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La Thuile 2001

Present and Future Long Baseline Neutrino Experiment in Japan

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Contents

Neutrino Oscillation

Neutrino Mixing

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

Weak eigenstates   Mass eigenstates

Maki-Nakagawa-Sakata Matrix

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix}$$

$s_{ij}=\sin\theta_{ij},\ c_{ij}=\cos\theta_{ij}$

Oscillation Probability

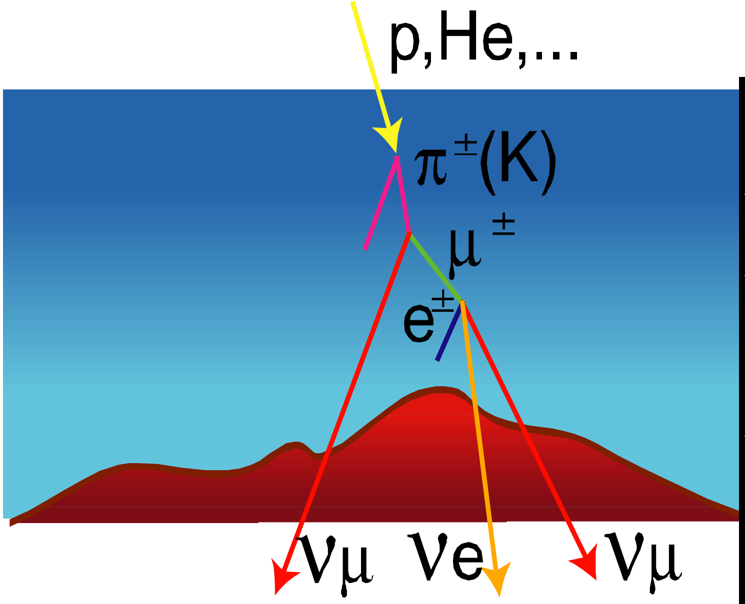
$$P_{l\to m} = \left|\langle \nu_m(t) | \nu_l(0)\rangle\right|^2 = \delta_{ml} - 2\sum_{i<j} \mathrm{Re}\left[\left(U^*_{mi}U_{li}\right)\cdot\left(U_{mj}U^*_{lj}\right)\cdot\left\{1-\exp\left(-i\frac{\Delta m^2_{ij}}{2E}L\right)\right\}\right]$$

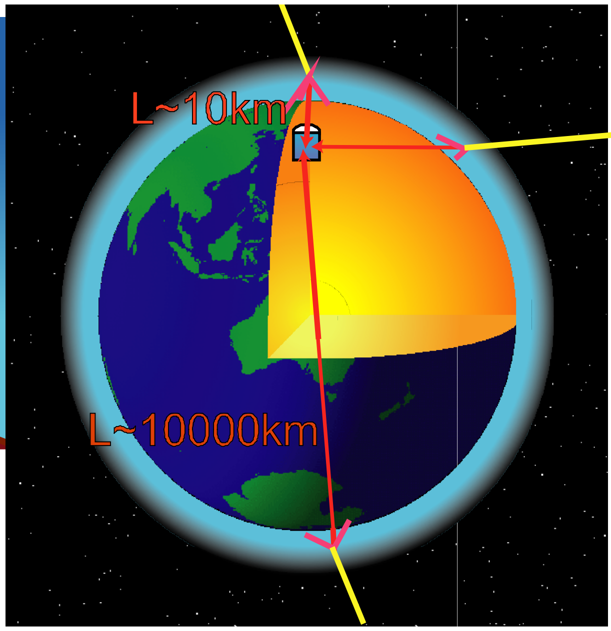
L : flight length, E : neutrino energy, $\Delta m^2_{ij} \equiv m_i^2 - m_j^2$, m_i : mass eigenvalues

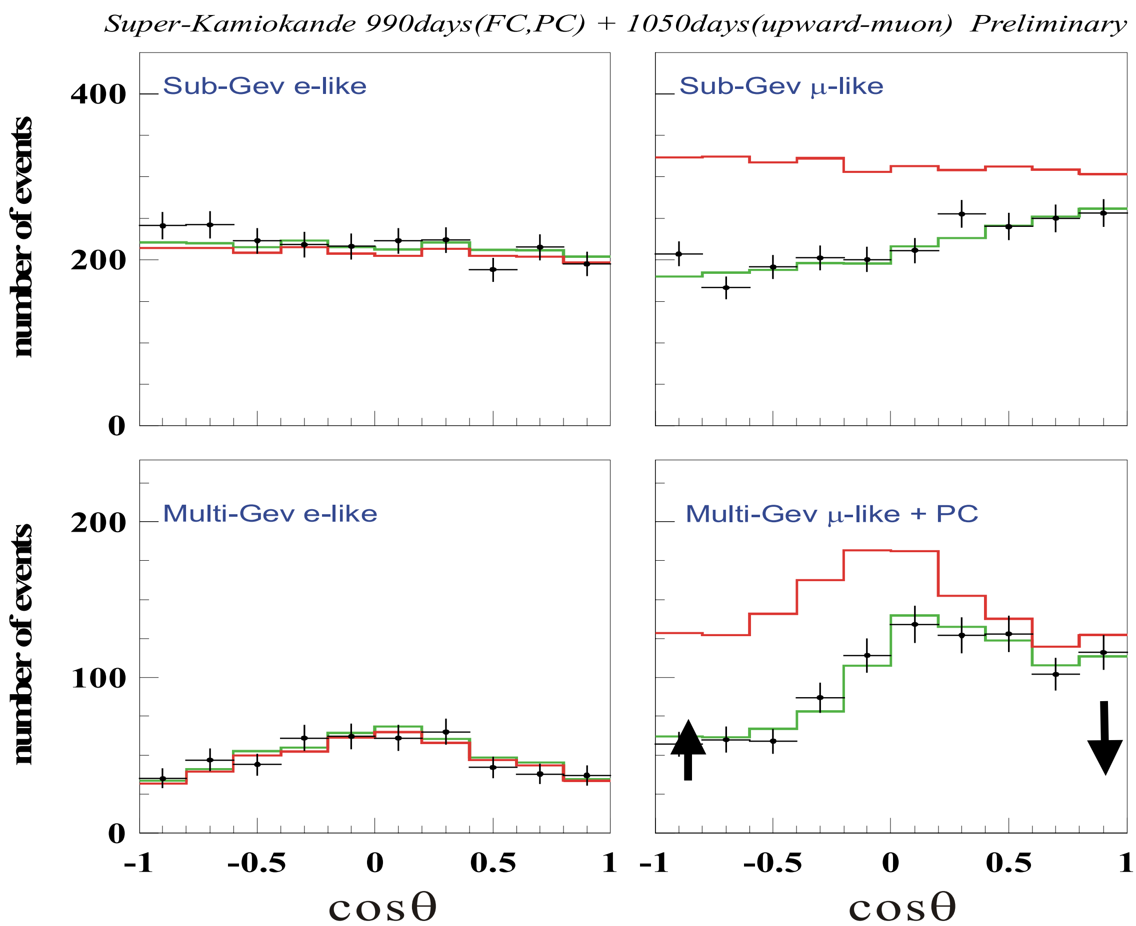
$$P_{l\to m} \neq \delta_{ml} \Leftrightarrow \Delta m_{ij} \neq 0$$

LFV

Atmospheric Neutrino







Evidence of oscillation(favor $\nu_\mu \rightarrow \nu_\tau$)

Motivation

Evidence of osc. in atm. ν observation by SK

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

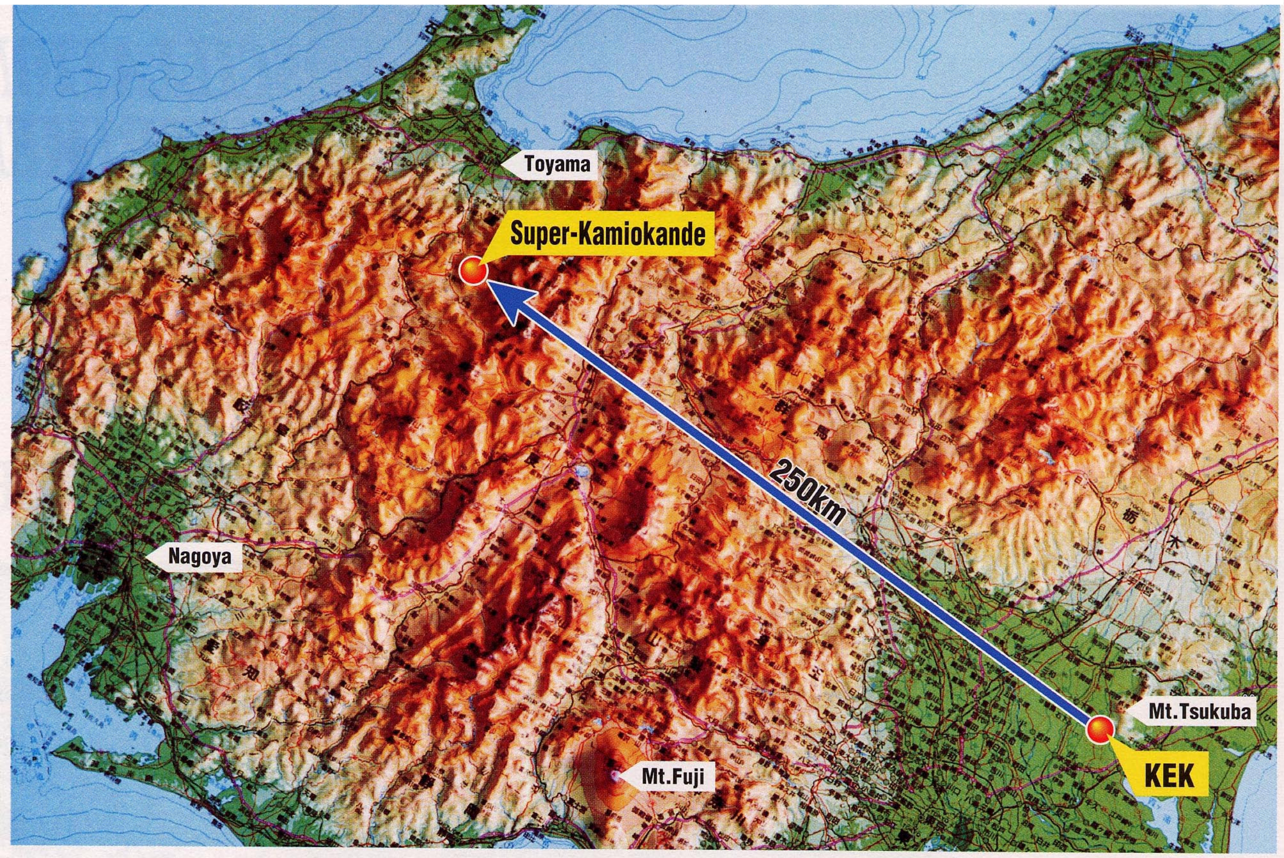
Neutrino Oscillation(2flavors)

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

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	$10\sim10^4$km	<5GeV	$0.5\sim5\times10^{-4}$	2/1
K2K	250km	∼1GeV	4×10^{-3}	99/1

K2K Overview

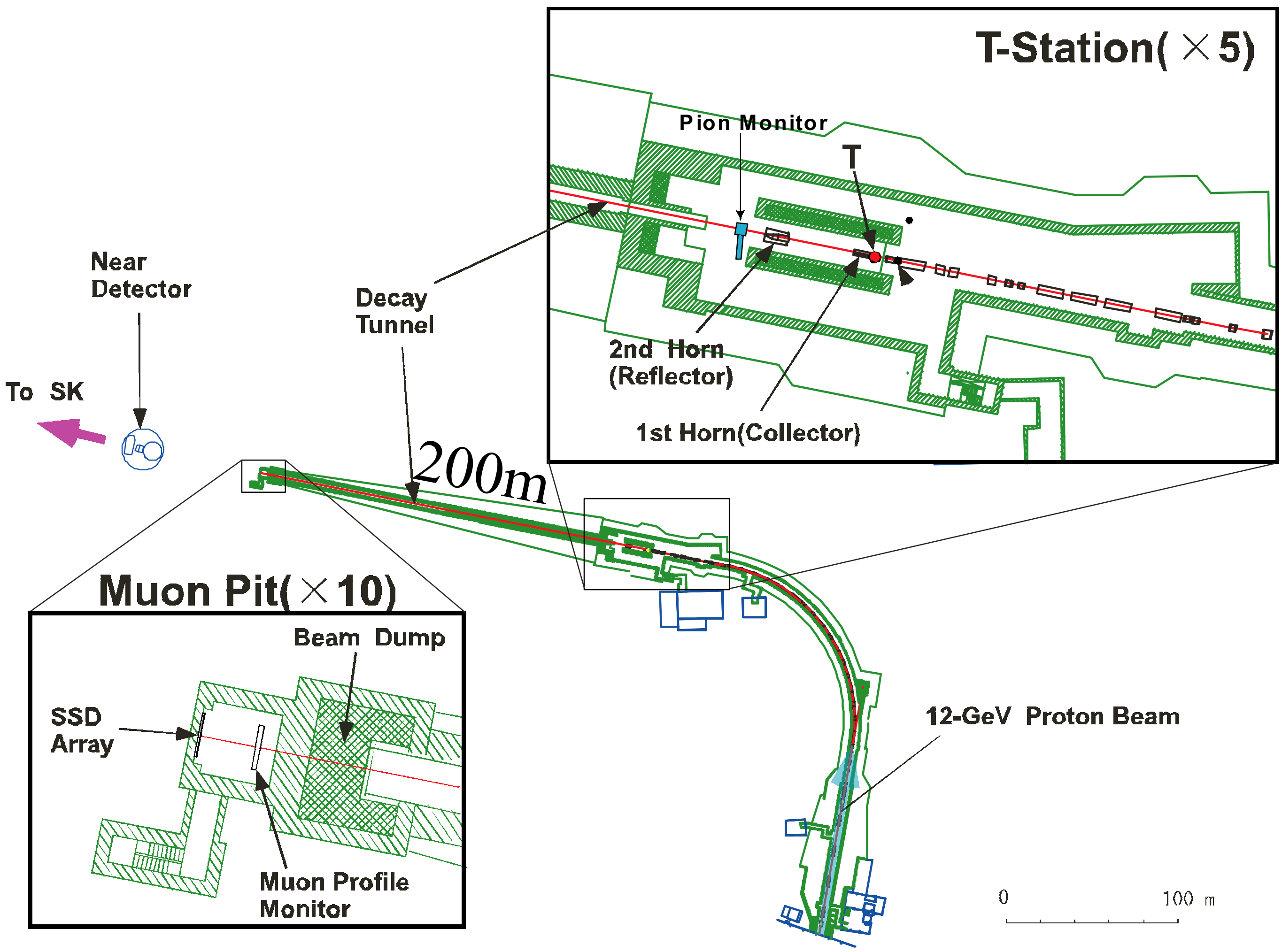


- almost pure ν_μ(99%) beam w/ $<E_\nu>$ ～ **1.3GeV**
- Far detector: Super Kamiokande(SK)@**250km**
- Most sensitive at Δm^2 ～ **7x10^{-3} eV^2**
- ν_μ disappearance and ν_e appearance

Neutrino Beam Production

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

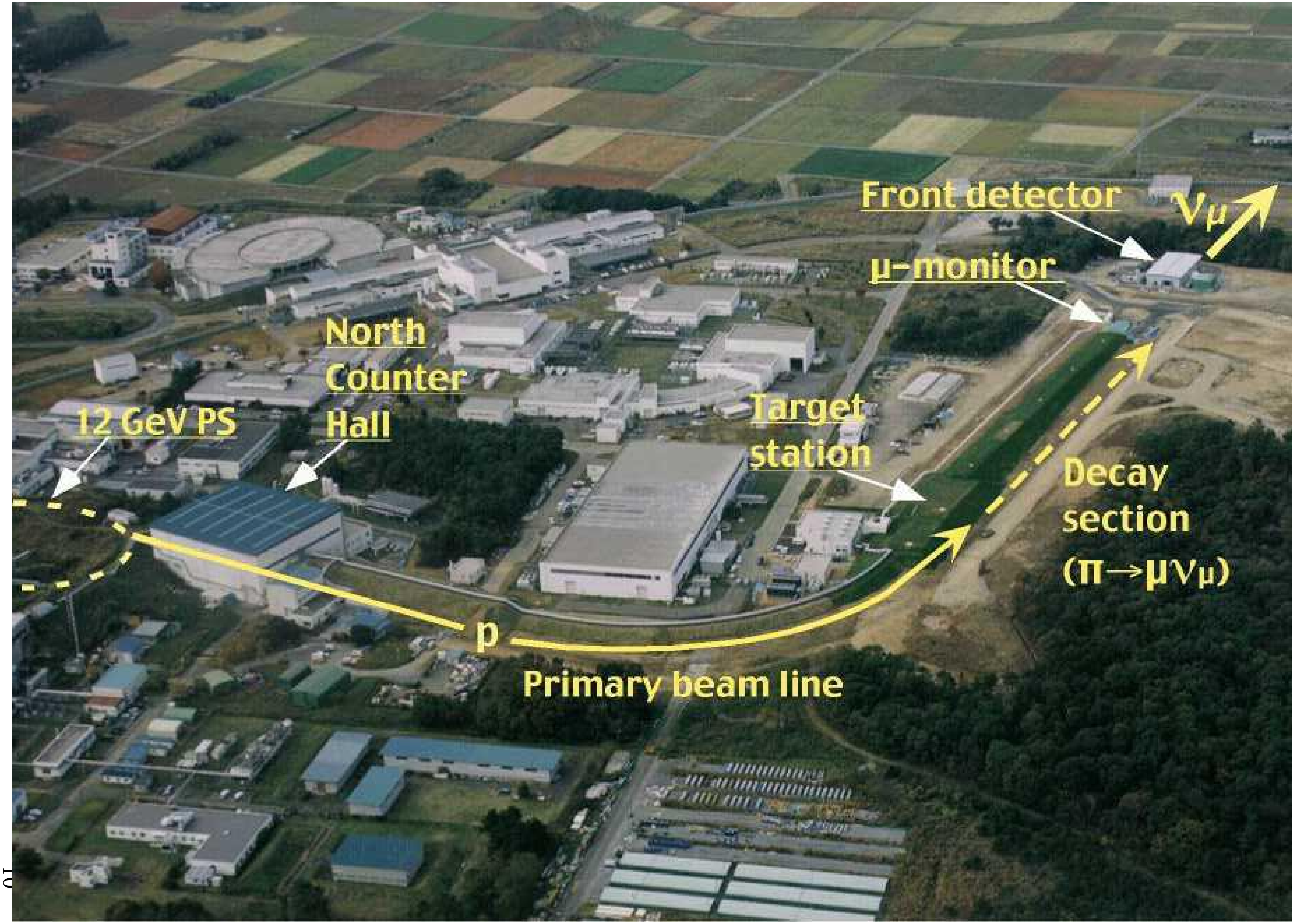
$\quad \hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu (1\%)$



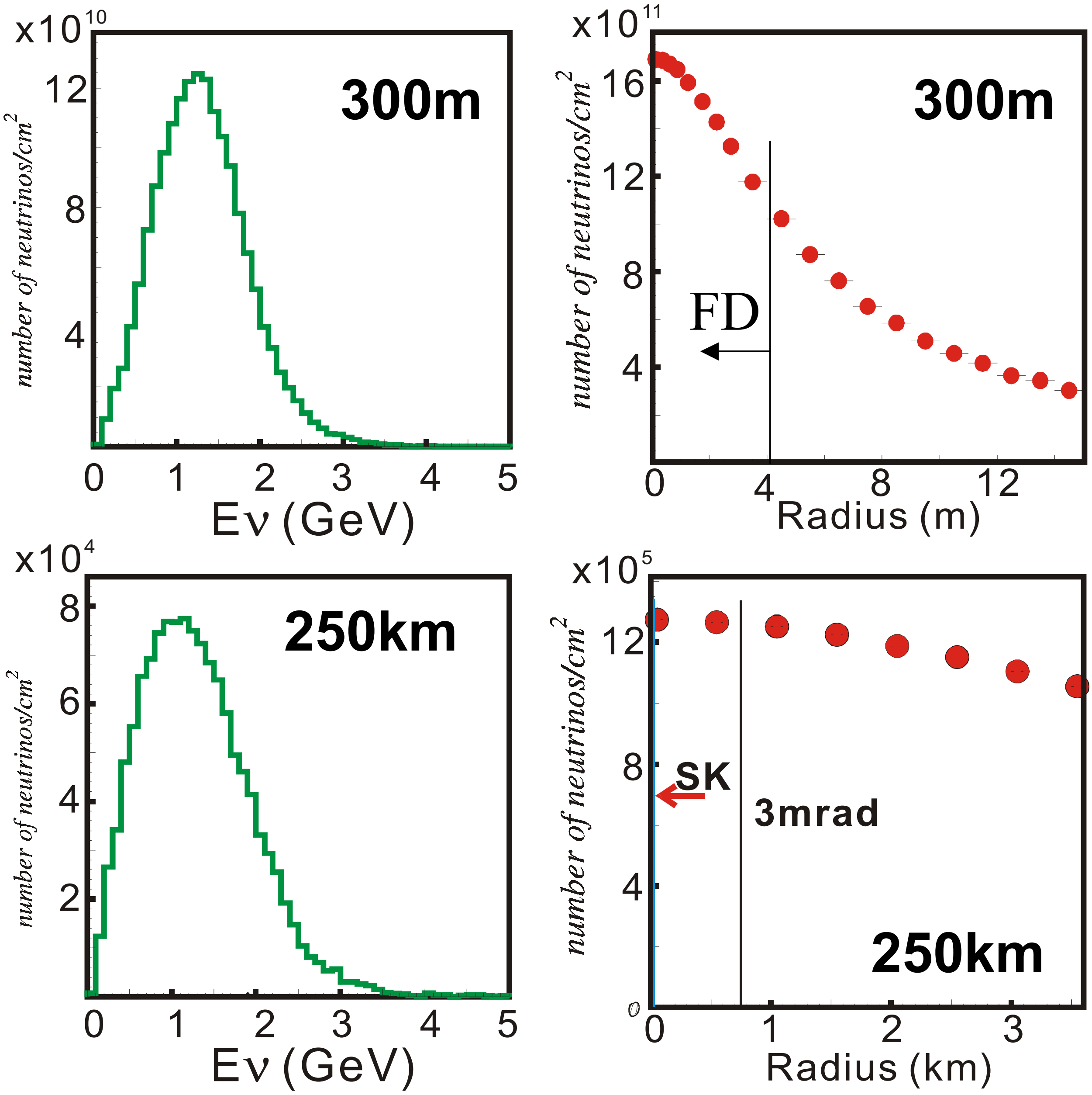
PS: 13GeV/c proton
1.1μsec spill/2.2sec
6x10^{12}protons/spill (design)

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

Decay pipe: 200m


Front detector
νμ
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

Pion Monitor

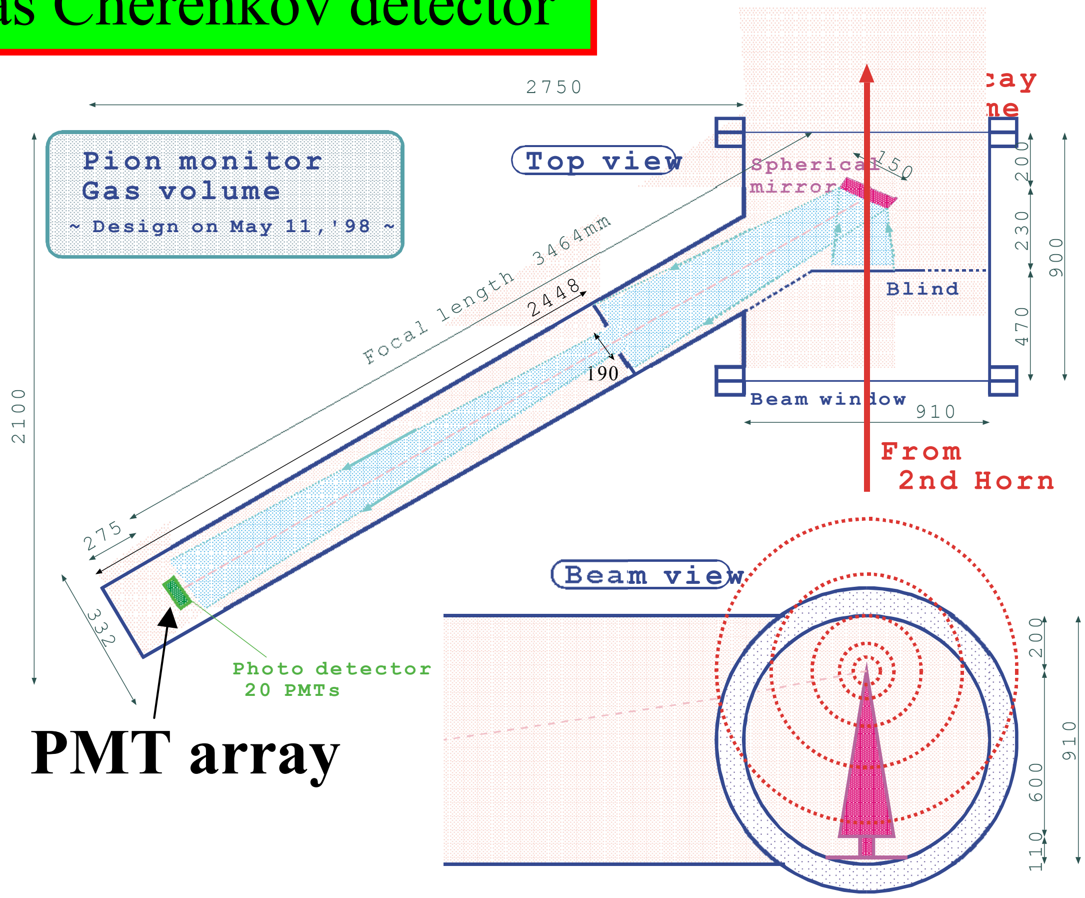
Purpose:Measure momentum and angular distribution of pions, $N(p_\pi, \theta_\pi)$

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

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

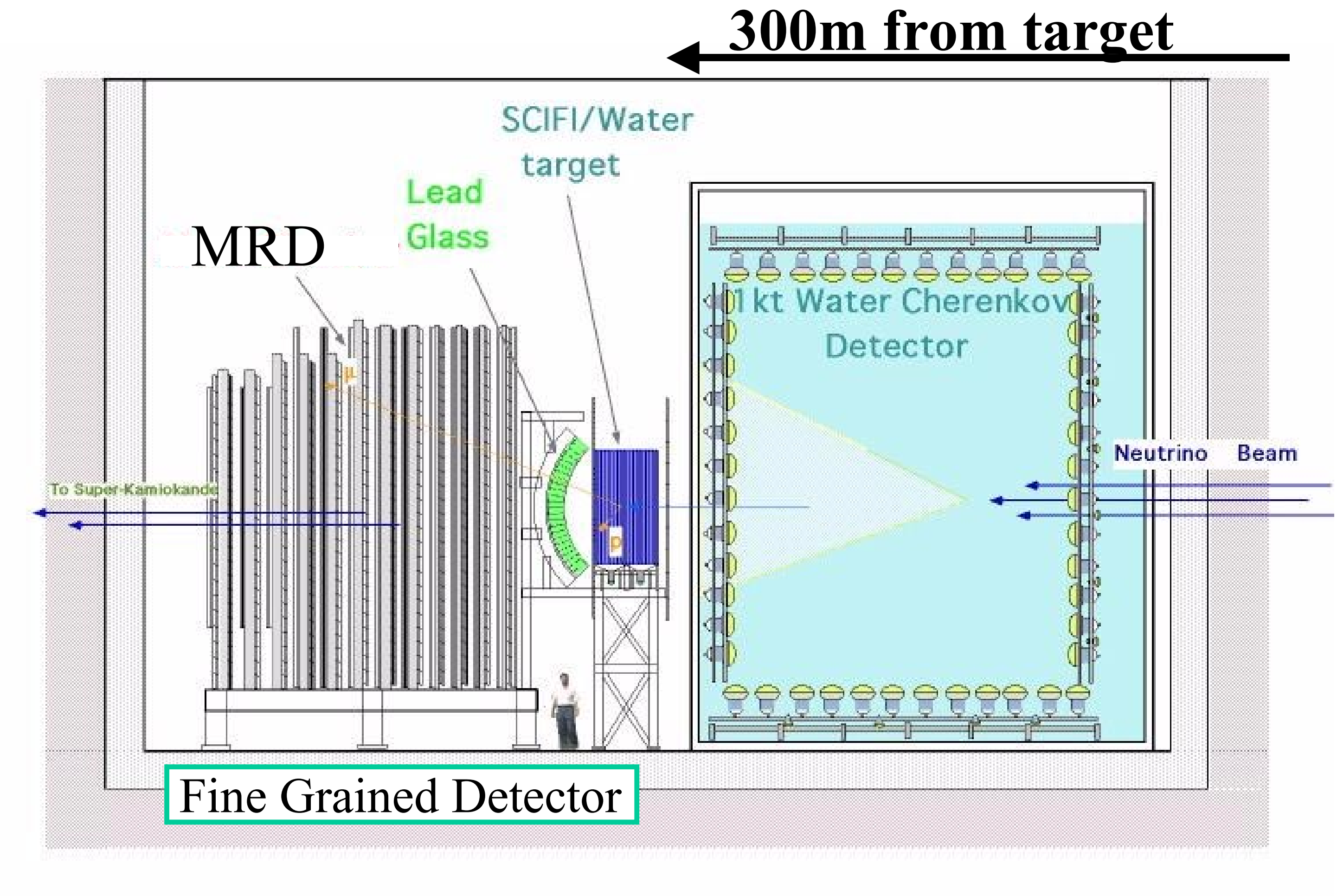
as a result of pion monitor

Gas Cherenkov detector



to avoid signal from 12GeV protons
→ insensitive to p_π<2GeV (E_ν<1GeV)

Front NeutrinoDetector(FD)



Purpose

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

1kt water Cherenkov detector

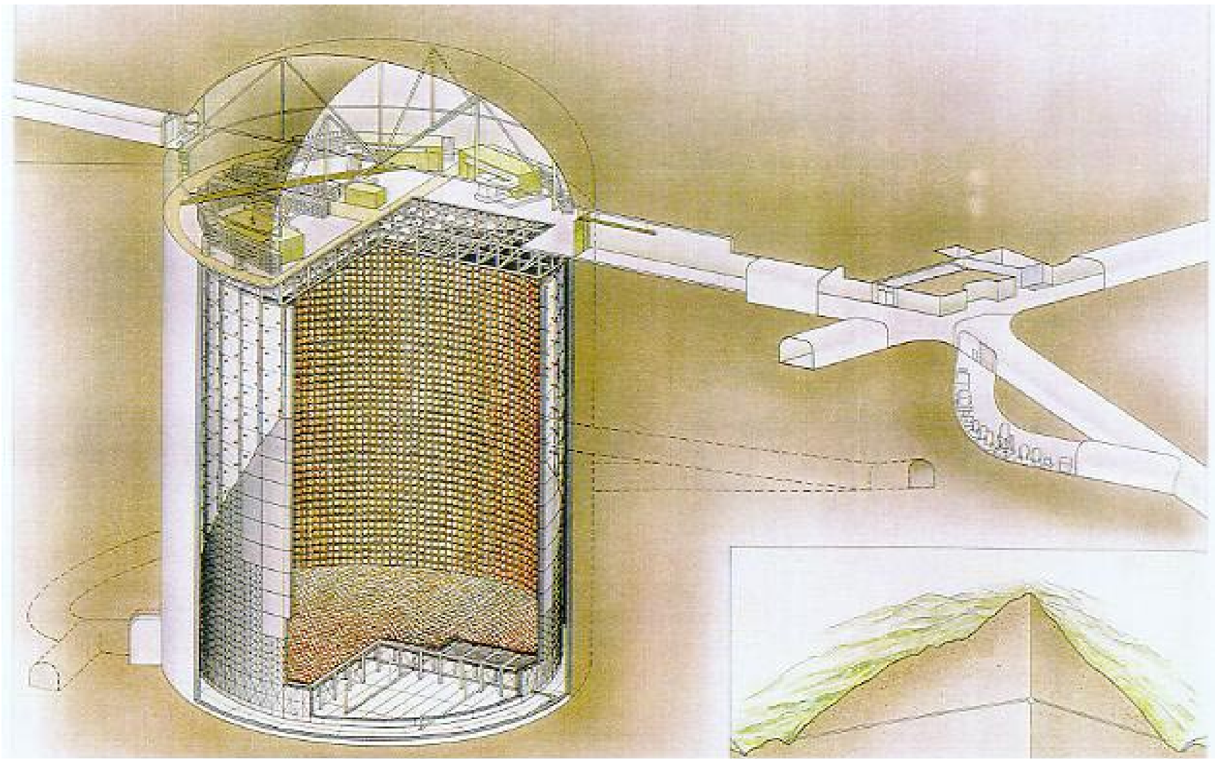
Scintillation Fiber Tracker(SFT): SF sheets+water(6cm)

Electromagnetic calorimeter : lead glass

Muon rande detector (MRD) : drift chamber+iron plates

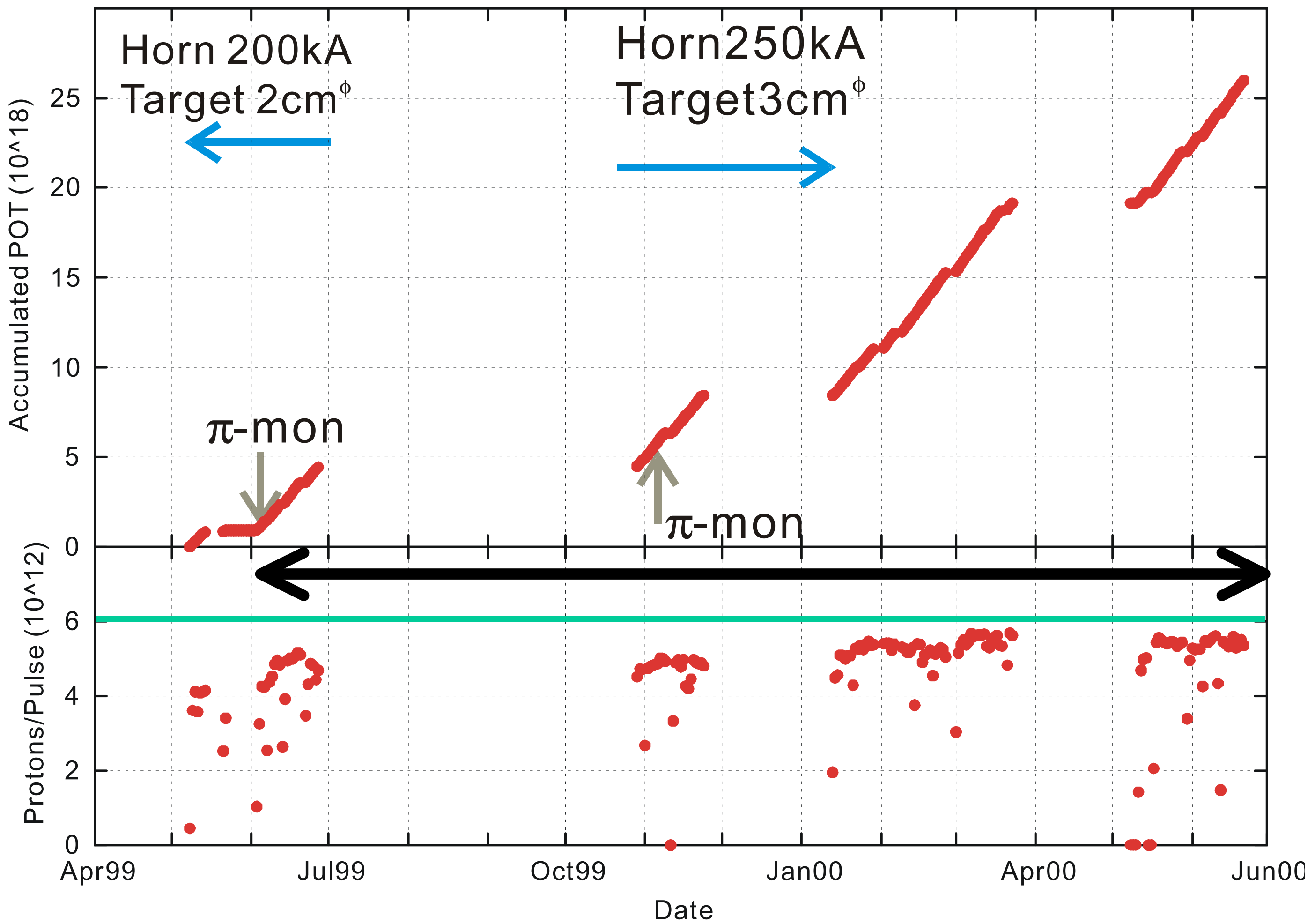
Far Detector

Super-Kamiokande
@Kamioka (250km from KEK)



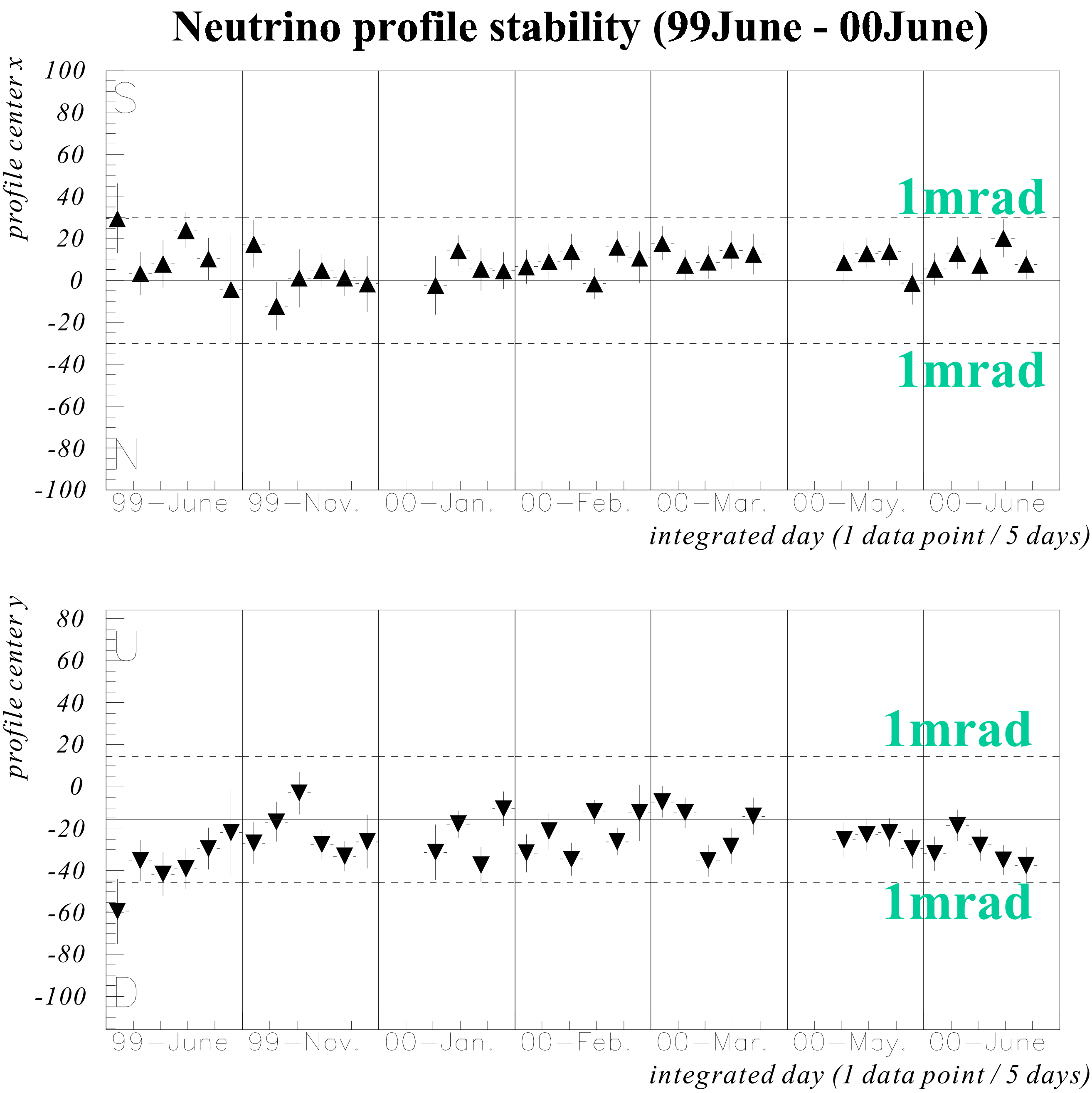
- 1000m underground @ Kamioka
- ~40m$^{\phi}$, ~40m high
- 50,000t Pure water as target
- 11146 PMTs in inner tank
- 22.5kt Fiducial Volume
- Outer detector (OD) :active VETO

Delivered Beam



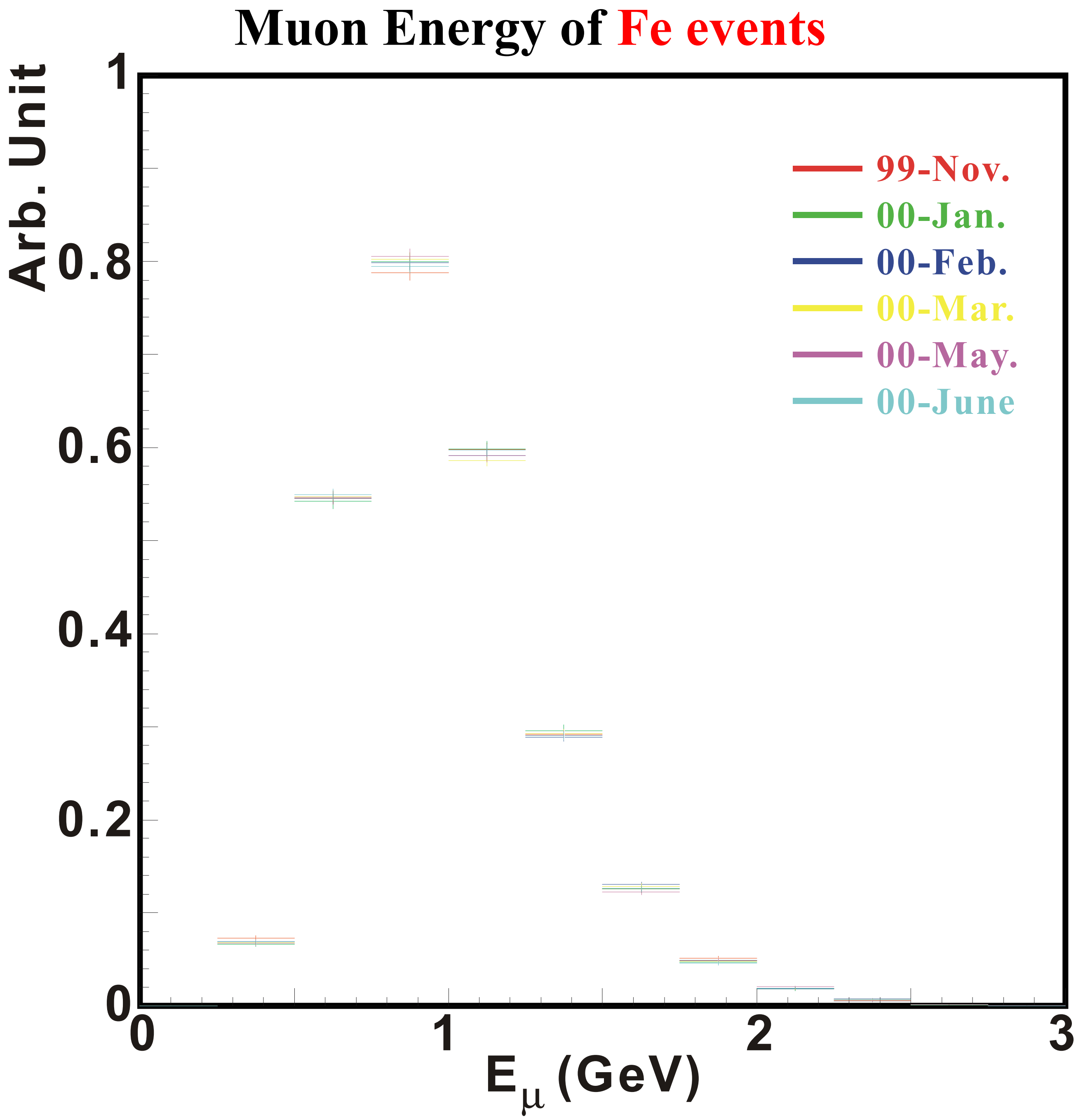
- Design Proton Int. 6×10^{12} protons/pulse almost achieved (5.5×10^{12})
- ~2.6×10^{19}POT delivered by the end of Jun. '00
- SK Live = **2.29×10^{19}** POT(Jun99-Jun00)

Stability of Profile Center (Fe event)



Stable within ±1mrad.

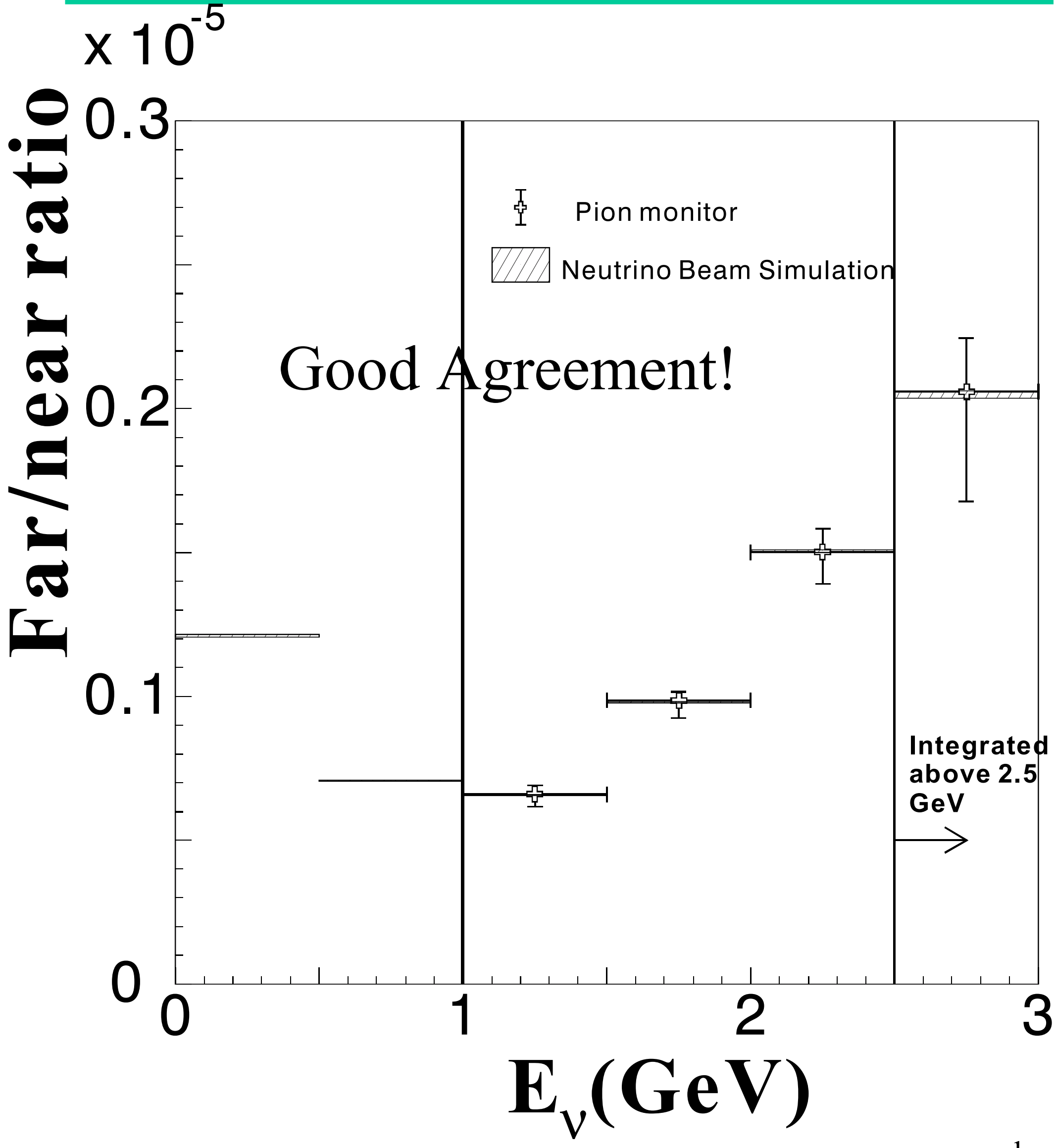
Stability of Spectrum



Stable within stat. error

Flux Ratio from Pion Monitor

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



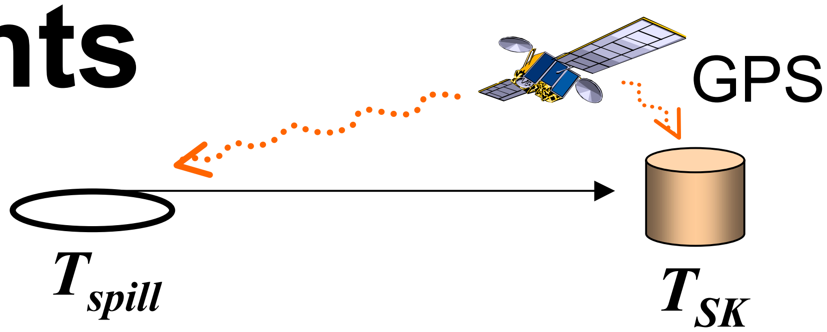
For integrated far/near ratio $\boldsymbol{R}$ in $N_{SK}^{\exp} = \frac{N_{FD}^{obs}}{\varepsilon_{FD}} \cdot R \cdot \varepsilon_{SK}$

use MC for central value

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

(for 1kt)

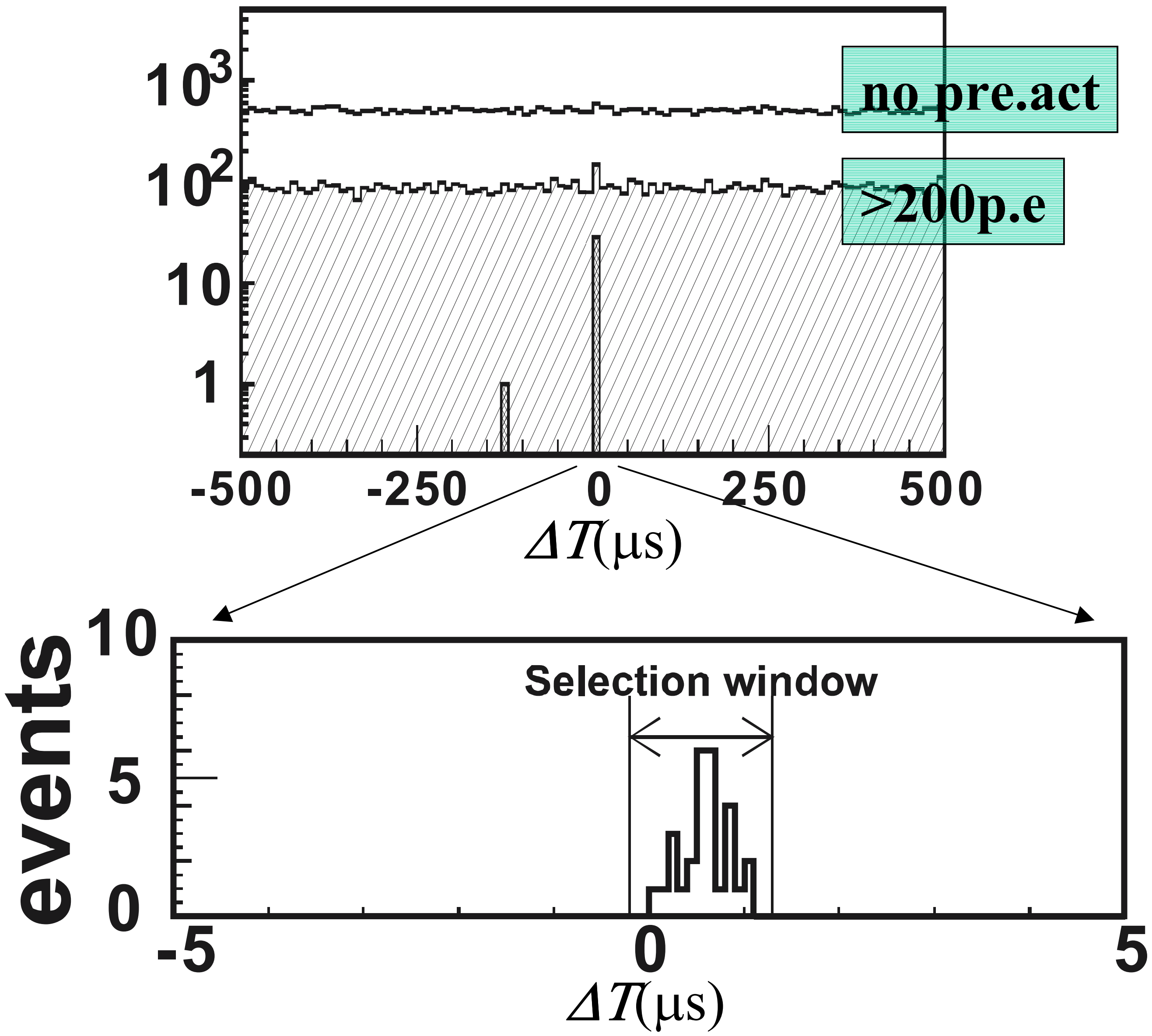
SK Events



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

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.

Expected # of SK events from 1kt detector

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

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

N_{kt}^{obs}	:	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)

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

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

: $N_{SK}^{\mathrm{exp}} = 37.2^{+4.6}_{-5.0}$ (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 $\Delta V/V$	$\pm 4\%$
Multi Event	$\pm 3\%$
Spectrum(eff.)	$\pm 2\%$
SK(mainly $\Delta V/V$)	$\pm 3\%$
Total	$^{+9}_{-10}\,\%$

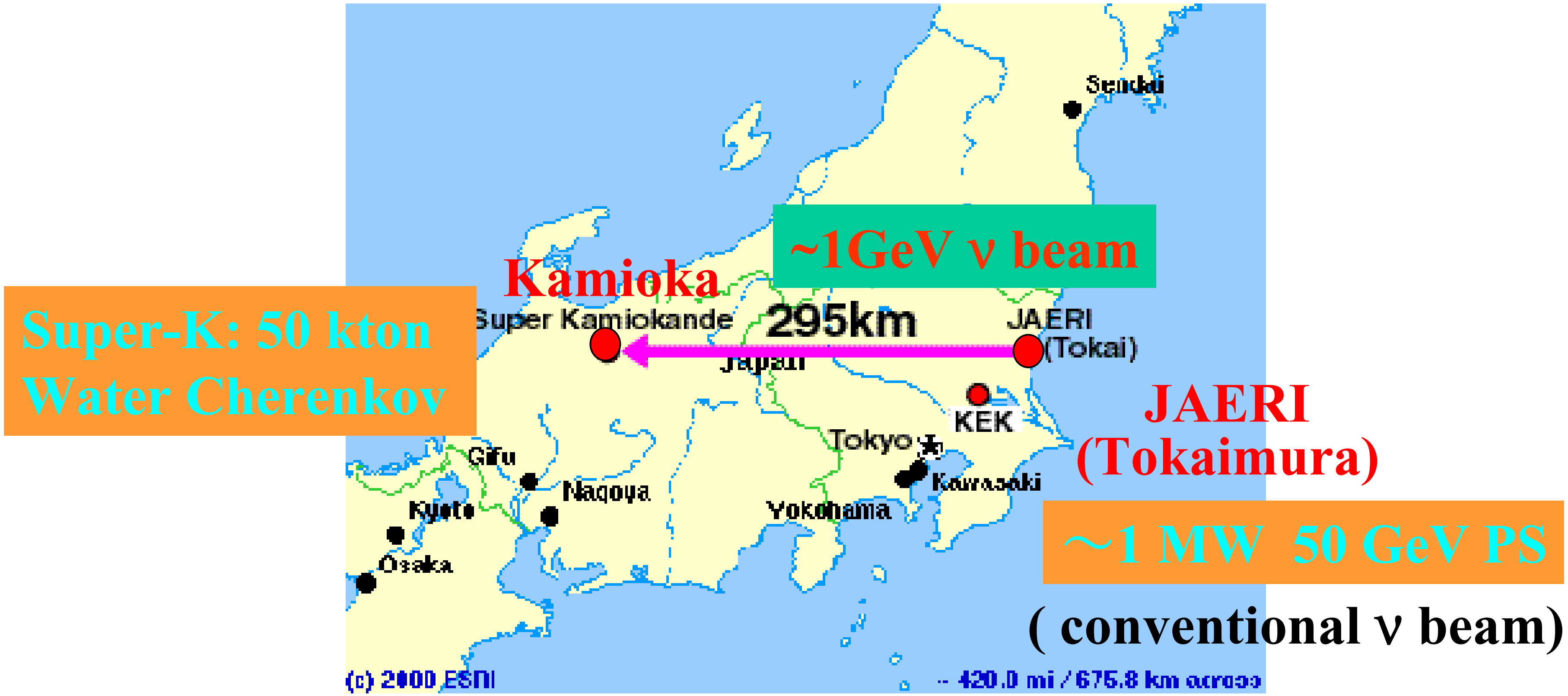
of observed and expected events @ SK

	Obs.	No Ocsi.
FC 22.5kt	28	$37.8 \; {}^{+3.5}_{-3.8}$
		(25)
1-ring	15	22.7 ± 3.2
		(13)
μ-like	14	20.8 ± 3.2
		(12)
e-like	1	1.9 ± 0.4
		(1.6)
multi ring	13	15.1 ± 2.5
		(11)

( ): w/ osc. $\Delta m^2 = 3 \times 10^{-3} eV^2$

Preliminary

Overview



- $\nu_\mu \rightarrow \nu_x$ disappearance
- $\nu_\mu \rightarrow \nu_e$ appearance
- NC measurement

JHF Neutrino Working Group

ICRR/Tokyo-KEK-Kobe-Kyoto-Tohoku-TRIUMF

Y. Itow, T. Kajita, K. Kaneyuki, M. Shiozawa, Y. Totsuka
(ICRR/Tokyo)
Y. Hayato, T. Ishii, T. Kobayashi, T. Maruyama, K. Nakamura,
Y. Obayashi, M. Sakuda (KEK)
S. Aoki, T.Hara, A. Suzuki (Kobe)
T. Nakaya, K. Nishikawa (Kyoto)
T. Hasegawa, K. Ishihara, A. Suzuki (Tohoku)
A.Konaka (TRIUMF, CANADA)

Dec.99: Working group formed.
Mar.00: Letter of Intent prepared (http://neutrino.kek.jp/jhfnu)
Now : Working to prepare a proposal

Physics motivation

1. **Test our current picture of 3 flavor neutrino oscillation**
   - Spectrum shape of ν_μ disappearance
     - Test exotic models (decay, extra dimensions,….)
   - Appearance of ν_e at the same Δm^2 as ν_μ disappearance
   - NC measurements
     - No additional "neutrino"?
2. **Precise measurement of Δm^2 and mixing angles (θ_{23}, θ_{13})**
   - mixing matrix in quark sector: well known
   - understanding of mixing in lepton sector
   - understanding of mass structure

     → hints on physics beyond the SM (GUTs,…)
3. **Discovery of ν_e appearance**

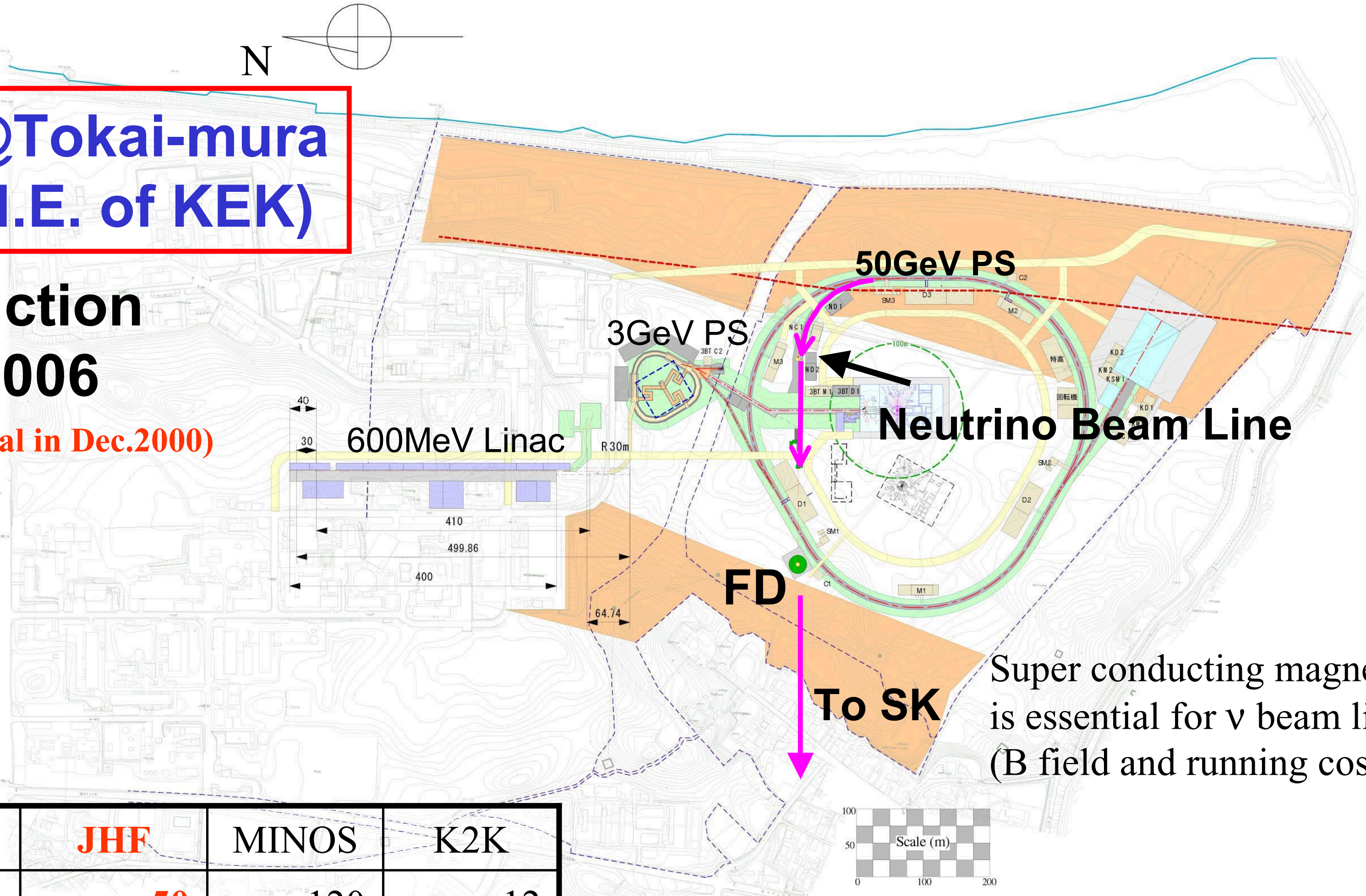
   → Open possibility to detect CPV effect in lepton sector

JHF project and neutrino beam line

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

Construction
2001～2006

(Expect approval in Dec.2000)



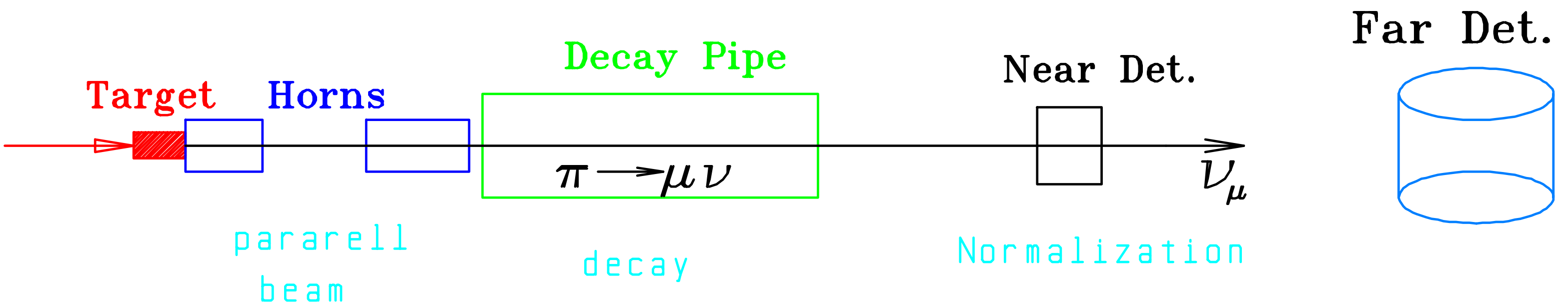
Super conducting magnet
is essential for ν beam line
(B field and running cost)

	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

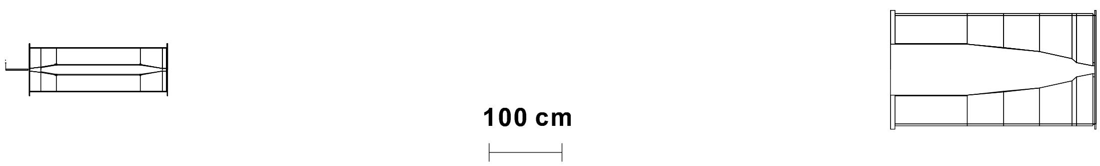
10^{21}POT(130day)≡ "1 year"

High intensity low energy ν beam

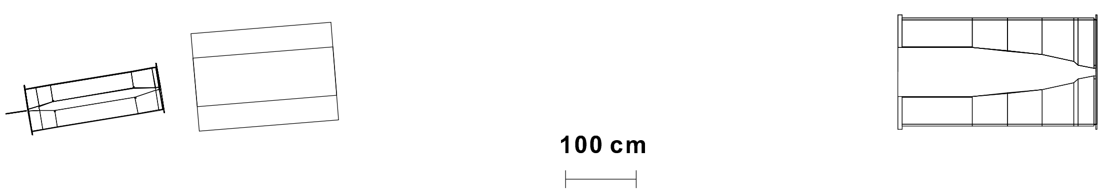
- Conventional ν_μ beam using horns



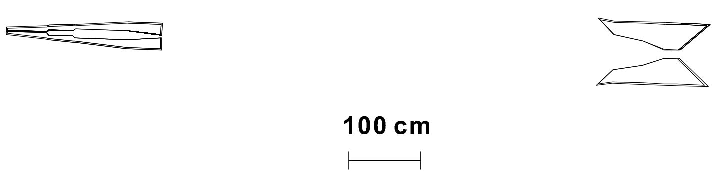
Wide band beam (similar to K2K, NUMI, CNGS)



Narrow band "dichromatic" beam



Off axis beam (ala BNL-E889 proposal)



- Critical points in the beam design

High intensity

Suppression of high energy tail (narrow band)

Suppression of ν_e contamination

Understanding the beam systematics (beam monitoring)

Three ν beams

Number of CC int. in SK

10^{21}POT～100days

◆**Wide Band Beam**

Intense

~4200int/22.5kt/yr

◆**Narrow Band Beam**

~830int/22.5kt/yr

(2GeV/c π)

well understood beam

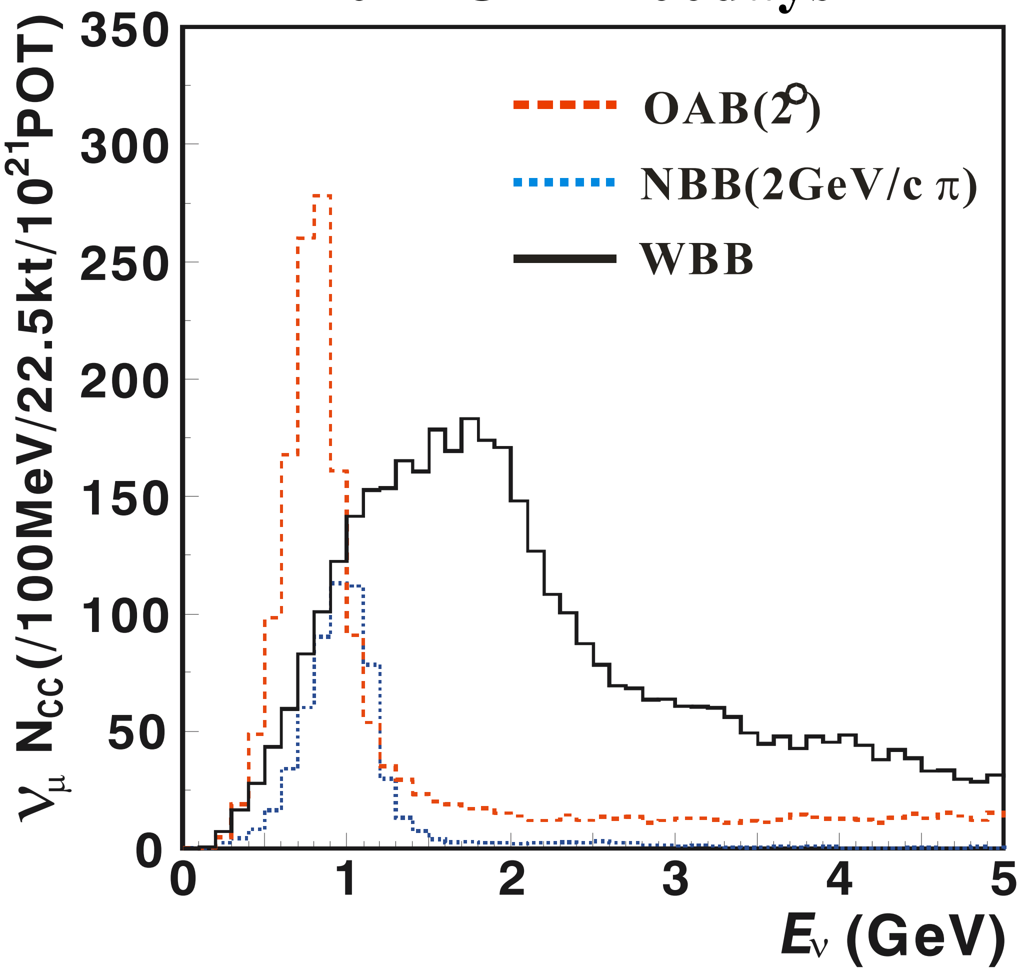
from monochromatic π

◆**Off Axis Beam**

~2200int/22.5kt/yr(2deg)

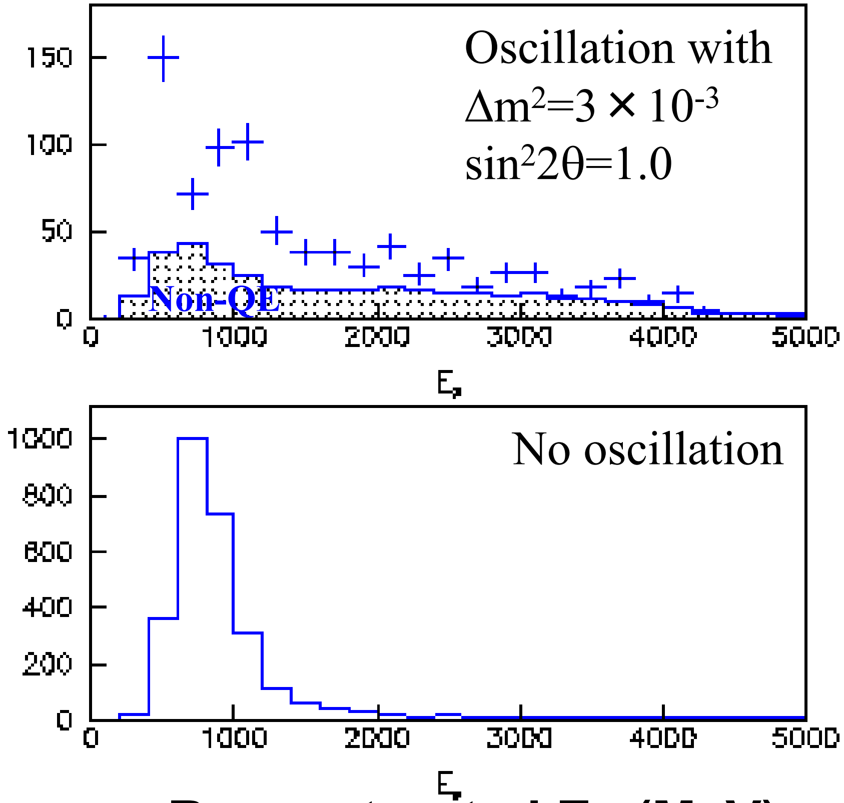
intense narrow band option

High energy tail



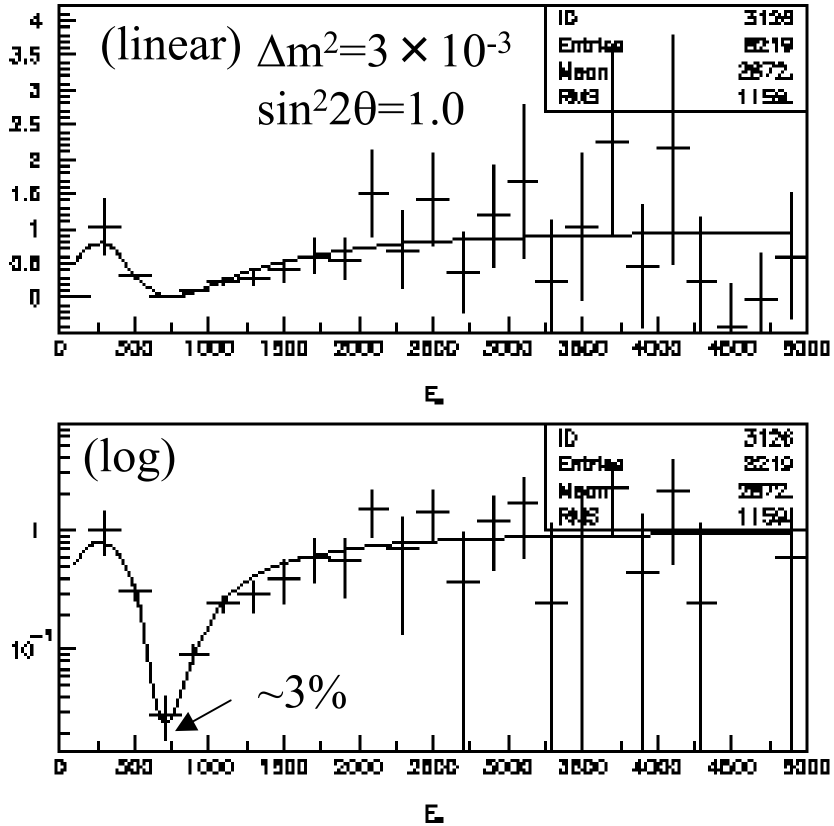
ν_μ disappearance

1ring FC μ-like



Reconstructed Eν (MeV)

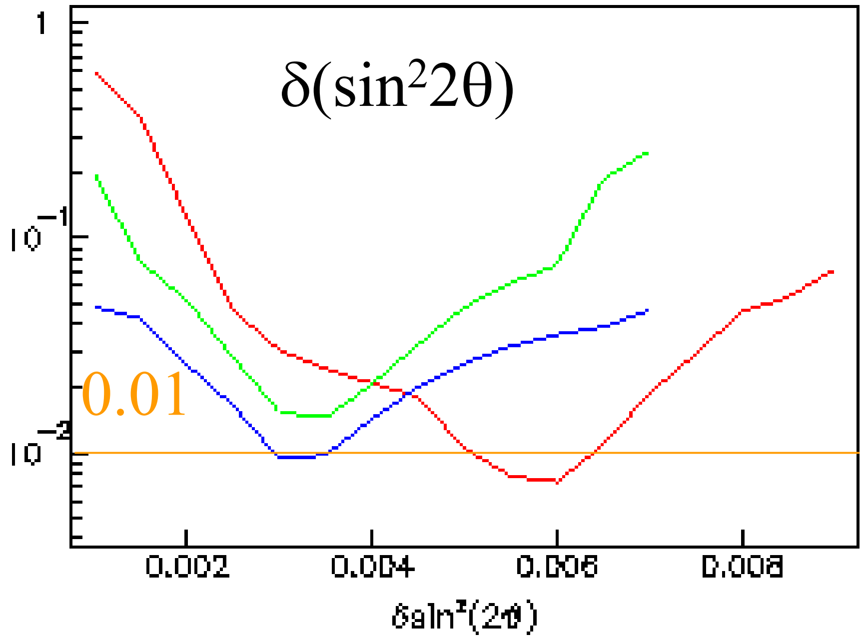
Ratio after BG subtraction

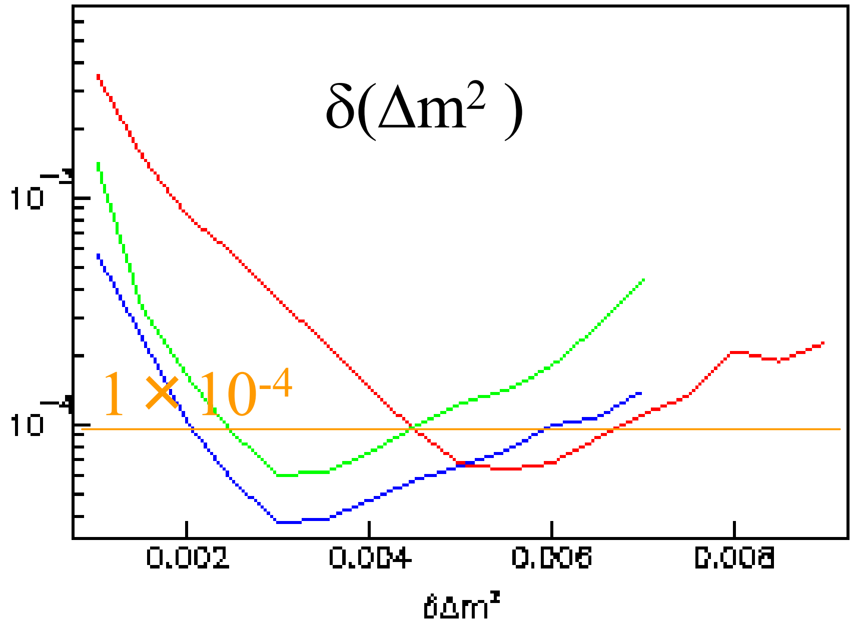


Fit with 1-$\sin^2 2\theta \cdot \sin^2(1.27\Delta m^2 L/E)$

5 years precision

NBB-3GeVπ, OAB-2degree, NBB-1.5GeVπ



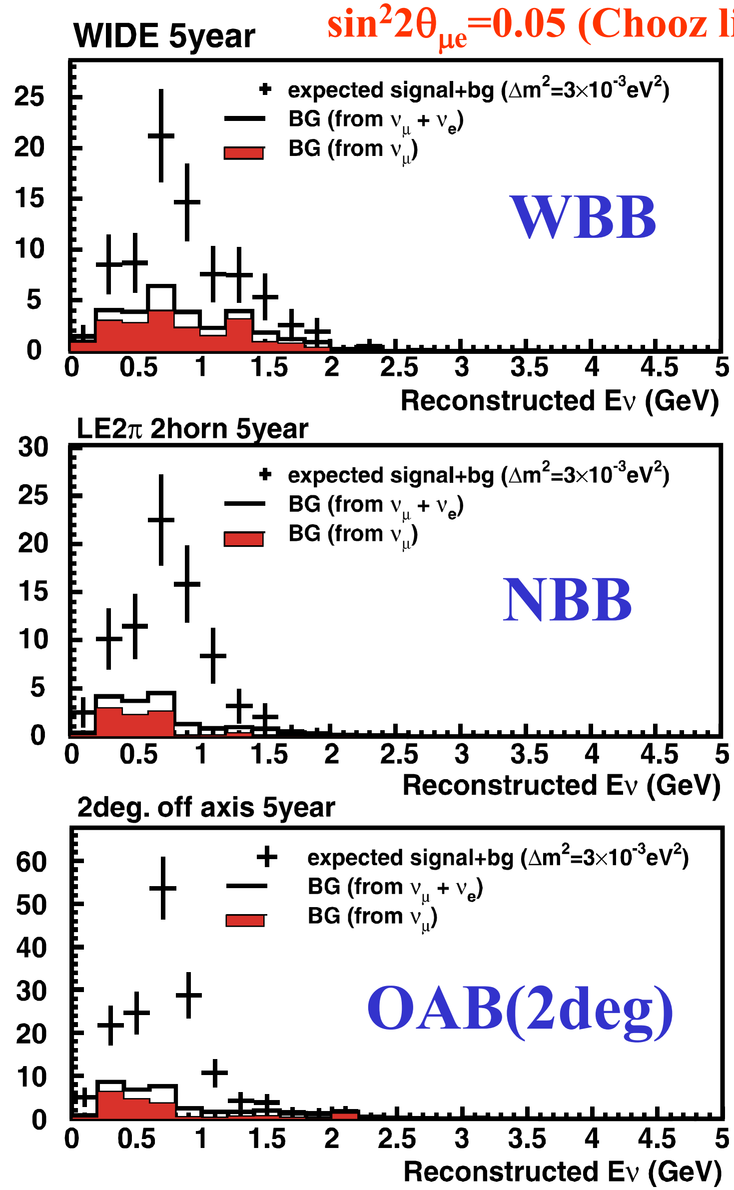


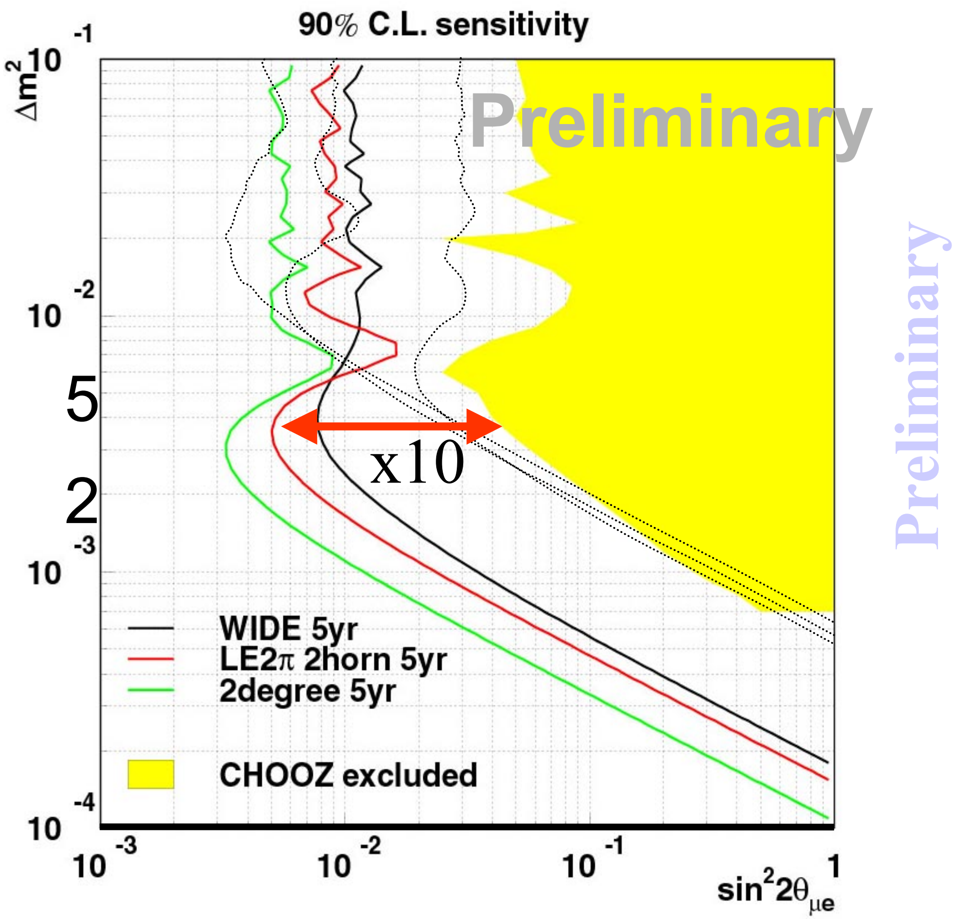
$\delta(\sin^2 2\theta) \sim 0.01$ in 5 years

$\delta(\Delta m^2) \quad \sim <1 \times 10^{-4}$ in 5 years

ν_e appearance

$\sin^2 2\theta_{\mu e}$=0.05 (Chooz limit)





Dashed lines: MINOS Ph2le, Ph2me, Ph2he from right

(A.Para, hep-ph/0005012)

Summary

K2K

- **2.29×10^{19}POT** @ SK from Jun '99 to Jun '00
- Neutrino beam is well under control
  - ➢ Direction: 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

$$\text{Expected}: 37.8^{+3.5}_{-3.8} \text{ (w/o osc.)}$$

- Experiment resumed **Jan. 2001**

JHF

- Low energy conventional ν_μ beam w/ MW 50GeV PS
- SK as far detector at L=295km
- E_ν tuned at osc. max.
- Great precision thanks to high intensity & large det.
  - ✓ $\delta\sin^2 2\theta_{23} \sim 0.01$
  - ✓ $\delta\Delta m_{23}^2 < 1 \times 10^{-4}\text{eV}^2$
  - ✓ $\sin^2 2\theta_{13} \sim 5 \times 10^{-3}$ (90% CL)
  - ✓ ν_s existence can be tested
- Design and R&D work have just been started.
- Expect data taking in 2006-7