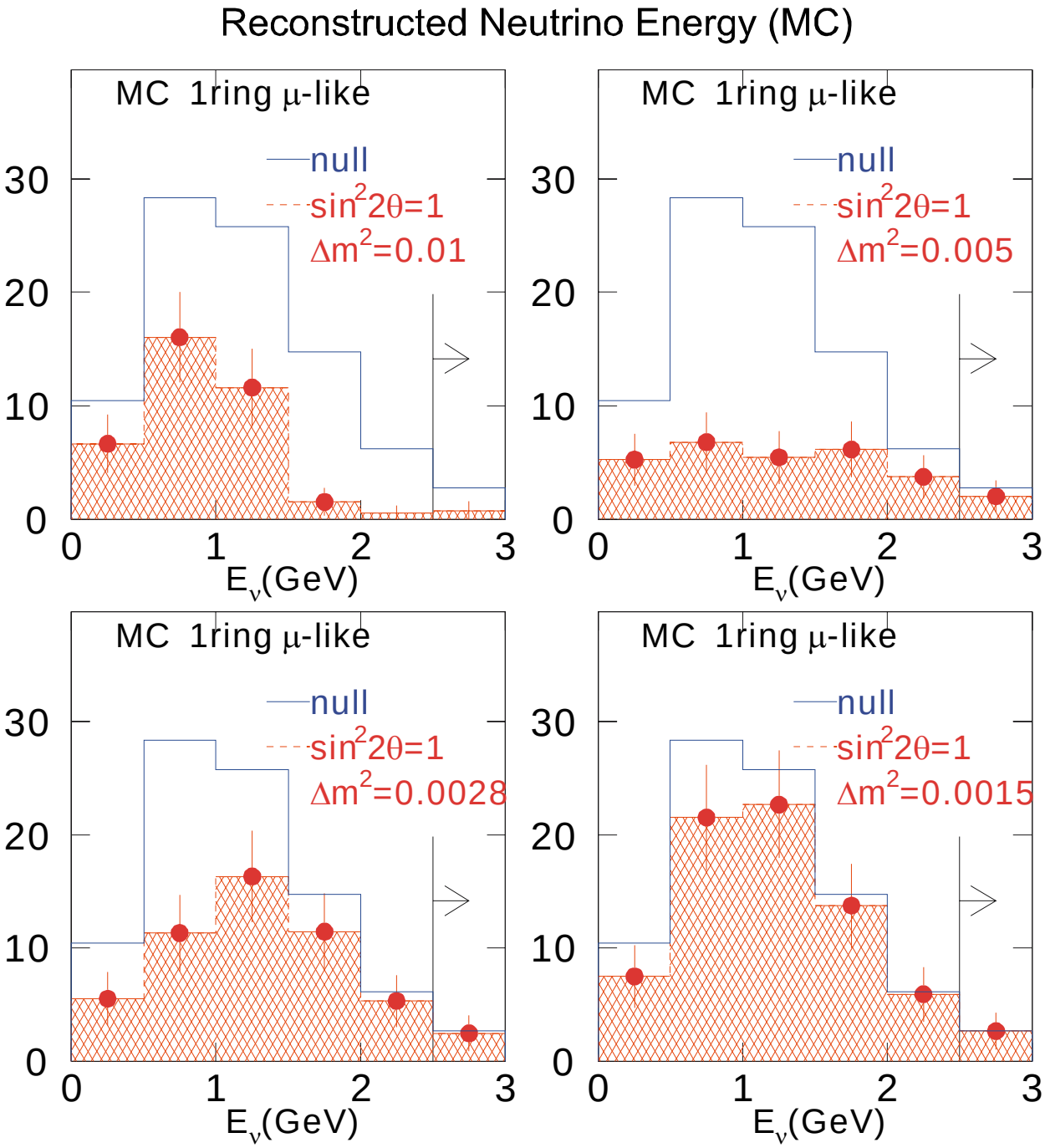
Inelastic scattering w/ invisible pion(s) give wrong energy

Expected Allowed Region

10^{20} POT ~ 5 years

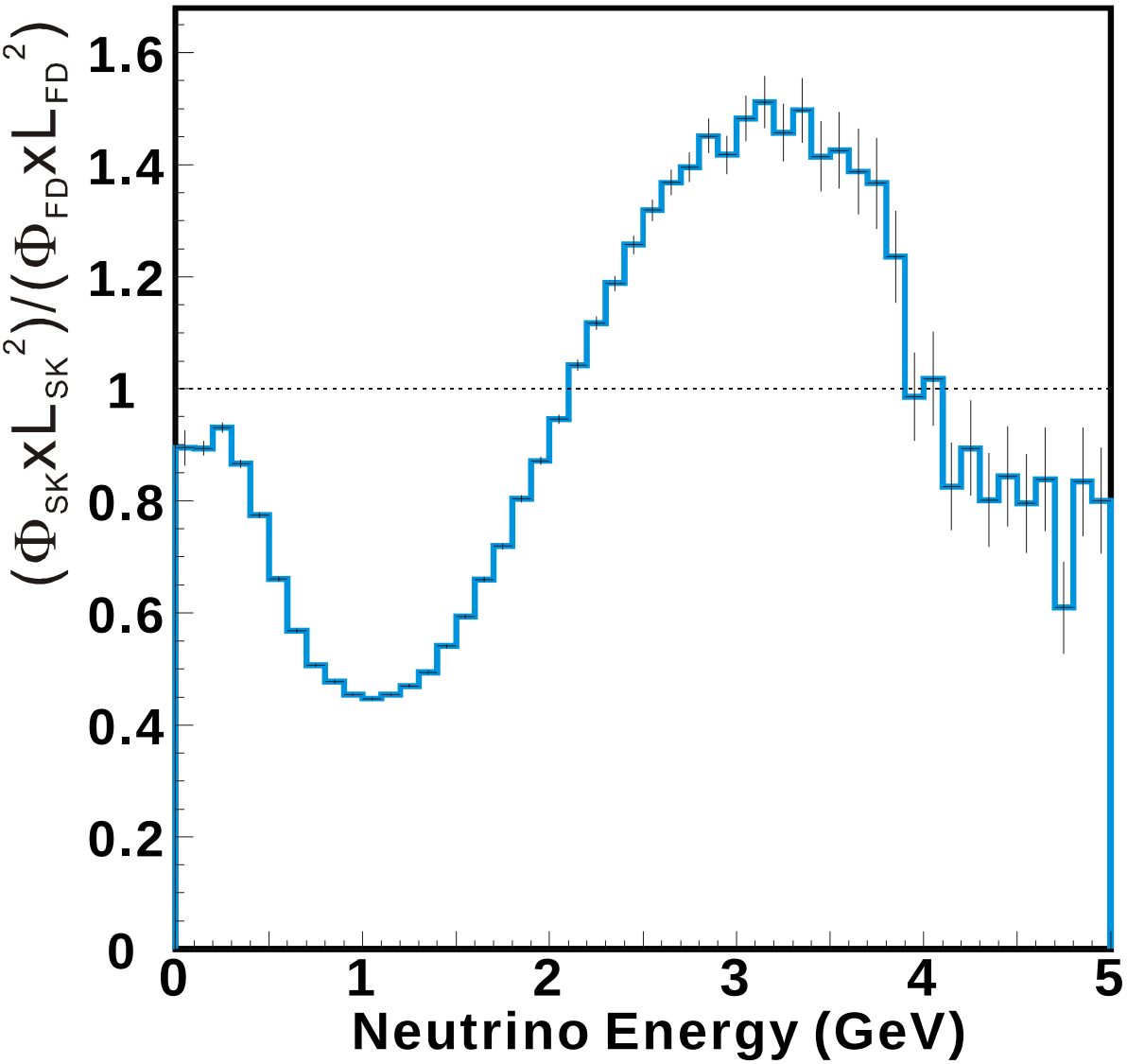


Expected Signal



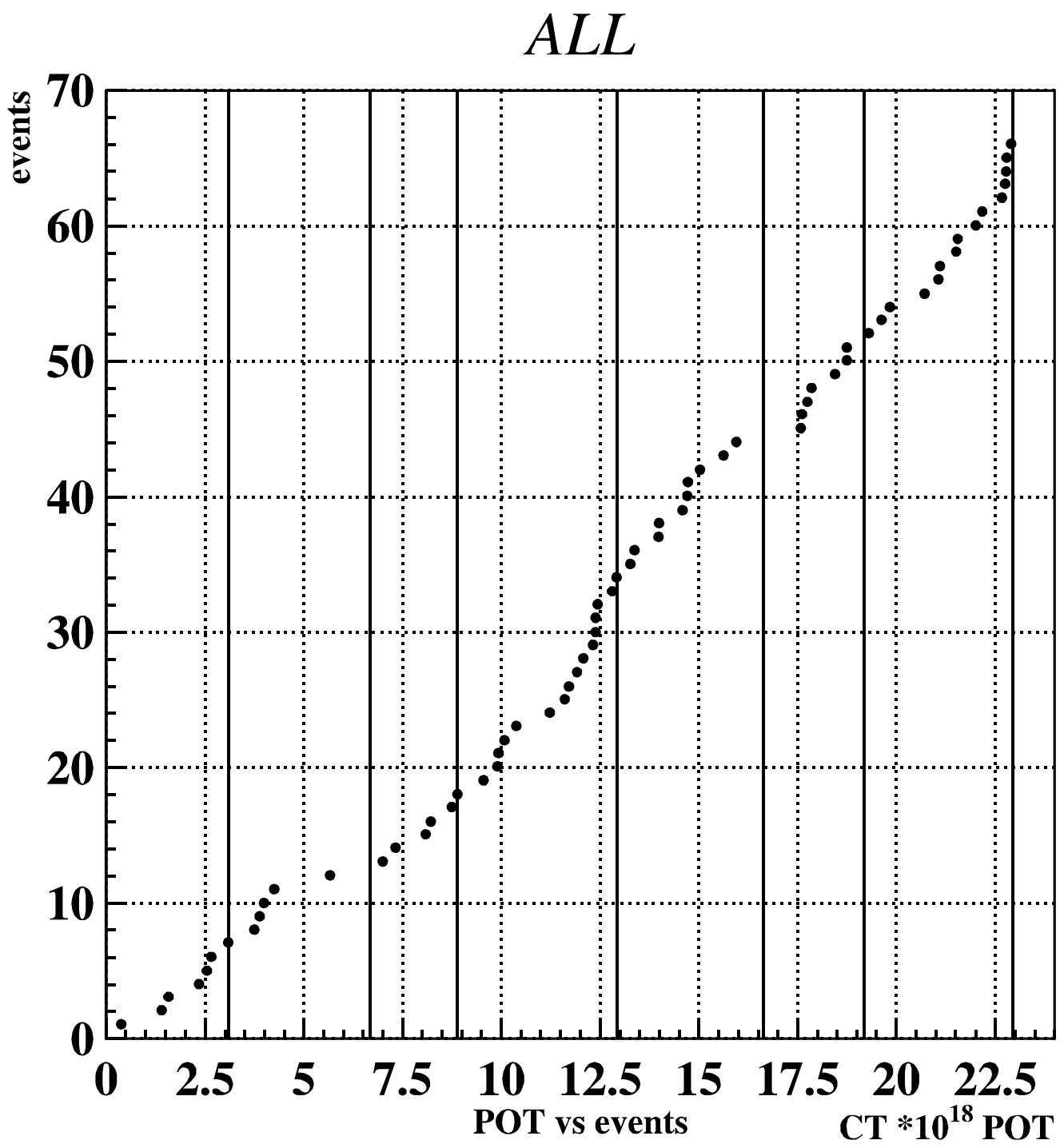
Far/Near Spectrum ratio

(MC)

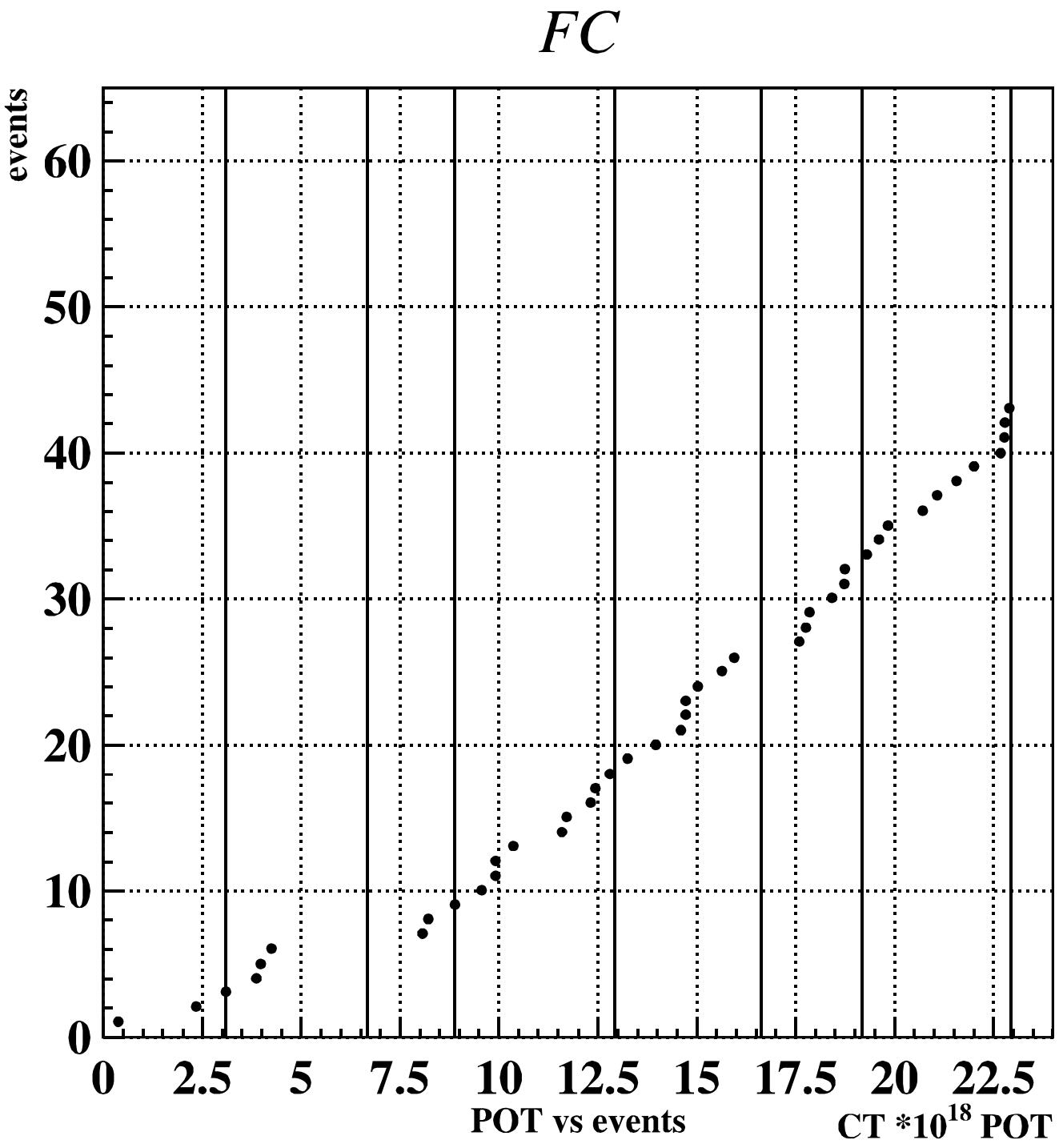


Event POT (All)

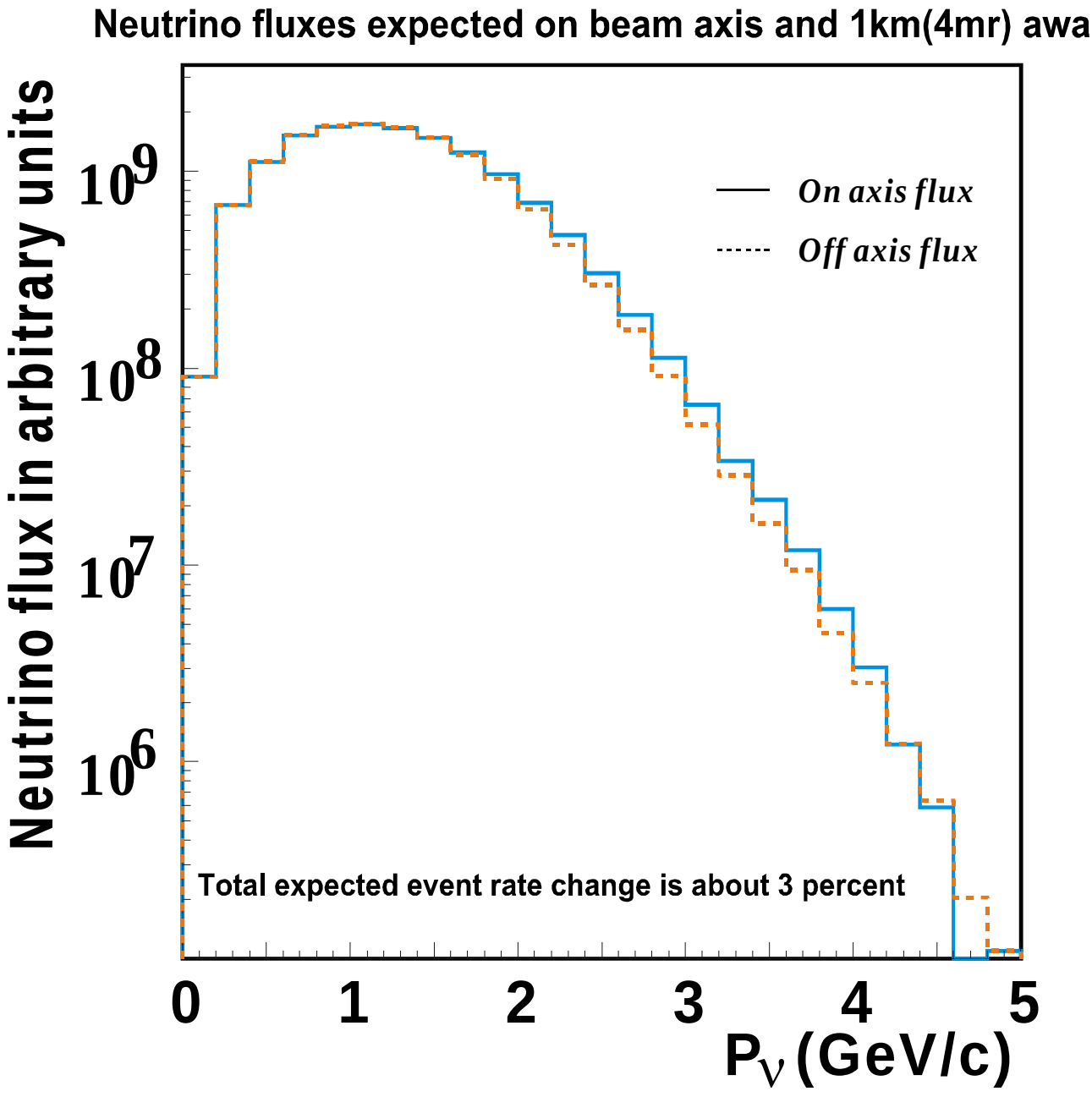
FC+OD events



Event POT (FC all)



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

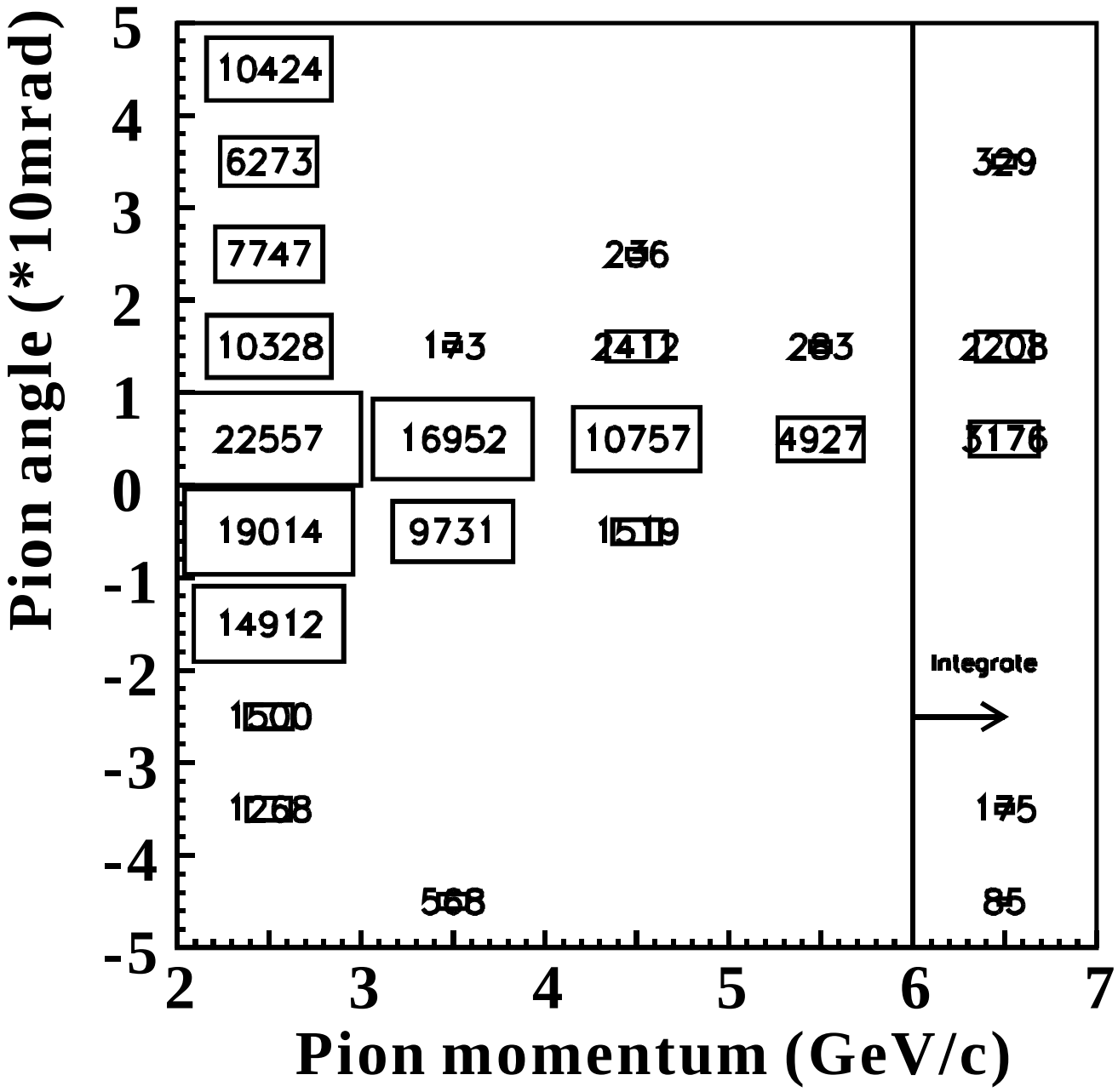


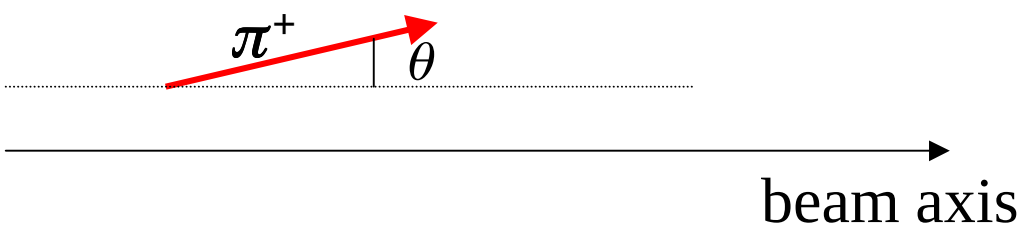
Systematic Error of Flux Ratio

Errors on spectrum ratio (Nov.)	0.0-0.5	0.5-1.0	1.0-1.5	1.5-2.0	2.0-2.5	>2.5GeV
Fitting error			$^{+2.2\%}_{-2.9\%}$	$^{+2.2\%}_{-2.1\%}$	$^{+3.2\%}_{-2.9\%}$	$^{+1.0\%}_{-0.9\%}$
PMT saturation correction			—	—	—	—
PMT relative gain correction			—	—	—	—
Mirror reflectivity			-1.2%	-1.1%	+0.5%	-0.3%
Refractive index measurement			—	—	—	—
Wave length dep. of the ref. index			-3.7%	-1.8%	-3.3%	-2.6%
Low and high beam intensity			-1.9%	-3.7%	-1.9%	+2.9%
Beam stability (pion monitor run)			—	—	—	±0.5%
ϕ asymmetry of the magnetic field			-2.6%	-2.4%	-2.4%	-1.0%
Pion monitor alignment			—	—	—	—
The injection point of protons			—	+1.2%	—	—
Invisible light subtraction			—	—	—	—
Electro-magnetic subtraction			—	—	—	—
Fitting method			+4.0%	$^{+1.4\%}_{-3.0\%}$	$^{+3.2\%}_{-4.6\%}$	-14.5%
Pion beam profile (fitting function)			—	—	—	±0.3%
Pion decay before the pion monitor			±0.7%	±0.7%	±1.7%	±0.5%
Pion beam profile (neutrino rec.)			—	±0.5%	±1.3%	±8.5%
Kinematic bin of the pion			-2.1%	—	+1.7%	-7.1%
Beam stability (normal run)			$^{+1.6\%}_{-1.8\%}$	$^{+1.5\%}_{-2.1\%}$	$^{+1.2\%}_{-1.4\%}$	+9.0%
Hadron model (MC)	$^{+5.1\%}_{-9.5\%}$	$^{+7.3\%}_{-2.5\%}$				
Total	$^{+5.1\%}_{-9.5\%}$	$^{+7.3\%}_{-2.5\%}$	$^{+4.9\%}_{-6.5\%}$	$^{+3.3\%}_{-6.5\%}$	$^{+5.4\%}_{-7.5\%}$	$^{+12.8\%}_{-18.5\%}$

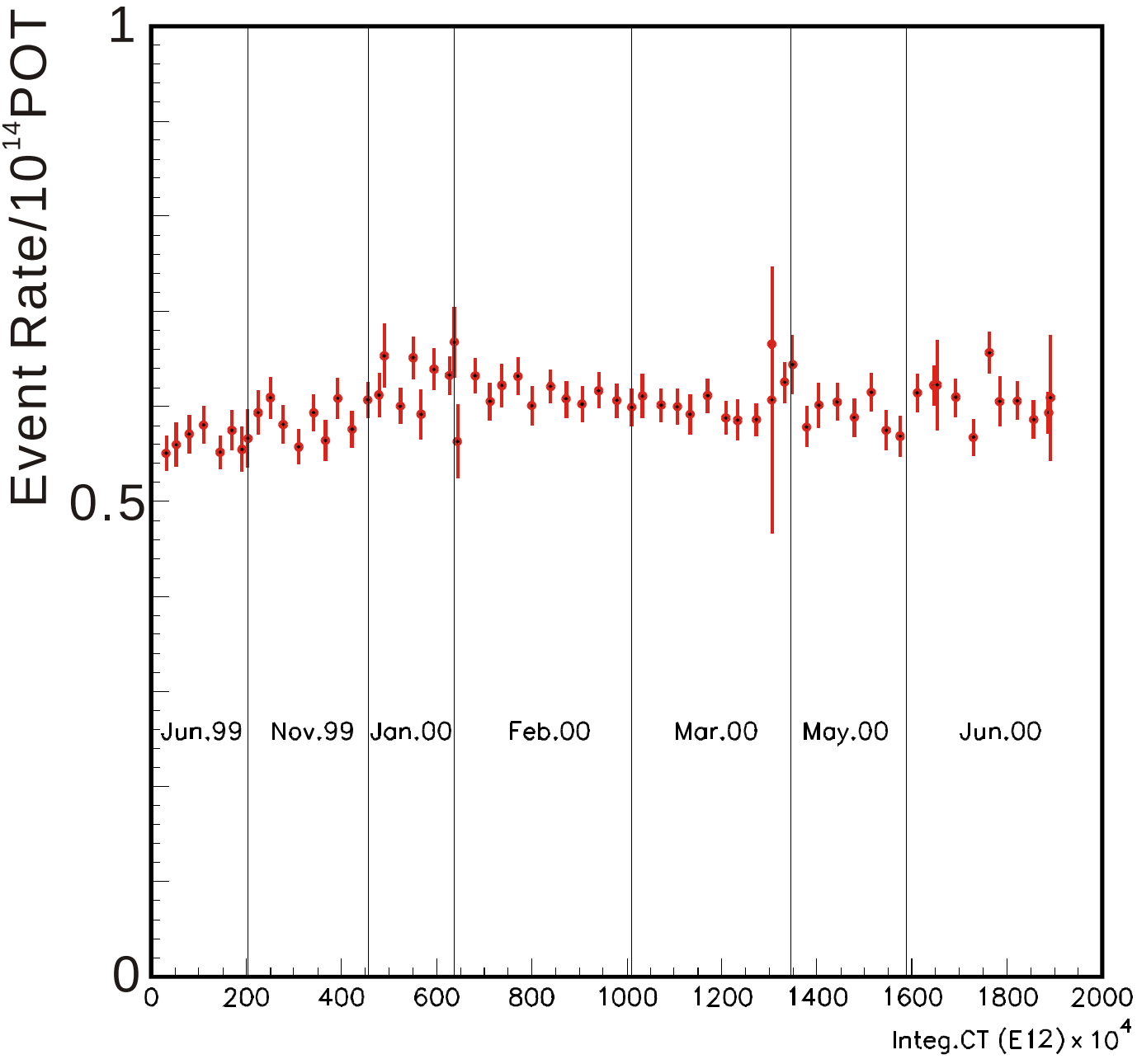
Pion Monitor Result

Relative Pion Distribution in p_π-θ_π plane





Rate of 1kt events



Summary

Total spill 4405617
Ctsum 22.9×10^{18}

$\pm 500\,\mu$ sec decay-e cut			168710
HE trigger			16817
$\Sigma_{300nsec}$p.e.>200p.e.			8798
Σp.e. < 50000p.e.			3350
max p.e./ $\Sigma_{300nsec}$p.e.<0.2			3216
flasher cut			3204
nhitac<10			51
$nhita_{800nsec}$<50			51
goodness>0			50
Tgps $-0.2\,\mu \sim 1.3\,\mu$ sec			43
Dwall>2m			27
FC in fid	27		
1ring		15	
1ring μ			14
1ring e			1
multi ring		12	
FC out	16		

Neutrino Oscillation

Neutrino Mixing

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

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

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

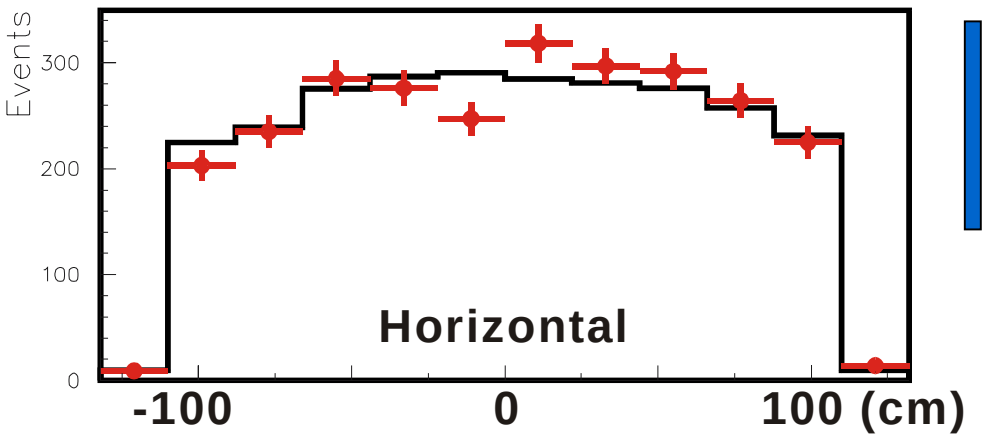
$$= \delta_{ml} - 2\sum_{i<j} \mathrm{Re}\left[\left(V_{mi}^* V_{li}\right)\cdot\left(V_{mj}V_{lj}^*\right)\cdot\left\{1-\exp\left(-i\frac{\Delta m_{ij}^2}{2E}L\right)\right\}\right]$$

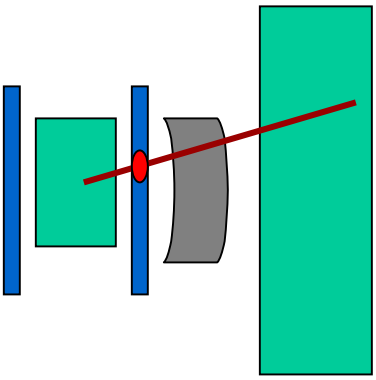
L : flight length, E : neutrino energy, $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$

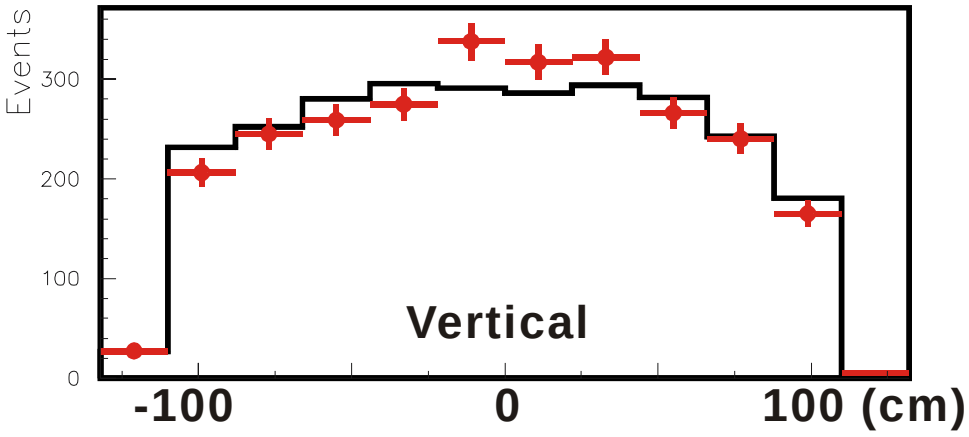
mass eigenvalues

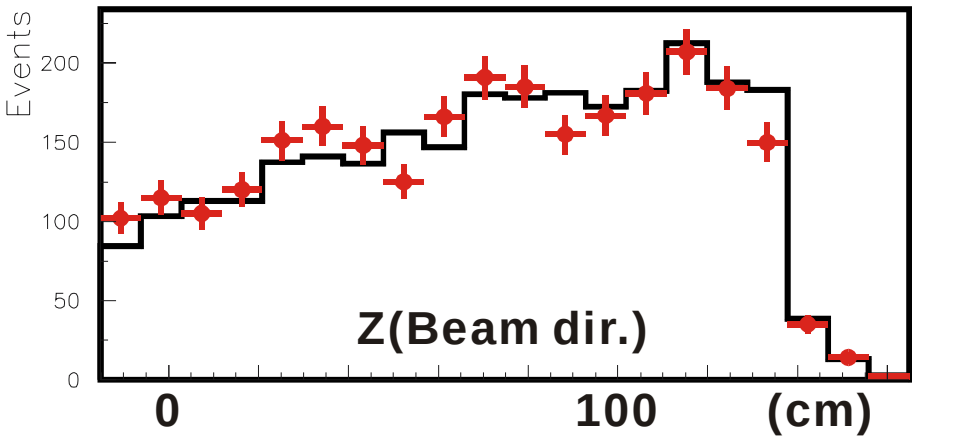
$$P_{l\to m} \neq \delta_{ml} \;\Leftrightarrow\; \Delta m_{ij} \neq 0$$

Vertex Dist. of SFT events









Agree well

Non neutrino (cosmic, μ from upstream, fake)
BG : negligible

of observed events and expected events 1999/06-2000/06

	Obs.	Exp.	$\Delta m^2(\times 10^{-3} eV^2)$ 3	5	7
FC 22.5kt	27	$40.3\ ^{+4.7}_{-4.6}$	$26.6\ ^{+3.4}_{-3.3}$	$17.8\ ^{+2.3}_{-2.2}$	$14.9\ ^{+1.9}_{-1.9}$
1-ring	15	24.3±3.6	14.4±2.3	9.4±1.5	8.6±1.4
μ-like	14	21.9±3.5	12.4±2.1	7.5±1.3	6.8±1.2
e-like	1	2.4±0.5	2.1±0.4	1.9±0.4	1.8±0.4
multi ring	12	16.0±2.7	12.2±2.1	8.4±1.5	6.3±1.1
out-of-FV	16	17.2	11.2	7.6	6.7